



Asphalt Research Consortium

Annual Work Plan for Year 2 April 1, 2008 – March 31, 2009

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**RESEARCH PLAN FOR YEAR 2 OF FEDERAL HIGHWAY
ADMINISTRATION CONTRACT DTFH61-07-H-00009
“ASPHALT RESEARCH CONSORTIUM”**

INTRODUCTION

This document is the proposed Research Plan for Year 2 of the Federal Highway Administration (FHWA) Contract DTFH61-07-H-00009, the Asphalt Research Consortium (ARC). The Consortium is coordinated by Western Research Institute with partners Texas A&M University, the University of Wisconsin-Madison, the University of Nevada Reno, and Advanced Asphalt Technologies.

The Year 2 research plans are an extension of the Year 1 research plans and are grouped into seven areas, Moisture Damage, Fatigue, Engineered Paving Materials, Vehicle-Pavement Interaction, Validation, Technology Development, and Technology Transfer. In July 2007, the Consortium members received a set of written reviewer comments on the Year 1 Work Plan from FHWA Co-AOTR's Dr. Jack Youtcheff and Mr. Eric Weaver. Following the Introduction, the comments, as received from FHWA, are listed. Following the list of reviewer comments is the list of responses from the ARC.

The Year 1 Work Plan, with some amendment, was approved by the Co-AOTR's on July 19, 2007 and work commenced. In mid-December 2007, after discussions between the Consortium and the FHWA Co-AOTR's, it was decided to amend the performance year of the contract from January 1 – December 31 to April 1 – March 31. The change was agreed upon because it provides time for the Annual Work Plans to be reviewed by the three Expert Task Groups (ETG) which generally meet in the month of February. Therefore, the Year 2 Work Plans cover the time period of April 1, 2008 to March 31, 2009.

The format of the work plans follows the format that was presented in the Year 1 Work Plan with sections added for the progress during Year 1 and the plans for Year 2. Additionally, a Materials Selection Plan was prepared and is shown at the beginning of the Work Plan. The Moisture Damage and Fatigue areas contain work elements that are interrelated and thus will work together to advance the knowledge of mechanisms and models in these areas. In addition, there are some work elements that compliment one another by investigating a common principle using different methods. Using two different methods provides a check on one another so that the true significance and importance of each can be evaluated and related to performance properties. There are also examples of Modeling activities that compliment each other in a similar fashion. The Consortium members firmly believe that this approach makes the research more robust.

The research areas of Engineered Paving Materials, Vehicle-Pavement Interaction, and Validation generally contain work elements that are more “stand-alone” in nature but this doesn't mean that these work elements will operate independently because in most cases, at least two Consortium partners are teaming to conduct the work. These work elements will also provide

useful information to the other research activities in the Consortium and are designed to provide solutions to specific problems.

Finally, the areas of Technology Development and Technology Transfer are the areas where the research deliverables will get transmitted to the user community. The Technology Development area will take promising research developments and refine them into useful tools for engineers and technologists involved in the design, construction, and maintenance of flexible pavement systems. In the first year, six promising methods were identified and have been forwarded to the three ETG's for review. The Technology Transfer area will also transfer Consortium research findings to the asphalt community using the Consortium website, presentations, publications, and workshops.

The Asphalt Research Consortium members strongly believe that the proposed research is responsive to the needs of asphalt engineers and technologists, state DOT's, and supports the FHWA Strategic Goals and the Asphalt Pavement Road Map.

FHWA Feedback to the Asphalt Research Consortium on Year 1 Workplan.
July 12, 2007

Reviewer 1. 6/26/07

Comment 1. The plan, subplans, etc. are well thought out and well written. They seem to provide sufficient detail regarding the scope of work."

Comment 2. With respect to early technology development efforts/deliverables, the work plan states that these "will focus on products developed in past FHWA research studies completed by WRI." (p. 126) What about products developed out of other FHWA sponsored studies completed by others? My concern here is that we may overlook/neglect other significant works/developments. Specifically, I'm concerned with what seems to be predetermined test methods for study (e.g. moisture susceptibility). I have read some of the papers involving the WP and USD approaches and they seem viable and technically sound. However, I fear we may overlook other promising, more simplistic approaches.

Reviewer 2, Saturday, June 23, 2007

1) I still don't see the "Big Hairy Audacious Goals" clearly articulated in this workplan. I think that WRI's BHAG is to develop a chemical model for asphalt binders that will enable a priori design of the material rather than just evaluation of what comes out of the refinery ("Better Living--or at least roads--Through Chemistry"). Pauli's work plans are certainly along these lines. Some of the other work elements are a bit more tangential.

I think the ARC's BHAG, at least in the moisture/fatigue area, is to lay a solid foundation of material and other models that will support the next step of advance toward fully mechanistic pavement analysis (although I don't think the work plan spells it out this explicitly). The BHAGs for the grab bag of other topics in the ARC work plan are less well articulated.

2) I repeat my concern that the ARC not view permanent deformations as a "solved" problem. This may be the situation for Superpave and SMA mixes we are putting down today, but as we adjust mix designs to deal with fatigue, moisture damage, and other issues, it is likely that we will pay a price in terms of increased rutting in hot climates. Rutting is implicitly included in the viscoplastic component of the unified continuum model, but we must make sure that it doesn't slip off the table.

3) The management issue is still a question mark in my mind. At the last ETG, in response to my comments, Dallas described the overall management structure of advisory boards, annual meetings, etc. This is all fine, but my concerns are really more on the day-to-day management. There will be an awful lot of people working on an awful lot of separate topics/projects, and keeping everything coordinated, on track, and on topic with regard to the overall work plan will take serious day-to-day effort on the part of someone (perhaps many people). Will anyone at WRI/ARC be 100% devoted to overall management of the project(s)-- i.e., zero technical role?

Comment [e1]: Clarify the overall management resources available to ensure coordination among ARC partners and their activities

ARC STRATEGIC PLAN

I realize that the strategic plan is a high-level mission statement and that many of the details will be fleshed out in the work plans. I therefore defer most of my comments to the work plans themselves. However, there are a few points worth mentioning here:

1. The key deliverable under the moisture damage area is the “prediction of moisture damage susceptibility.” I think this needs to be clarified and/or expanded. I believe that the researchers do not plan to simply predict susceptibility—e.g., develop a screening test to identify mixes with potential moisture problems—but also to predict the consequences that moisture has on the fundamental properties and behavior of the mix—e.g., on stiffness, fatigue and permanent deformation resistance, etc.
2. I understand the researchers major focus on fatigue, but this does seem to contradict other lines of research by FHWA and others directed toward perpetual pavement designs. If we are designing pavements that do not fail in fatigue (e.g., by limiting strains below the endurance limit, if this in fact exists), then why do we need sophisticated material characterization and prediction models?

Comment [e2]: Please clarify how the prediction of moisture susceptibility relates to the overall assessment of pavement damage.

Of course, perpetual pavement designs really address only the classical bottom-up fatigue. There will still be the potential for top-down fatigue and reflection cracking (also a form of fatigue, albeit more localized and often lower cycle). It is unclear on which fatigue mode the researchers plan to, or alternatively whether they think their fatigue approach will be a “one size fits all” system that will apply equally well to all of the modes.

Comment [e3]: Please explain whether the unified model addresses this issue.

Regarding top-down fatigue cracking, it is likely that changes in mix design required to reduce this distress may have the simultaneous detrimental effect of increasing the rutting potential. The researchers in past meetings have justified not considering rutting because this problem was solved by Superpave. However, I think what we may have is a swinging pendulum: the dry, low rutting Superpave mixes with their greater tendency toward durability and surface cracking problems may represent one end of the arc, and as we address the durability and surface cracking problem we will inevitably swing back toward more rutting issues. I am not proposing that the researchers add rutting to their portfolio, which is already quite full, but simply to be more explicitly cognizant of these interactions.

3. The scope of the engineered pavement materials area seems a bit diffuse, not crisply defined, and potentially very large. The list of deliverables seems unrealistically ambitious.
4. The friction topics in the vehicle-pavement interaction area seem misplaced. Do we really need to analyze the vehicle-pavement interaction to estimate the maximum shear applied to the surface? Emergency braking would seem to be the controlling factor, with the implications for friction then being “more is always better.” Friction

Comment [e4]: Deliverables included in the workplans are expected as part of the agreement.

seems more appropriately located under the engineered materials area. Also, the reference to noise seems tacked on as an afterthought.

5. One of the stated objectives in the validation area is to “Assist State DOT’s with the implementation of the MEPDG. Validation through MEPDG Sites and Revisions of the MEPDG Asphalt Materials Models.” Is this really an appropriate area of effort for ARC? This seems at odds with the overall consortium focus on fundamental research.

ARC FIRST YEAR WORK PLAN

I congratulate the authors of this work plan, especially the moisture damage and fatigue sections, for their excellent job in laying out not just the first year work plan but also the context and schedule for the entire five year duration with associated levels of effort for each major work element. It is clear that the researchers have put much thought into where they want to be at the end of the project and the necessary path to reach this destination.

Specific comments and questions are as follows:

1. The fourth objective in the moisture program area addresses evaluation of moisture susceptibility of mixes. I find the term “susceptibility” to be ambiguous here, in that in many contexts it is interpreted simply as screening for mixtures with a high potential for stripping (e.g., AASHTO T283). I think the researchers are interested in more than this, and the objective should be clarified as development and evaluation of models for the impact of moisture damage on the fundamental engineering properties and behavior of the mixture.
2. In the moisture program area, the amount of time (2 years) and effort (\$300K) devoted to 4a-3 “Unified Continuum Model” seems insufficient. Development and validation of such a model will be a major effort. However, since this effort spans both the moisture and fatigue program areas, perhaps some of the effort is lodged under fatigue? The fatigue area does seem to have appropriate resources for this type of effort: 5 years and \$5.45M for unified model plus same time/effort for the micromechanics model. The amount of effort for final model validation (Work Element 53d in the fatigue area) also seems light: the 3 year duration is obviously constrained by the schedule of the preceding work tasks, but \$325K may be insufficient—depends how much field work, additional material testing, etc. will be required during the validation effort.
3. In the fatigue program area, Work Element F3d on calibration and validation: (a) Early on the researchers should confirm sufficient availability of materials for all of the proposed sites. Experience on NCHRP 9-30A suggests that less material than expected is also the case. Specifically, I think that some of the modified binders from the ALF sections may be in short supply. (b) My understanding is that the WRI field sections, which were designed to evaluate the interaction between environment and

Comment [e5]: Please provide the requested clarification

Comment [e6]: Agreed, it is likely that future work plans may need to include more effort in this area.

Comment [e7]: Agreed, we discussed this at the post-award meeting. Please provide a proposal for discussion and come to an agreement. We also need a formal process for material collection, labeling, tracking, transport and storage.

asphalt source, have not yet exhibited any significant load related distresses. If this is true, this makes them of relatively small utility for validation.

4. Does objective 3 in the engineered pavement materials area overlap with other work already currently underway by others (e.g., guidelines for warm mix asphalt, high RAP mixes)?
5. The engineered pavement materials area is a very large basket of only loosely connected topics. Some of the individual areas are quite sizeable (\$1.7M for high-RAP mixes), and overall this area represents about 25% of the total project effort. Given the major commitments of many of the consortium members on other program areas and WRI commitments in their own separate fundamental materials contract, I question whether there is sufficient manpower within the consortium to accomplish all of these tasks. FHWA should closely examine the proposed manpower levels and other commitments (e.g., teaching for University researchers) over the life of the project.
6. Related to the preceding comment, with so many tasks running concurrently—some loosely connected, some more tightly overwoven—project management skills will be as critical as technical expertise. There is nothing in the work plan (in either work plan, in fact) that addresses project management. Presumably FHWA has this for their internal review.
7. My comment 3a above in this section is relevant to the entire validation program area. Experience from NCHRP 1-37A, 9-30A, and other projects is that there are not large numbers of existing sites available that have adequate stockpiles of materials and significant levels of distress. Constructing new validation sections is not feasible, in that they will not have accumulated sufficient distresses to be of value in this project. Validation using APT sections may need to be relied upon very heavily.
8. The description of the vehicle-pavement interaction area is very thin. No budget is estimated for category VP3 Modeling. It is therefore difficult to ascertain what new developments are planned in this area beyond what is already known.

Comment [e8]: The relation to other relevant work shall be clarified.

Comment [e9]: Future workplans will require further clarification on how the work will be distributed and accomplished

Comment [e10]: Same as e1

Comment [e11]: Future workplans should provide explanation on how lack of performance within the agreement performance period will be handled – and alternatives for future monitoring

The amount of funds allocated to the technology development and technology transfer elements seems very inadequate. By my calculations, the combined budgets for these areas (~\$1.5M) is only 6.5% of the total project budget (\$22.7M). Is FHWA planning to pick up the development and technology transfer activities after the end of this project, similar to what it did after SHRP?

Reviewer 3, 6/24/2007

Consortium Work Plan

Coupling of fatigue with aging and with moisture damage is an excellent approach. Although not thought to be caused by load, block cracking is the primary distress from aging. Since cracking is induced by stress, regardless of origin, it would be very helpful if the research plan could include block cracking as well as fatigue cracking.

Moisture Damage:

- I am glad to see the emphasis the work plan places on recent work by Niki Kringos and Tom Scarpas. That model clearly differentiates mastic damage caused by flow of water through the mix under pressure from debonding at the asphalt-aggregate interface. AASHTO T-283 seems to capture debonding, but only saturated wheel-tracking tests like Hamburg seem to capture the mastic damage. This second damage mechanism, which explains deleterious effects of clay, reemulsification of PPA/amine modified asphalts, and other mastic failures needs priority attention, because these failures occur even though mixes pass AASHTO T-283.
- I would recommend rewriting this task to place much more emphasis on the mastic failure mechanism. Suggest you consult with Tom Scarpas and Niki Kringos for ideas. In particular, look at clay contamination of mineral fillers, and PPA/amine additive blends with about 1% PPA and 0.5% amine antistripping. Kansas also used a limestone containing quartzite on an SPS project near Greensburg that has some interesting moisture implications.

Aging

- Task F1c-1: I just completed a state-of-the-art review of asphalt durability for on AAPT 05-07 – Non-load related airport pavement distresses. It should be quite relevant to this task. I will send it once it receives approval from PI Doug Hanson and Project Manager Monte Symons.
- Task F1c-4: Critical task from perspectives of pavement preservation, fog seals, and recycling. It would be very helpful if this task could evaluate rejuvenators as added to aged asphalt to restore initial relaxation/fracture properties. If possible, we need mechanical mixture tests which can determine strength, relaxation, and fracture properties with thin specimens so we can characterize aging very near the pavement surface.

Task E:

- Most tasks in this section are well defined and very much needed.
- Task E1b-2: Thin Films
 - What is the budget for this task? Treat as idea project, with limited funds for exploratory work. Evaluate progress and need before further funding.
- Task E1c-1: Warm Mixes

- Many of these work elements sound much like those proposed for a similar NCHRP Project led by AAT. How will these two projects be coordinated to minimize any duplication?
 - Task E1c-2: Cold mix volumetric design (Note: Task incorrectly numbered as E1b-2)
 - Cold mix design process is needed. What work will be done to classify emulsion residues using SuperPave tools? In particular, high float mixing grade emulsion residues will be strongly gelled, exhibiting a yield stress and highly non-newtonian behavior under shear. This subject needs to be dealt with early in the project for high float anionic emulsions.
 - Task E2-b: Use of RAP
 - Please put a heavy emphasis on the relaxation and fracture properties of the binder when RAP is blended with virgin asphalt. Any negative effects will show up in fatigue and/or low temperature thermal or block cracking, not rutting and moisture damage. Don't study the wrong distress mechanisms!
-

Comment [T12]: Please provide clarification in the workplan as requested

Reviewer 4,

6/21/2007

- 1) Geosynthetic uses in pavement applications have tremendously increased in state Dot's work across the nation, while design procedure is not well established. Therefore, appropriate pavement modeling and design with Geosynthetic need to be addressed.
- 2) Asphaltic concrete pavements are non-fading memory materials, it is not clear how the chemical modeling and atomic structure analysis will capture the stress history?
- 3) Craziing zones is generally used for crack initiation when brittle fracture condition prevails, while this is true for pavement at very low temperatures and extremely fast moving traffic loading, it is not clear how it can be used to model crack initiation in ductile or time dependent fracture situation (Creep- Fatigue interactions).
- 4) Visual index for each of the addressed problem can be very helpful to adopt consistent terminology, an example of such visual index is shown below.

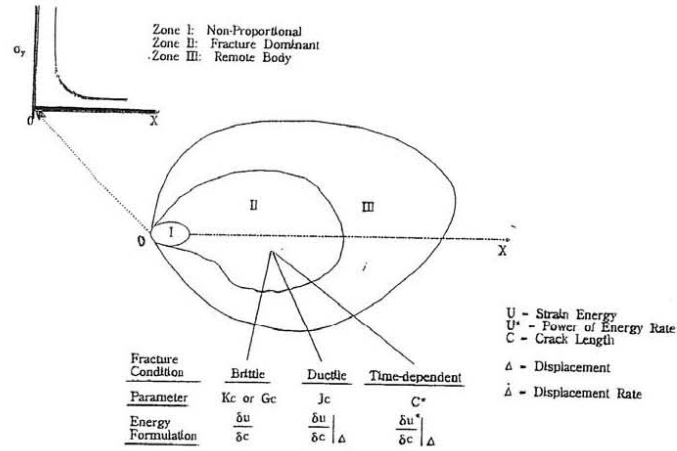


Figure 1 Visual Index of Fracture Mechanics Criteria
(After Abdulshafi ASTM STP 1147)

Fatigue

1. The controlled stress (load?)/controlled strain (stroke?) setup for testing is not based on **consensus** among researchers for thick/thin pavement sections but rather based on plane stress/plane strain boundary value application. **Page 25**
2. No description is presented for the proposed predictive models that rely on the fundamental theories of integrating continuum /fracture/micro/macro mechanics. **Page 26**

Comment [T13]: Specifically describe the process for model testing and selection
3. It is not clear what the authors mean with “**viscoplastic strain**” in the last sentence at the end of **Page 33**.

Comment [T14]: Please clarify
4. The authors use constitutive laws with Damage models trying to develop a unified model that can encompass both. More detailed discussion is needed to explain how the mathematical/ statistical principles will be used to achieve that especially when dealing to merge micromechanics with macro mechanics. **Page 50**

Comment [T15]: Same as comment T17
5. It must be realized that there are no **elastic/ viscoplastic /... materials!!** These are behavior of the examined material under specific condition.
6. The authors ignored that when damage occurs, the damage zone controls material behavior and continuum mechanics approach may become inapplicable.

Comment [T16]: Describe how Richard Kim’s work plans to address this issue.
7. A unified continuum model as suggested in **Page 50** is rather ambiguous.
 The authors ignored the fact that in order to relate and bridge the gap between micromechanics and macro mechanics models, the Unified Model need to be based on more recent advanced mathematical models such as the **String Theory** and the **number of axis** to be used must include **more than the traditional four axes (x, y, z, and t)**.

Comment [T17]: Same as other comments, this requires significant clarification
8. The authors’ tests of hypotheses are not defined or for that matter the design of experiment, only the objectives to be achieved are presented. The proposal should be expected to have a much more refined and well thought-out plan to arrive at a meaningful outcomes, tools, and solutions.

Comment [T18]: Take a close look at each hypothesis to ensure that it meets criteria of the scientific method

Reviewer 5, 6/21/2007

On the strategic plan...

- Fatigue Damage - [TXDOT did a research project with TTI on Fatigue damage. The Hypothesis presented was tested. My concern no need to repeat work already done.]
- Comment [T19]:** How is this work different from that done previously? Please provide clarification on this point in the workplan

Engineered Pavement Materials - How does this work coordinate or plan with the ongoing NCHRP project on warm mix and the upcoming NCHRP projects on the use of RAP and warm mix ?

Comment [T20]: Provide clarification on this point in the workplan

Vehicle Pavement Interaction – Predicting effect of dynamic loads on pavement response
Several models already exist? Will the new models be better than the existing models?

Comment [e21]: Clarify how the proposed models are an improvement over existing ones.

Skid resistance and Friction are more suitable topics under Engineered Materials not Vehicle Pavement Interaction.

Validation - The NCAT test track is a good source for validation

Reviewer 6

New moisture damage test: The pull off test has shown some utility in measuring moisture damage. The proposed DSR test seems to be a variation, we are going to torque the sample instead of pulling it. I am not an expert but I wonder how will the aggregate slices be prepared? We have done some preparation of 1/4 inch thick slices for Audrey Copeland's work and it is not at all easy to do. It is especially difficult to maintaining the two faces of the slice exactly parallel. A prerequisite for the DSR is that the plates are parallel and the gap between them precisely known.

How will texture of the cut surface of the aggregate affect the results?

How representative of the aggregate in the mix will the sample be since it is a slice cut from a large piece of aggregate?

Would a DOT ever be able to run such a test?

DSRs are also \$40,000 each.

Use of AFM (Atomic Force Microscopy) – what does this add to the work being done at Texas A&M on surface energy?

Oxidation of polymer modified binders – It has been known for many years that the diene double bond in SBS polymer is readily oxidized and would be expected to lead to a reduction in elastic properties. Why are we looking at this?

Comment [T22]: Describe what is anticipated in advancing the PM aging model.

Warm mix – A lot of work is being done here and at NCAT. The NCAT work is of course sponsored by NAPA. Are we repeating what they are doing?

Comment [T23]: Please include relevance to other work in the workplan.

Why is there a section headed nanotechnology? Is that an FHWA focus issue?

I am not sure that phosphoric acid research should be Federally funded. This is a commercial product, as is Sasobit for warm mix, and the producers should pay for the research. Until the current work at TFHRC is finished, and a recommendation to use it or not, it is premature for WRI to research it further and investigate such esoteric things as the chemical mechanism of its action for instance. We are due to finish our study at the end of this year. Perhaps we should revisit this issue then

Comment [e24]: Describe the coordination of your work with the activities of FHWA.

Reviewer 7 – 6/29/2007

Overall Comments:

The research plans for moisture and fatigue damage are coherent, detailed and compatible with the FHWA vision for advanced pavement material characterization. The level of analysis for fatigue damage is understandably more advanced than that of moisture damage. The plan for engineered materials is more empirical (less fundamental) in nature than those for moisture and fatigue damage, in terms of both characterization and modeling. It would be useful to seek better linkages between these areas. This could be done by phasing the latter area behind the more fundamental work being done at TAM/TTI. The plan for vehicle-pavement interaction is weak, and disconnected from the rest of the program areas. It does not offer in its present form a realistic solution for incorporating the essential elements proposed in the damage modeling presented under the first two program areas. It is therefore recommended that a more detailed and realistic plan for this program area be developed within the first year of the 5-year study. In this regard, the workshop on super singles should be used as a starting point for an in-depth discussion of a more realistic strategy for incorporating vehicle-pavement interaction and tire-pavement interaction in the framework of advanced mechanistic modeling of asphalt pavement response and damage evolution. The plan for validation is reasonable, although it lacks some details/specifics about the way the validation exercise would be undertaken, with more explicit linkages (in terms of both input parameters and output/distress development) with the four research program areas.

Comment [e25]: Please offer some response to this recommendation, as we feel that it has merit.

Additional Comments by Program Area:

PROGRAM AREA: MOISTURE DAMAGE

Under 'deliverables', there is a discussion about model development to predict performance, but it is not clear how such model will be incorporated in a 'comprehensive' structural response and material damage model.

PROGRAM AREA: FATIGUE

More details need to be provided for the structural model. There is mention of the NCSU structural model; however, it is my understanding that this model is an axisymmetric FEM model that uses simple loading conditions (circular disk loads). Such model would not enable the full incorporation of the damage models proposed under moisture and fatigue damage.

PROGRAM AREA: ENGINEERED MATERIALS

While the plan is rational and implementable, it presents some weaknesses; notably, the methods proposed are more empirical (less fundamental) in nature, and do not appear to be compatible with the work proposed under moisture damage and fatigue damage. It is recommended that the research undertaken under this program area should take better advantage of the developments to be achieved in the preceding program areas (fundamental material characterization and mechanistic damage modeling).

PROGRAM AREA: VEHICLE-PAVEMENT INTERACTION

1. The proposed dynamic UNR model (3DMOVE) is not compatible with the damage prediction models proposed under fatigue and moisture, and therefore is not suitable for incorporating such advanced models. Using a 'finite layer' model, it will not be possible to model non-linear, inelastic material behavior and the heterogeneous nature of pavement materials. Instead, it would be more appropriate to look into 3-D FEM, or better yet multi-scale modeling that would include incorporating multiple modeling zones using different techniques within each zone and providing transition zones connecting the different zones. Examples of such modeling techniques would be micromechanics-based discrete/distinct element or BEM in the immediate vicinity of the tires, FEM in the intermediate zone and BEM and continuum mechanics in the far field.
2. The discussion in this area implies the assumption of one-way interaction; i.e., assuming the pavement profile as a rigid (rough) surface in order to predict the dynamic truck axle loads; then inputting the dynamic load histories in the pavement response model to calculate the response. While this assumption (decoupling the truck from the pavement) is valid for calculating the 'global' response that would be needed within the framework on standard mechanistic-Empirical (mE) methodology, it may not be appropriate for a more detailed, Mechanistic-empirical (Me) damage prediction-oriented modeling framework. It is recommended that a two-way interaction between tires and pavement be envisioned, instead. This would entail modeling both tire and pavement using FEM so that tire compliance is allowed.
3. It is not clear what is meant by 'database' under this task.
4. For the part concerned with noise and friction, it is not clear whether modeling of tire-pavement surface interaction will be done.
5. Concerning the workshop, it is not clear what the workshop agenda will be. Perhaps, it would be useful to enlarge the focus of the workshop to include the topic of tire-pavement interaction (instead of just focusing on super singles) and comprehensive structural modeling that would enable incorporating all pertinent factors: dynamic (vibrating) moving loads; two-way tire-pavement interaction; 3-D tire pavement stresses; non-linear, inelastic material modeling to enable mechanistic damage prediction within the framework of 3-D FEM, DEM, BEM and other numerical approaches; and use of sub-regions for the near field, intermediate zone and far field.

Comment [T26]: Please clarify the purpose and objectives of the workshop.

PROGRAM AREA: VALIDATION

1. It would be useful to envision using more advanced NDT technology to better characterize spatial variation of material deficiencies in the field and localized, early damage detection.
2. Incorporate the assessment of variability of pavement materials in the field and corresponding localized material deterioration.
3. Within the framework of vehicle-pavement interaction, it would be very useful to validate the concept of “weak” and “hot” spots within pavement sections, which would lead to accelerated pavement deterioration in localized areas:
 - a. “weak” = localized material weakness; moisture issues; compaction issues; segregation; etc.
 - b. “hot” = concentration of roughness generated dynamic loads (95th percentile) and repeatability of dynamic load traces with mixed traffic (truck) population.
4. Under M-E PDG implementation to design, investigate the contribution to damage from multiple wheel and axle configurations. The current M-E PDG procedure uses simplified approaches that treat the moving axles as stationary, quasi-static loads. Research by this reviewer points to the fact that such simplified approach may underestimate damage contribution from multiple axle combinations (tandem, tridem).

Comment [T27]: Will spatial variability be included in the ARC experimental matrix?

Reviewer 8 – 6/22/2007

Warm Mix: from the work plan, it appears a lot of the testing and fabrication will be done in the lab. In my experience, and from what I have heard from others, how effectively the warm mix additives work can depend on the mixing method. For example, we haven't been able to reproduce the improvement in workability in the lab with the zeolite additive, but it is very apparent when mixed in a plant. This needs to be taken into consideration by the research team. Also, there is a plan for revising mix design procedures for warm mixes – isn't there a NCHRP project on this? Is some of this duplication of effort?

Comment [e28]: See earlier comments on relevance to other work.

RAP: the industry needs to start talking about RAP in terms of binder replacement percentage and not just RAP percentage. For example, 20% of a RAP that has 3%ac will be very different than 20% of a RAP with 5%ac. Also, the group needs to work with the new RAP ETG and the RMRC on these efforts. Another important aspect to consider when dealing with higher percentages of RAP is just simply QC of the piles, how to handle the stockpiles, and just the practicality and potential issues with moisture, fumes, etc. than can be the limiting factors for a particular plant.

Reviewer 9 - June 28, 2007

1st Year Work Plan – Asphalt Research Consortium (Contract No. DTFH61-07-H-00009)

Program area: Moisture Damage

Objectives

The first objective is to identify the mechanisms that contribute to moisture susceptibility of mixes. At this point, I believe there has been significant research into identifying the mechanisms. It would be helpful to identify the **most critical mechanisms** that actually lead to pavement damage/failure and quantify the impact of these mechanisms by determining (i.e. quantifying/associating) a likelihood of each mechanism to result in damage/failure.

Category M2: Cohesion

Work Element M2a: Work of Cohesion Based on Surface Energy

Subtask M2a-1: Methods to Determine Surface Free Energy of Saturated Asphalt Binders

Why are i) and ii) necessary if research already conducted at Texas A&M has shown the Wilhelmy plate may be used to accurately determine surface free energy of binders and (from what I have heard) is superior to the sessile drop method? Perhaps it would be better to concentrate this effort on improving the Wilhelmy plate method, determining the repeatability and reproducibility of this method, and focusing on the change in magnitude of work of cohesion under various temperatures and saturation conditions as indicated in the opening paragraph of this subtask.

Comment [T29]: Please provide an explanation in the workplan.

Subtask M2a-2:

Please provide explanation on the purpose of flocculation titrimetry. What information will it provide?

Comment [T30]: Please provide this information.

Subtask M2b-1: Measurements of Diffusion in Asphalt Mixtures

In part ii), FTIR appears to be a very promising method for determining diffusivity of asphalt binders, however other methods should be considered or at least a literature review performed to evaluate various methods (e.g. electronic impedance spectroscopy). Is there a reason only this method is proposed?

Comment [T31]: Please provide this clarification

Part iv), a combination of experimental results and models may be used to determine the effect of pore pressure. Consideration of available models for determining pore pressures would be useful (e.g. Emin Kutay's model)

Subtask M2c-1: Evaluate Load and Deflection Measurements using the Modified PATTI Test

If possible, I suggest using imaging techniques (i.e. cameras, video) to document tensile cohesive and adhesive failure during testing. This will provide information on 2

where failure occurs and hopefully provide images of the exact location of the onset of damage (cracking/crack growth).

Reviewer 10 – June 8, 2007

Regarding Contract 00009...

I think the research tasks are directed at some very challenging issues related to moisture susceptibility, fatigue, healing, and some Engineered Pavement Materials (EPM). Since we do not have most, if any, of these pieces of equipment in our labs, I cannot comment on the details.

But I am very glad to see that Cold Asphalt Concrete is being incorporated in the research, even if it appears to be only a relatively low level lab study.

I do think they should at least look into and measure some fatigue properties of the most encouraging mixes (I see fatigue with the HMA and RAP materials, but I don't see it with the CMA.) Thermal properties of CMA should also be evaluated just as the HMA with RAP, since low temp cracking will be critical with these materials and how the binders blend also. Finally, I see no field validation nor any feed into the MEPDG for CMA results, as there seems to be for HMA. With FHWA's emphasis on green and materials friendly to the environment, furthering the development of CMA seems to be underweighted again. More research into the sound impacts of surfaces seems to be redundant to other work going on in this area and this funding could be better directed to the other parts of the workplan.

Comment [e32]: Explain why not.

Comment [e33]: Will there be validation sites using CMA, if not, why?

Comment [e34]: Reference other work and how what is proposed is similar or different.

Reviewer 11:

There are a number of concerns in their thought process behind what they are trying to accomplish with cold mixes. They are starting out with very negative attitudes to cold mixes and there is a lack of understanding as to how they work. Just because water is used they believe that will make the mixes more moisture susceptible. This is mentioned many times and shows the lack of understanding of the process. I only need to reference micro-surfacing as an example. This is the best asphalt material to fill ruts in a pavement and shows excellent rut resistance over time. This is also a cold mix that has probably has the most moisture in the aggregate, added in the mixing process, and also that in the emulsion itself. I have never seen a stripping problem on a micro-surfacing job. Micro-surfacing has about 10-12% air voids yet is virtually impermeable. I would like to see them explain that. There are some issues with how they describe the rheology of the mixes (calling foamed asphalt a cold mix is pretty laughable as well) and the rheology of the Superpave grading. They mention the concern about the lack of short term aging hurting the rut resistance, but failed to mention the positive aspects that are gained by not aging the asphalt. Does the lack of aging actually hurt the rut resistance (see micro explanation above)? They are right to be concerned about the emulsifiers (selection and concentration) and the workability, but I fail to see how they are going to dictate that. I also did not understand the ambient mix issue. It is a good thing that I have a chemical engineering background because that allows me to understand that the thermal mass of a cool, wet or moist, aggregate causes the temperature of the mix to go to the temperature of the aggregate very quickly. We try to adjust the temperature of the emulsion due to the chemical reactivity of the emulsion as it initially mixes with the aggregate. A reactive emulsion, with a warmer temperature than the aggregate, reacts quite differently in a mixture.

There are many other comments that I could make but I thought I would throw a few out. Bottom line is that I would hope they would not force cold mix into meeting their hot mix paradigms. This would be a disaster. I can see some good things coming out of the money being sent to WRI, but I hope they get a good focus and have some folks working on this that have some background in emulsions. Things that would be great would be proper residue recovery methods, appropriate mixing chambers, etc.

Comment [e35]: Please give this careful consideration. We would appreciate your comments.

Reviewer 12 :

What I think a project(s) should focus on is matching a mix design to a treatment, not lumping emulsion-made products into one category. Rough categories are:

Micro-surfacing (A mix design method is already being worked on by Caltrans)

CIR

FDR

Stockpile mixes (made with RAP or virgin aggregate)

Central plant mixes

Paver-produced mixes

Where the mixture is at within the structure should be considered. Will the mixture be a final wearing course (micro-surfacing)? Is it a base mix? Is it for construction or patching? Is it in place (CIR or FDR) or central plant? Will it be driven on before sealing or overlaying? These considerations will influence the tests to perform.

Other problems I have with the proposed study:

Don't define performance by its comparison to HMA. Consider what properties the mix needs and consider the other items I mention above. Benchmarking to some extent makes sense, but don't over-rely on it. HMA will be stiffer than emulsion-based products - that doesn't doom emulsion mixes to failure.

There seems to be a huge reliance on emulsion / binder properties with limited understanding of the mixture and mixture-emulsion interaction.

I have huge issues with emulsifier charge selection. It makes sense to coat an aggregate and keep it coated (though 100% coating is not needed for base mixes). However, selection on an emulsion on this characteristic alone is scary.

Emulsion content by CKE?? We can estimate better knowing gradation, amount of RAP, and absorption.

Mixing and compaction - Steve Cross has performed good work on this for CIR mixtures.

ASTM D 7196 is not a moisture susceptibility test. It is a raveling test, which is related to cure.

Please accept this feedback in the constructive nature in which it was provided.
Our staff can get emotional and frustrated with the hot-mix world trying to address cold mix concepts from a misapplied "reference point".

Reviewer 13

Asphalt Research Consortium

- **Moisture Damage:** I generally agreed with the proposed research directions. They seem to build on work already accomplished that show promise or at least potential.

- **Fatigue:** Too much attention on binder properties and modeling. Should emphasize mixture and structural effects on development of fatigue.
- **Engineered Materials:** Much of this area is highly speculative or duplicative of work already completed or in progress (e.g., SPT, Superpave, WMA, CMA, and RAP). This money would be better spent on topics not already researched by SHRP, FHWA, NCHRP, and others.
- **Vehicle-Pavement Interaction:** Good objectives, but effort is too narrowly defined and funded. Expand program with funds taken from Engineered Materials program area.
- **Validation:** Key program area. It would be worthwhile to beef this up with funds from **Engineered Materials**. Important to provide funds or resources for ongoing performance evaluation of field test sections.
- **Technology Development:** Good plan, but under funded.
- **Technology Transfer:** Good plan, but probably not adequately funded.

Reviewer 14

- 1) The plan is not clear if each program area will be testing/evaluating a common set of materials. This is alluded to in a number of sections, but it I don't get the sense that all Consortium members are on board with this. [Work on this agreement would have far more value if all elements are using common materials and the testing information is entered in a common database. (For example, the aggregates used in M3a should be the same as those used in M1 and M2.) The plan should clearly state what materials will be used, how they will be maintained/controlled, and how they will be shipped among members. Considering that the MRL recently received a box of cores from WRI with no labeling whatsoever, asking them to put thought into this would not be micro-managing.]
- 2) Any protocols developed under this effort shall be submitted to AASHTO and not ASTM.
- 3) While the ARC states that they believe it is healthy to have multiple parallel activities to achieve an objective, I did not see a concerted effort to coordinate/collaborate on those parallel activities. [There also is no process set up to objectively evaluate the parallel efforts midway downstream to see whether one is offering a better approach than the other.]
- 4) A number of statements are made without supporting references. (Example, second paragraph on page 1, first sentence on page 2.)
- 5) In comparing the tests under M1a, what is considered truth?
- 6) How does the work in M3a relate to the work FHWA is funding with ICAR. Check with Meininger for commonality of materials and/or duplication of effort.
- 7) Subtask F3c-2: Will the VEPCD model be linked to a fracture model? The description does not specifically state that this is what is considered to be a part of

Comment [T36]: Very good point, please provide clarification

Comment [e37]: Important from FHWA perspective.

Comment [T38]: This should be included in the experimental plans that the ARC will be preparing during year 1

Comment [T39]: Agreed please provide references to support statements included in the workplan.

Comment [T40]: Please provide this relationship.

- a comprehensive model. If not, it should be. FHWA and NCHRP have already invested a lot into getting the VEPCD to where it is and this is a needed element.
- 8) In addition to bridging the VEPCD model with fracture, healing should be incorporated into the VEPCD.
- 9) The ARC states that they are planning to use ALF materials. If they don't already have them, I believe those materials are in very short supply, if at all available.
- 10) The budget for F3 seems too small for what is planned.
- 11) How is Subtask E2d in the national interest if it is indeed a unique type of thermal cracking? I think the case needs to be made first that this is a different animal.
- 12) Even though they are scheduled for later starts, I question FHWA funding V2a and V2b, when we have trouble keeping our own ALF afloat. There is nothing that precludes ALF from being the APT site, if indeed one is needed under this agreement.
- 13) Work under V3b should be coordinated with the AASHTO Joint Technical Committee on Pavements and the MEPDG Lead States.
- Comment [T41]:** It is important that the ARC be specific about what is expected to be done with each model in NCSU, TTI, and Nebraska.
- Comment [T42]:** Verify that the ARC coordinate this with Dr. Gibson
- Comment [e43]:** Same as comment e6
- Comment [e44]:** Provide justification for why the FHWA ALF is not being proposed.
- Comment [T45]:** Emphasize that ARC work plans in this regard should be communicated with LSG, JTCOP and DGRIT

Reviewer #15

- The ARC should work with a technical writer to provide guidance on formulation of hypotheses, and to maintain consistency and relationships between the different work elements in the report.
- Comment [T46]:** Similar to comment T13

RESPONSES TO THE REVIEWERS FEEDBACK QUESTIONS

	Comment	Response
1	With respect to early technology development efforts/deliverables, the work plan states that these "will focus on products developed in past FHWA research studies completed by WRI." (p. 126) What about products developed out of other FHWA sponsored studies completed by others? My concern here is that we may overlook/neglect other significant works/developments.	This comment was addressed during development of the list of recommended early technology development projects that were included in the Year 2 work plan. ARC members considered all work completed in past FHWA projects with the WRI. Also, through the AOTR, we solicited the FHWA for applicable early technology delivery projects from other FHWA sponsored activities. None were identified. The recommended projects address a wide range of topics including asphalt compatibility, polymer modification, fatigue damage, moisture damage, and surface energies.
2	"Specifically, I'm concerned with what seems to be predetermined test methods for study (e.g. moisture susceptibility). I have read some of the papers involving the WP and USD approaches and they seem viable and technically sound. However, I fear we may overlook other promising, more simplistic approaches"	The USD and WP devices measure surface energy and all the components of surface energy that are required to calculate the dry and wet (in the presence of moisture) bond strength between binder and aggregate as well as the dry and wet cohesive bond strength within the mastic. In turn these values define the resistance of a mixture to moisture damage. These tests and these calculations are designed to be used in conjunction with other tests to be performed on the fine aggregate matrix (DMA) and mixture. With respect to tests that measure material properties, we certainly are not limited to the WP and USD approaches. However, it is important to note that as far as surface energy determinations are concerned we have already gone through a rigorous assessment of the best tests by which to measure surface energy in NCHRP Project 9-37. Following that rigorous process, the WP and USD clearly demonstrated their superiority. However, ARC research will address other alternatives for the determination of the tenacity of the binder-aggregate bond. These will include, i) use of modified DSR and PATTI tests (Task M1a), ii) use of a database of material properties generated based on USD and WP measurements, iii) combination of (i) with WP and USD measurements, depending on the extent to which the user intends to characterize the material. Applicable sections: M1a through M2c.

3	I still don't see the "Big Hairy Audacious Goals" clearly articulate in this work plan. I think that WRI's BHAG is to develop a chemical model for asphalt binders that will enable a priori design of the material rather than just evaluation of what comes out of the refinery ("Better Living—or at least roads—Through Chemistry"). Pauli's work plans are certainly along these lines. Some of the other work elements are a bit more tangential.	The reviewer is correct in pointing out that one of Troy Pauli's goals is to develop a chemical model of asphalt, even though there was very little description of the work contained in the year 1 plan and there was no work planned in year 1. Until a (chemical) model of the behavior of asphalt, with all of the variabilities from geologic source to processing to blending, is developed, the prediction of the true performance of asphalt will be impossible because without a model, estimation of performance will be based on phenomenological information. Early in the year 2 plan (beginning April 1, 2008), a detailed work plan for work elements M1b-2, M2a-2, F1d-7, and F3a will be developed and presented for review.
4	"I repeat my concern that the ARC not view permanent deformations as a "solved" problem. This may be the situation for Superpave and SMA mixes we are putting down today, but as we adjust mix designs to deal with fatigue, moisture damage, and other issues, it is likely that we will pay a price in terms of increased rutting in hot climates. Rutting is implicitly included in the viscoplastic component of the unified continuum model, but we must make sure that it doesn't slip off the table."	The ARC agrees with this comment, and we indeed are <u>not</u> considering permanent deformation as a solved problem. On the contrary, we have expanded the traditional view of permanent deformation from a phenomenon based totally on viscoplastic deformation to the consider the fact that permanent deformation may, in certain situations, be due to the impact of a certain density of microcracks that can weaken the asphalt layer and make it more prone to permanent deformation. Furthermore, consideration of the viscoplastic response and/or component is and integral and indispensable component of the complete formulation of the unified continuum damage model. In fact, subtask F3c-2 explicitly includes plastic deformation in the modeling work, as reiterated from the work plan here: "The modeling efforts are based on the following theoretical pillars: ... i) the strain hardening viscoplastic model for modeling plastic and viscoplastic behavior; ii) <i>the strain decomposition theory for integrating the nonlinear viscoelastic strain and the viscoplastic strain to describe the total strain; ...</i>" The research team is committed to the development of a unified model that is capable of dealing with permanent deformation as well as other distresses such as fatigue cracking and moisture damage. Rutting of asphalt binders and asphaltic mixture will also be extensively studied in work element E1b-1: Rutting of Asphalt Binder in Engineered Materials. Rutting of HMA mixtures under their critical conditions of temperature and loading rate will be studied in work element E2c: Critically Designed HMA Mixtures in Engineered Materials. Applicable sections: F3a, F3b, F3c, F3d, E1b-1, and E2c.

5	The management issue is still a question mark in my mind. At the last ETG, in response to my comments, Dallas described the overall management structure of advisory boards, annual meetings, etc. This is all fine, but my concerns are really more on the day-to-day management. There will be an awful lot of people working on an awful lot of separate topics/projects, and keeping everything coordinated, on track, and on topic with regard to the overall work plan will take serious day-to-day effort on the part of someone (perhaps many people). Will anyone at WRI/ARC be 100% devoted to overall management of the project(s)-- i.e., zero technical role?	The detailed management plan for the Consortium was presented in the proposal to FHWA and was not included in the work plan. A brief description of the management plan is as follows. Mr. P. Michael Harnsberger will serve as the Program Manager. As such, he will be the primary contact at WRI for the FHWA technical and contracting offices. In the capacity of Program Manager, Mr. Harnsberger will be responsible for oversight of the four Consortium partners. Dr. Raymond Robertson, Vice President of the Transportation Technology Business Unit (TT Unit) at Western Research Institute, will have general oversight of this program. The Consortium program has seven program areas: Fatigue, Moisture Damage, Engineered Materials, Vehicle Pavement Interaction, Technology Development, Validation, and Technology Transfer and a Consortium member will lead the coordination of activities and presentation of results in each area. Members from the five Consortium partners will form an Advisory Board. This Board will consist of Mr. Michael Harnsberger, Dr. Raymond Robertson, Dr. Dallas Little, Dr. Hussain Bahia, Dr. Peter Sebaaly and Dr. Ramon Bonaquist. Drs. Little, Bonaquist, and Robertson are co-chairs of the Models, Mixture, and Binder Expert Task Groups (ETG), respectively. This Board will be responsible for working with the FHWA AOTR to set the direction of the work for the Consortium. This Board will meet at least one time each year prior to development of the work plan for the following year for the purposes of discussing recommendations with FHWA regarding the strategic plan, preparation of annual work plans, preparation of annual financial plans, and the preparation of self evaluation plans. The Board will meet more often when deemed necessary by the AOTR and/or the Consortium partners. The Advisory Board, in cooperation with the AOTR, will also establish performance measures and be responsible for an annual self-assessment to ensure that the program goals are being achieved. The Advisory Board will also use the results of the annual self-assessment to correct any program deficiencies.
6	The key deliverable under the moisture damage area is the “prediction of moisture damage susceptibility.” I think this needs to be clarified and/or expanded. I believe that the researchers do not plan to simply predict <u>susceptibility</u>—e.g., develop a screening test to identify mixes with potential moisture problems—but also to predict the <u>consequences</u> that moisture has on the fundamental properties and behavior of the mix—e.g., on stiffness, fatigue and permanent deformation resistance, etc	The reviewer has correctly pointed out that the objective of the Moisture Damage work area is not merely to predict the moisture damage susceptibility but also its consequences on the mixture and pavement performance. The micromechanics, analytical, and unified continuum models in Task M4a are targeted to address this issue in conjunction with similar models in the Fatigue work area (which also includes plastic or permanent deformation). The hypothesis statement has been significantly revised from year 1 to reflect this idea more clearly. (See also response to comment 3). Applicable sections: M4a.

7	“I understand the researchers major focus on fatigue, but this does seem to contradict other lines of research by FHWA and others directed toward perpetual pavement designs. If we are designing pavements that do not fail in fatigue (e.g., by limiting strains below the endurance limit, if this in fact exists), then why do we need sophisticated material characterization and prediction models? Of course, perpetual pavement designs really address only the classical bottom-up fatigue. There will still be the potential for top-down fatigue and reflection cracking (also a form of fatigue, albeit more localized and often lower cycle). It is unclear on which fatigue mode the researchers plan to, or alternatively whether they think their fatigue approach will be a “one size fits all” system that will apply equally well to all of the modes.”	First of all, the ARC is working toward the development of a fundamental approach to predict damage. Such damage may be due to the development and growth of cracks or weakening of the mastic because of microcrack development with the manifestation of permanent deformation; or due to viscoelastic response with the manifestation of permanent deformation. Based on this approach, which is the basis for the predictive models that we are developing, damage will be predicted when a critical condition is reached whether it be to cause bottom up fatigue, top down fatigue, microcrack mastic weakening based permanent deformation or viscoplastic flow-based permanent deformation. The concept of the endurance limit is indeed an important one. ARC is keeping a close alliance with NCHRP project 9-44, “Developing a Plan for Validating an Endurance Limit for HMA Pavements”. Two ARC researchers participated by invitation in the HMA Endurance Limit Workshop. Furthermore, this project is being conducted by ARC team member Advanced Asphalt Technologies. The material properties that relate to viscoplastic flow and microcrack growth will be used as inputs for continuum constitutive models that are implemented using a numerical approach to provide a comprehensive damage model. This model will be used to determine the response of the pavement as a whole under various boundary conditions or pavement geometries. As such, this approach will be able to capture the different forms of fatigue cracking as discussed by the reviewer. Applicable sections: F3a, F3b, F3c, F3d, and F1d.
8	“Regarding top-down fatigue cracking, it is likely that changes in mix design required to reduce this distress may have the simultaneous detrimental effect of increasing the rutting potential. The researchers in past meetings have justified not considering rutting because this problem was solved by Superpave. However, I think what we may have is a swinging pendulum: the dry, low rutting Superpave mixes with their greater tendency toward durability and surface cracking problems may represent one end of the arc, and as we address the durability and surface cracking problem we will inevitably swing back toward more rutting issues. I am not proposing that the researchers add rutting to their portfolio, which is already quite full, but simply to be more explicitly cognizant of these interactions.”	Although the work area in the ARC is entitled “Fatigue” it is not true that the researchers are “not considering rutting” Please refer to response #2 for more details. In fact it is indeed <u>not</u> ARC’s stance that we are justified in not considering rutting. All of our approaches consider not only microcrack development and growth but also viscoplastic deformation and deformation that may be caused through microcrack weakening.

9	The scope of the engineered pavement materials area seems a bit diffuse, not crisply defined, and potentially very large. The list of deliverables seems unrealistically ambitious.	The engineered pavement materials area addresses two main areas: damage resistance and reduced use of energy and natural resources. The objectives for each work element provide a clear definition of the specific scope of each work element. The details are further explained in the Year 2 work plans.
10	The fourth objective in the moisture program area addresses evaluation of moisture susceptibility of mixes. I find the term “susceptibility” to be ambiguous here, in that in many contexts it is interpreted simply as screening for mixtures with a high potential for stripping (e.g., AASHTO T283). I think the researchers are interested in more than this, and the objective should be clarified as development and evaluation of models for the impact of moisture damage on the fundamental engineering properties and behavior of the mixture.	The objective was revised and replaced by the following two objectives: 4. Develop a model of the moisture damage process that is linked to and compatible with the model of fatigue damage being developed by the ARC (work element F3). 5. Develop and validate the utility of tests and models to evaluate the moisture susceptibility of mixtures and quantify the effect of moisture on pavement distress. (See also response to comment 2). Applicable section: Introduction and hypothesis
11	In the moisture program area, the amount of time (2 years) and effort (\$300K) devoted to 4a-3 “Unified Continuum Model” seems insufficient. Development and validation of such a model will be a major effort. However, since this effort spans both the moisture and fatigue program areas, perhaps some of the effort is lodged under fatigue? The fatigue area does seem to have appropriate resources for this type of effort: 5 years and \$5.45M for unified model plus same time/effort for the micromechanics model. The amount of effort for final model validation (Work Element 3d in the fatigue area) also seems light: the 3 year duration is obviously constrained by the schedule of the preceding work tasks, but \$325K may be insufficient—depends how much field work, additional material testing, etc. will be required during the validation effort.	The reviewer has rightly pointed out that the modeling effort is similar in moisture damage and fatigue work areas and, therefore, the cumulative effect of these two work areas must be considered. Furthermore, the bulk of the effort for field work is supported by the validation work area of this program. Researchers will also try to capitalize available information from existing testing sections to support this work element. Applicable section: F3d, M4a, and M5a.
12	In the fatigue program area, Work Element F3d on calibration and validation: (a) Early on the researchers should confirm sufficient availability of materials for all of the proposed sites. Experience on NCHRP 9-30A suggests that less material than expected is also the case. Specifically, I think that some of the modified binders from the ALF sections may be in short supply. (b) My understanding is that the WRI field sections, which were designed to evaluate the interaction between environment and asphalt source, have not yet exhibited any significant load related distresses. If this is true, this makes them of relatively small utility for validation.	The Consortium members are well aware that availability of materials from field sections is difficult if not impossible. That was the main driving force behind building the WRI sections and it is acknowledged that the WRI sections are not the complete answer. The Consortium will still make efforts to obtain available materials from field sites. The reviewer is correct in stating that the WRI sections have not exhibited significant distress since only one site is showing significant distress. In a related matter, a material selection plan is included with the Year 2 work plan.

13	Does objective 3 in the engineered pavement materials area overlap with other work already currently underway by others (e.g., guidelines for warm mix asphalt, high RAP mixes)?	The team will coordinate with current work underway as much as possible. This is expected to reduce or eliminate the extent of overlap. In the area of Warm Mix, the consortium research team has contacted the NCHRP research teams for: • NCHRP 09-43. Mix Design Practices for Warm Mix Asphalt. • NCHRP 09-47. Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies In the area of Recycled Asphalts, the consortium research team has contacted the NCHRP research team for: • NCHRP 09-46. Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content. • NCAT and UNR are currently working on a joint subtask to evaluate the impact of extraction method on the properties of RAP aggregates. Applicable sections E1c, E2b
14	The engineered pavement materials area is a very large basket of only loosely connected topics. Some of the individual areas are quite sizeable (\$1.7M for high-RAP mixes), and overall this area represents about 25% of the total project effort. Given the major commitments of many of the consortium members on other program areas and WRI commitments in their own separate fundamental materials contract, I question whether there is sufficient manpower within the consortium to accomplish all of these tasks. FHWA should closely examine the proposed manpower levels and other commitments (e.g., teaching for University researchers) over the life of the project.	The reviewer is correct in stating that the program is very ambitious and the Consortium plans on delivering. We believe that it is better to be ambitious and reach for high goals rather than being content to do very little and not try and use the funding to the maximum. The work plans were developed with careful attention to the required and available time and labor available for these activities. Consortium partners have hired, or in the process of hiring, additional qualified staff to achieve the stated goals. In the Foreword, it states that the Engineered Materials area is more focused on working on specific problems compared with the integrated fundamental research in moisture damage and fatigue.
15	Related to the preceding comment, with so many tasks running concurrently—some loosely connected, some more tightly overwoven—project management skills will be as critical as technical expertise. There is nothing in the work plan (in either work plan, in fact) that addresses project management. Presumably FHWA has this for their internal review.	The detailed management plan for the Consortium was presented in the proposal to FHWA and was not included in the work plan. A brief description of the management plan is as follows. Mr. P. Michael Harnsberger will serve as the Program Manager. As such, he will be the primary contact at WRI for the FHWA technical and contracting offices. In the capacity of Program Manager, Mr. Harnsberger will be responsible for oversight of the four Consortium partners. Dr. Raymond Robertson, Vice President of the Transportation Technology Business Unit (TT Unit) at Western Research Institute, will have general oversight of this program.

		The Consortium program has seven program areas: Fatigue, Moisture Damage, Engineered Materials, Vehicle Pavement Interaction, Technology Development, Validation, and Technology Transfer and a Consortium member will lead the coordination of activities and presentation of results in each area. Members from the five Consortium partners will form an Advisory Board. This Board will consist of Mr. Michael Harnsberger, Dr. Raymond Robertson, Dr. Dallas Little, Dr. Hussain Bahia, Dr. Peter Sebaaly and Dr. Ramon Bonaquist. Drs. Little, Bonaquist, and Robertson are co-chairs of the Models, Mixture, and Binder Expert Task Groups (ETG), respectively. This Board will be responsible for working with the FHWA AOTR to set the direction of the work for the Consortium. This Board will meet at least one time each year prior to development of the work plan for the following year for the purposes of discussing recommendations with FHWA regarding the strategic plan, preparation of annual work plans, preparation of annual financial plans, and the preparation of self evaluation plans. The Board will meet more often when deemed necessary by the AOTR and/or the Consortium partners. The Advisory Board, in cooperation with the AOTR, will also establish performance measures and be responsible for an annual self-assessment to ensure that the program goals are being achieved. The Advisory Board will also use the results of the annual self-assessment to correct any program deficiencies.
16	My comment 3a above in this section is relevant to the entire validation program area. Experience from NCHRP 1-37A, 9-30A, and other projects is that there are not large numbers of existing sites available that have adequate stockpiles of materials and significant levels of distress. Constructing new validation sections is not feasible, in that they will not have accumulated sufficient distresses to be of value in this project. Validation using APT sections may need to be relied upon very heavily.	The MEPDG sections will be used to obtain validation data for the duration of the ARC contract. In addition, as part of the validation task, the ARC researchers will work with the owner agencies to develop and implement a long-term performance monitoring plan to be followed after the conclusion of the ARC. The ARC team also has accelerated testing facilities available at Texas A&M and will work as much as possible with the ALF at FHWA. Applicable sections V2a, V2b, V3b.
17	Moisture Damage: I am glad to see the emphasis the work plan places on recent work by Niki Kringos and Tom Scarpas. That model clearly differentiates mastic damage caused by flow of water through the mix under pressure from debonding at the asphalt-aggregate interface. AASHTO T-283 seems to capture debonding, but only saturated wheel-tracking tests like Hamburg seem to capture the mastic damage. This second damage mechanism, which explains deleterious effects of clay, reemulsification of PPA/amine modified asphalts, and other mastic failures needs priority attention, because these failures occur even though mixes pass AASHTO T-283.	The work plan almost uniformly distributes effort for material characterization at different length scales; binder, mastic, fine aggregate matrix, and mixture. We feel that this is the proper approach. However, we agree with the reviewer that the mastic and fine aggregate matrix are relatively more important for moisture damage characterization. Test methods such as the DMA (task M1c) are being developed to quantify the deterioration in mechanical properties of the FAM with increase in moisture content. In fact, the development of the DMA to identify the impact of fatigue crack growth in both dry and moisture laden states for the fine aggregate matrix (FAM) was initiated at TAMU under the previous FHWA contract through WRI.

	I would recommend rewriting this task to place much more emphasis on the mastic failure mechanism. Suggest you consult with Tom Scapas and Niki Kringos for ideas. In particular, look at clay contamination of mineral fillers, and PPA/amine additive blends with about 1% PPA and 0.5% amine antistrip. Kansas also used a limestone containing quartzite on an SPS project near Greensburg that has some interesting moisture implications.	The information from the DMA on the FAM becomes one of the material properties that is used in the micro mechanics model to predict material performance and continuum model to predict structural deterioration based on the most critical damage mechanism. ARC has made a concerted effort to keep up with and include the excellent work that has been done and continues to be done at TU Delft by Dr. Scapas and colleagues. We will continue our interactions with Dr. Scapas and colleagues as a valued alliance. Applicable sections: M1b, M1c, and M4a.
18	Aging: Task F1c-1: I just completed a state-of-the-art review of asphalt durability for on AAPT 05-07 – Non-load related airport pavement distresses. It should be quite relevant to this task. I will send it once it receives approval from PI Doug Hanson and Project Manager Monte Symons. Task F1c-4: Critical task from perspectives of pavement preservation, fog seals, and recycling.. It would be very helpful if this task could evaluate rejuvenators as added to aged asphalt to restore initial relaxation/fracture properties. If possible, we need mechanical mixture tests which can determine strength, relaxation, and fracture properties with thin specimens so we can characterize aging very near the pavement surface.	Mixture characterization of relatively thin specimens through axial testing that includes relaxation modulus master curves in tension and compression, damage accumulation rate in repeated direct tension, and tensile strength to facilitate selection of testing conditions will be utilized for testing specimens cut from cores. This testing of prismatic specimens has been successful in compression, and tensile testing is currently ongoing. Testing of these thin specimens will capture aging near the surface and any effects of rejuvenators. These effects are also being examined specifically in ongoing TxDOT Project 0-6009 currently being conducted by ARC researchers. Applicable sections: F1c.
19	Task E: - Most tasks in this section are well defined and very much needed. - Task E1b-2: Thin Films - What is the budget for this task? Treat as idea project, with limited funds for exploratory work. Evaluate progress and need before further funding.	This subtask does not officially start until Year 2. However, some exploratory work has already been conducted in collaboration with University of Minnesota. The preliminary results seem to be promising, although more testing is needed. The task is considered an idea project with limited funds before greater funding commitments are made. Applicable section E1b-2.
20	- Task E1c-1: Warm Mixes - Many of these work elements sound much like those proposed for a similar NCHRP Project led by AAT. How will these two projects be coordinated to minimize any duplication?	AAT is a partner in the ARC. UW will work closely with AAT to ensure efforts are not duplicated. UW has been included as a “friend” of the FHWA Warm Mix Technical Working Group and attended their December 2007 meetings. UW will continue to attend these meetings to ensure that its work is not duplicating current efforts. UW will also request to sit on the panels of the two NCHRP Projects (9-43 and 9-47). AAT is the prime contractor on NCHRP Project 9-43, Mix Design Practices for Warm Mix Asphalt. The primary goal of NCHRP Project 9-43 is the development of an AASHTO Standard Practice for the design of warm mix asphalt. The design procedure will

		be based on current knowledge, and limited laboratory and field testing. In Task E1c-1, various warm mix processes will be reviewed in greater detail than can be done in NCHRP Project 9-43. It is envisioned that findings from Task E1c-1 will result in improvement of the methodology developed in NCHRP 9-43 and additional guidance for agencies and contractors considering the use of warm mix asphalt. Applicable section E1c-1.
21	• Task E1c-2: Cold mix volumetric design (Note: Task incorrectly numbered as E1b-2) ○ Cold mix design process is needed. What work will be done to classify emulsion residues using SuperPave tools? In particular, high float mixing grade emulsion residues will be strongly gelled, exhibiting a yield stress and highly non-newtonian behavior under shear. This subject needs to be dealt with early in the project for high float anionic emulsions.	The Subtask was incorrectly numbered and this has been corrected. The review of literature and of international standards for emulsion testing will take place in the first quarter of Year 2. Candidate test methods will be selected and evaluated at the end of Year 2. The behavior described in the question will need to be addressed in the evaluation phase. Applicable section E1c-2
22	• Task E2-b: Use of RAP ○ Please put a heavy emphasis on the relaxation and fracture properties of the binder when RAP is blended with virgin asphalt. Any negative effects will show up in fatigue and/or low temperature thermal or block cracking, not rutting and moisture damage. Don't study the wrong distress mechanisms!	Evaluating the fatigue and thermal cracking resistance of HMA mixtures containing RAP materials are crucial parts of the proposed research, as indicated in subtask E2b-4: Impact of RAP Materials on Performance of Mixtures. Applicable section E2b
23	Asphaltic concrete pavements are non-fading memory materials, it is not clear how the chemical modeling and atomic structure analysis will capture the stress history?	There should be no question that the chemical composition of asphalt drives its rheological properties. Furthermore, both the thermal and stress histories of this material will also be directly influenced by the chemical “molecular” composition of the asphalt. For example, compositional properties of bitumen, including molecular weight distribution, relative concentrations of aliphatic, aromatic, and alicyclic (cyclohexane-type) organic chemical types, amounts of polar constituent groups (e.g., carbonyl concentration and sulfur concentration) have each been shown to correlate with various mechanical properties such as low temperature stiffness, phase angle and complex modulus at mid-range temperature, moisture susceptibility, and age hardening due to oxidation reactions. It is also likely that distinct phases of an asphalt, wax crystals, and emulsion-like states

		(asphaltenes and maltenes), which relate to molecular compatibility of asphalt are both influenced by changes in thermal and stress states. Asphalts, if they indeed have different phases, will likely have different mechanical states for each phase, clearly, thermal treatment has shown that different phases of asphalt soften and harden in different temperature ranges. The polymer and colloid industries know of such phenomena oh too well, and often process their materials accordingly. Thus, it is in the best interest of the asphalt paving community to have a complete molecular understanding of its glue, given the ever increasing demand to modify these materials to often meet unrealistic specifications.
24	Crazing zones is generally used for crack initiation when brittle fracture condition prevails, while this is true for pavement at very low temperatures and extremely fast moving traffic loading, it is not clear how it can be used to model crack initiation in ductile or time dependent fracture situation (Creep-fatigue interactions).	According to the following citation: The Stress/Strain behavior of solid polymers can be categorized into several classes of behavior: http://www.eng.uc.edu/~gbeaucag/Courses/Characterization/StressStrainhtml/StressStrain.html 1) Brittle Fracture- characterized by no yield point, a region of Hookean behavior at low strains and failure characterized by chonchoidal lines such as seen in inorganic glasses. 2) Yield Behavior- characterized by a maximum in the stress/strain curve followed by yielding deformation which is usually associated with crazing or shear banding and usually ductile failure. Ductile failure exhibits a high extent of deformation on the failure surface. Yield behavior can result in necking which exhibits a close to constant load regime and a terminal increase in the stress. 3) Rubber-Like Behavior- characterized by the absence of a yield point maximum but exhibiting a plateau in an engineering stress/strain curve. Often rubber-like behavior exhibits a terminal increase in the stress followed by failure which results in a tear with little permanent deformation exhibited in the failure surface, e.g. Jell-O. Asphalts are known to have very broad glass transition states which extent from room temperature to well below -40°C which would suggest that fatigue cracking, which is likely compounded by thermal cycles, material heterogeneity, moisture, and load would be prime candidates for investigations relating to crazing. The so-called necking behavior has in fact been observed in asphalt at room temperature conditions when a technique referred to as pull-off force atomic force microscopy is employed. This phenomenon is also observed to be crude source dependent, which means that it is chemical composition dependent.

25	1. The controlled stress (load?)/controlled strain (stroke?) setup for testing is not based on consensus among researchers for thick/thin pavement sections but rather based on plane stress/plane strain boundary value application. Page 25 2. No description is presented for the proposed predictive models that rely on the fundamental theories of integrating continuum /fracture/micro/macro mechanics. Page 26 3. It is not clear what the authors mean with “viscoplastic strain” in the last sentence at the end of Page 33. 4. The authors use constitutive laws with Damage models trying to develop a unified model that can encompass both. More detailed discussion is needed to explain how the mathematical/ statistical principles will be used to achieve that especially when dealing to merge micromechanics with macro mechanics. Page 5 5. It must be realized that there are no elastic/viscoplastic /...materials!! These are behavior of the examined material under specific condition. 6. The authors ignored that when damage occurs, the damage zone controls material behavior and continuum mechanics approach may become inapplicable. 7. A unified continuum model as suggested in Page 50 is rather ambiguous. The authors ignored the fact that in order to relate and bridge the gap between micromechanics and macro mechanics models, the Unified Model need to be based on more recent advanced mathematical models such as the String Theory and the number of axis to be used must include more than the traditional four axes (x, y, z, and t). 8. The authors’ tests of hypotheses are not defined or for that matter the design of experiment, only the objectives to be achieved are presented. The proposal should be expected to have a much more refined and well thought-out plan to arrive at a meaningful outcomes, tools, and solutions.	1. It is not clear to the research team what is meant by plane stress/plain strain boundary value application. The researchers are aware that using linear elasticity, the stress at the bottom of a thick pavement remains almost constant with change in asphalt mix stiffness. In addition, the strain at the bottom of a thin asphalt layer remains almost constant with changes in asphalt mix layer stiffness. Furthermore, one of the objectives of this research (tasks F1b, F2b, and F2c) is to develop a methodology to quantify the evolution of fatigue damage in a form that can be implemented in a numerical scheme. The parameters for this form can be obtained using either mode of loading. This allows for the application of different boundary conditions to predict damage without relying on the mode of loading that was used to obtain the material response. 2. and 4. Additional description was added in work elements 3b and 3c in the year 2 work plan. The background information about the model development is available in publications by the research team members from NC-State and TAMU. A more detailed description of these methodologies will be provided in the forthcoming quarterly reports. 3. Viscoplastic strain refers to permanent deformation that remains in the material after the removal of load. Viscoplastic strain is a function of stress level as well as strain rate. 5. The researchers agree with the reviewer’s comment and this point will be taken into consideration in further development of research plans. 6. and 7. The researchers are well aware of the limitations of the continuum mechanics approach to characterize damage. The philosophy of developing a micromechanics modeling approach and continuum modeling approach is, at least in part, to address this factor. The micromechanics approach can be used to characterize damage evolution and its dependency on material properties in great detail. However, these techniques are computationally intensive and are best suited for material characterization rather than modeling the structural response of the pavement (at least with the computational power available today). The micromechanics models can nevertheless be used to model damage evolution and deterioration in the mechanical properties of the mixture at a macro scale. This information can then be used in continuum models to more efficiently model the pavement response. More clarification from the reviewer is required for comment 7. 8. The hypothesis statement for fatigue identifies the

		role of various material properties in damage evolution as well as the need to integrate these properties in a unified model. The various work elements and tasks are direct derivatives from this hypothesis. For example in the hypothesis the statement “the initiation of cracks to a critical size and the propagation of these larger cracks can be successfully explained and evaluated based on the principles of viscoelasticity and viscoplasticity, dissipated pseudo strain energy, micromechanics, and fracture mechanics” directly refers to work elements F1b, F2bc and F2c. The overall hypothesis also presents the broad vision with well specified deliverables for the fatigue work area. Individual hypotheses for each work element are not effective in defining the relationship of each work element to the overall objective of this work area. Furthermore, although the work plan is for only one year, researchers have spent the time and effort to think through the overall goal of this research in order to present the philosophy of research and work plan for the entire duration of this project. The details of the experiments will be developed when the research team reaches the point of verification and validation of the models. These experiments will be presented to the ETGs. Applicable sections: Introduction, Hypothesis, F1b, F2b, and F2c.
26	On the strategic plan... Fatigue Damage - TXDOT did a research project with TTI on Fatigue damage. The Hypothesis presented was tested. My concern no need to repeat work already done.	The work done by TTI on fatigue damage with TxDOT was a preliminary proof for the hypothesis based on limited testing of mixtures. Moreover, the unification of the different material properties (viscoelastic properties, healing, cohesive bond strength, and aging) to predict healing needs to be refined so that it can be implemented in a finite element or similar scheme for micro-mechanical modeling as well as the continuum model to predict pavement performance. Furthermore, properties such as healing also need to be incorporated in the fatigue life model. Applicable section: F1a and F1d.
27	Engineered Pavement Materials - How does this work coordinate or plan with the ongoing NCHRP project on warm mix and the upcoming NCHRP projects on the use of RAP and warm mix ?	This question was also asked by Reviewer 2. The team will coordinate with current work underway as much as possible. This is expected to reduce or eliminate the extent of overlap. In the area of Warm Mix, the consortium research team has contacted the NCHRP research teams for: • NCHRP 09-43. Mix Design Practices for Warm Mix Asphalt. • NCHRP 09-47. Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies AAT is the prime contractor on NCHRP Project 9-43, Mix Design Practices for Warm Mix Asphalt. The

		primary goal of NCHRP Project 9-43 is the development of an AASHTO Standard Practice for the design of warm mix asphalt. The design procedure will be based on current knowledge, and limited laboratory and field testing. In Task E1c-1, various warm mix processes will be reviewed in greater detail than can be done in NCHRP Project 9-43. It is envisioned that findings from Task E1c-1 will result in improvement of the methodology developed in NCHRP 9-43 and additional guidance for agencies and contractors considering the use of warm mix asphalt. In the area of Recycled Asphalts, the consortium research team has contacted the NCHRP research team for: • NCHRP 09-46. Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content. • NCAT and UNR are currently working on a joint subtask to evaluate the impact of extraction method on the properties of RAP aggregates. Applicable sections E1c, E2b
28	Vehicle Pavement Interaction – Predicting effect of dynamic loads on pavement response Several models already exist? Will the new models be better than the existing models? Skid resistance and Friction are more suitable topics under Engineered Materials not Vehicle Pavement Interaction.	The most notable improvements of the proposed model are: a) it conducts dynamic analysis of the pavement structure to account for the impact of moving loads, b) it handles non-uniform non-circular stress distribution at the tire-pavement interface in both the vertical and horizontal directions, c) it takes into consideration the viscoelastic behavior of the HMA layer, d) it can handle the impact of braking at intersections and off-ramps, and e) it is simple to use by practicing pavement engineers. Friction occurs at the interface between vehicle and pavement. Because engineered materials can be designed to enhance skid resistance, we do not feel a need for the suggested change. Applicable sections VP2a, VP3a.
29	New moisture damage test: The pull off test has shown some utility in measuring moisture damage. The proposed DSR test seems to be a variation, we are going to torque the sample instead of pulling it. I am not an expert but I wonder how will the aggregate slices be prepared? We have done some preparation of ¼ inch thick slices for Audrey Copeland's work and it is not at all easy to do. It is especially difficult to maintaining the two faces of the slice exactly parallel. A prerequisite for the DSR is that the plates are parallel and the gap between them precisely known. How will texture of the cut surface of the	UW is working with a geology/rock laboratory that is preparing the rock specimen disks for these tests. These specimens are lapped and faces are very near parallel. In the DSR setup, the parallelism is obtained by aligning the disk using the metal DSR shafts while the epoxy binder dries. This is described in further detail under Experimental Design Subtask M1a-2 for the Year 2 work plan for work element M1a. It is expected that varying texture could influence the results. For this reason, all mineral specimens are being tested with the same texture as obtained from identical sawing and lapping during specimen preparation. Maintaining constant texture and changing the aggregate type isolates the test parameters, and the effect of mineralogy in the moisture damage of

	aggregate affect the results? How representative of the aggregate in the mix will the sample be since it is a slice cut from a large piece of aggregate? Would a DOT ever be able to run such a test? DSRs are also \$40,000 each.	aggregate-binder systems may be evaluated. The purpose of the work is to measure the basic affinity of binders to aggregates. We feel it is almost impossible to represent the actual aggregates and their wide range of properties. The basic affinity, and the effect of water conditioning on the bond strength between binders and idealized mineral surface, are the target of the test. By selecting specific minerals to cover the main types of aggregates, we feel an effective testing protocol could be developed. Yes, DSRs are widely available to DOTs. If the test under development is successful, we plan on working with suppliers of testing equipment to produce simple tools to produce flat disks of aggregates that can be glued to the plates. Applicable section M1a.
30	Use of AFM (Atomic Force Microscopy) – what does this add to the work being done at Texas A&M on surface energy?	Atomic force microscopy has proven to be an invaluable tool in the coatings, polymer, and generally, the materials sciences. AFM work of adhesion techniques are a power tool for measuring the adhesive and cohesive strength of asphalts which is a function of both surface free energy and mechanical contributions. In this sense, AFM may be used to make a DIRECT measurement of the work of adhesion without the use of solvents, as is the case with other techniques including the Wilhelmy plate method. AFM further adds to the dimension or scaling of adhesive bonding in that measurements of work of adhesion are made at dimensions similar to that of mastic and filler particle dimensions. Furthermore, AFM techniques have recently shown that the nano-roughness of aggregate and filler particle surfaces correlates directly with their tendencies to produce “good” bonds. The paving industry could profit considerably from the information that nano-technology can provide regarding the composition-rheology relationship that is one of the primary drivers of pavement performance, particularly as new unknown materials and modifying strategies are continually being adopted by the industry.
31	Oxidation of polymer modified binders – It has been known for many years that the diene double bond in SBS polymer is readily oxidized and would be expected to lead to a reduction in elastic properties. Why are we looking at this?	The purpose here is an attempt to quantify the impact of oxidation and elasticity loss on fatigue behavior of binders. We feel this has not been studied well. Applicable section F2a.
32	Warm mix – A lot of work is being done here and at NCAT. The NCAT work is of course sponsored by NAPA. Are we repeating what they are doing?	UW is working to be involved in these activities. UW has been included as a “friend” of the FHWA Warm Mix Technical Working Group and attended their December 2007 meetings. UW will continue to attend these meetings to ensure that its work is not duplicating current efforts. UW will also request to sit on the panels of the two NCHRP Projects (9-43 and 9-47). Applicable section E1c-1.

33	Why is there a section headed nanotechnology? Is that an FHWA focus issue?	Using AFM as a tool to investigate asphalt materials is essentially looking at material properties at the near-molecular level, which is nanoscale. This is an important area which is also being used in the Portland cement concrete area. If this isn't a FHWA focus area, perhaps it should be. Applicable section M1b-2, M2a-2, F3a
34	I am not sure that phosphoric acid research should be Federally funded. This is a commercial product, as is Sasobit for warm mix, and the producers should pay for the research. Until the current work at TFHRC is finished, and a recommendation to use it or not, it is premature for WRI to research it further and investigate such esoteric things as the chemical mechanism of it action for instance. We are due to finish our study at the end of this year. Perhaps we should revisit this issue then	It is unclear to which work element or subtask the reviewer is referring. Asphalt additives such as PPA, polymers, warm-mix additives, etc., are being used on Federally funded highway projects by state DOT's and the DOT's need support for any potential problems or benefits. There is not any work in the Consortium on the chemical mechanism of PPA.
35	The research plans for moisture and fatigue damage are coherent, detailed and compatible with the FHWA vision for advanced pavement material characterization. The level of analysis for fatigue damage is understandably more advanced than that of moisture damage. The plan for engineered materials is more empirical (less fundamental) in nature than those for moisture and fatigue damage, in terms of both characterization and modeling. It would be useful to seek better linkages between these areas. This could be done by phasing the latter area behind the more fundamental work being done at TAM/TTI. The plan for vehicle-pavement interaction is weak, and disconnected from the rest of the program areas. It does not offer in its present form a realistic solution for incorporating the essential elements proposed in the damage modeling presented under the first two program areas. It is therefore recommended that a more detailed and realistic plan for this program area be developed within the first year of the 5-year study. In this regard, the workshop on super singles should be used as a starting point for an in-depth discussion of a more realistic strategy for incorporating vehicle-pavement interaction and tire-pavement interaction in the framework of advanced mechanistic modeling of asphalt pavement response and damage evolution. The plan for validation is reasonable, although it lacks some details/specifics about the way the validation exercise would be undertaken, with more explicit linkages (in terms of both input parameters and output/distress development) with the four research program areas.	All areas of the Consortium plan are coordinated and linked. For example, in the fundamental work under moisture and fatigue, in order to be validated, the effects of various additives need to be included. While moisture and fatigue plans will develop the best methods for testing and modeling, modifiers need to be tested to satisfy traffic and climate demands. The best approach is to have these activities work simultaneously. Furthermore, the needs for engineering asphalt extend beyond moisture and fatigue. Therefore, the engineered materials work plans encompass the development of materials selection guidelines that include factors other than just moisture and fatigue. The workshop on Wide-base tires highlighted the need to assess the impact of the new generation wide-base tires that are coming into the market at an increasing rate. The workshop recommended that the stress distributions at the tire-pavement interface be measured for the new generation of wide-base tires. The dynamic pavement model proposed under the vehicle-pavement interaction area will incorporate any new measurements of the stress distributions at the tire-pavement interface. In fact, the ARC researchers will cooperate on the testing of the new generation of wide-base tires.

36	PROGRAM AREA: MOISTURE DAMAGE Under ‘deliverables’, there is a discussion about model development to predict performance, but it is not clear how such model will be incorporated in a ‘comprehensive’ structural response and material damage model.	The Moisture Damage work area is not merely to predict the moisture damage susceptibility but also its consequences on the mixture and pavement performance. The micromechanics, analytical, and unified continuum models in Task M4a are targeted to address this issue in conjunction with similar models in the Fatigue work area (which also includes plastic or permanent deformation). The hypothesis statement has been significantly revised from year 1 to reflect this idea more clearly.
37	PROGRAM AREA: FATIGUE More details need to be provided for the structural model. There is mention of the NCSU structural model; however, it is my understanding that this model is an axisymmetric FEM model that uses simple loading conditions (circular disk loads). Such model would not enable the full incorporation of the damage models proposed under moisture and fatigue damage.	NCSU has developed a 3D finite element code under a separate FHWA project. An ongoing effort is to implement the damage model it. While we expect to incorporate simple loading conditions in the model at the beginning, we also expect to incorporate more realistic loading configurations will be considered once the model is verified. More details for the structural model will be included in the forthcoming quarterly report. Applicable section: F3c.
38	PROGRAM AREA: ENGINEERED MATERIALS While the plan is rational and implementable, it presents some weaknesses; notably, the methods proposed are more empirical (less fundamental) in nature, and do not appear to be compatible with the work proposed under moisture damage and fatigue damage. It is recommended that the research undertaken under this program area should take better advantage of the developments to be achieved in the preceding program areas (fundamental material characterization and mechanistic damage modeling).	The best test methods available are proposed as part of the engineered materials program area. Fundamental tests are included to understand mechanisms and when such tests are too complex, empirical tests are being evaluated to connect to practice.
39	PROGRAM AREA: VEHICLE-PAVEMENT INTERACTION 1. The proposed dynamic UNR model (3DMOVE) is not compatible with the damage prediction models proposed under fatigue and moisture, and therefore is not suitable for incorporating such advanced models. Using a ‘finite layer’ model, it will not be possible to model non-linear, inelastic material behavior and the heterogeneous nature of pavement materials. Instead, it would be more appropriate to look into 3-D FEM, or better yet multi-scale modeling that would include incorporating multiple modeling zones using different techniques within each zone and	A draft copy of the minutes of the Workshop has been developed by FHWA which clearly describe the overall objectives and recommendations of the workshop. Once the minutes are finalized, they will be posted on the Consortium web site: www.ARC.UNR.edu.

	providing transition zones connecting the different zones. Examples of such modeling techniques would be micromechanics-based discrete/distinct element or BEM in the immediate vicinity of the tires, FEM in the intermediate zone and BEM and continuum mechanics in the far field. 2. The discussion in this area implies the assumption of one-way interaction; i.e., assuming the pavement profile as a rigid (rough) surface in order to predict the dynamic truck axle loads; then inputting the dynamic load histories in the pavement response model to calculate the response. While this assumption (decoupling the truck from the pavement) is valid for calculating the ‘global’ response that would be needed within the framework on standard mechanistic-Empirical (mE) methodology, it may not be appropriate for a more detailed, Mechanistic-empirical (Me) damage prediction-oriented modeling framework. It is recommended that a two-way interaction between tires and pavement be envisioned, instead. This would entail modeling both tire and pavement using FEM so that tire compliance is allowed. 3. It is not clear what is meant by ‘database’ under this task. 4. For the part concerned with noise and friction, it is not clear whether modeling of tire-pavement surface interaction will be done. 5. Concerning the workshop, it is not clear what the workshop agenda will be. Perhaps, it would be useful to enlarge the focus of the workshop to include the topic of tire-pavement interaction (instead of just focusing on super singles) and comprehensive structural modeling that would enable incorporating all pertinent factors: dynamic (vibrating) moving loads; two-way tire-pavement interaction; 3-D tire pavement stresses; non-linear, inelastic material modeling to enable mechanistic damage prediction within the framework of 3-D FEM, DEM, BEM and other numerical approaches; and use of sub-regions for the near field, intermediate zone and far field	

40	PROGRAM AREA: VALIDATION 1. It would be useful to envision using more advanced NDT technology to better characterize spatial variation of material deficiencies in the field and localized, early damage detection. 2. Incorporate the assessment of variability of pavement materials in the field and corresponding localized material deterioration.	It is not currently planned to use spatial variability in the experimental matrix, however, this subject may need more discussion with FHWA. The ARC researchers will use the NDT techniques that are available to the owner agencies such as GPR, FWD, etc. for the MEPDG sites.
41	Warm Mix: from the work plan, it appears a lot of the testing and fabrication will be done in the lab. In my experience, and from what I have heard from others, how effectively the warm mix additives work can depend on the mixing method. For example, we haven't been able to reproduce the improvement in workability in the lab with the zeolite additive, but it is very apparent when mixed in a plant. This needs to be taken into consideration by the research team. Also, there is a plan for revising mix design procedures for warm mixes – isn't there a NCHRP project on this? Is some of this duplication of effort?	The Year 2 work plan specifically states that the results of the NCHRP report will be considered before revising any mixture design procedures (Work element E1c-1, Experimental Design Task 4). The research team hopes that this study will supplement the NCHRP project as needed. The testing proposed has very little redundancy to the NCHRP plan. AAT is the prime contractor on NCHRP Project 9-43, Mix Design Practices for Warm Mix Asphalt. The primary goal of NCHRP Project 9-43 is the development of an AASHTO Standard Practice for the design of warm mix asphalt. The design procedure will be based on current knowledge, and limited laboratory and field testing. In Task E1c-1, various warm mix processes will be reviewed in greater detail than can be done in NCHRP Project 9-43. It is envisioned that findings from Task E1c-1 will result in improvement of the methodology developed in NCHRP 9-43 and additional guidance for agencies and contractors considering the use of warm mix asphalt. The research team is represented on the RAP ETG (M. Harnsberger and H. Bahia are both members of the ETG). H. Bahia is a member of the RMRC research team and has participated in the strategic planning of the RMRC. Part of the research plan is evaluating the fractionation of the RAP. Two members of the UNR ARC group (Peter Sebaaly and Jon Epps) attend the RAP ETG meeting regularly. Peter Sebaaly is also an observing member of the NCHRP panel on RAP research. The variability of the RAP stockpiles will be investigated in subtask E2b-5: Field Trials

42	Subtask M2a-1: Methods to Determine Surface Free Energy of Saturated Asphalt Binders: Why are i) and ii) necessary if research already conducted at Texas A&M has shown the Wilhelmy plate may be used to accurately determine surface free energy of binders and (from what I have heard) is superior to the sessile drop method? Perhaps it would be better to concentrate this effort on improving the Wilhelmy plate method, determining the repeatability and reproducibility of this method, and focusing on the change in magnitude of work of cohesion under various temperatures and saturation conditions as indicated in the opening paragraph of this subtask.	The material properties of saturated asphalt binder or mastic are likely to be very different from the material properties of the unsaturated materials. The sessile drop method will serve only as an investigative tool to evaluate the effect of saturation on surface properties of the asphalt binder or mastic. For these specific cases, the sessile drop method offers real time contact angle measurement that may have certain advantages over the Wilhelmy plate method. The subtask M2a-1 was modified to reflect the above clarification. Applicable sections: M2a.
43	Subtask M2a-2: Please provide explanation on the purpose of flocculation titrimetry. What information will it provide?	Automated flocculation titrimetry is an experimental technique that rapidly “fingerprints” an asphalt in terms of its chemical composition (molecular compatibility). Furthermore, the AFT method has been shown to produce data which directly correlates the compositional properties to the rheological properties of an asphalt. For example, the tendency or rate for asphalts of different crude source to oxidatively age harden appears to be dependent on the “molecular compatibility” of the asphalt, where the more compatible asphalts harden more slowly with reaction with oxygen compared to less compatible asphalts. The AFT method also appears to be multi dimensional in its ability to characterize an asphalts compositional state, where new novel techniques have been developed to measure moisture resistance, compatibility with polymers, and flow properties. The AFT method is presently one of the methods of choice for the Petroleum industry, thus, it is in the pavement communities’ best interest to be on the same page as the oil industry when it comes to specifying the materials.
44	Subtask M2b-1: Measurements of Diffusion in Asphalt Mixtures In part ii), FTIR appears to be a very promising method for determining diffusivity of asphalt binders, however other methods should be considered or at least a literature review performed to evaluate various methods (e.g. electronic impedance spectroscopy). Is there a reason only this method is proposed? Part iv), a combination of experimental results and models may be used to determine the effect of pore pressure. Consideration of available models for determining pore pressures would be useful (e.g. Emin Kutay’s model)	The use of FTIR offers the advantage that both the time dependency related to moisture diffusion through the binder as well as the kinetics of debonding at the binder-solid interface (addressed in Subtask M2b-2) can be captured in real time with very little modification to the test set up. However, in addition to the use of an FTIR, the researchers will also coordinate with other research entities using alternate techniques such as electronic impedance spectroscopy to obtain similar measurements. The subtask was modified to reflect the comment. Applicable section: M2b.

45	Subtask M2c-1: Evaluate Load and Deflection Measurements using the Modified PATTI Test If possible, I suggest using imaging techniques (i.e. cameras, video) to document tensile cohesive and adhesive failure during testing. This will provide information on where failure occurs and hopefully provide images of the exact location of the onset of damage (cracking/crack growth).	In response to this comment, UW started using a video camera documentation to quantify the failure as cohesive or adhesive based on the percentage of the surface failure that has been “stripped” of binder. The research team is also trying to record a video of the sample during testing. This should provide better information on whether the failure is brittle versus ductile.
46	Regarding Contract 00009... I think the research tasks are directed at some very challenging issues related to moisture susceptibility, fatigue, healing, and some Engineered Pavement Materials (EPM). Since we do not have most, if any, of these pieces of equipment in our labs, I cannot comment on the details. But I am very glad to see that Cold Asphalt Concrete is being incorporated in the research, even if it appears to be only a relatively low level lab study. I do think they should at least look into and measure some fatigue properties of the most encouraging mixes (I see fatigue with the HMA and RAP materials, but I don't see it with the CMA.) Thermal properties of CMA should also be evaluated just as the HMA with RAP, since low temp cracking will be critical with these materials and how the binders blend also. Finally, I see no field validation nor any feed into the MEPDG for CMA results, as there seems to be for HMA. With FHWA's emphasis on green and materials friendly to the environment, furthering the development of CMA seems to be underweighted again.	Fatigue testing will be considered as a mixture performance test as specified in the Experimental Design for Subtask E1c-2 of the Year 2 work plan. Field Validation has been incorporated into the year 2 work plan for Subtask E1c-2. The Year 2 work plan provides a much more comprehensive outline of this research project in general.
47	More research into the sound impacts of surfaces seems to be redundant to other work going on in this area and this funding could be better directed to the other parts of the workplan.	The ARC effort is specifically focused on developing a test method to measure sound absorption characteristics of a Superpave Gyrotory sample. Although NCAT has done some of this work, we feel strongly that there is not enough information about this. There is a need to develop standard methods to include noise absorption characteristics of mixes as part of a next generation mixture design procedure. We feel this is achievable and that a model to predict noise absorption characteristics from aggregate gradation and volumetric properties could evolve out of this research. Applicable section VP2a.

48	There are a number of concerns in their thought process behind what they are trying to accomplish with cold mixes. They are starting out with very negative attitudes to cold mixes and there is a lack of understanding as to how they work. Just because water is used they believe that will make the mixes more moisture susceptible. This is mentioned many times and shows the lack of understanding of the process. I only need to reference micro-surfacing as an example. This is the best asphalt material to fill ruts in a pavement and shows excellent rut resistance over time. This is also a cold mix that has probably has the most moisture in the aggregate, added in the mixing process, and also that in the emulsion itself. I have never seen a stripping problem on a micro-surfacing job. Micro-surfacing has about 10-12% air voids yet is virtually impermeable. I would like to see them explain that. There are some issues with how they describe the rheology of the mixes (calling foamed asphalt a cold mix is pretty laughable as well) and the rheology of the Superpave grading. They mention the concern about the lack of short term aging hurting the rut resistance, but failed to mention the positive aspects that are gained by not aging the asphalt. Does the lack of aging actually hurt the rut resistance (see micro explanation above)? They are right to be concerned about the emulsifiers (selection and concentration) and the workability, but I fail to see how they are going to dictate that. I also did not understand the ambient mix issue. It is a good thing that I have a chemical engineering background because that allows me to understand that the thermal mass of a cool, wet or moist, aggregate causes the temperature of the mix to go to the temperature of the aggregate very quickly. We try to adjust the temperature of the emulsion due to the chemical reactivity of the emulsion as it initially mixes with the aggregate. A reactive emulsion, with a warmer temperature than the aggregate, reacts quite differently in a mixture. There are many other comments that I could make but I thought I would throw a few out. Bottom line is that I would hope they would not force cold mix into meeting their hot mix paradigms. This would be a disaster. I can see some good things coming out of the money being sent to WRI, but I hope they get a good focus and have some folks working on this that have some background in emulsions. Things that would be great would be proper residue recovery methods, appropriate mixing chambers, etc.	UW has worked extensively to provide more detail and clarify the research approach in the Year 2 work plan (see Experimental Design for work element E1c-2). It is clear that evaluation of emulsions and cold mixes must be application based. Potential construction/in-service properties of interest are mentioned in the Year 2 work plan. The research team will use the results of review of standards and input from the advisory panel to ensure that industry and academic concerns are addressed.

49	What I think a project(s) should focus on is matching a mix design to a treatment, not lumping emulsion-made products into one category. Rough categories are: Micro-surfacing (A mix design method is already being worked on by Caltrans) CIR FDR Stockpile mixes (made with RAP or virgin aggregate) Central plant mixes Paver-produced mixes Where the mixture is at within the structure should be considered. Will the mixture be a final wearing course (micro-surfacing)? Is it a base mix? Is it for construction or patching? Is it in place (CIR or FDR) or central plant? Will it be driven on before sealing or overlaying? These considerations will influence the tests to perform. Other problems I have with the proposed study: Don't define performance by its comparison to HMA. Consider what properties the mix needs and consider the other items I mention above. Benchmarking to some extent makes sense, but don't over-rely on it. HMA will be stiffer than emulsion-based products - that doesn't doom emulsion mixes to failure. There seems to be a huge reliance on emulsion / binder properties with limited understanding of the mixture and mixture-emulsion interaction. I have huge issues with emulsifier charge selection. It makes sense to coat an aggregate and keep it coated (though 100% coating is not needed for base mixes). However, selection on an emulsion on this characteristic alone is scary. Emulsion content by CKE?? We can estimate better knowing gradation, amount of RAP, and absorption. Mixing and compaction - Steve Cross has performed good work on this for CIR mixtures. ASTM D 7196 is not a moisture susceptibility test. It is a raveling test, which is related to cure. Please accept this feedback in the constructive nature in which it was provided. Our staff can get emotional and frustrated with the hot-mix world trying to address cold mix concepts from a misapplied "reference point".	This approach is outlined in the Year 2 Work plan. The Year 2 work plan specifies that properties for cold mixes will be evaluated using mixture performance tests to evaluate the best way they can be incorporated into pavement designs with the least impact on performance. The work plan was changed to eliminate the need to clarify differences from conventional HMA. International test methods will be reviewed, selected and evaluated to address the following: 1. Emulsion tests 2. Aggregate and surface condition tests 3. Performance tests of complete mixture or application Test methods proposed in Year 1 work plan were only ideas; Year 2 activities will refine these statements. The literature review will include Cross' work. Applicable section E1c-2.

50	Fatigue: Too much attention on binder properties and modeling. Should emphasize mixture and structural effects on development of fatigue.	The work plan almost uniformly distributes effort for material characterization at different length scales; binder, mastic, fine aggregate matrix, and mixture. The mastic and fine aggregate matrix are relatively more important for fatigue characterization because fatigue damage is concentrated in this phase. Furthermore, the mixture testing protocol (task F2c), micromechanics modeling (task F3b) and unified continuum model (task F3c) utilize these material properties to validate and/or predict the mixture and structural effects on fatigue. We understand and appreciate this comment, but we feel that our best approach at properly considering the impact of the “full mixture” is to essentially consider it “piece-by-piece” as we scale up from the binder to the mastic to the full mixture. Applicable section: F2a, F2b, F2c, F3b, and F3c.
51	Engineered Materials: Much of this area is highly speculative or duplicative of work already completed or in progress (e.g., SPT, Superpave, WMA, CMA, and RAP). This money would be better spent on topics not already researched by SHRP, FHWA, NCHRP, and others.	The Consortium work in this area will be coordinated with all other ongoing activities.
52	Technology Development: Good plan, but under funded.	The budget provided for the Technology Development Program Area is an initial estimate. This budget will likely increase as potential products emerge from the Moisture Damage, Fatigue, Engineered Materials, and Vehicle Pavement Interaction program areas.
53	The plan is not clear if each program area will be testing/evaluating a common set of materials. This is alluded to in a number of sections, but it I don’t get the sense that all Consortium members are on board with this. Work on this agreement would have far more value if all elements are using common materials and the testing information is entered in a common database. (For example, the aggregates used in M3a should be the same as those used in M1 and M2.) The plan should clearly state what materials will be used, how they will be maintained/controlled, and how they will be shipped among members. Considering that the MRL recently received a box of cores from WRI with no labeling whatsoever, asking them to put thought into this would not be micro-managing.	A common set of materials will be acquired to link the research. Having all Consortium members exclusively use the same materials is not practical but having a small common set materials is reasonable. A Material Selection Plan is included with the Year 2 work plan. Also a Material Database is defined in work element TT1d and will be available at the Consortium website, www.arc.unr.edu. WRI did not ship a box of unlabelled cores to the MRL. In most cases, other parties were also involved in the previous WRI validation sections and the referenced core samples may have come from someone else. WRI stores and tracks the materials from their validation sites on their own.

54	Any protocols developed under this effort shall be submitted to AASHTO and not ASTM.	Agreed. When it is identified that a standard method of test or practice should be developed from the ARC research, it will be prepared in AASHTO format. ARC team members understand that AASHTO is responsible for adoption of proposed methods and that the ETG's can be helpful in recommending that appropriate AASHTO Subcommittees consider specific test methods and practices.
55	While the ARC states that they believe it is healthy to have multiple parallel activities to achieve an objective, I did not see a concerted effort to coordinate/collaborate on those parallel activities. There also is no process set up to objectively evaluate the parallel efforts midway downstream to see whether one is offering a better approach than the other.	Testing with different approaches is required to verify hypotheses. At the end of the project, one or more of these tests will be finally selected. It is expected that the Consortium Advisory Board with input from FHWA and the ETG's will play a role in the evaluation.
56	A number of statements are made without supporting references. (Example, second paragraph on page 1, first sentence on page 2.)	It is unclear exactly what the reviewer is unfamiliar with in the statements of reference. These areas have been the subject of many reports and publications. The Consortium probably assumed that this work was of more common knowledge and specific references should have been made. The Consortium will gladly provide specific references to the reviewer if they request.
57	In comparing the tests under M1a, what is considered truth?	The DSR test is considered the standard in work element M1a, as the boundary and loading conditions are better controlled than in the case of the original PATTI tests. Most of the boundary conditions and loading and deformation rates will be controlled and/or measured with the proposed modified PATTI methodology. Additionally, researchers expect to find significant differences in the magnitude (while demonstrating similar trends for different material combinations) of interfacial adhesion measured using different test methods such as the thermodynamic approach versus mechanical testing. Nevertheless, testing with different approaches is required to verify hypothesis related to the damage mechanisms. Of course, at the end of the project, one or more of these tests will be finally selected to serve specific purposes in the moisture damage prediction system. In order to address whether or not the measured value of surface free energy is reasonable, the ARC has been using a molecular modeling approach. The initial results are very encouraging because the calculated surface energies based on molecular morphology and composition yield surface energies in a reasonable range of those measured by the WP. Perhaps such an approach can be extended to the aggregate. Or perhaps our approach of determining the surface energy of an aggregate based on the linear additive model approach

		described under work element M3a will be more appropriate. In this approach, we know the surface energies of the individual elements from published data via elemental mapping of the aggregate surface and the linear additive approach, reasonable values of aggregate surface energies can be obtained and compared to the measurements. However, for reasons too complex to address here, the determination of surface energy remains a somewhat relative determination. Therefore, the reliability or repeatability of surface energy measurements becomes more important. Applicable sections: M1a and M3a.
58	How does the work in M3a relate to the work FHWA is funding with ICAR. Check with Meininger for commonality of materials and/or duplication of effort.	The tasks in this program have been carefully designed to complement but not replicate efforts in other programs such as ICAR. For example, the micro calorimeter is being used to analyze the impact of warm mix production temperatures on interfacial adhesion as part of an ICAR funded project. As a result, in the ARC program, this particular task was eliminated (even before year 1 work plan) and more emphasis was placed on evaluation of factors such as mineral fillers on interfacial adhesion. Applicable sections: M3a.
59	Subtask F3c-2: Will the VEPCD model be linked to a fracture model? The description does not specifically state that this is what is considered to be a part of a comprehensive model. If not, it should be. FHWA and NCHRP have already invested a lot into getting the VEPCD to where it is and this is a needed element. In addition to bridging the VEPCD model with fracture, healing should be incorporated into the VEPCD.	As discussed earlier, the continuum model will be coupled with a fracture model. The strength of the fracture model is its ability to deal with damage initiation and localization. The results of the fracture model will be used as inputs in the continuum model. This will be accomplished by changing the continuum model parameters based on the damage predicted by the fracture model. Furthermore, one of the objectives of this project is to develop a comprehensive model that integrates the effect of damage and healing (as well as aging). Researchers from Texas A&M and North Carolina State are working in close coordination with each other to develop models using two approaches. One of these approaches builds upon the existing work cited by the reviewer. However, the apparent redundancy in having two approaches is justified by the researchers because competing approaches offers the ability to cross-examine the validity and results from both approaches as well as to ensure that each approach complements the shortcomings of the other. The complete details of the need for these two approaches and the interplay between them will be presented in forthcoming quarterly reports. Applicable section: F3c.
60	The ARC states that they are planning to use ALF materials. If they don't already have them, I believe those materials are in very short supply, if at all available.	The Consortium is interested in using ALF materials if they are available.

61	The budget for F3 seems too small for what is planned.	The budget for the F3 area is \$2.69M and the Consortium believes this is sufficient. However, as the program proceeds, this will become more clear and if additional resources are needed they can be applied.
62	How is Subtask E2d in the national interest if it is indeed a unique type of thermal cracking? I think the case needs to be made first that this is a different animal.	Thermal cracking is very sensitive to rate of cooling. Studying these conditions gives a better understanding of the mechanism of thermal cracking and the behavior of pavements during thermal cycling. The Year 2 work plan for work element E2d outlines the unique conditions in the intermountain region and how they impact thermal cracking of HMA pavements in this region.
63	Even though they are scheduled for later starts, I question FHWA funding V2a and V2b, when we have trouble keeping our own ALF afloat. There is nothing that precludes ALF from being the APT site, if indeed one is needed under this agreement.	The references to the Third-Scale Model Simulator and the Pecos Test Track are intended to serve to show that these are available for accelerated testing. No specific plans have been developed. This has been clarified in the Year 2 work plan. The Consortium intends to use the ALF as much as possible.
64	Work under V3b should be coordinated with the AASHTO Joint Technical Committee on Pavements and the MEPDG Lead States.	The ARC researchers are in contact with the MEPDG Lead States concerning this effort. Two members of the lead group may join this ARC effort.
65	The ARC should work with a technical writer to provide guidance on formulation of hypotheses, and to maintain consistency and relationships between the different work elements in the report.	The Consortium team believes that the work plan adequately defines the proposed work and is well integrated to the extent possible. Individual hypotheses for each work element are not effective in defining the relationship of each work element to the overall objective of this work area. Furthermore, the researchers have spent the time and effort to think through the overall goal of this research in order to present the philosophy of the research and work plan for the entire duration of this project.

MATERIALS SELECTION PLAN

INTRODUCTION

The goal of selecting a suite of materials (asphalt, aggregates, modifiers) for all Asphalt Research Consortium (ARC) members to use in their research studies is to assure that a wide range of variation in properties is considered and also to provide for the integration and commonality of the research results among the various subtasks and work elements. This type of material selection planning has occurred in the highway material industry since at least the 1950's with the most recent and perhaps the most prominent one being the Strategic Highway Research Program (SHRP) Material Reference Library.

The SHRP Material Reference Library contained eight "core" asphalts (unmodified) that had wide-ranging geologic and chemical properties, represented a range of different production (refining) processes, and also represented major supply sources. In addition to the "core" asphalts, the SHRP Library contained a large array of "non-core" asphalts (unmodified) with other variations and from other sources. The SHRP Material Reference Library also contained a set of 11 different aggregates, four of which were designated "core" aggregates. The goal of the SHRP Materials Reference Library was to provide a common set of materials for all of the researchers that had sufficient diversity in order to investigate whether newly developed test methods could be applied to all unmodified asphalts and aggregates. At this point in time, it is probably universally agreed that the SHRP Asphalt Materials provided an excellent source of variability for unmodified asphalts and aggregates. Although some of the "core" asphalts have been depleted from the SHRP Materials Library, many of the "non-core" asphalts are still available for use and provide a source of asphalts that have unique properties. Similarly, many of the aggregates have been depleted to the point where there is not a large amount of material remain, however, some of the aggregate sources have a useable supply. The SHRP Materials Reference Library, now called the FHWA-LTPP Materials Reference Library (MRL), is currently managed by Sierra Transportation Engineers located in Reno/Sparks, Nevada.

The selection of materials for each work element or task will depend on the hypothesis and objectives of that particular task. However, ARC partners will try to maximize the benefits of findings from each work element or task by utilizing a common set of materials wherever possible. To achieve this, ARC partners propose to develop a library of core materials. The core materials will be selected to represent a diverse range of properties as well as to span across the various geographic regions that fairly represent the U.S. The experiment design for various work elements or tasks by different ARC partners will incorporate (but will not be limited to) applicable core materials. Most of the work elements and tasks in years 1 and 2 are related to development of test methods. Therefore, the materials used at this stage may or may not be the core materials. However, after the development of test or analytical methods, the core materials will be included in various tasks to obtain relevant properties / data and in validation and verification testing. Because of the geographic diversity of the ARC members, they each have familiarity and knowledge of locally and regionally available materials. It is expected that each ARC partner will use locally and regionally available materials that represent different properties in much of the development research and then use the ARC core materials to confirm research

results when methods, tests, and models have progressed toward the application stage. The rationale for proceeding in this way is to minimize the costs associated with large volume sampling and transporting asphalt over long distances. Each ARC member will be responsible for obtaining their own supply of locally and regionally available materials. Additionally, recall that the FHWA-LTPP MRL “non-core” asphalts and some aggregates have reasonable availability and can be used in the ARC research.

Adequate quantities of the core materials will be procured and stored for use during the duration of the ARC research in order to reduce the effect of production and batch variability on the material properties. Quantities of core materials in excess of the requirements of the ARC partners are proposed to be shipped to the FHWA-LTPP MRL in Reno/Sparks, Nevada. All samples will be labeled prior to shipment.

In short, the core materials will be included in the experiment design for validation/verification testing for each test protocol that meets the standards required for development in the ARC program.

CORE ASPHALTS

The Asphalt Research Consortium (ARC) plan for asphalt selection is similar in some ways to the plan used for the SHRP program. It is planned that the ARC will obtain four unmodified asphalts that will be used by the Consortium members. The selection of the four asphalts will be based upon the following criteria:

- geologic/chemical properties
- production volume
- geographic area of use
- potential for significant use in the future

The goal of the selection the four asphalts is to obtain asphalts that have significantly different geologic/chemical properties, represent large supply lines in different areas of the U.S., and are expected to continue to be significant sources of supply.

Quantities and Sampling

After the four ARC asphalts are selected, it is anticipated that the refiners/suppliers will want to provide their own personnel for sampling because of safety and insurance issues. It is hoped that the refiners/suppliers will donate the cost of the asphalt and also the labor cost to sample the asphalts, but if not, the ARC can pay these costs. It is proposed for the ARC to request 200 gallons of each of the four selected asphalts. The ARC will obtain five-gallon sample containers and ship them to each of the four sites. After sampling, each refiner/supplier will be given a list of the quantity of asphalt to ship to each ARC member. It is proposed to ship the remainder of the sample containers to the Materials Reference Library in Reno/Sparks, Nevada.

Sample Identification and Tracking

It is proposed to identify the four selected ARC asphalts as ARC 2008A, ARC 2008B, ARC 2008C, and ARC 2008D. The sample containers that are shipped to the Materials Reference Library (MRL) for storage should be inventoried and tracked using current MRL practices and each container will be labeled prior to shipment to the MRL. Use of these materials by agencies/users outside of the Consortium will need to be approved by the Consortium Advisory Board, until the end of the Consortium contract.

CORE AGGREGATES

As described earlier, the list of core materials is not an exhaustive list of materials applicable for every work element or task. Instead, it is a minimum list of materials that are proposed to be incorporated in the applicable experiment designs of various tasks by ARC partners. We propose to identify at least six different types of aggregates for the core materials library. The following information was used primarily in identifying the six core aggregates: SHRP materials library database (Robl et al. 1991), mineral micro probing studies and surface energy measurement from project NCHRP 9-37 (Little and Bhasin 2006), field mixtures used for moisture sensitivity study in NCHRP project 9-34 (Solaimanian et al. 2007), field mixtures used for TxDOT project 4524 (Howson et al. 2007). Table 1 presents a list of the proposed six core aggregates.

In addition to these six aggregates, the following aggregates are also strong candidates for incorporation in various work elements:

- Granite from Georgia (SHRP designation RA; hard and durable aggregate but it has poor moisture damage resistance; very low specific surface area) (Little and Bhasin 2006).
- Gravel from Ohio (reportedly a poor performer in the field; improvement in moisture damage resistance was observed after blending the aggregate with limestone) (Masad et al. 2006).
- Limestone from Wisconsin (reportedly demonstrated poor moisture damage resistance).
- Aggregates from Kansas and Nevada test sections being monitored by WRI.

Table 1. Proposed List of Core Aggregates for the Asphalt Research Consortium

Aggregate Description and Source	Mineralogy	Surface Characteristics	Remarks
Limestone (from KS)	>97% calcite ⁽¹⁾	Relatively high surface area and relatively high base component of surface free energy compared to other limestones ⁽²⁾	SHRP designation RC; has high porosity
Limestone (from MD)	> 86% calcite ⁽¹⁾	Relatively low surface area and relatively base component of surface free energy compared to other limestones ⁽²⁾	SHRP designation RD; has low porosity and specific surface area
Granite (from CA)	38% quartz, 17% plagioclase, 17% Hornblende, 15% K-feldspar ⁽¹⁾	Relative very high base component of surface energy and very high specific surface area compared to other granites ⁽²⁾	SHRP designation RB; regarded as resistant to moisture damage;
Gravel (from AR) (also used in TX)	Gravel ⁽³⁾ (detailed mineralogical characteristics are not available)	Not available	Used in NCHRP 9-34; aggregate has poor moisture damage resistance as reported by field and 9-34 protocols but it has very high TSR (AASHTO T283); no field or lab problems were reported with the same aggregate after changing the binder ⁽³⁾
Gravel (Gulf states)	Complex mixture of chert and granite (60% quartz) and limestone (15% calcite)	Specific surface area is typical of most common aggregates but it has high base component and affinity of water ⁽²⁾	SHRP designation RL; regarded as susceptible to moisture damage;
Basalt from OR	94% basalt (38% iron oxide, 36% plagioclase, 13% augite)	Average value of surface energy components compared to other aggregates but exceptionally high specific surface area ⁽²⁾	SHRP designation RK; demonstrated mixed performance with respect to moisture damage with different binders ⁽⁴⁾ ;

(1) (Robl et al. 1991)

(2) (Little and Bhasin 2006)

(3) (Solaimanian et al. 2007)

(4) (Western Research Institute 2001)

MODIFIERS

For the ARC projects, it is proposed to include a core set of modifiers that are widely used and are known to have significant impact on performance. In addition, modifiers that are used in other countries or show a significant promise will be included. The modifiers are divided into 3 groups: Modifiers for pavement sustainability (to enhance resistance to traffic and climatic conditions); Modifiers for green pavements (to reduce heat energy during construction and/or allow increased use of RAP); and Emulsifiers. The following points describe the selection and sampling plan for each group:

1. Modifiers for Sustainability Mixtures (Target enhancement of resistance to traffic and environment):
 - a. Polymers: A wide range of polymers are used today in the global paving market. The three that appear to be used widely are SBS, Elvaloy, and EVA. These will be collected as the core polymer modifiers. Although there are multiple producers of these polymers, the chemical composition however appears to be very consistent. A number of suppliers in North America and Europe will be contacted and asked to supply 500 pounds of each of the additives. For the non-core polymers, SBR, low density poly-ethylene, and SEBS will be collected. The amount of 200 pounds of each of the non-core polymers will be requested from suppliers. The opportunity to supply new types of polymers to be included in the project will kept open with no promise to test these materials and each request from any supplier will be reviewed by the Consortium Advisory Board.
 - b. Poly-phosphoric Acid: There are a few grades of this acid used today. Based on initial testing and communication with suppliers, PPA with 105 % and 115 % concentration will be collected for the material library. Suppliers will be contacted to provide 100 gallons of each of the grades.
 - c. Anti-strip additives: Three core additives will be collected. Amine-based, phosphate esters, and lime. Depending on the storage stability of the liquid additives, the amount that will be stored will be determined. For the lime, a total of 500 pounds will be requested from suppliers. The non-core materials will vary depending on what is being used and the interest of suppliers to include there additives in the study.
2. Modifiers for Green Mixtures (Target reducing heat energy required for production and increase use of RAP)
 - a. Warm Mix Additives: The core modifiers will include wax-based and mineral-based additives. Similar to polymers, 500 pounds of each of these additives will be requested.
 - b. Emulsifiers (Cold Mix Additives): It is well known that emulsified asphalts are not very stable and thus selecting emulsifiers to be stored in the material library will require some research and understanding of these additives. The target will be to select the most widely used surfactants and additives used in production of cationic, anionic, nonionic, and polymer emulsions. The selection of the specific additives will be completed during the first half of Year 2 of the project and sufficient amounts of these additives will be collected and stored. The plan is to

produce emulsions at the time of research. The team has already contacted suppliers and is in the process of finalizing commitments for production of emulsions in a laboratory setting when needed for research. It is well recognized that the laboratory produced samples may not be the same as the field produced samples. It is however assumed that for the purpose of work plans, these laboratory produced samples are sufficient for meeting objectives and defining the performance of cold applied asphalt products.

In addition to the above modifiers/additives, ARC members could use in their research ready-made modified asphalts and ready-made emulsified asphalts. These materials will not be considered “core” materials. They are non-core materials and will be used for development of tests methods and validation of certain concepts. For the “core” additives, the UW-Madison team will be responsible for collecting the materials and help in producing the modified asphalts. For the non-core materials, each member of the ARC will be responsible for obtaining their own supply of locally and regionally available modified asphalts or emulsions.

Quantities and Sampling

After the ARC modifiers are selected, it is hoped that the suppliers will donate the cost of the additives and also the labor cost to sample, but if not, the ARC can pay these costs. It is proposed that a reasonable amount of modifiers be stored at UW-Madison and to ship the remainder of the sample containers to the Materials Reference Library in Reno/Sparks, Nevada.

Sample Identification and Tracking

It is proposed to identify the following system is used for sample identification:

1. Polymers: ARCPM001, ARCPM00x...
2. Acids: ARCAM105, ARCAM115, ...
3. Anti-Strip: ARCASM001, ARCASM00x,....
4. Warm Mix Additives: ARCWM001, ARCWM00x,.....
5. Emulsifiers: ARCEM 001, ARCEM00x, ...
6. For non-core modified binders: ARCPMB00x, ARCAMB00x
7. For non-core emulsified asphalts: ARCEMB00x, etc.

VALIDATION SITE MATERIALS

Validation sites consist of field sections that will be constructed during the duration of the ARC to validate the methodologies and concepts that will be developed during the ARC contract. It is anticipated that validation sites will be constructed throughout the U.S. to cover the various environmental zones, materials sources, and traffic distributions. Depending on the methodology that is being validated, some of the sites may include a single test section while others may include multiple field sections.

The involvement of the ARC researchers in the validation sites is expected at all stages of design, construction, and performance monitoring. At the design stage, the ARC researchers will develop the experimental plan and assist the owner agency in the structural and mix design of the test sections. During construction, the ARC researchers will obtain samples from the sites to be tested in the appropriate parts of the ARC research. After construction, the ARC researchers will monitor the performance of the validation sites for the duration of the ARC contract. It is expected that the owner agencies will continue the monitoring of the long-term performance of the validation sites according to the plans developed by the ARC researchers.

Materials samples from the validation sites may be obtained in the following categories:

- Raw Materials
 - Binder
 - Aggregate
 - RAP
 - Additives
- Loose mixtures during construction
 - Plant samples
 - Site samples
- Compacted field samples
 - Cores
 - Slabs

The raw materials samples will be used in the mix design of the validation sites. These materials will be characterized by the appropriate ARC researchers according to the mix design procedure that is being used.

In addition, the samples from all three categories of raw materials, loose mixtures, and compacted samples will also be subjected to additional testing as needed for the validation of the various ARC methodologies and processes. Therefore, the samples from the three categories will be shared among the ARC partners as needed.

The results of the various testing programs on samples from the validation sites and the long-term performance of the sites will be stored in the ARC Materials Database. A very efficient tracking and data checking system will be developed to insure the consistency and integrity of the data from the materials testing programs and performance monitoring.

This effort will follow as closely as possible the system that has been established and implemented by the Long Term Pavement Performance (LTPP) program, i.e. DataPave 3.0. It is anticipated that the ARC Database portion dealing with the Validation Sites will have the following four parts:

- Part I: Project Information
- Part II: Materials
- Part III: Testing Data
- Part IV: Performance Data

Part III will follow the Materials Testing Module scheme of the LTPP Database in DataPave 3.0. Part IV will follow the Pavement Monitoring Module scheme of the LTPP Database in DataPave 3.0.

The following lists the various elements of the four parts.

Part I: Project Information

- Project name
- State or Province
- Project Location
- Project mileage
- Construction date
- Construction information
- Pavement type
- Pavement structure
- Pavement layers
- Pavement materials
- Traffic information
- Environmental information (i.e. Ltpbind)

Part II: Materials

- Asphalt Binder
- Aggregates
- RAP
- Additives
- Loose HMA mixtures
- Compacted samples

Part III: Testing Data

- Laboratory tests that may be conducted:
 - Mix design information
 - Aggregate testing and characterization
 - Binder testing and characterization
 - Dynamic modulus tests to develop master curve
 - Moisture damage characterization
 - Fatigue characterization
 - Permanent deformation characterization
 - Aging characterization
 - Thermal cracking characterization
- Field tests that may be conducted: Deflection, GPR

Part IV: Performance Data

- Date on which the distress surveys were made
- Values for the magnitude and severity of the distresses

The above lists are not meant to be exclusive, they will be subject to revisions based on input from stakeholders and owner agencies as the validation sites are identified and constructed.

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PROGRAM AREA: MOISTURE DAMAGE

This work plan for year 2 of the Asphalt Research Consortium (ARC) was prepared by revising the five year work plan submitted in May of 2007. In that work plan the first year work effort was identified and emphasized within the five year plan. The same general approach was taken here with the second year work being emphasized. According to this approach, the overall work plan was modified in order to accommodate the feedback received from FHWA on the year 1 work plan, reflect accomplishments made in year 1 including revisions based on year 1 accomplishments and findings, and reflect the area of emphasis and milestones for year 2.

INTRODUCTION

The Moisture Damage Process

It is generally agreed among highway engineers that moisture damage in asphalt pavement is one of the most wide-spread and most severe forms of pavement distress that leads to early pavement failure. Moisture damage occurs in all types of climates including hot, dry, and desert climates. Moisture damage may result in stripping, raveling, fatigue damage and/or permanent deformation, i.e., moisture invasion into pavement reduces its structural strength thereby promoting one or more of the above described (visible) forms of distress.

There are, no doubt, multiple mechanisms by which moisture changes (reduces) the structural strength of the pavement. It has been shown that water can etch certain types of aggregate surfaces to disrupt the asphalt-aggregate bond, and it has been shown that asphalt can and will transport water thereby making it available at an aggregate surface. It has been shown that asphalts generally oxidize more rapidly when they are wet than when dry, and further, that oxidation produces small amounts of highly surface-active materials which are capable of emulsifying and/or softening asphalt. There is strong evidence that microorganisms cause damage to the pavement, especially in hot, wet climates, but the severity of this mechanism of damage is not yet clear.

Research Needed to Better Understand and Evaluate Moisture Damage

Numerous test methods have been developed over the past 50 or so years that were designed in order to predict the moisture sensitivity of any asphalt-aggregate mixture. These are empirical tests which, for the most part, do not correlate well with observed moisture sensitivity of the pavement in the field. One test (the Hamburg wheel-tracking test) is so severe that some moisture-insensitive pavement mixtures could fail the test. Another, the Lottman test, is considered by many to be a relatively reliable predictor of moisture sensitivity, but it requires so much time (several weeks) to perform that it normally cannot be used in the pavement design process. Other tests give mixed results. A major problem with all empirical tests, except the Lottman test, is that they do not provide information on mechanisms or causes of moisture damage. Therefore, engineers cannot use the test results to optimize the mixture resistance to moisture damage.

The mission of this program is to elucidate all of the major mechanisms of failure that result from the presence of moisture in the pavement. A most promising concept for investigating the propensity of the pavement to suffer moisture damage is to identify the adhesive bond between the asphalt binder and the aggregate as well as the cohesive strength of the asphalt mastic within the mixture. The basis of the calculation of both adhesive and cohesive bond strengths is the measurement of the surface energies of asphalt and aggregate. The calculations of adhesive bond strength between the asphalt and aggregate can be made dry and in the presence of moisture. Fundamental thermodynamic measurements of surface energy and the subsequent bond strength calculations show that the wetting of the aggregate surface with water is preferred over the wetting of the aggregate surface with asphalt. However, a pressing need is to understand and model the kinetics (rate) of displacement of asphalt by water.

Previous research has shown that aggregate surface energy is the major variable that influences the binder-aggregate adhesive bond. However, this finding is primarily based on measurements of newly prepared mixes, i.e., using new (unaged) asphalts. Clearly, asphalts age in the pavement and consequently the properties of asphalt change and probably vary substantially with age. So, in the future the concept of using fundamental thermodynamic measurements to predict moisture sensitivity must consider aged asphalts. Furthermore, the correlation of thermodynamic stability with the kinetics of displacement must be established. This type of relationship has been established for other chemical systems, so, in principle, it can be done for asphalt-aggregate systems as well.

Moisture damage that leads to early pavement failure consumes a disproportionate amount of highway maintenance funds. Therefore, development of a rapid, reliable method to predict moisture sensitivity of pavement mixtures is imperative. In summary, one of the primary goals of this program will be to develop a system to match asphalts (new and aged), aggregates, and additives to form a mixture that is highly resistant to moisture damage. The process of formulating such a mixture must be expedient enough so that it can become part of the pavement design process. Since surface energy is defined by composition, some portion of a comprehensive system to match asphalts, aggregates, and additives very likely will involve chemical analyses which are very rapid compared to physical tests.

In addition to the selection of materials, this program will target the development of tests and models that will be used to evaluate and quantify the resistance of asphalt mixtures to moisture damage. It is envisioned that the test methods will be similar to those discussed in the fatigue work plan. These tests will focus on the dynamic mechanical analysis of asphalt mastics and fine portion of the mixtures and the repeated dynamic loading of full mixtures. The models will be similar to the micromechanical and unified continuum models discussed in the fatigue work plan. The main difference is that the influence of moisture will be included in the models' parameters.

HYPOTHESES

The development of tests and models that reliably predict the moisture susceptibility of mixtures depends on the identification of the mechanisms that contribute to moisture susceptibility.

Multiple mechanisms are responsible for moisture damage, and the synergistic effects of all of these mechanisms must be considered in an effective model of the process of moisture damage and in developing tests for material and mixture properties as input to the model. The working hypotheses for the development of a methodology to rapidly and reliably predict moisture susceptibility of mixtures is:

The moisture susceptibility of a mixture is determined based on the combined effect of material properties and mixture properties. The material properties must include the composition of the asphalt as well as the changes in composition upon aging of asphalt, the impact of the nature of the water at the aggregate-asphalt interface as reflected by pH levels of the water, aggregate structure and composition and the effect of aging and compositional changes in the aggregate surface over time of exposure to the local environment, surface energies of the asphalt and the aggregate that can be used to assess adhesive and cohesive bond strengths (dry and in the presence of moisture), and the hydraulic conductivity of the asphalt mastic. The mixture properties that must be considered include mixture volumetrics with a focus on air void distribution within the mixture.

OBJECTIVES

1. Identify the mechanisms that contribute to moisture susceptibility of mixture.
2. Understand the contribution of material properties such as aging of the asphalt, pH of the water, aggregate structure, diffusion properties of the binder or mastic, and surface energies of the asphalt and aggregate to the moisture susceptibility of mixes.
3. Understand the contribution of mixture properties such as internal void structure and diffusivity of the mixture.
4. Develop a model of the moisture damage process that is linked to and compatible with the model of fatigue damage being developed by the ARC (work element F3).
5. Develop and validate the utility of tests and models to evaluate the moisture susceptibility of mixtures and quantify the effect of moisture on pavement distress.

EXPERIMENTAL DESIGN

Although it is premature at this point to propose an exact experimental design, the development of an experimental design will be among the initial subtasks of each work element. The experiment design will be communicated to the AOTR before the work is begun for each individual work element, and each experimental design or plan will be approved and/or developed by the project statistician, who is in our case Dr. E. S. Park of the Department of Statistics at Texas A&M. Dr. Park has a research appointment with TTI and is very familiar with the design of experiments in asphalt related research. She has served as team statistician on several asphalt related research projects including NCHRP Project 9-37, "Using Surface Energy Measurements to Select Materials for Asphalt Mixtures".

The TTI team will use the Buckingham PI theorem of experiment design to identify dimensional ratios of material properties to minimize the size of the experiment and maximize the information to be obtained from them. This approach was used successfully in many fields of mechanics such as fluid flow and aerodynamics.

WORK ELEMENTS

Category M1: Adhesion

Work Element M1a: Affinity of Asphalt to Aggregate

Task Lead: Dante Fratta

Introduction

It is well recognized that adhesion and cohesion both between the coarse aggregate and the binder and within the mastic itself are important parameters that contribute to the mechanical properties of bonded materials. The performance of asphalt pavement is deeply related to the presence of moisture and the loss of chemical and physical affinity between asphalt binders and aggregates. In order to evaluate the susceptibility of asphalt pavement to moisture damage, the chemical and physical affinity is measured using loose asphalt mixtures or compacted asphalt mixtures in field-simulated environments. Although some of the tests show results comparable with real field responses, these tests fail to address the structural complexities of asphalt mixtures. Furthermore, these tests provide little insight for the development of analytical analysis.

Exploratory studies at the University of Wisconsin-Madison have shown a good correlation between binder adhesion and cohesion testing results and moisture effects on asphalt mixtures as measured by various tests such as the Hamburg wheel test and the tensile strength ratio (TSR). Recent work at Texas A&M University has also indicated that surface energy measurements and the estimated adhesion and cohesion derived from these measurements can explain some of the moisture damage behavior observed in the laboratory.

This work plan will study the possible relationship between adhesion and cohesion measured directly using a Dynamic Shear Rheometer (DSR) device modified to include the mineral surface and the surface energy measurements collected with the Universal Sorption Device. The intent is to compare the effectiveness of each system and propose a simple and practical surrogate binder-specific test to evaluate affinity of binder (or mastic) to the mineral aggregate surface. This study will be based on the use of simplified specimen geometries based on the DSR device and processed rock disks. Preliminary results using this newly developed moisture damage test have shown the applicability of the methodology to evaluate various testing conditions. Furthermore, the results will be correlated to data from the pull-off (PATTI) test, which is the focus of another work plan of the Consortium. This work plan will also allow building on the progress achieved so far and extend the work to mastics and effects of fillers in general on moisture damage.

Relationship to FHWA Focus Areas

The moisture damage work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property and pavement performance.

Hypothesis

The hypothesis is that the adhesive bond between asphalt binders and aggregates, along with the cohesive characteristics of the binders, are the main factors controlling moisture damage in asphalt-aggregate mixtures. Although it is difficult to predetermine which aggregates will be used with a binder, using model aggregate mineralogies that are typical of aggregates used in practice could allow for better binder selections.

Objectives

The main purpose of this work element is to find and evaluate physical/engineering correlations between mixture moisture damage test results with binder test results collected with the modified DSR procedure for different asphalt mixtures and mastics. In addition, new testing protocols for the evaluation of the potential of moisture damage using the DSR will be proposed based on the results from the planned experimental tasks. This objective will be achieved by carrying out the subtasks discussed here.

Experimental Design

The objective of this subtask will be addressed as follows:

Subtask M1a-1: Select Representative Asphalt Binders and Mastics, and Aggregate Materials (Year 1 start).

The data collected in this task will be shared with other Consortium members to decide on a set of binders, fillers, and aggregates that will be used in this and other Consortium work elements focused on moisture damage. It is expected that the materials will include at a minimum the following material parameters:

1. Asphalt binders:
 - a. Several PG grades: 58, 64, 70, and 76
 - b. Base binders should be from two different sources
 - c. Modification methods: styrene-butadiene-styrene (SBS), terpolymer (Elvaloy), ethylene vinyl acetate (EVA), PPA, and chemical modification
2. Three different fillers:
 - a. acidic (quartzite)
 - b. basic (calcite)
 - c. neutral (such as Ottawa sand)

3. Aggregates:
 - a. Mineralogy: limestone (with two different moisture-susceptibility histories) and granite (with two different moisture-susceptibility histories)
 - b. Angularity and gradation: one coarse aggregate and one fine aggregate with significant differences in their surface areas
4. Conditioning water:
 - a. distilled water
 - b. sodium chloride solution
 - c. calcium chloride solution

Subtask M1a-2. Use the Modified DSR Tests to Evaluate Various Moisture Testing Conditions, Including Control of Rate and Temperature and to Measure Affinity of Asphalts to Aggregates and also Cohesion of Binders (Year 1 start)

In this subtask, the modified DSR device will be used. The testing system consists of composite sample of two cored rock disks (25 mm diameter and 5 mm thickness) sandwiched with asphalt binder (1 mm film thickness). The two disks are glued on the DSR metal spindle and the base metal plate respectively. In the DSR setup, the parallelism is obtained by aligning the disk using the metal DSR metal shafts while the epoxy binder dries. A water cup circumscribing the composite sample is used to allow the sample to be submerged. Shear stress sweeps are then used to measure the change of rheological properties according to increased stress before and after conditioning with water. Results for selected combinations will be also compared to PATTI test results. It is expected that texture may influence the results. For this reason the attempt is made to test all different mineral specimens with the same texture as obtained from the sawing and lapping during specimen preparation. Maintaining a constant texture and changing the aggregate type isolates testing parameters and allows evaluation of the effect of mineralogy in the moisture damage of aggregate-binder systems.

This test setup will be used to collect data for shear stress sweep at different times of conditioning, temperatures, and rates of loading. A wide range of combinations of materials based on the results of Subtask M1a-1 will be included. The results will be analyzed in coordination with Texas A&M University research activities to verify that what is being measured is, in fact, explainable by fundamental surface energy measurements and that the conditions selected for measurements are effective in determining adhesive bond strength as well as cohesive strength.

Subtask M1a-3: Evaluate the Moisture Damage of Asphalt Mixtures with Selected Material Combinations by the TSR Test or an Alternative Test System

Based on the results of Subtask M1a-2, a reduced number of aggregates, binders, water conditioning parameters (time, temperature, media), and testing temperatures will be selected. A detailed work plan will be developed to test moisture damage resistance of mixtures using the most recent protocol for TSR, or any newly developed moisture susceptibility test. A detailed literature review and phone interviews with researchers involved in developing mixture moisture damage tests will be conducted and tests will be selected accordingly.

Subtask M1a-4: Correlate Moisture Damage as Measured by the Modified DSR Test with the Mixture Test Results – Analyze Results on Each Combination and Material

In this subtask, the relationships between the modified DSR test results and the mixture test results will be analyzed using statistical analysis as well as using the surface energy measurements. If meaningful correlations are found, modeling of the relationships will be pursued to give physical/engineering explanations to the correlations and to sort the important variables that should be considered in using asphalt–aggregate tests. In addition, the probability of success of a binder-specific test will be determined and compared to the probability of success of the selected mixture moisture damage test.

Subtask M1a-5: Propose a Novel Testing Protocol

Based on the results of Subtask M1a-4, a final testing protocol will be developed. The cost of modification of DSR devices and the practicality of the test will be analyzed. Manufacturers of DSR devices in the US will be contacted to discuss possible commercialization of the test protocol. Also, selected state DOTs will be contacted to get feedback on the use of these tests. Based on collected feedback, a protocol will be developed in the AASHTO format.

Major Findings from Year 1

During Year 1, the materials and testing conditions for the plan were selected, as shown in table M1a.1. Materials prepared under ARC Work Element F2a are also included in this study. This will help in the investigation of the influence of different modifiers over the moisture damage properties of binders. On the aggregate side of the materials list, three types of filler (acidic, basic, and neutral) have been identified and acquired (sandstone, limestone, and Ottawa sand respectively).

Table M1a.1. Matrix of materials and conditions.

Neat Binders	PG 58-28	Mineral Fillers	Limestone
	PG 64-22		Sandstone
Modifiers	D1101 Kraton SBS		Ottawa Sand
	D1184 Kraton SBS	Conditioning Media	Distilled water
	Elvaloy AM		NaCl (aq)
	Elvaloy 4170		CaCl ₂ (aq)
	PPA 115 (or 105)	Conditioning Time	24 hours
Testing Temperature	19 °C		No Time
	25 °C	Conditioning Temperature	60 °C
Aggregate	Limestone, Granite	Granite	Sandstone

A testing procedure has been developed for this project based on the stress sweep test and tack test developed at UW-Madison. The preliminary conclusions of the year one testing can be summarized as follows:

- The developed modified DSR moisture damage test can evaluate moisture effects of asphalt-aggregate interaction and can differentiate between different materials. The key benefit of this test is that it allows isolation of the physical and chemical effects of the interactions from mixture variables, which commonly confound the evaluation of moisture damage.
- The parameter defined as W/D YSS Ratio (that is, wet-conditioned yield shear strength / dry-conditioned yield shear strength) is sensitive enough to evaluate moisture effects of asphalt-aggregate combinations.
- The use of linear viscoelastic (LVE) G^* as a performance-related parameter is shown to be insensitive to effects of moisture effects between the limestone and sandstone, as shown in figure M1a.1. This raises some concerns regarding the practice of using LVE rheology to evaluate moisture effects.

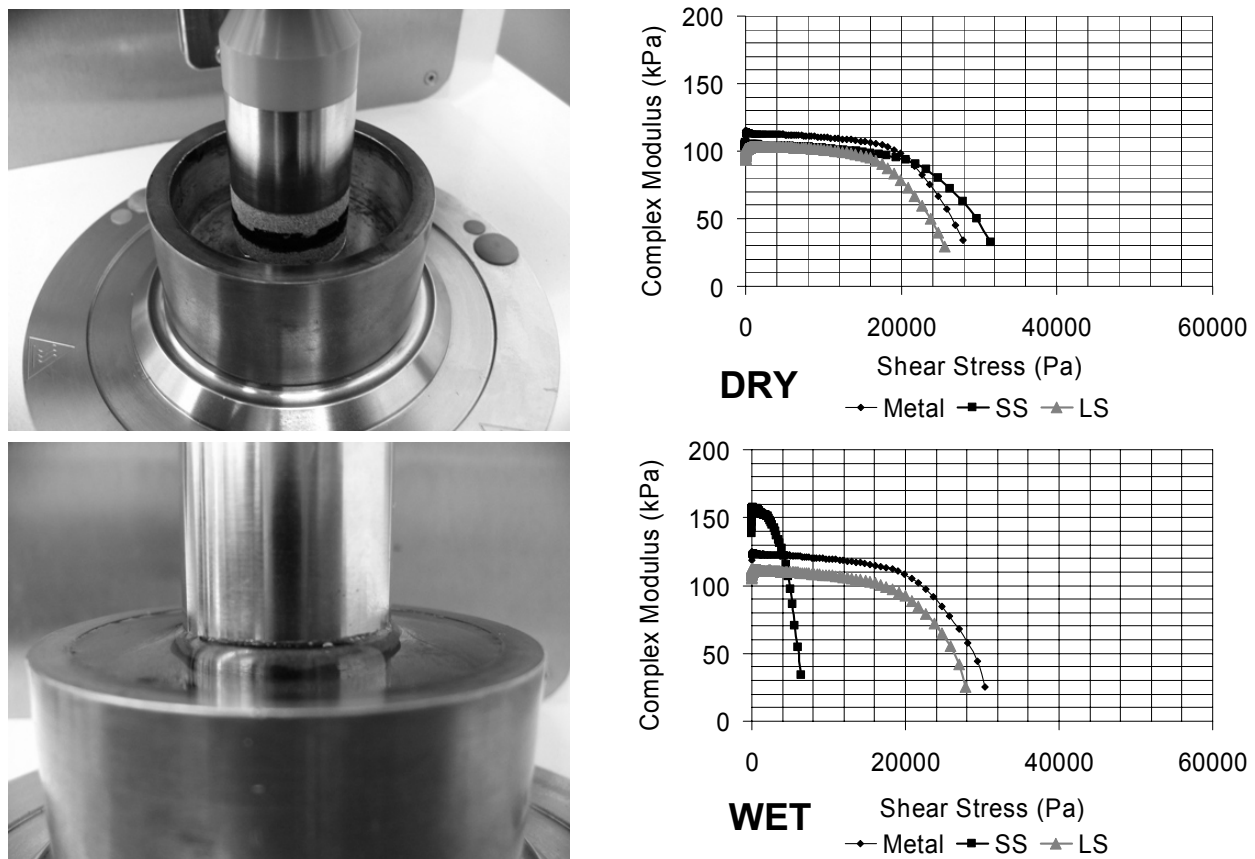


Figure M1a.1. Charts with photos. Representative data for the modified DSR test with wet and dry testing.

Year 2 Work Plan

The test setup will be used to collect data for shear stress sweep at different conditioning conditions, temperatures, and rates of loading. A wide range of combinations of materials will be included. The results will be analyzed in coordination with Texas A&M University research activities to verify that what is being measured is, in fact, explainable by fundamental surface energy measurements and that the conditions selected for measurements are effective in determining adhesive bond strength as well as cohesive strength. Figure M1a.2 depicts the research approach defined for this work element.

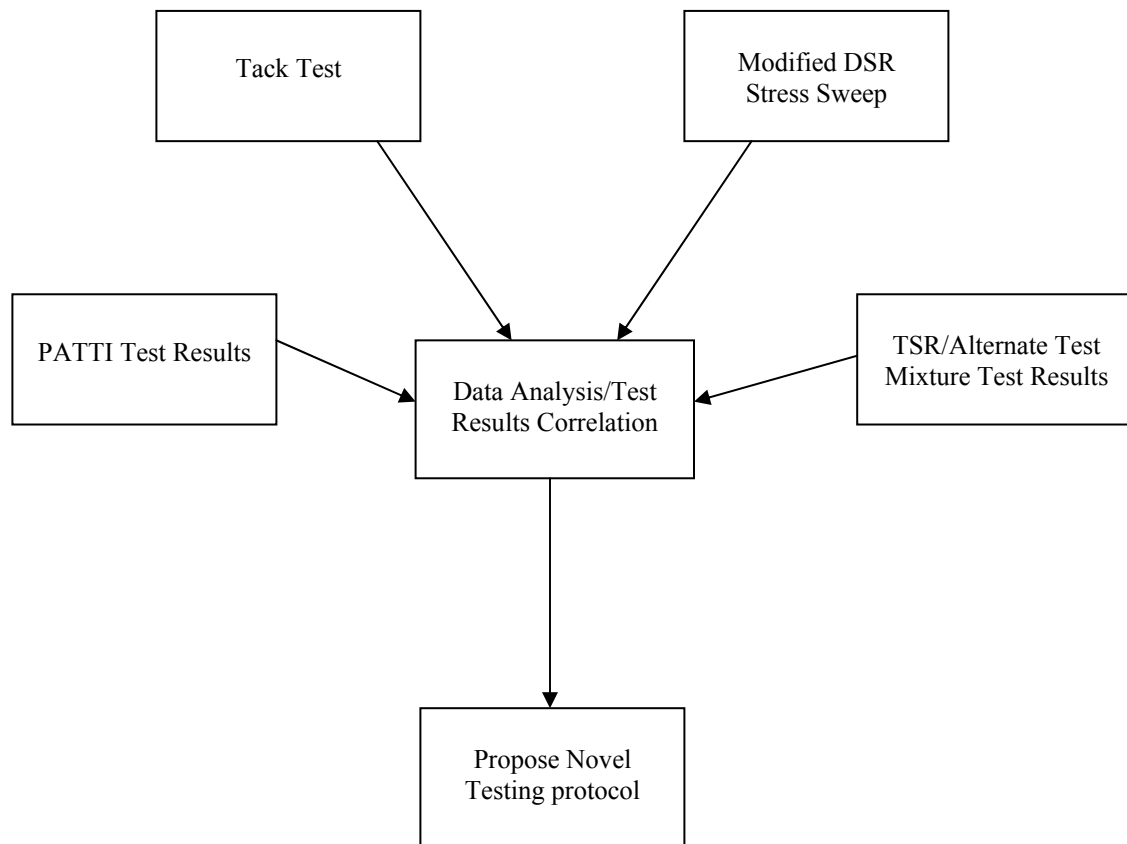


Figure M1a.2. Chart. Flow chart for research approach.

Year 2 Milestones

- Finalize the materials selection for tests in Year 2
- Start conducting modified DSR tests
- Start conducting moisture damage tests on asphaltic mixtures

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Select materials	X	X			
ii. Conduct modified DSR tests	X	X			
iii. Evaluate the moisture damage of asphalt mixtures		X	X	X	
iv. Correlate moisture damage between DSR and mixes tests		X	X	X	
v. Propose a novel testing protocol		X	X	X	

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
i. Select materials	X			
ii. Conduct modified DSR tests	X	X	X	X
iii. Evaluate the moisture damage of asphalt mixtures				X
iv. Correlate moisture damage between DSR and mixes tests				
v. Propose a novel testing protocol				

Budget

The estimated budget for this subtask is \$300,000 over the four years. The work will be conducted by the University of Wisconsin-Madison.

Work Element M1b: Work of Adhesion Based on Surface Energy

Subtask M1b-1: Surface Free Energy and Micro-Calorimeter Based Measurements for Work of Adhesion (Continued in Year 2).

The work of adhesion between asphalt binder and aggregate computed using surface energy components is due to the physio-chemical interactions between these two materials. The presence of active functional groups or chemically active fillers in asphalt binders may also contribute to adhesion by the formation of chemical covalent bonds (Bhasin and Little 2006). The contribution of these reactions to the work of adhesion will be assessed in this subtask using a micro-calorimeter. The objective of this subtask will be achieved as follows:

- Determine surface energy components of modified and unmodified asphalt binders and model compounds that represent functional groups within the asphalt binder using the Wilhelmy plate device and/or sessile drop method (materials may overlap with subtask F1a-3).
- Determine surface energy components of aggregates and representative pure minerals using the Universal Sorption Device (materials may overlap with subtask F1a-3).

- iii. Determine the total energy of adhesion between asphalt binders and aggregates using the micro-calorimeter.
- iv. Evaluate methods to determine work of adhesion from total energy of adhesion measured using the micro-calorimeter to eliminate the contribution of entropy.
- v. Compare total energy of adhesion versus work of adhesion due to surface free energy and quantify contribution of chemical bond formation to interfacial adhesion.

Significant developments were made in the development of a methodology to achieve objective (iii) in year 1 of this project. Preliminary results indicate that the micro calorimeter has very good sensitivity and precision to differentiate between the energy of adhesion of different types of aggregates. The procedure to address objective (iii) and testing of select materials to achieve objectives (i) through (iii) will be undertaken in year 2 of this project.

Subtask M1b-2: Work of Adhesion at Nano-Scale using AFM (Year 2 start)

Thermodynamics and mechanical properties of asphalt binder adhering to aggregate surfaces compounded by the presence of water are directly related to the physico-chemical properties of each of these materials (asphalt, water, aggregate). To date still much is unknown regarding the processes of soft condensed matter wetting in terms of molecular orientation and phase ordering, that fall within the realm of surface entropic events, in even much simpler systems than the system considered here. Nano-technological methodologies, which include the wide range of scanning probe microscopy techniques, presently make it possible to investigate, at and near molecular scale, entropic events that may be crucial to adhesion in asphalt pavements compounded by moisture attack.

- i. Work elements for the present subtask will include investigation via AFM imaging and nano-mechanical techniques of thin-film materials of wet and dry oxidized asphalt binder, mastic samples damaged by freeze-thaw cycle experiments, and core samples, to de-convolute the entropic nature of adhesion mechanisms between asphalt and aggregate, polymer, filler, etc.
- ii. Coordinate with research focusing on the fundamental physical-chemical properties of both asphalt and aggregate, by such methods as flocculation titrimetry with an emphasis on hydrogen-bonding mechanisms, NMR imaging techniques to directly quantify asphalt-water interfacial surface free energy as a function of time and temperature, and characterization of the changes in functional composition of the asphalt binder of both wet and dry aged and unaged binder materials. This may include FTIR microscopy and advanced chromatographic techniques.

Year 2 Work Plan

A detailed work plan will be developed for this subtask at the beginning of Year 2. The work plan will be submitted for review by FHWA and pertinent reviewers.

Subtask M1b-3: Identify Mechanisms of Competition Between Water and Organic Molecules for Aggregate Surface (Continued in Year 2).

Thermodynamic descriptions of the work of adhesion between asphalt binders and aggregates are based on macroscopic properties of these materials. Work at TTI-WRI under funding administered by the FHWA has demonstrated that electrostatic interactions are small but important interactions that affect the impact of moisture on the strength of the aggregate-bitumen interaction. Other molecular-scale interactions that are likely to be important include electron-donor acceptor reactions between aromatic organics and specific surface functional groups on the aggregate surface, hydrophobic interactions, organic hydrolysis reactions, and secondary precipitation reactions between inorganic salts and organic molecules.

Asphalt binders as well as aggregates are highly heterogeneous in terms of their chemical or mineralogical composition. Identification of the molecular mechanisms of interaction between specific organic functional groups and mineral surfaces will allow prediction of the degree of adhesion in heterogeneous materials through an additive mixing model. This subtask will investigate molecular mechanisms responsible for adhesion and debonding using pure representative minerals and model organic compounds (representing functional groups in asphalt binder). This research will couple spectroscopic characterization of water and organic bonding at the mineral and aggregate surface using sum frequency generation spectroscopy, infra-red and Raman spectroscopy, and other microscopic and macroscopic tests. This information is extremely important in order to: i) provide tools by which to make informed modifications to the asphalt binders and/or aggregates that will improve the mixture's resistance to moisture damage, and ii) refine the existing methods used to measure material properties such as surface free energy.

Major Findings from Year 1 for Work Element M1b

A methodology to determine the total energy of adhesion between the asphalt binder and aggregate at room temperature was developed. This methodology was found to be repeatable and sensitive to the type of aggregate used. A brief description of this methodology and some results were presented in the quarterly report (ending September 2007). Work is in progress to evaluate the sensitivity of this methodology (using a micro calorimeter) to different types of asphalt binders and fillers.

In addition to use of the micro calorimeter as discussed above, a dual mode flow adsorption calorimeter was also developed in year 1. The flow adsorption calorimeter measures the strength of the interfacial bond between different adsorbates and adsorbents in terms of the molar heats of reaction. The flow adsorption calorimeter will be used in Subtask M1b-3 to determine the mechanisms of competition between water and organic molecules for aggregate surfaces using model compounds to represent asphalt binder functional groups and pure mineral specimens to represent the most commonly found mineral phases on aggregate surfaces.

Year 2 Milestones for Work Element M1b

- i. Finalize a test protocol in AASHTO format to determine the energy of adhesion between the asphalt binder and aggregate using a micro calorimeter.
- ii. Use the micro calorimeter to determine the energy of adhesion for select combinations of asphalt binders and aggregates as well as certain model compounds that represent functional groups in the asphalt binder and aggregates.
- iii. Continue the use of USD and WP test methods to determine the surface free energy and concomitant energy of adhesion for select materials and model compounds.
- iv. Complete the development of a flow micro calorimeter and conduct initial tests using model organics and minerals.

Work Element M1c: Quantifying Moisture Damage Using DMA

The Dynamic Mechanical Analyzer (DMA) provides a unique tool to quantify the impact of moisture damage in fine aggregate matrix (FAM) of asphalt mixtures. The fine aggregate matrix is comprised of binder, filler, and aggregate particles finer than the #16 sieve. Several field studies and observations have shown that the fine portion of the mixture is responsible for most of the resistance to moisture damage. This phase holds coarse aggregate particles together in an asphalt mixture. The DMA provides exclusive characterization of the FAM by eliminating the complex interaction effects due to the heterogenous air void structure with coarse aggregate particles present in an asphalt mixture. However, since the FAM utilizes fine aggregates that represent mineralogy of coarse aggregates used in the whole asphalt mixture, the test procedure does consider the influence of mineral aggregate–binder interaction, which is at least partially responsible for stripping. The DMA will be used to quantitatively assess the relative impact of:

- i. work of adhesion,
- ii. work of cohesion, and
- iii. provide the rate of energy dissipation, which is an important parameter for the analytical model discussed in section F3c-1 of the fatigue work plan and section M2a of the moisture work plan.

Major Findings from Year 1 for Work Element M1c

All moisture damage analysis methods that have been developed in the past are deterministic. These methods compare mixtures at a fixed number of cycles and they do not take into account material and/or testing variability. A probabilistic method to determine the effect of moisture sensitivity on the fatigue cracking of the fine aggregate matrix (FAM) was developed and evaluated using different materials with known performance. This method takes into account the variability in the results of a laboratory based fatigue test. It can be applied to fracture mechanics based models that were previously developed at Texas A&M to quantify crack growth in the FAM under DMA loading. A brief description with results to demonstrate the application of this method was presented in the quarterly report ending September 2007. The developed probabilistic approach provides comparative analysis of different mixtures based on the probability that these mixtures can survive a certain number of cycles. The results obtained

in Phase 1 have shown that some mixtures can be similar in their performance for a certain number of cycles, but they significantly differ at a higher number of cycles. As such, the analysis provides useful information about the suitability of certain mixtures for a given number of cycles.

Year 2 Milestones for Work Element M1c

The experimental and analytical procedure to evaluate the performance of moisture conditioned FAM specimens is very similar to the procedure used for unconditioned or dry specimens (developed in work element F2b). However, in the case of the former, the FAM specimens are moisture conditioned prior to testing. In year 2 of this project, the final protocol for moisture conditioning FAM specimens will be developed and used with select materials for evaluation using the DMA.

Category M2: Cohesion

Work Element M2a: Work of Cohesion Based on Surface Energy

Work of cohesion within the asphalt binder or mastic is a fundamental material property that dictates the magnitude of work required for crack growth within these materials. Previous research at the Texas A&M University has led to the development of test methods to determine the surface energy components of asphalt binders.

Moisture damage can occur due to disintegration of the adhesive bond between the asphalt binder and the aggregate as well as due to inherent deterioration in the mechanical properties of the asphalt binder or mastic. Deterioration or degradation within either the binder or mastic can be due to fatigue damage, moisture damage or a combination of the two processes. It is important to determine the work of cohesion of asphalt binders or mastics, after the mastic or binder has been saturated with water. This work element will be addressed in the form of the following two subtasks:

Subtask M2a-1: Methods to Determine Work of Cohesion of Saturated Asphalt Binders (Continued in Year 2).

Work of cohesion of asphalt binders is an important material property input for various analytical and micromechanics models. It is important to determine how the magnitude of this material property changes for an asphalt binder that is saturated with moisture and how its can be measured. The objective of this subtask will be to address this question. This will be achieved as follows:

- i. Explore the possibility of using existing static (sessile drop) and dynamic test methods (Wilhelmy plate) to determine the surface free energy and work of cohesion for saturated asphalt binders or mastics. Investigate the limitations or considerations in using such techniques to derive the parameters of interest. The sessile drop method will serve only as an investigative tool to evaluate the effect of saturation on surface properties of the

asphalt binder or mastic. For these specific cases, the sessile drop method offers real time contact angle measurement that may have certain advantages over the Wilhelmy plate method.

- ii. Review methods to determine practical work of cohesion (and work of adhesion) using a combination of mechanical tests with analytical techniques that are based on computation of fracture energy. The efforts in this task will be conducted in close coordination with the efforts in task M2c to avoid duplication of effort. A significant difference between this approach and the objectives of task M2c is that in this case, the objective is to use a combination of mechanical tests and advanced analytical approaches to determine the change in fundamental material properties of the asphalt binder before and after moisture conditioning. For example, Craton and Lakrout (2000) and Shull (2002) have presented extensive analysis on mechanisms of failure of thin compliant films between rigid substrates. This analytical approach can be potentially combined with conventional mechanical tests such as the mandrel, fixed arm and T peel methods (Kawashita et al. 2006) in order to determine the work of cohesion and adhesion for dry as well as saturated asphalt binders. Adhesive failure between the rigid substrates and the asphalt binder can be avoided with the use of special treatments / compatibilizers at the substrate-binder interface that will promote cohesive failure even under saturated conditions. In the absence of such treatments, adhesive or apparent adhesive failures may occur. For such cases, researchers will conduct a detailed analysis of the fracture surface to determine the nature and amount of residual binder on the rigid substrates. This will be accomplished using an Atomic Force Microscope.

This task will be accomplished in coordination with research activities at the University of Nottingham and the Adhesive group of Imperial College. The TTI researchers have a collaborative program with these institutions on research areas that directly focus on experimental measurements of work of adhesion and work of cohesion. This collaborative program includes exchange of researchers between the three institutions. More information about this collaborative program is available on the website <http://acim.civil.tamu.edu/intproject.html>

Subtask M2a-2: Work of Cohesion Measured at Nano-Scale using AFM (Year 2 start)

The thermodynamics and mechanical properties of asphalt binder and cohesive properties compounded by the presence of water are directly related to the physico-chemical properties. Just as with adhesion, cohesive processes of molecular orientation and phase ordering in the native binder fall within the realm of entropic events.

- i. Work elements for the present subtask will include investigation of thin-film materials of wet and dry oxidized asphalt binder, via AFM imaging and nano-mechanical techniques. The emphasis will be on AFM force-distance analysis employing chemically functionalized cantilever tips to investigate components of surface free energy, spin coating techniques to investigate dynamic wetting based on lubrication theory, and micro/nano-contact mechanics approaches based on scanning probe technologies.

- ii. Again, coordination with research of investigation of the fundamental physical-chemical properties, with the emphasis on the asphalt binder, by such methods as flocculation titrimetry with an emphasis on hydrogen-bonding mechanisms, NMR imaging techniques to directly quantify asphalt-water interfacial surface free energy as a function of time and temperature, and characterization of changes in functional composition of the asphalt binder of both wet and dry aged and unaged materials based on spectroscopic techniques including FTIR microscopy.

Year 2 Work Plan

A detailed work plan will be developed for this subtask at the beginning of Year 2. The work plan will be submitted for review by FHWA and pertinent reviewers.

Year 2 Milestones for Work Element M2a

The effort in year 2 for this subtask will be to develop an experimental plan to measure the practical work of cohesion for dry and saturated asphalt binders. The experiment plan will include details of the test setup, the test procedure, and methods of analysis. The ongoing collaboration between researchers from the Texas A&M University and the materials faculty from University of Nottingham, UK, and Imperial College of London will facilitate the development of this work plan. This detailed plan will also address objectives related to work element F1a.

In addition, experiments will be conducted to determine the feasibility of using the Wilhelmy plate device or the sessile drop method in order to determine the thermodynamic or theoretical work of cohesion based on surface free energy measurements. The primary outcome of this task is to determine material properties (viscosity, plasticity) that influence the relationship between the theoretical work of cohesion and the practical work of cohesion.

Work Element M2b: Impact of Moisture Diffusion in Asphalt Mixtures

The equilibrium state and the potential difference between the current and equilibrium state that drives moisture damage in asphalt mixtures can be determined based on principles of thermodynamics. However, in order to combine environmental conditions and external loads into a model used to predict realistic pavement responses, it is imperative to consider kinetics of moisture damage in addition to these thermodynamic properties. The following three components dictate the time required for moisture to cause debonding under given environmental (boundary) conditions: (i) flow and retention of moisture in the pavement structure, which is governed by the void structure of the mixture; (ii) diffusion of moisture from voids to aggregate-binder interfaces, which is governed by the diffusivity rates of the binder or mastic films; and (iii) debonding of aggregate-binder interface, which is governed by the thermodynamic potential and kinetic rate constants at the interface. The various subtasks within this work element will be designed to formulate the three components listed above into a form that can be implemented in a numerical scheme to simulate moisture damage in asphalt mixtures under any given environmental boundary conditions and loads.

Subtask M2b-1: Measurements of Diffusion in Asphalt Mixtures (Continued in Year 2)

Diffusion of moisture through air voids, asphalt binder or mastics is an important rate controlling phenomenon in the moisture damage process. There is a lack of repeatable and reliable methods for measuring this important property. This subtask will develop experimental methods to measure moisture diffusion in asphalt mixtures and their constituents. The following steps will be carried out in this subtask:

- i. Identify and develop test methods to measure diffusion of moisture through asphalt binder / mastic films and asphalt mixtures. Based on previous experience, the use of psychrometers to measure relative humidity (or suction) appears to be a very good candidate. The experimental results will be modeled using a composite model that considers that diffusion in the binder, air voids and aggregates in calculating the diffusion in the asphalt mix composite. This model considers the percentage and tortuosity of each of the mixture phases.
- ii. Determine diffusivity of different types of asphalt binders and mastics. Analytical techniques such as Fourier Transform Infra-Red (FTIR) have been used in the past to determine the rate at which water displaces the asphalt binder from its interface with standardized surfaces (Nguyen et al. 1996). The attenuated total reflectance (ATR) technique is used with FTIR and allows the interface to be subjected to a variety of boundary conditions. Using different controlled thicknesses of asphalt binder films or mastics, one can determine the rate of diffusion of moisture through the binder or mastic films. The use of FTIR offers the advantage that both the time dependency related to moisture diffusion through the binder as well as the kinetics of debonding at the binder-solid interface (addressed in Subtask M2b-2) can be captured in real time with very little modification to the test set up. However, in addition to the use of an FTIR, the researchers will also coordinate with other research entities using alternate techniques such as electronic impedance spectroscopy to obtain similar measurements.
- iii. Determine the absorption-desorption-absorption rates for different asphalt binders. In other words, determine the diffusivity of the asphalt binder after subjecting it to one or more cycles of absorption and desorption. The hypotheses here is that diffusivity rates of dry asphalt film are significantly smaller than diffusivity rates of an asphalt film that has been subjected to one full cycle of moisture absorption and desorption. The ATR-FTIR technique, as described in (ii) above will be used to make these measurements.
- iv. Determine the effect of pore pressure on the diffusivity rates for asphalt binders / mastics. The action of external loads can induce pore pressure in entrapped water, especially if the mixture is in the pessimum void structure range. This pore pressure due to external loads can accelerate diffusion of the moisture through the binder or mastic film. The ATR-FTIR technique as described in (ii) above will be used to make these measurements on the binder and mastic films. Due to equipment limitations, the magnitude of water pressure that can be allowed on the binder or mastic film might not be equivalent to that of the pressure exerted due to wheel loads on the pavement. However, within certain limits, the impact of pore pressure on the diffusivity constants of the binder or mastic can be easily estimated using this test technique.

Subtask M2b-2: Kinetics of Debonding at the Binder-Aggregate Interface

This subtask will evaluate factors that influence kinetics or rate of debonding after moisture reaches the aggregate-binder interface. The purpose of this subtask is to verify the hypothesis that once water is at the binder-aggregate interface, the rate of debonding is mostly influenced by the thermodynamic potential for water to cause debonding (determined using surface energy components) and micro texture of the aggregate surface. This will be accomplished as follows:

- i. Determine and compare rate of debonding for different binder-aggregate interfaces as a function of the thermodynamic potential for moisture damage determined using surface energy components. The aggregate surfaces will be prepared to have uniform roughness.
- ii. Determine influence of aggregate surface texture or specific surface area (sub micron scale) on the rate of debonding for different binder-aggregate interfaces.

Major Findings from Year 1 for Work Element M2b

Significant advances were made in the development of a method to measure the rate of diffusion of moisture through the asphalt binder. The FTIR-ATR cell was used to make these measurements. A simple gravimetric method was also used to determine the rate of diffusion of moisture through FAM specimens. A more detailed description of the test methods is presented in the quarterly report ending September 2007.

A method was developed for measuring moisture diffusion in FAM and full mixtures using psychrometers. The method was applied for mixtures with different binder sources, aggregate sources and volumetrics. The current work focuses on modeling the mixture diffusion using a composite model.

Year 2 Milestones for Work Element M2b

- i. Determine the diffusivity of water through select asphalt binders using the FTIR and gravimetric methods and compare results from other techniques where available.
- ii. Determine the rate of debonding by water at the binder – solid interface for select systems and compare it to the thermodynamic potential based on surface energy measurements.
- iii. Predict mixture diffusion using a composite model based on the diffusion of the individual constituents and distribution (percentage and tortuosity) of these constituents.

Work Element M2c: Measuring Thin Film Cohesion and Adhesion Using the PATTI Test and the DSR

Task Lead: Codrin Daranga

Introduction

In order to evaluate the susceptibility of moisture damage within asphalt pavements, the chemical and/or physical affinity is commonly measured with loose asphalt mixtures or

compacted asphalt mixtures in a field-simulated environment. Although some of these tests show results comparable with real field data, the actual mechanism of moisture damage and the role of components in the failure response cannot be sorted from these tests. Therefore, there is significant room for improvement, mainly because of the structural complexity of asphalt mixtures and the confounding effects that result from it. The difficulty of accurately measuring the role of the various variables (e.g., binder cohesion, adhesive bond, airvoids, aggregate surface characteristics and shape, etc.) makes an analytical approach for selecting materials that will resist moisture damage very complex. The use of simplified testing systems that can separate the contribution of different components under the effect of water could provide a more effective method for moisture damage analysis and prediction of damage risk. Among the many ideas proposed in the last 10 years, two systems show the greatest potential for satisfying the simple analytical approach criteria. One of these is the Pneumatic Adhesion Tensile Testing Instrument (PATTI) and the other is the testing procedure developed using a Dynamic Shear Rheometer (DSR) to measure cohesive strength (Cho and Bahia 2007).

The PATTI device was initially developed by the National Institute of Standards and Technology (NIST) and was utilized by Youtcheff and Aurilio (1997) at FHWA to evaluate the adhesive loss of asphalt-aggregate systems exposed to water. The PATTI device is advantageous for several reasons: it allows the use of aggregate surface, the sample specimen is conditioned in water after applying asphalt between the pull stub and aggregate surface, and the test allows one to observe the failure surface to define adhesive versus cohesive failure. In addition, the device is low-cost, simple, and well described by an ASTM standard. The PATTI device and methodology are therefore considered as a good testing procedure for measuring moisture damage properties of binders.

The DSR thin film cohesion test was developed more recently based on concepts widely used in paint and adhesive fields (Kanitpong and Bahia 2003). The main advantage of using the DSR test is the very precise control of factors such as temperature, film thickness, and rate of loading. The DSR test allows precise measurements of time-based responses such as load, deflection, and rheological properties. The DSR test also permits the application of different loading paths (e.g., shearing and uniaxial loading). The initial testing data show the potential of the methodology for measuring factors affecting moisture damage for a wide variety of testing conditions. For example, combining different aggregate-made discs and varying the binder film thickness will yield more insight on the binder's cohesive properties and aggregate-binder adhesive responses.

Moisture damage is also affected by polymer modification. Using these new measurement systems, modified asphalt cements have shown to have better cohesion and adhesion properties than their non-modified counterparts. Better understanding of the influence of different types of polymer modifiers on the binder's cohesion properties, as well as the interaction with mineral surfaces of the different chemical modifiers, is desired. This better understanding will help develop enhanced testing methods and the selection of procedures for improving the resistance to moisture damage of pavements.

Moisture damage is also known to be affected by mineral fillers. The effect of fillers on moisture damage has not been explored carefully. Mineral filler constitute a major portion of the

surface area of the binder- mineral aggregate interface. These two systems are suitable for testing cohesion and adhesion of mastics and thus could give some specific insight of effects of fillers.

Relationship to FHWA Focus Areas

The moisture damage work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property and pavement performance.

Hypothesis

The moisture damage in asphaltic mixtures is a very complex mechanism and is affected by many variables. The use of simplified testing systems that can separate the contribution of different components under the effect of water could provide a more effective method for moisture damage analysis and prediction of damage risk.

Objectives

This work element includes objectives focused on the PATTI and DSR thin film rheology test. It is expected that both of these systems will be evaluated to define factors that have significant effect on responses:

- Modification of the pull-off test (PATTI) to allow measurement of load, deflection and control film thickness. The cost and practicality of the modification as well as the precisions will be evaluated.
- Further development of the DSR thin film test by evaluating the following factors:
 - The effect of different pulling rates on the PATTI and DSR responses.
 - The testing temperature plays an important role in adhesion and cohesion. The effects of testing temperature on the results will be quantified and used to define role of climate on moisture damage. The testing temperature will also help in establishing relationships between different mixture testing temperatures.
 - Changing loading frequencies in the shear mode will have an important effect on the cohesion and adhesion test results and it will better simulate different traffic speed.
 - The temperature during the water conditioning plays an important role in effect of water on cohesion and adhesion of binder or mastic.

Experimental Design

The objective of this subtask will be addressed as follows:

- i. Evaluate Load and Deflection Measurements using the Modified PATTI Test (Year 1 start). The pull-off test is a simple and efficient way to investigate the combined effect of cohesion and adhesion properties of binders and changes due to moisture effects.

However the test in its current format is not able to produce stress-strain curves. It measures maximum pressure which can only be used as an index. This task will focus on evaluating the possibility of modifying the pull-off test so that it would produce load vs. deflection responses. This modification will enable the calculation of the total energy to failure and the study of how the failure process by identifying trends in the behavior of the binder during loading. The differentiation between cohesive and adhesive failure will also be studied. A consideration of a metal or glass surface that allows full adhesion could be used to measure cohesion. The dry and wet testing on aggregate surfaces could be used to study effects of aggregate interactions with or without water conditioning. Imaging will be used to quantify the failure as cohesive or adhesive based on the percentage of the surface failure that has been “stripped” of binder. This should provide better information on the type of failure.

- ii. Evaluate Effectiveness of the Modified PATTI Test for Detecting Modification Effects (Year 1 start). Modified binders will be prepared using different “base” virgin and modifiers. Each “base” binder will be modified using the selected chemical additives. Preliminary testing at the selected conditions will be conducted in this task. The results will validate the applicability of the test methods to modified asphalts and their effectiveness in measuring the contribution of modifiers in the cohesive behavior of binders. The results will lead to the selection of a reduced number of combinations to be tested in the following task.
- iii. Validation of the Modified PATTI Test using Results from DSR Testing. Selected samples of the modified and unmodified binders tested in the previous task will be tested using the DSR instrument. This testing will be used to validate the results from the modified PATTI test and to indicate which modification is necessary and which is not to measure important in the evaluation of binder cohesion and aggregate-binder adhesion behavior. The tests will be structured to investigate the influence of the temperature of testing, the conditioning temperature, and the pulling rate. In addition, the comparison between the axial pull-off testing and shear stress sweep will be included in the testing.
- iv. Testing of Mastics Using Modified PATTI and DSR Tests. The same testing protocol used for testing binders will also be used for the testing of selected mastics. The results will identify suitability of the test systems to binder-filler mastics.
- v. Commercialization and Practicality Evaluation of the Modified PATTI Test. The increase in cost of the PATTI device and the information gained by the modification will be analyzed to make a recommendation regarding the use of the test for studying thin film cohesion and affinity of binders and mastics to aggregates. In this task, manufacturers of the PATTI device will be contacted to explore the cost and commercialization possibilities the modified PATTI test. State DOTs and consulting labs will be contacted to collect feedback about the practicality of the test system and the merits of standardizing the modified PATTI test for the evaluation of binder cohesion and aggregate-binder adhesion. Presentations at the binder and mixture ETGs will be prepared and delivered to collect feedback from experts. The feedback will be summarized and used to make modifications in the developed system.
- vi. Analysis and Recommendations for the Modified PATTI Test. The objective of this task is to analyze experimental data and evaluate the responses collected during the various

tasks to make recommendations regarding the modified PATTI test and its applicability to moisture damage of asphalt mixtures. The results of binder and mastic will be shared with other work elements to evaluate the relationship to surface energy and the results of the Sorption Device.

Major Findings from Year 1

During year one, the materials and testing conditions for the plan were selected and are shown in table M2c.1. A testing plan was also developed and the proposed tests are shown in table M2c.2.

Table M2c.1. Matrix of materials and conditions.

Mineral surfaces	Granite	Conditioning environment	Air
	Limestone		0.5 M NaCl (aq)
	Glass Plate		0.5 M CaCl (aq)
Binders	neat PG58-22 binder		
	PG64-22 SBS-modified binder		
	PG64-22 Elvaloy-modified binder		

Table M2c.2. Proposed tests on asphalt binders and mixes.

Testing technique	Modified PATTI	Binding temperatures	Two (65 and 135 °C)
	DSR	Condit. temperature	One (65 °C)
Mineral surfaces	Three	Testing temperatures	Two (10 and 25 °C)
Binders	Three	Pullout rates	Two (slow and fast)
Conditioning environments	Three		

Since the start of Year 1 work plan, the team has extensively evaluated the modification of the traditional pullout test methodology and the proposed modification on the measured parameters. Major findings include:

- Design and build the testing component. The different component of the modified PATTI test methodology were selected and put together. These components include an 8-channel data acquisition card, pressure transducer, displacement transducer and support for the pullout stub, and displacement transducer frame. The system was put together and testing and evaluation began.
- Design of the test methodology. The proposed testing methodology was developed considering all testing parameters and condition. The step-by-step methodology is detailed here.

Binder preparation. Put the binder in the oven at 135°C until it becomes fluid. Stir the hot binder in one direction to homogenize the temperature in the binder. Pour the molten binder in a clean silicone mold. Dress the binder as shown in figure M2c.1 and let the binder cool down to room temperature.



Figure M2c.1. Photo. (a) Prepare clean silicone molds. (b) Pour the molten binder. Let the binder to cool down to room temperature (approx. one hour). (c) Dress the binder with a heated putty knife (Picture by Kitae 2005).

Aggregate surface preparation. Place the flat surface of the aggregate to be tested on a hot plate or oven set at the required preparation temperature (typically 135°C). Leave the aggregate surface on the plate until the surface temperature of the aggregate equilibrates with the temperature of the hot plate. The aggregate surface temperature is measured with an infrared thermometer. At the same time, place the bottom of the pullout stub on the surface of the hot plate or in an oven set at 135°C. The stub needs to be heated to allow binding to the asphalt binder.

Place the binder onto the heated aggregate surface. Remove the aggregate from the hot plate or oven (however, keep the pullout stub on the hot plate). Measure the aggregate surface temperature with the infrared thermometer (this is the preparation temperature). Place the silicone mold face down on the heated aggregate surface so that the binder makes contact with the heated aggregate.

Remove the silicone mold. Let the binder-mineral system cool to room temperature and carefully remove the silicone mold (to facilitate the binder demolding, place the silicone mold and binder in a refrigerator for about 5 minutes). The silicone mold should be easily removed and the binder must remain on the aggregate surface. If the binder peels off from the aggregate, repeat procedure from step 1 using a fresh mineral surface.

Attach the pullout stub to the binder. Place the split pull-off stub support around the binder. Remove the pullout stub from the hot plate and rapidly place it on the center of the pullout stub support (see figure M2c.2). This support leaves a binder thickness equal to 0.5 mm. Let the system pullout stub cool down until it reaches the ambient temperature.

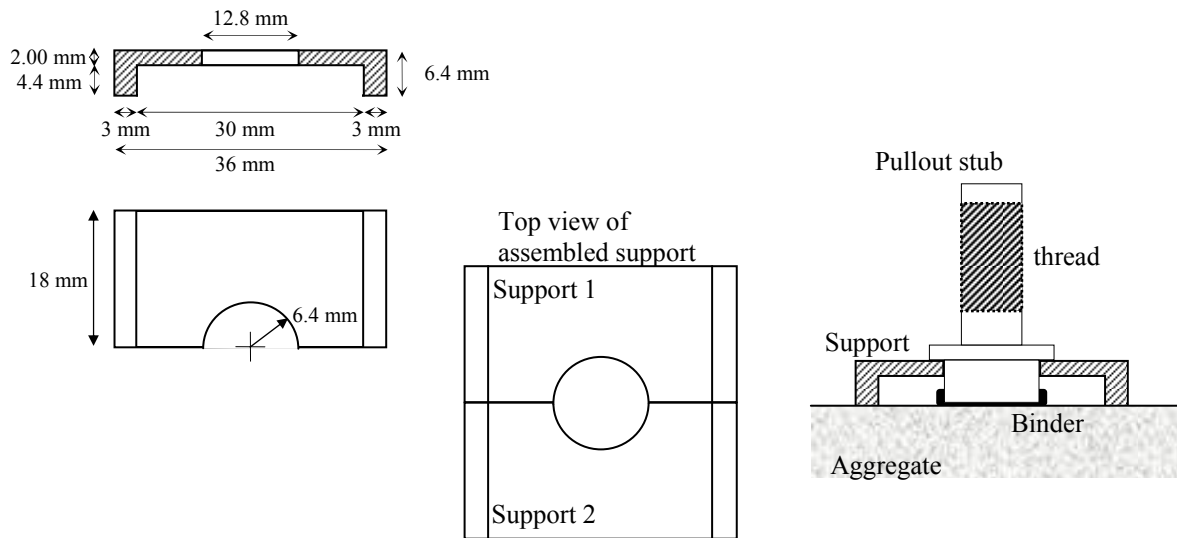


Figure M2c.2. Diagram. Details of the split pullout stub support and assembled aggregate, binder, support and pullout stub.

Binder mineral conditioning. Submerge the assembled aggregate-binder-pullout stub system in a temperature-controlled water or salt aqueous-solution bath for a predetermined period of time. Once this process is complete, the aggregate-binder system is ready for the pullout testing. If the system will be tested without conditioning, let the system equilibrate with the testing temperature for at least one hour.

Setting the pullout test. Place the aggregate, binder and pullout system on a bench top for ambient temperature testing or in an environmental chamber for temperature control testing. Separate the split support and use them as spacer (figures M2c.3 and M2c.4). Assemble the PATTI test pressure ring (on top of the spacers), silicone gasket, and the pressure line to the PATTI pressure controller. The added spacers allow a pullout deformation of about 6 mm (at total strain of 1200%). The operation includes the following procedures.

- Screw the self-aligning bearing plate following the procedure described in ASTM standard D4541.
- Set the three-leg LDVT frame on top of the mineral rock and align the high resolution LVDT on the top of the pullout stab. The modified PATTI test also includes a pressure transducer to monitor the pressure history during the test (see figures M2c.4 and M2c.5).
- Connect the pressure transducer and LVDT to the data acquisition card. The recorded data allow for the reconstruction of the deformation-force history and the evaluation of the energy dissipated during the pullout test.
- Set the pullout rate in the PATTI pressure controller; the test is ready to begin.

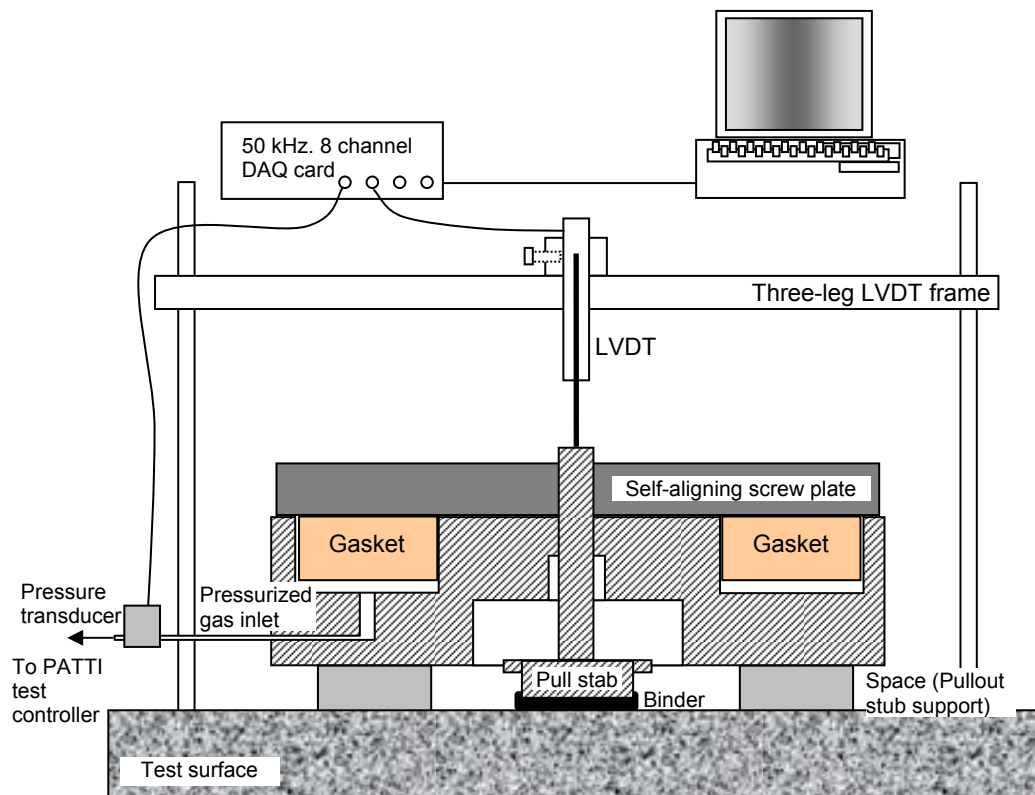


Figure M2c.3. Diagram. Schematic of the complete ensemble modified PATTI test.

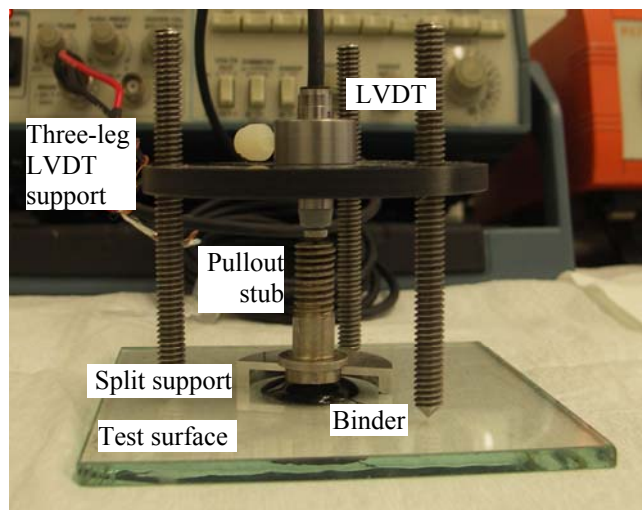


Figure M2c.4. Photo. Picture of the ensemble modified PATTI test setup (the PATTI pressure ring is not shown).

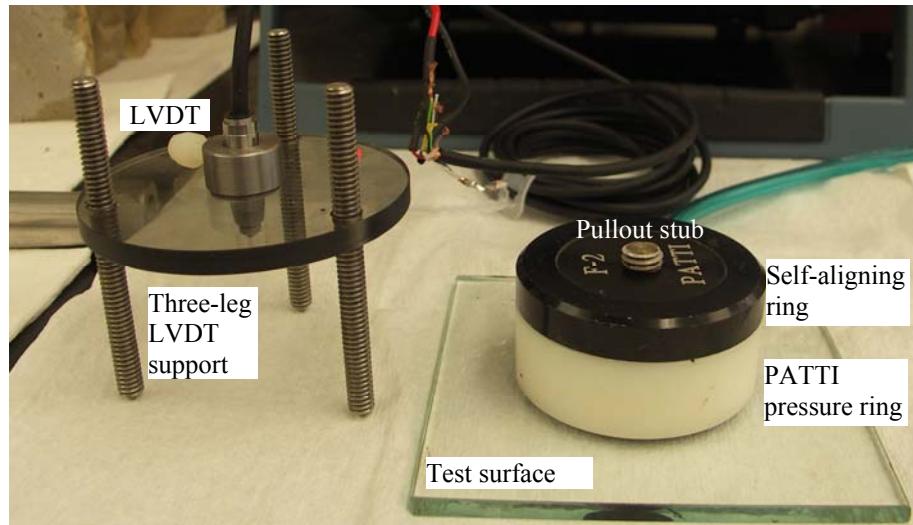


Figure M2c.5. Photo. Picture of the ensemble modified PATTI test setup (the PATTI pressure ring is not shown).

Run the pullout test. Set the pressure rate in the PATTI pressure control panel. Run the test by applying pressure to the line. The data acquisition system will collect the data post-failure. Once the test is completed, remove the pullout stab and take a picture of the failure surface to document if the failure was cohesive or adhesive. Use the deformation-load history data to evaluate the energy dissipated during testing and the type of failure (ductile or brittle).

- c. Evaluation of the modified testing methodology. Several controlled tests were run to calibrate and validate the proposed methodology. These tests include:
 1. The calibration of the pressure transducer and linear variable displacement transducer and linear potentiometer
 2. The calibration of the pressure rate applied by the PATTI pressure panel
 3. The evaluation of the relative location of the pressure transducer to reduce the air pressure losses
 4. The initial evaluation of the binder-aggregate response

Initial set of results are presented in figures M2c.6 and M2c.7.

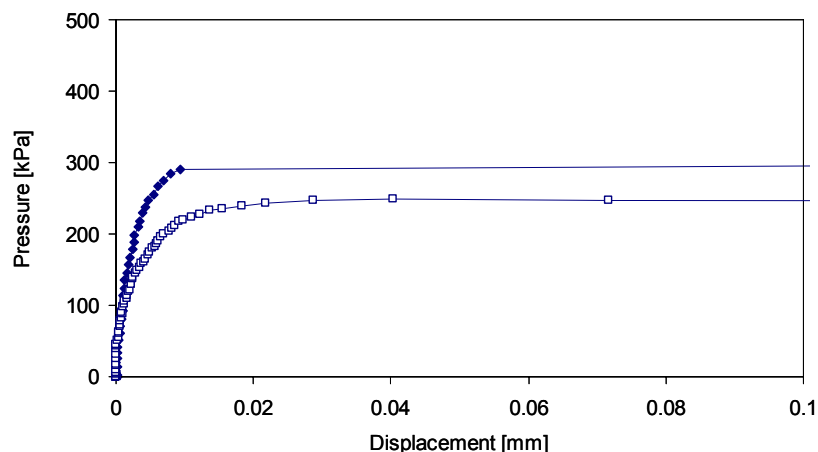


Figure M2c.6. Chart. Typical modified PATTI test results: PG 58-22 neat binder, glass plate test surface and slow and fast pressure rates.

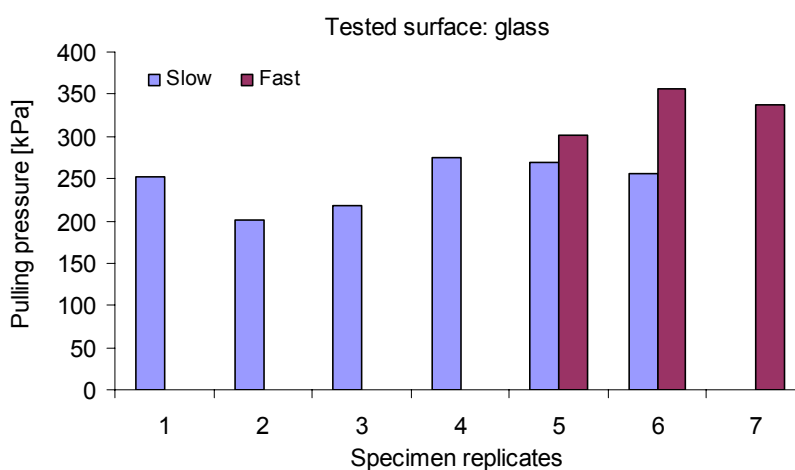


Figure M2c.7. Chart. Summary modified PATTI pulling pressure test results: PG 58-22 neat binder, glass plate test surface and slow and fast pressure rates.

Year 2 Work Plan

During Year 2, the research team at the University of Wisconsin-Madison will complete the validation of the modified PATTI test methodology and will further evaluate the results by comparing binder-aggregate system behavior with results using the DSR testing methodology. Additional tests will be performed using different mastics. If the methodology is validated, efforts will be placed on evaluating moisture damage with the modified PATTI test.

The analysis methodology proposed is a statistical evaluation of the tested parameters. PATTI tests have problems with repeatability: the evaluation of the maximum pullout pressure, the

energy dissipated, and failure type (adhesion vs. cohesion) variability during testing allow identification of spurious events and affect the quality of the data. Once the validity of the testing results is confirmed, material behavior will be evaluated. Moisture damage studies will be performed to evaluate material behavior with the proposed new methodology. Emphasis will be placed on the evaluation of the conditioning environment and surface mineralogy on the strength and failure mechanism of the aggregate-binder system.

Figure M2c.8 depicts the research approach defined for this work element.

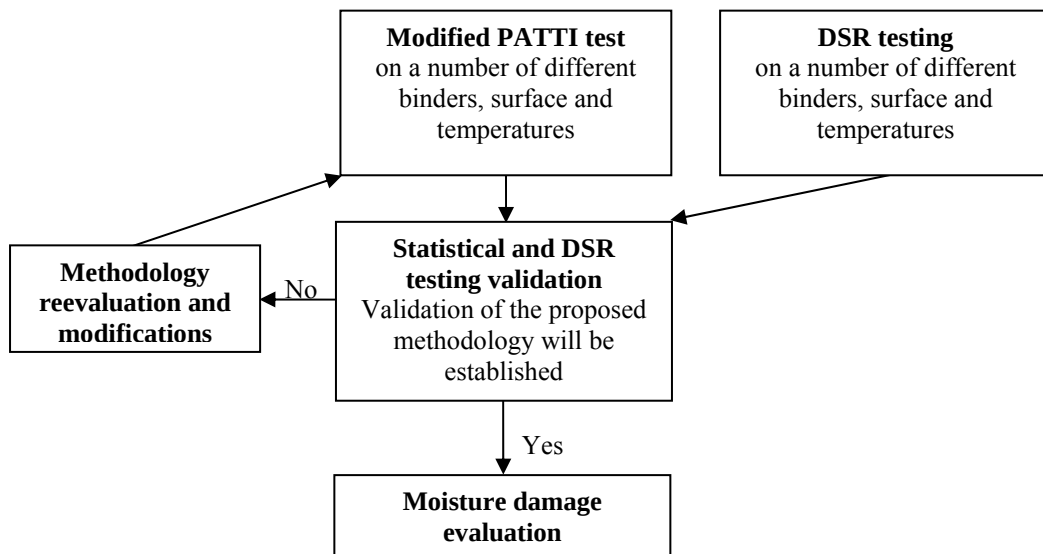


Figure M2c.8. Chart. Flow chart for research approach.

Year 2 Milestones

- Complete report on review of literature for rutting of asphalt binders and asphaltic mixtures
- Finalize material selection and experimental plan
- Conduct the proposed tests on asphalt binders and prepare for mix tests
- Develop framework for emulsion selection and design of surface treatments

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Evaluate load and deflection measurements using the modified PATTI test	X	X			
ii. Evaluate effectiveness of the modified PATTI test for detecting modification	X	X			
iii. Conduct testing		X	X	X	
iv. Analysis & interpretation		X	X	X	
v. Standard testing procedure and recommendation for specifications		X	X	X	

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
i. Evaluate load and deflection measurements using the modified PATTI test	X			
ii. Evaluate effectiveness of the modified PATTI test for detecting modification	X			
iii. Conduct testing	X	X	X	X
iv. Analysis & interpretation	X	X	X	X
v. Standard testing procedure and recommendation for specifications				

Budget

The estimated budget for this subtask is \$350,000 over the four years. The work will be conducted by the University of Wisconsin-Madison.

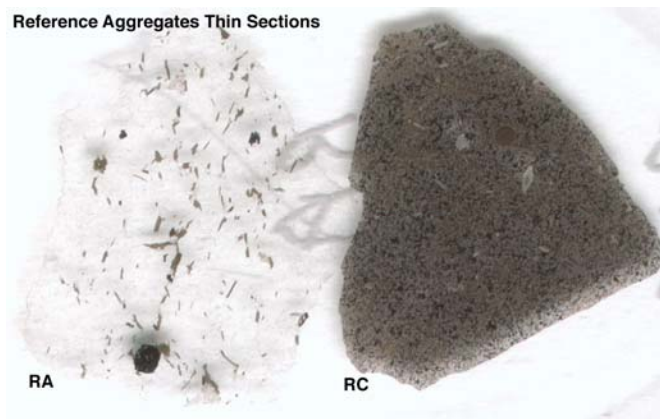
Category M3: Aggregate Surface

Work Element M3a: Aggregate Surface

Physical and chemical properties of aggregates at the macro and micro scale influence the performance of asphalt mixtures. These properties control the nature and durability of the bond between the aggregates and the bitumen in wet and dry conditions and its resistance to moisture induced damage and fatigue cracking.

Recent research by Little and colleagues (Little and Bhasin 2006) has shown that surface energy of the aggregate-bitumen interface is a reliable predictor of engineering properties of the asphalt mixture. Current understanding of the aggregate and bitumen properties that control and shape surface energy is limited, limiting our ability to *a priori* predict surface energy of any given aggregate-bitumen combination. We propose to develop a predictive model of aggregate surface energy based upon a linear additive model of the surface energies of individual minerals that

compose the aggregates. While aggregate properties are very heterogeneous, most aggregates are composed of a relatively few minerals (table M3a.1). The image to the right shows thin sections of two common aggregates. The images clearly show the mineralogical heterogeneity of the aggregates.



Our task will be to characterize the chemical properties of representative minerals given in table M3a.1 using elemental mapping by electron microprobe, backscatter electron spectroscopy and X-ray dispersive spectroscopy.

Steps involved in the detailed characterization of the aggregates:

- i. Examine a comprehensive range of representative aggregate materials to determine mineralogical content, grain size and texture. This will initially be done by optical petrography techniques (polished thin sections), followed by elemental distribution maps acquired on an electron microprobe using wavelength-dispersive (WDS) X-ray as well as backscattered electron (BSE) signals. The compositions of the individual aggregate minerals will then be determined by quantitative individual-point X-ray WDS analyses on the electron microprobe.
- ii. Based on the mineralogy of the aggregates, acquire suitable individual mineral reference materials for further testing. These minerals will include both compositional end-members and intermediate members of the common rock forming minerals found in the aggregate materials. For example, in the plagioclase feldspar series, nearly pure Na plagioclase (albite), Ca plagioclase (anorthite) and intermediate Na-Ca plagioclase compositions (andesine, and/or labradorite, etc.) will be acquired and analyzed so that these individual well-characterized mineral components can be used in some of the aggregate-asphalt experiments.

Examples of properties of aggregates that will be characterized include:

- specific surface area for different size fractions,
- major mineralogical composition,
- chemical composition (major oxide) of minerals, and
- concentration of water and acid solubles.

Results from this task will also be extremely useful to explain mechanisms from other tasks such as effect of binder aging on the properties of the binder-aggregate interface.

Table M3a.1. Chemical and mineralogical properties of common aggregates.

Mineral	Group	Chemical Formula	Occurrence
Microcline	Feldspar	KAlSi_3O_8	
Na-Plagioclase	Plagioclase Feldspar ¹	$\text{NaAlSi}_3\text{O}_8$	Dominant feldspar in andesite, an igneous rocks. Minor component in granite and metamorphic rocks.
Labradorite	Plagioclase Feldspar ¹	$\text{Ca}_{(0.5-0.7)}\text{Na}_{(0.3-0.5)}(\text{Al},\text{Si})\text{AlSi}_2\text{O}_8$	
Andesine	Plagioclase Feldspar ¹	$\text{Na}_{(0.5-0.7)}\text{Ca}_{(0.3-0.5)}(\text{Al},\text{Si})\text{AlSi}_2\text{O}_8$	Dominant feldspar in andesite, an igneous rocks. Minor component in granite and metamorphic rocks.
Olivine ²	Nesosilicates	$(\text{Mg},\text{Fe})_2\text{SiO}_4$	Olivine is found in ultramafic igneous rocks and marbles that formed from metamorphosed impure limestones.
Augite	Pyroxene	$(\text{Ca},\text{Na})(\text{Mg},\text{Fe},\text{Al})(\text{Al},\text{Si})_2\text{O}_6$	An important rock-forming mineral in many igneous rocks, especially in gabbros and basalts. Augite is also found in some hydrothermal metamorphic rocks.
Hornblende ³	Amphibole	$\text{Ca}_2(\text{Mg},\text{Fe},\text{Al})_5(\text{Al},\text{Si})_8\text{O}_{22}(\text{OH})_2$	An important rock-forming mineral in many igneous rocks, especially in gabbros and basalts.
Ilmenite	Oxyhydroxides	FeTiO_3	Ilmenite forms as a primary mineral in mafic igneous rocks
Magnetite	Oxyhydroxides	Fe_3O_4	
Dolomite	Carbonates	$\text{CaMg}(\text{CO}_3)_2$	A common sedimentary rock-forming mineral, dolomitic limestone.

¹ The plagioclase series comprises minerals that range in chemical composition from pure $\text{NaAlSi}_3\text{O}_8$, Albite to pure $\text{CaAl}_2\text{Si}_2\text{O}_8$, anorthite. Andesine by definition must contain 70-50% sodium to 30-50% calcium in the sodium/calcium position of the crystal structure.

² Olivine is actually a name for a series between two end members, fayalite and forsterite. Fayalite is the iron rich member with a pure formula of Fe_2SiO_4 . Forsterite is the magnesium rich member with a pure formula of Mg_2SiO_4 .

³ Hornblende is actually the name given to a series of minerals that are rather difficult to distinguish by ordinary means. The iron, magnesium and aluminum ions can freely substitute for each other and form what have been distinguished as separate minerals. The minerals are given the names Magnesio-hornblende, Ferrohornblende, Alumino-ferro-hornblende and Alumino-magnesio-hornblende.

Year 2 Milestones

Specimens for representative mineral phases identified in this task will be collected from different sources. Purity of the specimens will be established by testing them for their mineralogical composition using electron microprobing and other techniques. The specific surface area and surface free energy of the minerals will be determined.

Category M4: Modeling

The modeling efforts and approaches will be similar to those discussed in the fatigue work plan. These approaches are summarized here for completeness.

Work Element M4a: Micromechanics Model

Similar to the fatigue work plan, it is envisioned that the lattice and cohesive zone models will be the primary methods to develop the micromechanical analysis framework. The asphalt mix microstructure will be captured using X-ray CT imaging at multiple resolutions. The measured material properties with the influence of moisture (adhesive and cohesive bonds, viscoelastic properties) will be assigned to the various constituents of the microstructure. Furthermore, multi-scale methods can be applied in order to link the experimental measurements conducted at constituent-level scales to the global scale where damage-associated performance behavior of asphaltic composites induced by moisture effects will be modeled.

Major Findings from Year 1 for Work Element M4a

An extensive review of the micromechanics-based computational models to characterize damage-dependent behavior of asphalt materials and mixtures was conducted by ARC researchers at the University of Nebraska. Some of the findings from this review are:

- i. The model developed needs to be the one that can successfully represent material properties (viscoelastic properties) and fracture behavior (both adhesive and cohesive fracture) influenced by moisture effects.
- ii. The model parameters should be obtainable from well-designed testing protocols which are based on theoretical rigor and also practically applicable. Other tasks associated with the development of testing methods in this project need to be closely incorporated with this modeling effort.
- iii. For a more accurate characterization and modeling of damage in asphaltic materials, inelastic (e.g. viscoelastic) fracture should be included in the process. Asphalt demonstrates a significant complexity of rate-dependent and inelastic damage behavior.
- iv. In order to better simulate heterogeneity and corresponding interactions among mixture components in the asphalt mixture, the concept of micromechanics with the aid of computational techniques (such as the finite element method) and advanced image analysis techniques (e.g. X-ray CT imaging) should be pursued.

- v. The model being developed at the University of Nebraska is based on the cohesive zone concept to simulate initiation and propagation of viscoelastic damage. This approach looks reasonable, since the cohesive zone modeling can be applied to both cohesive and adhesive fracture within the same theoretical-numerical framework. An appropriate modification and/or improvement to the current model would provide a tool to predict the inelastic damage incorporated with the moisture effects.

Year 2 Milestones for Work Element M4a

- i. Continue the literature review related to the micromechanics-based computational modeling techniques.
- ii. Modify and/or elaborate the current cohesive zone model to incorporate fracture and damage characteristics including moisture effects so that the model can be better fit with material and damage properties that will be measured and provided by the TAMU and UWM.

Work Element M4b: Analytical Fatigue Model for Mixture Design

The same fracture model developed for fatigue will be used here. The main difference is that the model will include parameters that are obtained from testing specimens subjected to moisture conditioning. The model accounts for the energy dissipated in fracture, energy dissipated in permanent deformation, physio-chemical properties of mixture (adhesive and cohesive bonds), and viscoelastic properties (Masad et al. 2006). This model can also be used to analyze experimental measurements conducted on the mastic and fine portions of the mixture using the dynamic mechanical analysis and on full mixtures using repeated loading. As discussed in the fatigue work plan, the testing protocols will be developed under work element F2b and F2c. In the Moisture work plan, we will develop the methods for moisture conditioning of mastic, FAM and mixture specimens.

Major Findings from Year 1 for Work Element M4b

During the first year, the researchers developed a fracture model that accounts for mixture viscoelastic properties and bond energy. These model parameters vary based on the material state (dry versus wet). The model was demonstrated to capture the influence of changes in materials and volumetrics (mixture design) on moisture susceptibility. This model was extended to account for the probability of failure as a function of loading cycles. The fracture model was also extended to account for the nonlinear viscoelastic response of asphalt mixtures in dry and wet states.

Year 2 Milestones from Year 1 for Work Element M4b

The research in Year 2 will focus on the development of a damage nonlinear-viscoelastic model for the analysis of fatigue response of asphalt mixtures under dry and wet states. This model is an extension of the fracture model that was developed during Year 1. However, it has the advantage that it is a constitutive model that can be formulated in the general three dimensional

form that can be implemented in a numerical scheme for the analysis of performance under various loading and boundary conditions.

Work Element M4c: Unified Continuum Model

The unified continuum model described in the fatigue plan will be further developed in order to account for the effects of moisture. This will be achieved by solving the coupling between the fluid flow equations and the constitutive equations that govern the mixture mechanical behavior. The fluid flow equations will be solved to determine the moisture distribution within the mixture. The constitutive equations will be solved to determine the mechanical behavior given the moisture presence in the mixture.

Moisture will be treated as an external variable that influence the evolutions of the model's parameters and functions. The model yield surface will evolve as a function that combines stresses (hydrostatic and deviatoric) and moisture content. All the model parameters will be determined by testing specimens after moisture conditioning. This approach is similar to developments in geo-environmental studies that account for the coupling between the concentration of chemicals and the constitutive behavior of geomaterials. The presence of moisture in asphalt mixtures will be modeled analogous to the presence of chemicals in geomaterials.

The basics for developing the continuum model with the effect of moisture are documented in the literature. In the past few years, considerable developments have been achieved in coupling the chemical reactions with the performance of geomaterials (Hueckel 2002). In the asphalt pavement area, researchers have developed numerical models for the simulation of fluid flow in the asphalt mixture microstructure (Al-Omari and Masad 2004 and Kutay et al. 2007). The researchers at Delft have made significant advances in developing a model that couples the fluid flow equations with the constitutive equations governing the mechanical behavior (Kringos and Scarpas 2005, 2006). The processes that are considered in the Delft model are summarized in table M4c.1. This work element will build on recent advances by focusing on making the improvements listed in table M4c.2.

Major Findings from Year 1 for Work Element M4c

Most of the components of the continuum model have been implemented in finite element. The model includes a nonlinear viscoelastic component and a viscoplastic component. However, the influence of moisture on the model parameters and response has not been accounted for yet.

Year 2 Milestones for Work Element M4c

The model will be fully implemented in finite element during the second year. It will be evaluated using based on its ability to predict experimental measurements conducted at TAMU and NC-State on various mixtures during the past three years. In addition, the researchers will utilize the comprehensive testing database available at the University of Nottingham to validate and calibrate the model. The model verification during the second year will focus on the tests conducted on dry mixtures.

Table M4c.1. Processes simulated in the model of moisture damage of Kringos and Scarpas (2005, 2006).

Damage process	Description	Comments
Desorption of the mastic (process 1)	Loss of mastic that is washed away by a non-stationary flow (advective flow). The process occurs in a short timescale and affects the outer layers of the binder that surround the aggregates.	Macroscopic phenomenon. Advective transport will not occur without flow.
Dispersion of the mastic (advective dispersion) (process 2)	Deterioration in the material's cohesive bond (loss of concentration or dispersion) caused by moisture diffusion into mastic. The process occurs on a long timescale.	Microscopic phenomenon. Requires the presence of a water flow field although the process is dominated by the diffusion coefficients of the material.
Deterioration of the aggregate-binder interface (process 3)	Long term process due to a combined effect of moisture diffusion and mechanical loading.	Microscopic phenomenon. An energy-based model was developed to include moisture content as a control parameter.

Table M4c.2. Accomplishments of the current model and future work.

Accomplishments	Future work
Mathematical formulation of fluid flow in asphalt mixtures using two different methodologies	Calibrate current models.
Mathematical formulation of three important processes related to moisture damage	Include more complex and realistic geometry.
Successful numerical implementation of aforementioned processes	Include pore pressure and any other relevant effects.
Simulation of damage with a mechanical and thermodynamic coupled model	Analyze moisture damage processes in different types of mixtures.
Better understanding of moisture damage mechanisms in open graded friction courses	Analyze the validity of the current damage evolution law and consider new formulations for coupling micro- or mesodamage with macrodamage. Determine the relevance of material properties in terms of the time required for the manifestation of damage.

Category M5: Moisture Damage Prediction System

This work element will be performed in close coordination with other agencies in the Technology Development work area of this Consortium. Accordingly, some part of the budget for this work element has been allocated in the Technology Development work area.

This task will develop a moisture damage prediction system that will consist of the following components:

- i. A method for the selection of materials with good resistance to moisture damage. This method is based on the components of surface energy of asphalt binders and aggregates.
- ii. An experimental method that accounts for the resistance of asphalt mastic and fine portion of the mixture to moisture damage. This will be done primarily using the dynamic mechanical analyzer.
- iii. An experimental method for measuring the resistance of the full mixture to moisture damage.
- iv. Models that account for the material, microstructure, and loading factors that affect moisture damage.

SCHEDULE

		2008	2009	2010	2011
M1a	Affinity of Asphalt to Aggregate - Mechanical Tests	X	X	X	
	1a-1 Use of modified DSR and PATTI tests	x	x	x	
	1a-2 Evaluate moisture damage of asphalt mixtures	x	x	x	
	1a-3 Compare moisture damage from 1a-1 and 1a-2	x	x	x	
	1a-4 Propose a novel test protocol		x	x	
M1b	Work of Adhesion	X	X	X	X
	1b-1 Adhesion using Micro calorimeter and SFE	x	x	x	x
	1b-2 Evaluating adhesion at nano scale using AFM	x	x	x	x
	1b-3 Mechanisms of water-organic molecule competition	x	x	x	x
M1c	Quantifying Moisture Damage Using DMA	X	X	X	X
M2a	Work of Cohesion Based on Surface Energy	X	X	X	X
	2a-1 Methods to determine SFE of saturated binders	x	x		
	2a-2 Evaluating cohesion at nano scale using AFM	x	x	x	x
M2b	Impact of Moisture Diffusion in Asphalt	X	X	X	
	2b-1 Diffusion of moisture through asphalt/mastic films	x	x		
	2b-2 Kinetics of debonding at binder-aggregate interface	x	x	x	
M2c	Thin Film Rheology and Cohesion	X	X	X	
	2c-1 Evaluate measurements from PATTI test	x			
	2c-2 Evaluate PATTI test to detect effect of modifications	x			
	2c-3 Validating PATTI test based on results from DSR	x	x	x	
	2c-4 Mastic testing using PATTI and DSR tests		x	x	
	2c-5 Practicality evaluation of modified PATTI test		x	x	
	2c-6 Recommendations for modified PATTI test			x	
M3a	Impact of Surface Structure of Aggregate	X	X		
	3a-1 Aggregate surface characterization	x	x		
M4a	Development of Model	X	X	X	X
	4a-1 Micromechanics model development	x	x	x	x
	4a-2 Analytical fatigue model for use during mixture design	x	x	x	x
	4a-3 Unified continuum model		x	x	x
M5a	Moisture Damage Prediction System			X	X

RELATIONSHIP TO FHWA FOCUS AREAS

The moisture damage work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property and pavement performance.

BUDGET

		Year 1	Year 2	Year 3	Year 4	Year 5
M1a	Affinity of Asphalt to Aggregate - Mechanical Tests (UWM)	75,000	75,000	75,000	75,000	
M1b	Work of Adhesion (TAMU)	75,000	75,000	50,000	50,000	25,000
	Work of Adhesion (WRI)		134,500	146,000	152,500	126,500
M1c	Quantifying Moisture Damage Using DMA (TAMU)		75,000	75,000	100,000	75,000
M2a	Work of Cohesion Based on Surface Energy (TAMU)	75,000	75,000	75,000		
	Work of Cohesion Based on Surface Energy (WRI)		134,500	146,000	152,500	126,500
M2b	Impact of Moisture Diffusion in Asphalt (TAMU)	75,000	150,000	150,000	175,000	
M2c	Thin Film Rheology and Cohesion (UWM)	75,000	100,000	75,000	75,000	
M3a	Impact of Surface Structure of Aggregate (TAMU)	75,000	100,000	125,000		
M4a	Development of Model (TAMU)		125,000	125,000	125,000	150,000
M5a	Moisture Damage Prediction System*				150,000	150,000
TOTAL		450,000	1,044,000	1,042,000	1,055,000	653,000
		4,244,500				

Note* Tentatively only budget from TAMU is reflected here but this element will involve coordination from all agencies.

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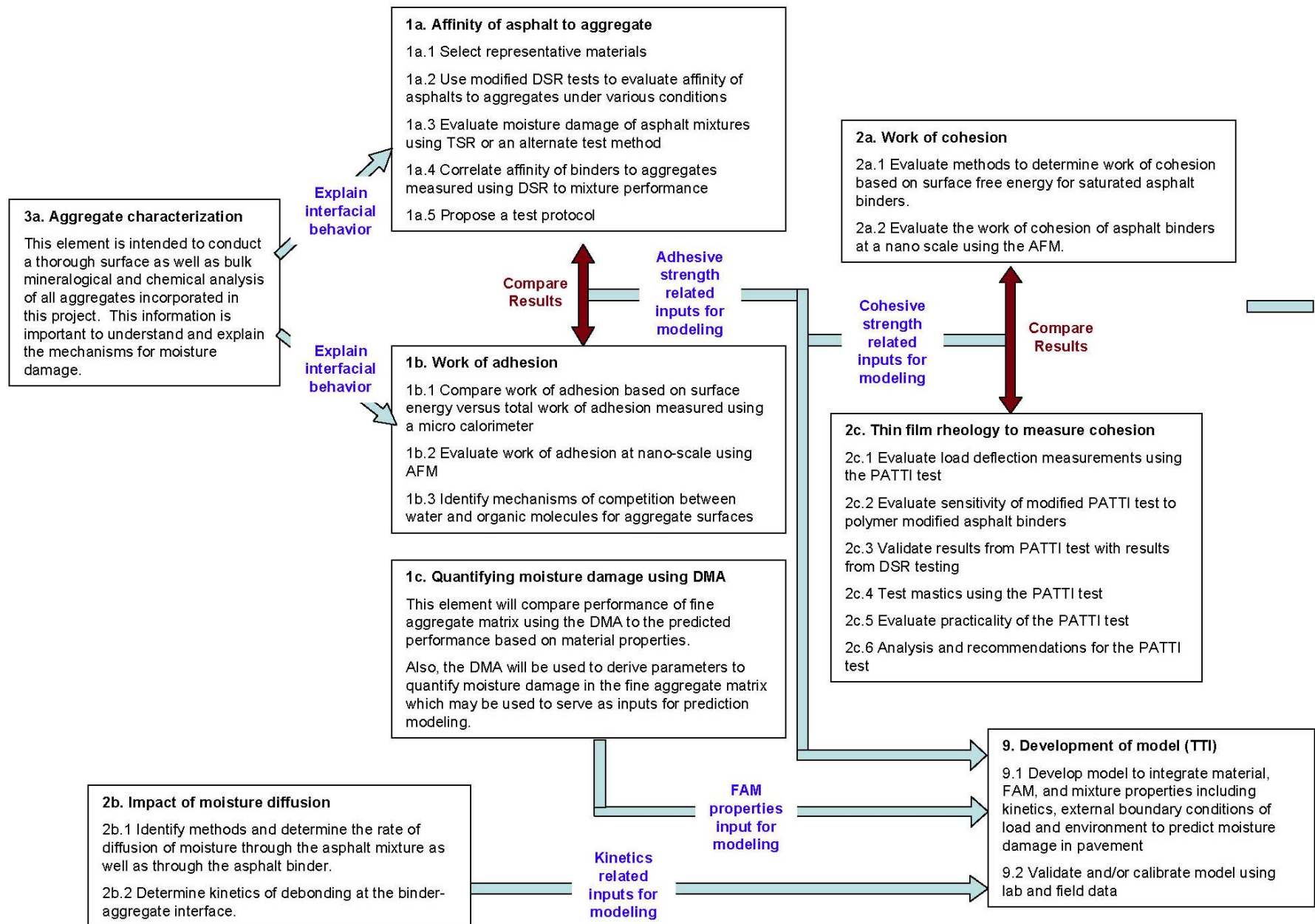
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Appendix M1

Flow Chart Illustrating Integration of Elements for Moisture Damage Work Area



PROGRAM AREA: FATIGUE

This work plan for year 2 of the Asphalt Research Consortium (ARC) was prepared by revising the five year work plan submitted in May of 2007. In that work plan the first year work effort was identified and emphasized within the five year plan. The same general approach was taken here with the second year work being emphasized. According to this approach, the overall work plan was modified in order to accommodate the feedback received from FHWA on the year 1 work plan, reflect accomplishments made in year 1 including revisions based on year 1 accomplishments and findings, and reflect the area of emphasis and milestones for year 2.

INTRODUCTION

The Fatigue Process

Fatigue damage is normally defined as incremental damage that occurs gradually in the pavement due to stresses induced by traffic loading. The fatigue cracking mechanism can be divided into two stages: initiation of cracks of sufficient length to grow under repeated loading and propagation of these cracks due to repeated loading. When a sufficient number of cracks develop within a wheel path, severe distress results and pavements quickly lose serviceability. However, fatigue may also manifest as permanent deformation or rutting in the wheel path. Such permanent deformation is traditionally considered to be due to plastic flow, but it can also be the result of weakening of the mixture due to a concentration of small cracks caused by a fatigue process. Researchers in the Asphalt Research Consortium (ARC) consider both of these mechanisms to be part of the fatigue process. We also consider recovery during rest periods to be part of the fatigue process or that the fatigue process is actually a balance between crack propagation on the one hand and healing on the other. Healing is quantified by the recovery of the mechanical ability of a material to store and release fracture energy and the result of healing is extended fatigue life. The reality and significance of the impact of healing during rest periods has been proven in previous WRI-directed research and is now well established in the literature by some of the most respected research entities in the world.

Complicating the fatigue process is the changing nature of the binder over time due to oxidative hardening in pavements. Evidence is mounting that binders oxidize in pavements, and well below the surface. This oxidation reduces healing, reduces stress relaxation of the binder, and increases binder stiffness. These combined material property changes result in a binder that is more susceptible to fatigue, a hypothesis that has been confirmed by laboratory mixture tests.

Research Needed to Better Understand and Evaluate Fatigue Damage

Historically fatigue damage has been quantified in the laboratory as the number of load cycles applied to a specimen that causes the specimen to fail due to crack growth. Such fatigue tests normally either apply the same level of stress at each load cycle (controlled-stress) or apply the same level of strain at each load cycle (controlled-strain). The consensus among materials and pavement engineers has been that thick, stiff pavements should be tested in a controlled-stress

mode, while thin pavements should be tested in a controlled- strain mode. The results of these tests are hard to compare simply based on the number of cycles to failure. A pressing need has been to develop a unified method, based on sound mechanics, by which to evaluate both modes of fatigue testing. In addition to the mode of introducing load in a fatigue experiment, several other factors impact the fatigue damage characteristics of asphalt mixtures. These include adhesive and cohesive bond strengths within the mixture, anisotropy of the aggregate matrix, composition of the mastic portion (including interaction between mineral filler and asphalt), aging, and the ability of the mixture to recover during rest periods (healing). The WRI and Texas A&M research teams have demonstrated the importance of adhesive and cohesive bond strengths in the fatigue process. Further, they have developed protocols to measure surface energies of the mixture components (binder and aggregate) from which bond strengths can be reliably calculated.

Recent work at Texas A&M has demonstrated that a unified model based on dissipated pseudo strain energy and fracture mechanics and including bond strength can indeed unify the stress-controlled and strain-controlled modes of loading. A first generation version of this approach has been developed and reported as a deliverable of research at Texas A&M under the recently completed WRI-led contract with FHWA (DTFH61-99C-00022). This approach is based on separating the dissipated pseudo strain energy measured during cyclic, torsional fatigue testing into the components associated with permanent deformation, change in the phase angle, and changes in stiffness among load cycles. It is critically important to finalize this analysis methodology and to validate the efficacy of this approach.

Work at Texas A&M has demonstrated that well-dispersed fillers (aggregate smaller than about 75 μm) substantially affect the growth of microcracks and that the effect of the fillers is determined by their mineralogy and physical properties. Healing during rest periods has a profound impact on fatigue life and also impacts the potential for mixtures to exhibit an endurance limit. Research at Texas A&M has shown that the healing process is related to the filler properties of the mastic and the adhesive and cohesive bond strengths of the mixture. This work needs to be completed and expanded.

Of course, when studying the fatigue damage process, it is absolutely necessary to consider the impact of moisture. Moisture affects the cohesive strength of the mastic as well as the bond strength between the asphalt binder and/or mastic and the aggregate particles. The ability to measure surface energy and to calculate cohesive and adhesive bond strengths (dry and in the presence of moisture) has provided a tool by which to scientifically investigate the effects of moisture on fatigue. We will focus on the asphalt -aggregate interaction as it affects the fatigue process, dry and in the presence of moisture. We will also focus on the impact of moisture on the cohesive bond strength of the mastic. In fact two major concept areas within the ARC project (Moisture Damage and Fatigue Damage) will work “hand-in-hand” for the duration of the ARC to synergistically consider the mechanisms of damage due to moisture and load-induce fatigue.

This research must remain focused on the deliverables that the ARC is committed to provide. In the area of fatigue, the ARC is committed to provide tools capable of assessing the fatigue damage process and of identifying specific factors that influence fatigue damage, i.e., aggregate properties, binder properties, mixture volumetrics, presence of moisture, filler type, etc. We are

committed to developing and delivering predictive models that rely on the fundamentals of integrated fracture mechanics, micromechanics, and elasto-visco-plastic continuum damage mechanics. We are also committed to developing the most promising characterization tools into ASTM and AASHTO type specifications. One such tool that continues to surface as an excellent method by which to assess fatigue damage potential, the impact of rest periods, the impact of moisture, and the impact of fillers is dynamic mechanical analysis (DMA). Our goal is to develop this into a guideline type specification test in the second year of the grant.

Other tests that have been proven to be useful in characterizing the bond strength in asphalt mixtures are the Wilhelmy plate, universal sorption device, sessile drop apparatus and the micro-calorimeter. We will continue to develop these test methods in order to deliver practical and easy-to-use test methods that can be integrated into the routine analysis of asphalts and aggregates. We will work closely with FHWA in order to determine the relationship between bond energy and compliance calculations and more direct measurements of bond strength such as the pull-off test being developed at FHWA.

In this research, we will utilize the most recent technologies in imaging and nondestructive evaluation to understand the mechanisms of crack initiation and propagation in asphalt mastics and mixtures. In recent years, the research at Texas A&M has made significant strides in nondestructively measuring crack distribution and evolution in asphalt mixes using X-ray Computed Tomography and image analysis techniques. These measurements will be used in our efforts to validate the models that will be developed by the Consortium.

HYPOTHESES

Fatigue damage is the result of the growth of small cracks and voids to form larger cracks that result in damage. The initiation of cracks to a critical size and the propagation of these larger cracks can be successfully explained and evaluated based on the principles of viscoelasticity and viscoplasticity, dissipated pseudo strain energy, micromechanics, and fracture mechanics. A unified model of fatigue damage must be based on sound principles of mechanics and pertinent materials characteristics and must also consider adhesive and cohesive bond strengths of the mixture, the ability of the mixture to heal or recover damage between load cycles, the impact of the mixture's internal structure on stress distribution within the mixture, and the impact of moisture on mixture properties and the rate of damage and healing in the composite mixture, including the changes in all of these properties with oxidative aging. The damage model should be able to predict fatigue damage from the material properties discussed above and from the dissipated pseudo strain energy measurements derived from fatigue experiments whether they are performed in the controlled-stress or controlled-strain mode of loading.

OBJECTIVES

1. Develop a fundamental understanding of the material properties and mechanics associated with fatigue.

2. Develop a unified fatigue damage model that incorporates and integrates the important mixture properties and responses that affect fatigue life. These properties and responses include cohesive and adhesive bond strengths, viscoelastic properties, fracture properties, energy dissipation, cohesive and adhesive bond strengths, healing and/or recovery during rest periods, effect of binder aging, and the internal structure of the mixture composite. The unified model will be capable of evaluating fatigue when loading is applied in either the controlled-stress or controlled-strain mode.
3. Assess the impact of modification and aging on the binder and mastic and the impact of filler type and quantity on the mastic and/or fine aggregate matrix using the unified model.
4. Develop testing protocols for mixture, mastic, and binder characterization that provide the information required in the unified model for binder, fillers, mastic, and the total composite mixture.
5. Implement the unified fatigue damage model by integrating it into a numerical scheme to assess the fatigue behavior of mixtures under different laboratory and field boundary conditions.
6. Develop micromechanical models that are based on fundamental material properties and can be used to study the interaction among the mixture constituents and their influence on mixture performance. These micromechanical models will be used to relate the parameters of the unified fatigue model to material properties.
7. Verify the unified model using microstructural measurements of fatigue damage by monitoring crack evolution through such non-destructive techniques as computer assisted x-ray tomography.
8. Validate the unified model and testing methods through comparisons of predictions made based on the model and full scale field testing and evaluation of pavement test sites.
9. Develop component selection guidelines for perpetual pavements based on the unified approach.

These objectives will be achieved in coordination with other research activities on similar topics. Specifically, our research will be coordinated among all members of the ARC with other ongoing activities at the Federal Highway Administration (FHWA), LCPC in France, University of Nottingham in Britain, and Delft University in the Netherlands.

Our proposed research plan will complement and be coordinated with the current work at FHWA. The results from the accelerated loading facility (ALF) of the FHWA will be extremely useful to our validation efforts. This is a well controlled experiment with different modified and unmodified binders and different pavement structures. Furthermore, the advances made by the FHWA on binder characterization will be very useful for our research. The FHWA has shown that the binder behavior is highly nonlinear and the differentiation among asphalt binders can only be accomplished through considering the influence of stress level on response. Our fatigue modeling framework considers the nonlinear response of asphalt binders and mixtures among other important factors such as aging and healing effects. Our modeling approach is applicable to asphalt binders, asphalt mastics, and mixtures. Therefore, we plan to develop testing protocols

for these materials. Specifically, we will focus on the development of a simple method for the characterization of binder fatigue resistance. This method needs to be simple, efficient, and capable of being implemented into binder specifications. This is necessary given the shortcomings of the current Superpave system in properly characterizing asphalt binders. We strongly believe that the concepts that have already been developed for characterizing fatigue in asphalt mixtures can be adopted, with proper modifications, to characterize binder fatigue resistance.

EXPERIMENTAL DESIGN

The development of an experimental design will be among the initial subtasks of each work element. The experiment design will be communicated to the AOTR before the work is begun on each work element, and each experimental design or plan will be approved and/or developed by the project statistician, who is in our case Dr. E. S. Park of the Department of Statistics at Texas A&M. Dr. Park has a research appointment with TTI and is very familiar with the design of experiments in asphalt related research. She has served as team statistician on several asphalt related research projects including NCHRP Project 9-37, “Using Surface Energy Measurements to Select Materials for Asphalt Mixtures”.

The TTI team will use the Buckingham PI theorem of experiment design to identify dimensional ratios of material properties to minimize the size of the experiment and maximize the information to be obtained from them. This approach was used successfully in many fields of mechanics such as fluid flow and aerodynamics.

WORK ELEMENTS

Category F1: Material and Mixture Properties

The work in this category will focus on determining material properties that are needed for the development of the unified model and micromechanics models.

Work Element F1a: Cohesive and Adhesive Properties

Subtask F1a-1: Critical Review of Measurement and Application of Cohesive and Adhesive Bond Strengths (Continued in year 2)

Adhesive and cohesive bond strengths are fundamental material properties that can be used to model crack growth in asphalt materials both in wet as well as dry conditions. Work of adhesion between the asphalt binder and the aggregate and the work of cohesion of the asphalt binders can be determined using their individual surface energy components. Initial studies conducted under the FHWA contract DTFH61-99-C-00022 (Fundamental Properties of Asphalts and Modified Asphalts) demonstrated the feasibility of using this approach to model fatigue crack growth in asphalt mixtures. In a recently completed NCHRP project 9-37 (Little and Bhasin 2006) test protocols to determine surface free energy components of asphalt binders and aggregates were

developed. The project results also included parameters based on surface energy measurements that may be used to select combinations of materials that are more resistant to moisture damage. The impact of modification due to aging, addition of fillers, addition of polymers, and/or chemical additives on the work of cohesion or adhesion was addressed in limited detail in these and other previous studies. There is a need to critically review the existing methods with respect to determining viscoelastic properties and work of adhesion or cohesion for use with modified asphalt binders.

There is a difference between the magnitudes of work of adhesion or cohesion computed using the thermodynamics approach (surface energy) versus these quantities determined using mechanical tests (commonly referred to as practical or mechanical work of adhesion or cohesion). Existing literature provides detailed information on the various sources of this difference for elastic as well as viscoelastic materials. Examples of sources for this difference are energy dissipation due to plastic deformation and branching and coalescence of microcracks (Sharon et al. 1996). It is important to review and reconcile the source of these differences in order to improve the fatigue crack growth model for asphalt mixtures.

The detailed literature review will be continued from year 1 to address following areas relevant to the cohesive and adhesive bond strengths of materials:

- i. Need for revision and/or improvement of existing methods to determine work of adhesion and cohesion for modified asphalt binders and recommendations for changes or improvements that may be required.
- ii. Experimental and analytical methods to determine the work of cohesion or adhesion using mechanical tests, including approaches based on contact mechanics.
- iii. Sources of differences between thermodynamic work of adhesion or cohesion and mechanical work of adhesion or cohesion, and methods to account for these differences.
- iv. Acid-base scale to determine the surface free energy components of asphalt binders and aggregates and use of an alternate scale that may improve the sensitivity of the measured surface energy components and is consistent with the use of dissipated energy partitions applied to fracture mechanics and viscoplasticity.
- v. Effect of oxidative aging on the surface free energy components of the asphalt binder.

During year 1 of this project, researchers from the Texas A&M University visited University of Nottingham and Imperial College in the United Kingdom as a part of the “Collaborating for Success through People” program sponsored by the United Kingdom. Researchers from the Imperial College, London, led by Professor Kinloch, have pioneered the development of several industry standards that are used to determine the practical work of adhesion and cohesion for different polymeric adhesives. Professors Little and Masad from Texas A&M University had a detailed discussion on the recently developed methodologies and experience related to the use of test methods to determine the practical work of adhesion and cohesion with Professor Kinloch and his team (Subtask F1a-4). During year 2 of this project and part of year 3, there will be an exchange of researchers from these Universities for durations ranging from one to twelve weeks. This research exchange, sponsored by the “Collaborating for Success through People” program of UK will greatly benefit the Asphalt Research Consortium, particularly for this work element.

Subtask F1a-2: Develop Experiment Design (Continued in year 2)

A detailed experiment design will be developed to accomplish the objectives identified in the work element F1a. The first part of this experiment design will be comprised of adaptation and use of test methods developed at the Imperial College, London for asphalt binders (in conjunction with tests from task M2a-1). The test method will be further refined after the results of preliminary tests using this methodology.

Subtask F1a-3: Thermodynamic Work of Cohesion and Adhesion (Continued in year 2)

The work of adhesion and cohesion can be computed using surface energy components of the asphalt binder and the aggregate. This subtask will evaluate existing protocols to determine surface energy of modified asphalt binders as well as asphalt mastics. The work of adhesion and cohesion for several different types of binders and binder-aggregate combinations will also be determined in this subtask. This information will be used in the subsequent subtasks to provide the mechanical work of adhesion and cohesion as inputs for the micro-mechanics and continuum fatigue model.

In summary, the following analytical and experimental elements are envisioned in this subtask:

- i. Previous research at the Texas A&M University has led to the development of detailed test protocols to measure the surface free energy components of asphalt binders (Bhasin and Little 2006; Hefer et al. 2006). However, these protocols were developed based on neat asphalt binders. In year 1 of this project, existing protocols to determine surface energy components for modified asphalt binders and mastics were assessed. Preliminary tests were also conducted to determine the surface free energy components of polymer modified asphalt binders using the Wilhelmy plate method. Researchers were able to obtain smooth surfaces for polymer modified binders by separation of the polymer phase after it has physio-chemically interacted with the binder matrix. Researchers are currently evaluating the use of this methodology for asphalt mastics. This methodology will be further developed in year 2 and results will be cross-examined using analytical methods and alternate experimental techniques such as the static sessile drop method.
- ii. In year 2, the revised test protocol to measure surface free energy as well as guidelines to use and interpret these measurements for modified asphalt binders and mastics will be finalized.
- iii. Measure surface free energy of selected unmodified and modified binders (including aged binders) and mastics using the Wilhelmy plate device. The recommended protocols from the aforementioned subtask will be used for these measurements. The common materials library for the ARC will be used to select binders for these measurements.
- iv. Measure surface energy of selected unmodified and surface treated aggregates using the Universal Sorption Device (USD). A common example of surface treatment of aggregates that effects the aggregate-binder work of adhesion is application of hydrated lime slurry to the aggregate surface. The common materials library for the ARC will be used to select aggregates for these measurements.

- v. Determine the thermodynamic work of adhesion and cohesion for different combinations of asphalt binders, mastics, and aggregates using their individual surface energy components.

Subtask F1a-4: Mechanical Work of Adhesion and Cohesion

Sources of energy dissipation on a larger scale, such as plastic energy and micro branching, also contribute to the work required for cohesive fracture in asphalt binders or mastics, albeit the energy dissipated from these additional sources is related to the work of cohesion due to surface free energy of the binder. The contribution of these secondary sources to the total work of adhesion and cohesion will be investigated in this subtask using a combination of analytical and experimental methods. The experimental methods will be developed in coordination with tasks under element F2a and M2a-1.

In summary, the following analytical and experimental elements are envisioned in this subtask:

- i. Identify and develop protocols for one or two test methods based on the literature review from 1a-1 to determine the material viscoelastic properties and mechanical work of adhesion and cohesion.
- ii. Determine the viscoelastic properties and work of cohesion and adhesion for different asphalt binders and binder-aggregate combinations using the selected test method(s).
- iii. Develop a model to enable back calculation of the work of adhesion or cohesion from the mechanical tests, incorporating the influence of film thickness and viscoelastic effects.
- iv. Reconcile the effect of scale and other energy dissipation mechanisms and develop the relationship between the thermodynamic parameters from subtask 1a-3 and the equivalent back calculated parameters from mechanical tests conducted in this subtask.
- v. Develop framework(s) for the work of cohesion or adhesion with appropriate modifications so that it can be incorporated into the micromechanics or continuum damage models in subsequent tasks. This framework will be based on both thermodynamic measurements and mechanical tests.

This subtask will be conducted in conjunction with sub task M2a-1 for materials in dry condition. As described previously in sub task M2a-1, these experiments will combine the use of mechanical tests and advanced analytical techniques to determine the practical work of cohesion and adhesion for different materials. Also as mentioned before, this subtask will capitalize on the experience of research conducted at the Imperial College, London under an ongoing research exchange program sponsored by UK.

Subtask F1a-5: Evaluate Acid-Base Scale for Surface Energy Calculations

The surface free energy components of aggregates and binders are computed using adsorption isotherms and contact angles with different probe liquids. Thus far, these computations were made using surface energy values for probe liquids recommended as per the Good-van Oss-Chaudhary (GVOC) scale. The GVOC scale is based on the assumption that the acid and base components of surface energy of water are equal. Several researchers in the field of physical

chemistry have pointed out that this scale introduces a bias which results in an apparently high magnitude for the base component and apparently low magnitude for the acid component of surface energy (Della Volpe and Siboni 2000). Alternate scales for the surface energy components of various probe liquids are also recommended in the literature.

In this subtask the work of adhesion and cohesion will be determined using surface energy components that are derived using different scales. This analysis will determine whether or not the use of a different scale can improve sensitivity of the computed surface energy components of asphalt binders and aggregates. This is especially important for the acid component of asphalt binders which are typically very small in magnitude but are significant contributors to the work of adhesion. This sub task will utilize the data from the Universal Sorption Device (USD), Wilhelmy plate and sessile drop devices obtained from other elements of this subtask as well as other subtasks.

Year 2 Milestones for Work Element F1a

- i. A comprehensive document that summarizes the following: i) the differences between thermodynamic work of adhesion and cohesion versus practical work of adhesion and cohesion, ii) different experimental and analytical methods to determine the practical work of adhesion or cohesion using simple laboratory tests.
- ii. Develop and experiment plan and conduct preliminary tests to determine work of adhesion and cohesion (in conjunction with work element M2a-1).

Work Element F1b: Viscoelastic Properties (Continued in Year 2)

The focus of this work element will be on developing experimental protocols and analysis methods to determine linear and nonlinear viscoelastic properties of the binder, mastic, and mixture.

As discussed later in work element F3c-1, one of the important inputs to the fatigue damage model is the rate of growth of dissipated fracture pseudo strain energy. The determination of this parameter necessitates separating the energy dissipated in nonlinear viscoelastic deformation from the energy dissipated in fracture damage. The difficulty in doing so stems from the fact that nonlinear viscoelastic deformation, plastic deformation and fracture damage are dependent on the stress level.

Subtask F1b-1: Separation of nonlinear viscoelastic deformation from fracture energy under cyclic loading

Cyclic loading is used in the testing of asphalt binders (dynamic shear rheometer), mastics (dynamic mechanical analyzer) and asphalt mixtures (cyclic axial or shear). It has been a challenge to use these tests to separate nonlinear viscoelastic from plastic deformation and fracture due to the following reasons: (1) the stress value could change within a load cycle from the linear response to the nonlinear response, (2) the stress varies radially within the specimen under shear loading, (3) the loading and unloading within each cycle causes energy to dissipate due to plastic deformation but permanent deformation is fully reversed within each cycle.

The nonlinear response will cause the viscoelastic properties (phase angle and modulus) to change within the cycle. In year 1 of this research, Schapery's nonlinear viscoelastic model was applied under the boundary conditions of cyclic loading to obtain functions for viscoelastic material properties within a loading cycle. This allows separation of the nonlinear response from the linear response predicted using properties measured at small stresses. The correct quantification and separation of non linear response is necessary to obtain an accurate estimate of damage that occurs during cyclic loading. This methodology developed in year 1 will be verified using select materials. Details of this methodology were presented in the quarterly report ending September 2007.

Subtask F1b-2: Separation of nonlinear viscoelastic deformation from fracture energy under repeated and monotonic loading

The continuum modeling of asphalt mixtures has relied on separating the strain into its viscoelastic and viscoplastic components. All available methods assume linear viscoelastic response, which makes the separation of the strain components straight forward (Huang et al. 2007). However, this assumption leads to erroneous decomposition of the strain components. In this subtask, we will develop a repeated loading-unloading testing protocol and analysis methods to separate the nonlinear viscoelastic and viscoplastic components. The mathematical basis for this subtask has been derived recently at Texas A&M University and presented to the expert task group in its meeting in Phoenix Arizona in February 2007. It relies on using statistical fitting for the unloading portion of the repeated test to determine the total permanent strain and one of the nonlinear viscoelastic parameters. These parameters are used in the mathematical form for the loading portion and fitted to the experimental measurements to obtain the remaining nonlinear viscoelastic parameters and the viscoplastic strain as a function of loading time.

Major Findings from Year 1 for Work Element F1b

A methodology was developed to identify the threshold value for the stress or strain amplitude that can be applied to a specimen without causing damage. A non linear viscoelastic model to characterize the response of the FAM subjected to cyclic loading was also developed (Details are included in the quarterly report ending September 2007). The model includes a damage parameter that can be monitored to quantify the evolution of damage with number of load cycles. The efficacy of the model was evaluated using limited data and the results are summarized in this report. On going work will extend the model to analyze the accumulation of damage with time within each load cycle.

Year 2 Milestones for Work Element F1b

- i. Present the fully developed constitutive relationship to model the non-linear viscoelastic response of fine aggregate matrix (FAM) specimens subjected to dynamic loading. The model will be extended to the general three dimensional formulation.
- ii. Conduct preliminary tests to support the model using select material specimens tested under a variety of dynamic loading conditions.

Work Element F1c: Aging

Oxidative aging changes binder composition. These changes have dramatic effects on binder (viscoelastic, cohesive, and adhesive) and mixture (viscoelastic, fracture, and permanent deformation) properties. Therefore, it is necessary to understand the material and microstructure factors that influence aging and the factors that govern the response of binders and mixtures to aging. The experiments and analyses will focus on characterizing the influence of aging on fundamental material properties that are included in the parameters of the models discussed in Category 3. Ultimately, the results must be able to provide insight to the asphalt microstructural model, the micromechanics model, and the unified continuum fatigue model and activities of this work element of Category 1 will coordinate with those of Category 3.

The planning and results of the above subtasks will be coordinated with other elements of the Consortium effort. As mentioned above, results that relate to fundamental binder and mixture properties will be communicated to the Micromechanics Model and Unified Continuum Fatigue Model elements. Results of the transport model of binder oxidation in pavements and on mixture parameters that maximize fatigue resistance will provide guidance on engineering mixtures to have enhanced pavement durability.

Subtask F1c-1: Critical Review of Binder Oxidative Aging and Its Impact on Mixtures (Continued in year 2)

This subtask will develop detailed objectives of this work element within the context of previous work and the objectives of the Consortium deliverables in the fatigue area (and other areas as appropriate). Pertinent prior work includes binder oxidation kinetics, binder hardening that results from oxidation, binder oxidation and hardening in pavements, and the effects of binder hardening on mixture properties. Additionally, effects of oxidation on binder cohesion and binder/aggregate adhesion will be reviewed and coordinated with activities in other work elements.

Subtask F1c-2: Develop Experimental Design (Continued in year 2)

A detailed experimental design will be developed to accomplish the objectives identified in subtask F1c-1 and to be carried out in subsequent subtasks, below. This subtask will include selecting binder and aggregate materials, mixture types and aggregate gradation, binder and mixture aging protocols, and test procedures for assessing the impact of binder oxidation on binder and mixture properties. Also, climate regions of interest for transport modeling, and the selection of relevant field sites for validating the transport modeling of binder oxidation will be selected.

Subtask F1c-3: Develop a Transport Model of Binder Oxidation in Pavements (Continued in year 2)

As an essential element in the process of modeling fatigue damage in mixtures and pavements, the oxidative aging of binders in pavements must be considered. A significant body of data is accumulating that oxidation of binders in pavements is an ongoing process and that it occurs to a

significant depth below the surface. The rate at which this oxidation occurs in different climates and pavement types is a factor to understanding pavement performance. The oxidation rate of binders is accelerated exponentially with temperature, but also depends on the transport of oxygen to the binder. Data strongly suggest that if the accessible air voids in a pavement are sufficiently high, then the access of oxygen is not a limiting factor and that a model that relies solely on the pavement temperature might do very well at estimating binder oxidation rates in pavements. However, for pavements that have sufficiently restricted air voids, the transport of oxygen appears to be a significant factor, more in line with our expectations.

This subtask will address the development of a thermal and oxygen transport model for estimating binder oxidation in pavements. Such a model will require binder oxidation kinetics parameters (activation energies and oxygen reaction order values, plus early rate information), a model for calculating temperature as a function of time and depth in pavements, and a model for describing oxygen transport and diffusion to the binder.

The transport model will require fundamental material properties, including binder oxidation kinetics, diffusivities of oxygen in binders and mastics, and thermal diffusivities of pavements. It is likely that thermal diffusivities can be estimated quite well from existing measurements of pavement temperature as a function of time and depth, as can the impact of nationwide climate differences on pavement temperature. Oxygen diffusivities, however, will be measured as part of this subtask, as will some binder reaction kinetics parameters for which data are not yet available.

Such a model will provide calculations of binder properties in the pavement as a function of both time and depth, properties that can then be passed to the micromechanics and unified continuum fatigue models.

Subtask F1c-4: The Effects of Binder Aging on Mixture Viscoelastic, Fracture, and Permanent Deformation Properties (Continued in year 2)

Another critical element to understanding the impact of binder oxidation is the extent to which binder oxidative hardening impacts mixture, and thus pavement, properties. Recent data have shown that the hardening and embrittlement of binder that occurs as the result of oxidation causes dramatic decreases in mixture fatigue resistance under controlled-strain conditions. Furthermore, the data have shown that different mixtures can exhibit very significant differences in the extent to which binder hardening impacts this decline of fatigue resistance. Understanding these differences between mixtures is critically important to fatigue prediction. Furthermore, understanding the impact of binder oxidation on fatigue resistance and pavement durability in a controlled-stress environment must be better understood.

The objective of this subtask is to determine the fundamental mixture parameters that establish the extent to which fatigue resistance declines with binder oxidative hardening and thus the reasons that some mixtures are inherently more durable than others. Mixture parameters that likely affect fatigue resistance are binder composition, binder content, air voids content, aggregate gradation, and perhaps aggregate type. To the extent such parameters impact mixture fatigue, the fatigue problem is really a mixture/binder problem rather than simply a binder

problem. Of course, the binder oxidation rate in pavements (Subtask F1c-3) will also impact pavement durability.

This subtask will conduct carefully designed experiments to determine the impact of binder oxidative hardening on fundamental mixture properties that govern mixture fatigue resistance, and for a variety of mixture parameters. The property measurement and the results will be coordinated with the efforts on the micromechanics and unified continuum fatigue models.

Subtask F1c-5: Polymer Modified Asphalt Materials

Polymer modification of asphalt binders offers unique opportunities for improving binder behavior, but also unique questions that must be better understood. Modifiers typically improve the elongational properties of binders and may improve their cohesive and adhesive strengths. However, oxidative aging of modified binders typically reduces the elongational flow improvement to the point that with enough aging, the modified binder behaves like the aged unmodified binder.

The interaction of the polymer modifier and the base asphalt binder appear to be critical in establishing the beneficial effects of the modifier and these interactions need to be better understood. Fluorescence microscopy imaging provides useful qualitative information on polymer-asphalt morphology and its changes with oxidative aging which, combined with measurements of binder rheology, mixture rheology, and mixture fatigue, can provide an improved understanding of polymer modification and its impact on pavement durability.

The work of this subtask will address polymer asphalt interactions and their impact on binder and mixture properties for a variety of modifiers and base binders and particularly as a function of oxidative aging. The work will provide important fundamental data for the asphalt microstructural model, the micromechanics model, and the unified continuum fatigue model.

Major Findings from Year 1 for Work Element F1c

Note: This section is more detailed than the section on “Major Findings in Year 1” in other parts of this work plan. This is because the details of major findings in other work elements were presented in the quarterly report dated September 30, 2007 and cited in this work plan. This was not the case for the work on aging, therefore a more detailed discussion of major finding in this area is presented here.

- i. Based on a literature review targeting film thickness and the use of surface area factors to characterize mixtures from previous TxDOT Projects 0-4468 and 0-4688, a more sophisticated methodology is needed to characterize this important mixture parameter that may explain differences between mixtures in terms of their reduction in fatigue life with oxidation. The more advanced methodology will include the use of X-ray computed tomography (CT) to the limit of its resolution and theoretical modeling of particulate composites to obtain the distribution of binder thickness throughout the mixture. [Subtasks F1c-2, F1c-4].

- ii. Dimensionless parameters including ratios of short-term to long-term healing energies, fracture energy to rate of fatigue damage accumulation, crack size at failure to binder film thickness, vertical to horizontal moduli, and possibly a parameter to capture accessible air voids may provide the basis for experimental design, although a preliminary investigation utilizing mixtures from previous TxDOT projects 0-4468 and 0-4688 showed that additional parameters will have to be evaluated to explain the differences in the decline of mixture fatigue life with oxidation. [Subtasks F1c-2, F1c-4].
- iii. Mixture characterization of relatively thin specimens through axial testing is required on specimens cut from cores. This testing includes relaxation modulus master curves in tension and compression, damage accumulation rate in repeated direct tension, and tensile strength to facilitate selection of testing conditions. This testing of prismatic specimens has been successful in compression, and tensile testing is currently ongoing. [Subtask F1c-4].
- iv. Crack growth index will be utilized as the mixture response parameter, following the analysis for fine-graded mixtures that is independent of mode of loading. [Subtask F1c-4].
- v. Materials from the field validation sections currently monitored by WRI will be utilized. In addition, materials will be selected from previous TxDOT projects 0-4468 and 0-4688 to ensure longer time periods (and corresponding long-term fatigue distress) are captured for validation. In terms of aging, APT is not a viable option for model validation. [Subtask F1c-2]. A fairly simple pavement oxidation model has been developed based on three governing phenomena: (i) binder oxidation and hardening due to the oxidation, (ii) diffusion of oxygen through asphalt films and (iii) the proximity of air to the binder. Binder oxidation kinetics focuses on the chemical reaction properties of the asphalt binder and the resulting physical changes to the binder, i.e., viscosity change with the formation of carbonyl compounds, and as a function of temperature. Temperature plays a role through both the Arrhenius reaction rate and through the effect of temperature (without reaction) on physical properties such as viscosity. Second, the diffusivity of oxygen into asphalt binder (a strong function of asphalt binder viscosity) dictates how fast oxygen can penetrate into an asphalt binder and initiate the oxidation process. Because binder viscosity is a function of the binder oxidation state and temperature, the diffusivity also depends upon the oxidation state and temperature. Finally, the availability of oxygen to the binder (air voids size and the distance between air voids) is hypothesized to play an important role in the pavement oxidation model. Calculations using the PDE model (formulated in a cylindrical coordinate system) yield the oxygen partial pressure as a function of time and distance between two air voids, together with binder oxidation and hardening rates throughout the model pavement. These hardening rates as a function of position will be passed on to pavement performance prediction models. This PDE model has been solved in cylindrical coordinates at constant temperature. The kinetic data for five binders, available from the literature, were used to study the effects and sensitivity of the model parameters. The effect of the distance between two air voids on the oxygen partial pressure profile between the two air voids was assessed. [Subtasks F1c-1, F1c-3].

Year 2 Milestones for Work Element F1c

- i. Identify important mixture parameters that govern decline in mixture fatigue life. [Subtasks, F1c-1, F1c-4].
- ii. Test and analyze cores from selected field sections for one or two aging periods as materials are available from previous projects and for one aging period from new projects. [Subtask F1c-3].
- iii. Perform tests on laboratory mixtures and field materials to verify testing procedure to obtain fatigue measurements on field cores. [Subtask F1c-4].
- iv. Compare the binder oxidation model to literature pavement aging data. [Subtask F1c-3].
- v. Initiate binder oxidation kinetics and diffusion studies on selected binder materials and binder mastics. [Subtask F1c-3].

Work Element F1d: Healing

Subtask F1d-1: Critically Review Previous Work on Healing under FHWA Contracts DTFH61-C-92-00170 and DTFH61-C-99-00022 (Continued in Year 2)

During previous FHWA contracts on Fundamental Properties of Asphalts and Modified Asphalts, DTFH61-92-C-00170 and DTFH61-99-C-00022, Texas A&M University hypothesized that healing of microcracks is related to the surface energy of the crack face. Intuitively, most healing is cohesive or within the mastic, instead of adhesive or between asphalt or mastic and aggregates faces. As a result the surface energies that affect healing are those of the binder and/or mastic. The existing data strongly demonstrate that higher total surface energies of the binder are related to improved healing. The data also convincingly indicates that healing is best in binders with high acid-base components of surface energy but that healing is impeded by a high Lifshitz Van der Waals surface energy component.

Previous work at Texas A&M has also shown that molecular morphology affects healing and that longer, less branched molecules promote healing as opposed to shorter, highly branched molecules. Texas A&M researchers have developed a model for healing rate that can be incorporated in the fatigue model. This model uses a Ramberg-Osgood function to represent the time rate of healing and its cumulative effect with time. This Ramberg-Osgood approach unites short-term (non polar) healing rate and long-term (polar) healing rate together with overall cumulative bond recapture capacity (ratio of polar to non-polar bond energies).

The healing mechanism will also be studied using the recently proposed approach that represents healing with the convolution integral form proposed by Wool and O'Connor (1981) for polymers. This form combines the effect of wetting (due to surface energy) when crack surfaces are pressed back together followed by diffusion and randomization. The diffusion and randomization processes are affected by molecular morphology.

In year 1 of this project, a detailed literature review on the mechanisms related to self healing in asphalt binders as well as methods to quantify healing was conducted. A framework to quantify healing and incorporate it in fatigue models was also developed. This information was presented

in the quarterly report ending September 2007, and was also synthesized in other publications (Little and Bhasin 2007, Bhasin, Little et al. 2008). The literature review and refinement of this framework will continue in year 2.

Subtask F1d-2: Select Materials with Targeted Properties (Continued in Year 2)

A significant part of the research in the area of fatigue will utilize materials that are selected from the common material library for the Consortium project. However, in order to verify the elements of the healing mechanism, binders or mastics with a targeted range of properties will be required. This subtask is aimed at determining these properties for different asphalt binders and mastics as well as modifying the binders using model compounds or additives to achieve the targeted range of properties, as required. This will be achieved as follows:

- i. Select binders and mastics to evaluate effect of surface energy on the wetting and healing of micro cracks. This will involve measurement of surface free energy components of different binders using the Wilhelmy plate device. Binders will be modified by addition of chemical additives and/or addition of model compounds to achieve variable surface characteristics of the asphalt binder. This process will ensure that the morphology of the asphalt molecules is not significantly altered.
- ii. Select binders and mastics to evaluate effect of molecular morphology on diffusion and healing. This will involve measurement of surface free energy of different binders using the Wilhelmy plate device. Unlike subtask F1d-2, (i), the objective of this subtask will be to identify or formulate asphalt binders that have significantly different molecular morphology, compliance, and diffusivity, but similar surface energy characteristics. Important characteristics pertaining to the molecular morphology of the asphalt binders (e.g., average chain length, molecular weight distribution) will be determined in other tasks of this research project. This information will be used to blend different binders to achieve the desired differences. Previous research at the Texas A&M University has identified parameters such as methyl to methylene ratio, determined using the FTIR, as a parameter that reflects on the molecular properties related to healing. The selected or blended asphalt binders will be evaluated using this parameter.

This subtask was initiated in year 1 of this project. Molecular modeling software was used to model the healing response of different model asphalt binders. The objective of this modeling exercise is to conduct a parametric analysis of the compositional factors (e.g., chain length, distribution of phases, etc.) that have the most significant impact on the healing mechanism. This in turn will facilitate optimal selection of materials for this work element. One very reassuring discovery from the molecular modeling work was the magnitude of surface free energy obtained using molecular modeling is of the same order of magnitude as that measured using the laboratory tests such as the Wilhelmy plate method. This is important not only because surface free energy impacts fracture and healing from a fundamental perspective but also because our framework for the healing process is based on the convolution effect of wetting of the crack faces as they are pushed back in contact during the rest period and the molecular diffusion of molecules across the crack interface during and following the wetting process. The molecular modeling and material selection efforts will continue in year 2 of this project.

Subtask F1d-3: Develop Experiment Design (Continued in year 2)

Once the appropriate set of binders and additives are selected, an experiment design that will provide a statistically reliable assessment of the impact of surface energy (and its components), compliance, diffusivity, and molecular morphology will be developed in coordination with the project statistician, as described in the Experiment Design section. The materials incorporated in the experiment design will be based on the selections made in subtask F1d-2.

Subtask F1d-4: Investigate Test Methods to Determine Material Properties Relevant to Asphalt Binder Healing (Continued in year 2)

The propensity of an asphalt binder to heal over time can be considered as a time dependent function of material properties. The measurement of surface energy and its components will most likely be determined by the Wilhelmy Plate method, based on extensive earlier work. Pulse guided – nuclear magnetic resonance, PG-NMR, may be used to measure self diffusivity constants for the binder. However, other methods of assessing the morphology and diffusion and migration potential of molecular species will be investigated. The surface energy (wetting), compliance, diffusivity, and molecular morphology properties of the binders will be compared with the mechanical DMA quantification of healing. A comprehensive evaluation of healing that integrates properties such as compliance and bond energy will be conducted. The correspondence between the measured diffusion properties and the measured compliance will be determined. The most appropriate testing methodologies will be identified and recommendations for further development made in subtasks F2a and F2b.

In year 1 of this project, a test method using the DSR was developed to determine the intrinsic healing rate of the binder. Preliminary results from this method are consistent with the hypothesis for the healing mechanism developed in subtask F1d-1. Details of the test method and preliminary results were presented in the quarterly report ending September 2007. In addition, pilot tests using PG-NMR techniques to determine the self diffusion properties of binder molecules are in progress. Researchers are also developing methodologies using the molecular modeling techniques in order to obtain estimates of the self diffusion properties of the asphalt binder. Preliminary results related to these techniques will be included in the quarterly report ending December 2007.

The test methods in this subtask will be further developed in year 2. It is important to note that not all of the techniques evaluated or developed in this subtask are intended for routine use by practitioners in the future. However, some of these methods and tools allow the researchers to evaluate properties and/or validate the hypothesis relevant to the healing mechanism. This information will also be extremely useful in selecting candidates and developing a simple test method or analytical procedure to quantify the role of healing in asphalt mixtures on a routine basis.

Subtask F1d-5: Testing of Materials (Continued in year 2)

The binders and additives selected in subtasks F1d-2 and F1d-3 will be tested using the methods identified in subtask F1d-5 to determine their surface energy properties (total surface energy and

non-polar and polar components of surface energy) and molecular morphology. These values will be compared with measurements of healing probably by using Dynamic Mechanical Analysis (DMA). In the DMA experiment the binder (neat or modified) will be mixed with a standard filler and fine aggregate. The sample will be subjected to cyclic, torsional loading in the DMA experiment. Multiple rest periods will be introduced and recovery of energy dissipated due to various mechanisms during these rest periods will be monitored as an indicator of healing. The objective will be to identify the effect of surface energy on the healing through the wetting mechanics and the effect of compliance and diffusivity as determined by molecular morphology through the diffusion and randomization mechanism.

Subtask F1d-6: Evaluate Relationship Between Healing and Endurance Limit of Asphalt Binders (Continued in year 2)

Subtask Lead: Carl Johnson

Introduction

During the last 10 to 15 years the understanding of healing and endurance limits of asphalt mixtures has advanced significantly. Research on binder fatigue and development of binder fatigue tests are relatively new and have not included two important aspects of fatigue: healing and endurance limits. It is expected that advancements in characterizing and modeling of healing and endurance limits of mixtures can be applied to fatigue measurements of binders in the dynamic shear rheometer (DSR). This task will focus on two main areas, applying methods developed for healing of mixtures to results of binder fatigue testing in the DSR, and developing methods for estimating the endurance limits of binders using the DSR.

A comprehensive plan for measuring healing potential of binders with and without modification using the DSR will be developed after a critical review of the advancements in mixtures and mastics. The data published on binder fatigue during the last few years will be gathered to introduce a binder fatigue model that allows an estimate of the effect of stress/strain on fatigue life and also the prediction of endurance limits. An attempt will be made to include healing in the endurance limit prediction model. The task will also include limited validation of the endurance limits and effect of modifiers on altering the limits. The work will be coordinated carefully with the other tasks of this area.

Relationship to FHWA Focus Areas

The fatigue work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property and pavement performance.

Hypothesis

Healing in asphalt binder greatly affects the fatigue performance of asphalt binders and the performance of asphaltic mixtures. The healing properties of asphalt binders have to be characterized to properly predict the performance of the asphalt binders and asphaltic mixtures.

In addition, healing will be an important factor in establishing the endurance limit for asphalt binder and asphaltic mixtures.

Objectives

One of the objectives of this task is to include healing in the endurance limit prediction model. The task will also include limited validation of the endurance limits and effect of modifiers on altering the limits.

Experimental Design

The following tasks will be completed in order to achieve the objectives of this research effort:

- i. Develop a protocol to measure healing of fatigue damage for asphalt binders. This task will include a comprehensive literature review of the worldwide literature on methods for measuring healing of asphalt mixtures and other viscoelastic materials. Based on the review, a set of testing protocols with potential to quantify healing of binders will be selected. Preliminary testing of a set of 4 binders will be conducted to evaluate the practicability and feasibility of the tests. The tests will be restricted to using the DSR and the BBR devices.
- ii. Evaluate testing protocols. Further testing of 6 binders (2 unmodified and 4 modified) will be conducted to evaluate the practicability and feasibility of the tests identified in Task 1. The tests will also be restricted to using the DSR and the BBR devices. The best protocol will be defined by its ability to differentiate among binders, cost in terms of time and effort, repeatability, and simplicity of analysis. The outcome of this evaluation will be selected in coordination with other work elements on the unified fatigue damage model. In other words, the outcome should include parameters that can be used as input in the unified fatigue model.
- iii. Evaluate factors affecting healing of binders. In this task, the factors known to affect healing, as identified in Task 1, will be used to develop a comprehensive experimental plan for testing and quantifying the change in healing due to variation of these factors. The factors will include, at a minimum, temperature, chemical composition, modification types, aging, loading rate, rest periods, and stress or strain used in testing. Statistical experimental design will be used to minimize the number of combinations.
- iv. Evaluate possible surrogate measures. This task will compare the results from testing conducted in Task 3 with simple chemical, physical, or rheological properties already measured in binder surrogate fatigue testing (stress sweep), slope of the master curve, the $m(60)$ value, and other measures that are already in the PG specification or can be an extension of the PG testing. This will be done to investigate whether healing can be estimated from other simple measures, eliminating the need for a healing-specific test.
- v. Evaluate role of mineral surface in healing. Selected binders will be mixed with 3 types of mineral fillers (acidic, basic and neutral) to study role of mineral surface on healing results. Based on the results, limited testing of actual mixtures will be conducted to validate the effect of the mineral surface and define the importance of aggregate presence on healing.

- vi. Make final recommendations for a binder healing test and specification parameter. Based on the results of Tasks 2 through 5, a final recommendation will be made regarding the practicality of including a healing test and specification parameter in practice. Guidelines will be developed for a test protocol and analysis method, and specification limits will be proposed. Suggestions for future research will be also listed.

Major Findings from Year 1

During year one, the materials and testing conditions for the plan were selected and are shown in table F1d-6.1. A testing plan was also developed and the proposed tests are shown in table F1d-6.2. During Year 1, a critical review of literature related to healing of asphalt mixtures and binders was conducted. The results of this were used to draft the conceptual outline.

Table F1d-6.1. Matrix of materials and conditions.

Neat Binders	PG64-22
Modifiers	SBS
	Elvaloy
	PPA
Mineral Fillers	Granite
	Ottawa sand
	Limestone
	Hydrated lime
	Cellulose

Table F1d-6.2. Proposed tests on asphalt binders and mixes.

Asphalt Binder and Mastics	Interrupted Cyclic Fatigue	Strain level	3%
			5%
			7%
		Frequency	5 Hz
			10 Hz
		# of Rest Periods	0
			1
			2
			5
			10
	Modified Resilient Modulus Test	Duration of Rest Periods	4 min
			8 min
			12 min
			16 min
			20 min
	Haversine Pulse Loading	Load Pulse Spacing	0 s
			1 s
			3 s
			9 s

The ultimate fatigue performance of a pavement relies on many factors, but the two that this study will focus on is the ability of asphalt binder both to resist damage from occurring and also to heal the damage that has already occurred. Fatigue performance of asphalt mixtures has been widely tested in the lab, but binder fatigue characterization is still in progress. This section will discuss two concepts that have been applied to mixtures and how they can be applied to binder testing.

1. Sinusoidal Cyclic Loading with the Inclusion of Rest Periods (RP's)

Typical fatigue testing, also known as time sweep testing, is performed by applying sinusoidal cyclic loading at a given frequency and controlled level for either a specified amount of time, or specified level of achieved damage (e.g., 50% loss of G^* , max phase angle). The healing qualities of the material are typically measured by comparing the differences of the measured material properties between standard time sweep tests and those that have had rest periods introduced into them. It has been clearly shown that RP's increase the number of cycles that a sample can withstand before reaching its predetermined failure criterion. Below are two examples of this method:

a) *TTI's Method* (Kim et al. 2003; Song et al. 2005)

A standard strain-controlled time sweep is applied to the material until failure, in this case δ_{max} . Another time sweep test is then run with the addition of multiple RP's of predetermined duration spaced at equal intervals. The length of the interval depends on the ability of the material to withstand damage; weaker materials will be assigned shorter intervals in order to recover some of the accumulated damage. An example of these tests is shown below in figure F1d-6.1.

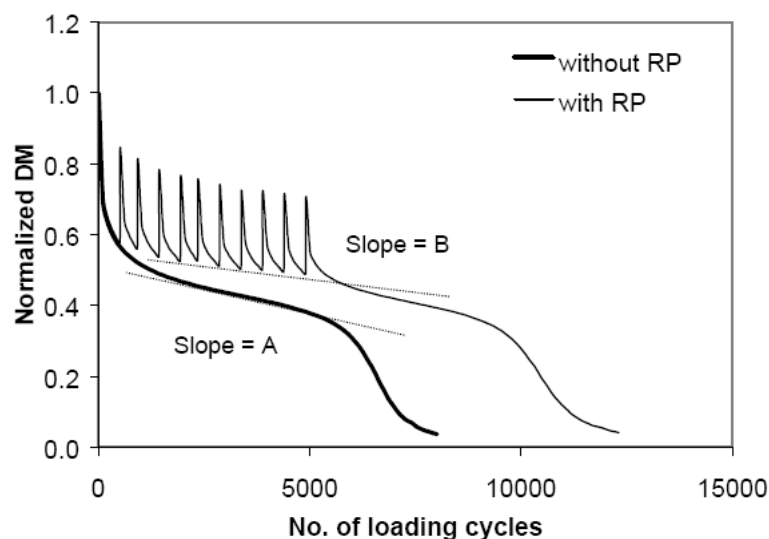


Figure F1d-6.1. Chart. Effect of microdamage healing due to rest periods.

The quantification of the material's healing index is then calculated using a parameter known as the Healing Potential Index (HPI):

$$HPI = \frac{A - B}{A} \quad (1)$$

Where A and B equal the absolute value of the slope representing microcracking speed (shown in figure F1d-6.1) with and without rest periods, respectively.

Performing this analysis method requires time sweep testing with and without rest periods. It also requires a predetermined failure criterion and a systematic way of determining rest period interval spacing.

b) *Baglieri's Method* (Baglieri 2007)

Similar to the previous method, this method involves measuring the comparison between time sweep tests with and without rest periods. However, the basis for comparison lies within measuring the Dissipated Energy Ratio (DER) over the course of the time sweep test. A standard stress-controlled time sweep is run in this case, and the DER is plotted for the duration of the test. Then, depending on the amount of damage in the specimen that the healing properties of the material to be evaluated, one RP is inserted into the time sweep at the desired level of damage (e.g., DER_{max} , $75\% DER_{max}$, $50\% DER_{max}$). The duration of this RP is equal to three times the duration of the time sweep test up until introduced RP, measured from the previous time sweep with no RP's. The test then resumes until the predetermined failure criterion is reached.

The Healing Index (HI) is calculated as follows:

$$HI = \left| \frac{W_{Reload} - W_{Load}}{W_{Load}} \right| \quad (2)$$

Where W_{Load} is the dissipated energy per cycle at the end of the loading phase and W_{Reload} is the dissipated energy per cycle at the first cycle of the reloading phase.

Performing this analysis method requires time sweep testing with and without rest periods. It also requires a predetermined failure criterion, but the duration of the RP is determined as described above. The point at which the RP is introduced must be predetermined.

2. Repeated Haversine Loading

This method of fatigue and healing testing is derived from the method of determining resilient modulus of asphalt mixtures using the Superpave Indirect Tension test (IDT). Typically, a 0.1 second loading pulse is applied to the material, followed by a rest period of 0.9 seconds in order to simulate the action of traffic on a pavement. As the number of loading pulses increases, the internal structure of the material begins to accumulate damage and the specimen becomes unable

to withstand additional loading. The testing can either be run to a specified number of cycles, or until a failure criterion is reached (e.g., 50% loss in dynamic modulus). The RP's are introduced either directly after the loading pulses by controlling the length of the repeated RP's, or after a certain number of loading cycles with standardized RP's during each cycle. An example of each is shown below:

a) *Carpenter's Method* (Carpenter and Shen 2006)

Rest periods using this method are controlled by adjusting the length of the RP directly after the pulse. Typically, a 0.9 sec rest period is applied after each 0.1 sec loading pulse; by changing the length of the RP, the material has more opportunity to heal accumulated damage.

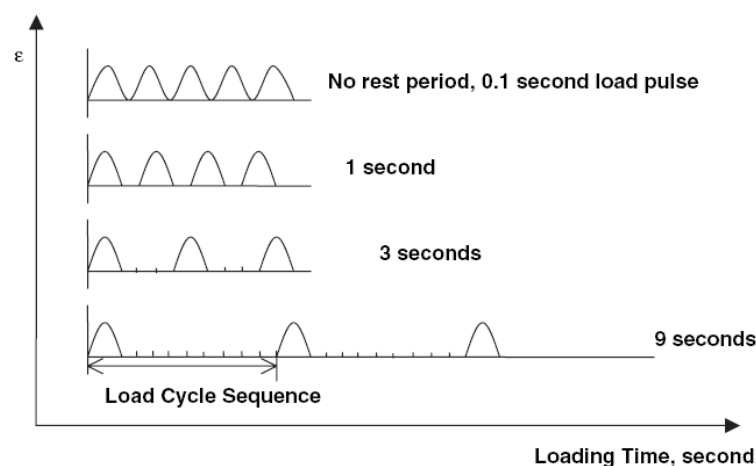


Figure F1d-6.2. Chart. Haversine load pulse sequence of fatigue-healing test.

By measuring number of cycles until failure (typically defined as 50% loss in stiffness) for each RP duration, a characteristic curve can be developed. This curve can be used to predict the duration of the RP needed to reach a predetermined number of cycles to failure; this idea can be extrapolated to the idea of a pavement's fatigue endurance limit. By lowering the strain level of the loading pulse, the duration of the RP needed to achieve the predetermined number of cycles to failure shortens. Once this duration reaches a level that is applicable to a desired traffic loading, the material can be engineered to perform within the expected loading levels. That is, pavement layer thicknesses can be calculated so that the asphalt concrete experiences strain levels at or below the material's fatigue endurance limit.

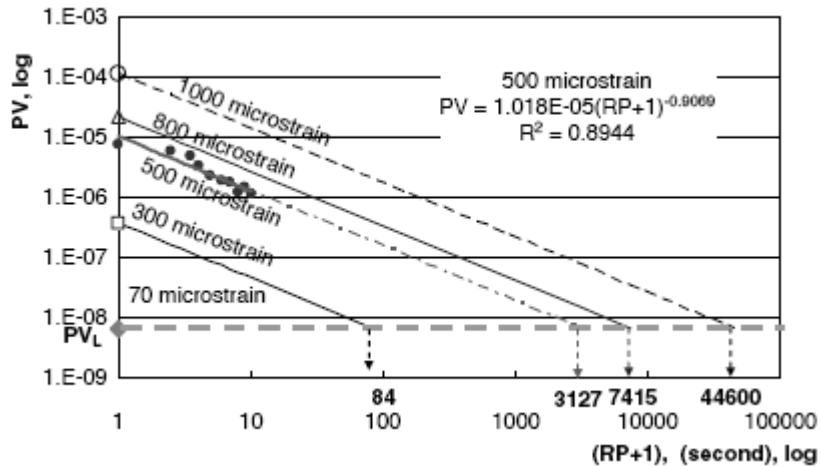


Figure F1d-6.3. Chart. Plot of PV versus Rest Period Duration + 1 (PV is a parameter derived from the inverse of N_f).

This method requires the ability to test using haversine loading, with the ability to adjust the duration between load pulses. The number of cycles to failure can be plotted against the duration of the RP's in order to evaluate the material's healing potential.

b) *Roque's Method* (Kim and Roque 2006)

This method uses the procedure set forth in AASHTO TP 31-94 to determine resilient modulus as its basis. In other words, the repeated haversine loading is standardized at 0.1 sec of loading with 0.9 sec of rest. Healing is evaluated by interrupting the loading cycles to include RP's of varying durations, then comparing the level of damage in the material before and after RP's. Damage is accounted for by measuring the deformation in the specimen against the number of loading cycles.

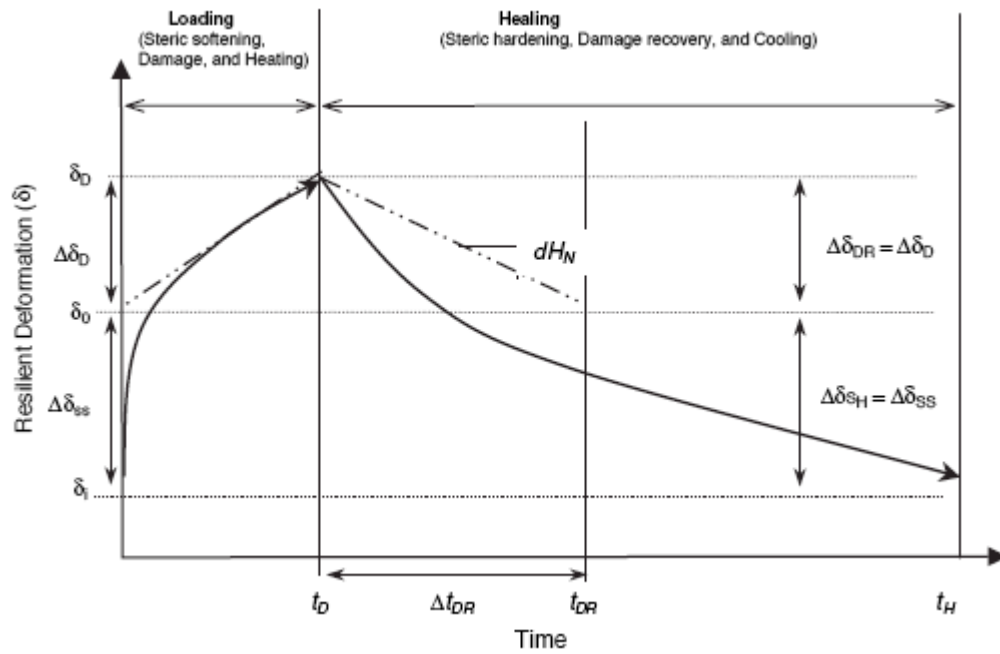


Figure F1d-6.4. Chart. Resilient deformations during loading and healing.

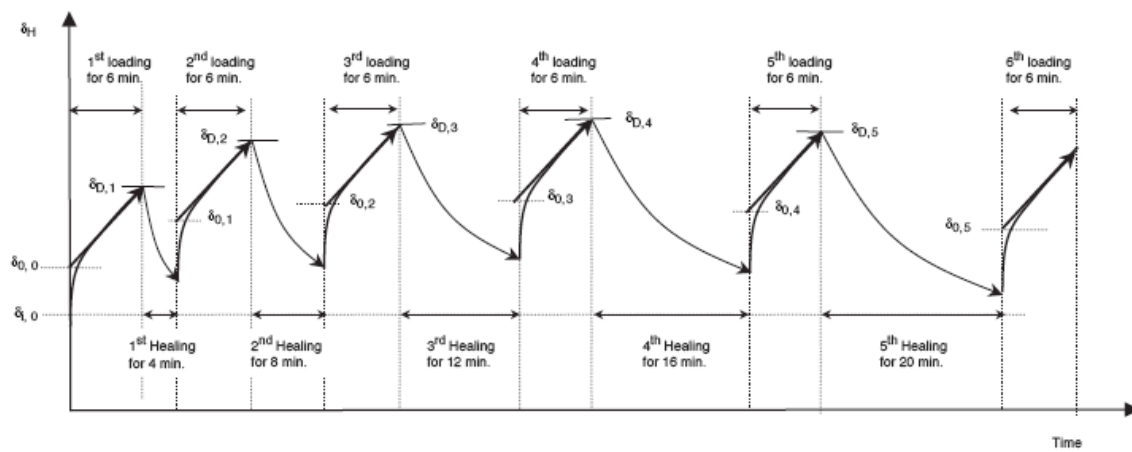


Figure F1d-6.5. Chart. Concept of repeated loads for determining damage recovery rate.

From Roque (Kim and Roque 2006), the healing characteristics are calculated as follows using the parameters as shown:

Net normalized damage:

$$(D_{NN,i}) = (\delta_{D,i} - \delta_{0,i-1}) / \delta_{0,i-1} \quad i = 1 \sim 5$$

Normalized damage:

$$(D_{N,i}) = D_{NN,i} + D_{NR,i-1} \quad i = 1 \sim 5, D_{NR,0} = 0$$

Remaining normalized damage:

$$(D_{NR,i}) = D_{N,i} - H_{N,i} \quad i = 1 \sim 5$$

Normalized damage recovery:

$$(H_{N,i}) = (\delta_{D,i} - \delta_{0,i}) / \delta_{0,i-1} \quad i = 1 \sim 5$$

Relative damage recovery:

$$H_{N,i} / D_{N,i} \quad i = 1 \sim 5$$

With the relative damage recovery plotted with rest periods, the rate of normalized damage recovery (dH_N) was determined as the slope of a linear regression curve. Time to the full recovery of damage (Δt_{DR}) was then calculated by extrapolation of the regression curve (figure F1d-6.4).

To complete this analysis, haversine loading needs to be applied to the specimen at the standard 0.1 sec loading with 0.9 sec of rest per loading cycles. Testing can then be suspended at predetermined intervals in order to allow the specimen to heal, at which point the material's healing characteristics can be evaluated.

An experimental work plan was then designed by this team in order to evaluate prospective testing protocols and begin preliminary analysis on the factors affecting binder healing. A procedure for interrupted cyclic loading has already been completed, with an example of the data shown in figure F1d-6.6.

Further work still needs to be done in order to develop other test protocols, but the project will focus on evaluating the ability of the materials to heal applied damage, and how the level of damage in the material affects the healing potential of the materials.

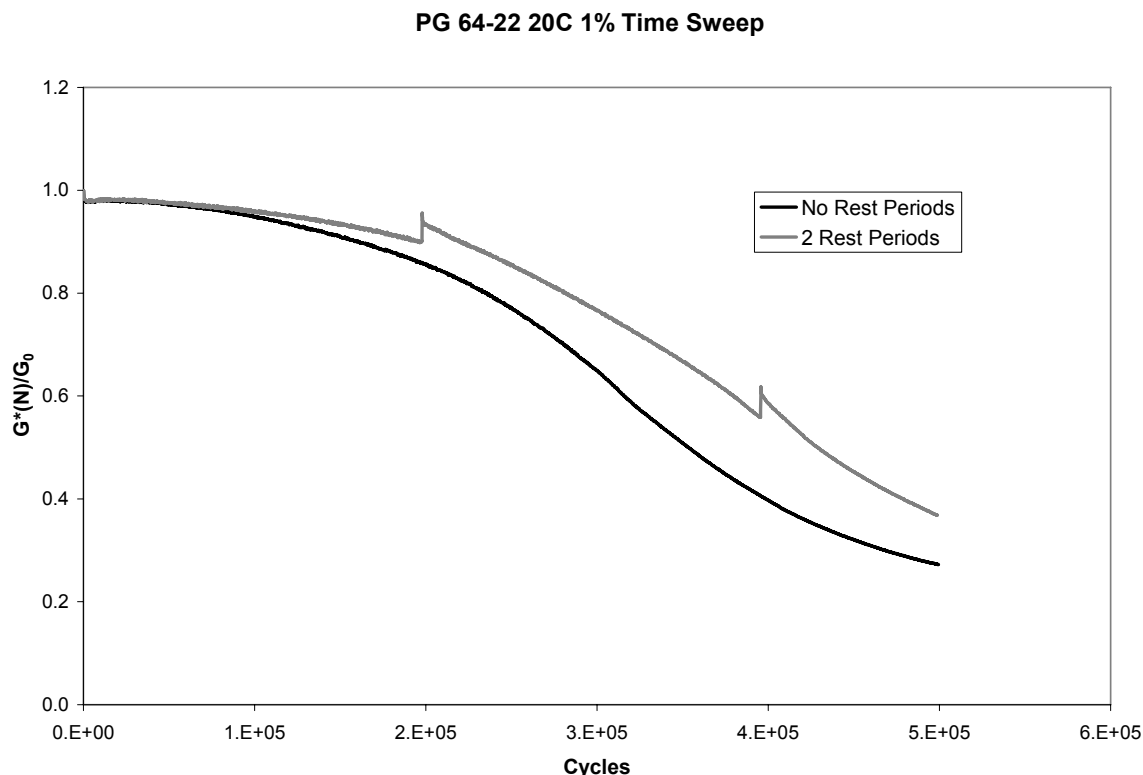


Figure F1d-6.6. Chart. Example data from interrupted cyclic loading procedure for asphalt binders.

Year 2 Work Plan

The experimental plan incorporates both the ability to evaluate proposed test methods as well as the ability to begin preliminary analysis on the factors affecting binder healing.

a. Development and evaluation of testing protocols

Further binder testing will be conducted to evaluate the practicability and feasibility of the tests identified in Task 1. The best protocol will be defined by its ability to differentiate among binders, cost in terms of time and effort, repeatability, and simplicity of analysis. The outcome of this evaluation will be selected in coordination with other work elements on the unified fatigue damage model. In other words, the outcome should include parameters that can be used as input in the unified fatigue model.

b. Evaluation of factors affecting the healing of binders

In this task, the factors known to affect healing, as identified in Task 1, will be used to develop a comprehensive experimental plan for testing and quantifying the change in healing due to variation of these factors. The factors will include, at a minimum, temperature, chemical composition, modification types, aging, loading rate, rest periods, and stress or strain used in testing. Statistical experimental design will be used to minimize the number of combinations. A general methodology for analysis is shown in figure F1d-6.7.

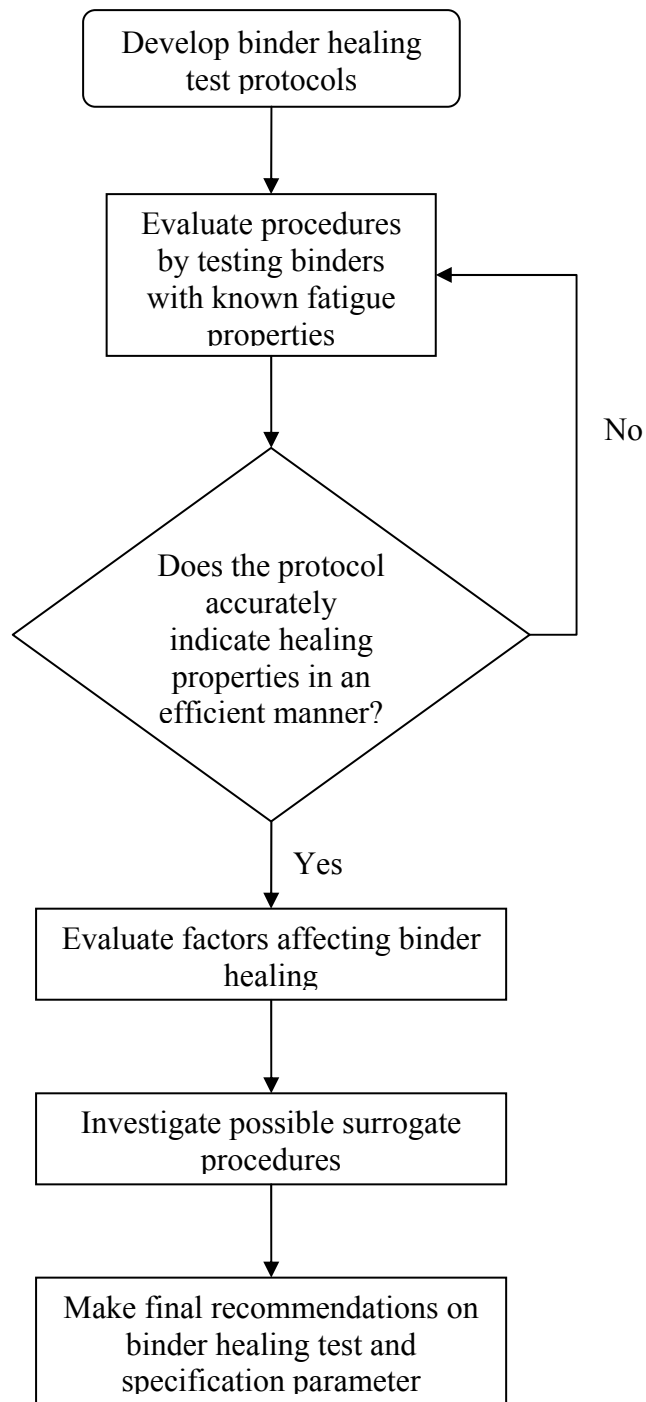


Figure F1d-6.7. Chart. Flow chart for the proposed research program.

Year 2 Milestones

- Complete report on review of literature
- Finalize test protocols for healing of asphalt binders
- Conduct the proposed tests to identify factors affecting the healing of asphalt binders

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Develop a protocol to measure healing	X	X			
ii. Evaluate testing protocols and develop an efficient testing procedure	X	X			
iii. Evaluate factors affecting healing of binders		X	X	X	
iv. Evaluate role of mineral surface on binder healing			X	X	
v. Evaluate possible surrogate procedures			X	X	
vi. Make final recommendations on binder healing test and specification parameter				X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
i. Develop a protocol to measure healing	X			
ii. Evaluate testing protocols and develop an efficient testing procedure	X			
iii. Evaluate factors affecting healing of binders		X	X	X
iv. Evaluate role of mineral surface on binder healing				
v. Evaluate possible surrogate procedures				
vi. Make final recommendations on binder healing test and specification parameter				

Budget

The estimated budget for this subtask is \$350,000 over the five years. The work will be conducted by the University of Wisconsin-Madison.

Subtask F1d-7: Coordinate with Atomic Force Microscopic (AFM) Analysis (Year 2 start)

As described previously healing characteristics of an asphalt binder depend on its surface properties as well as the molecular morphology. AFM imaging and interaction measurements on the asphalt binders selected in this task will provide valuable insight at a nano scale into understanding the mechanism and modeling of the healing phenomenon.

In this effort nanotechnology (AFM imaging; friction and morphology, contact-force AFM, nanoindentation AFM, chemical-force AFM, etc.), interpreted based on contact mechanics and

statistical mechanics theories of irreversible energy dissipation at diffuse interfaces may be adopted to describe/model material integrity (equilibrium compositional and phase transformation stability, inter and intra molecular compatibility) fracture, slow crack growth and crazing phenomena. Nanoindentation techniques may for example be adopted for measuring stiffness and creep relaxation properties of asphalt binder material thin-films. Sample thin films may be analyzed by AFM imaging techniques, force-distance work of adhesion measurements (nano-contact mechanics) and nanoindentation, each conducted as a function of time and temperature. The results that obtained from these experiments will be compared between AFM methods and with other methods of analysis, including bulk thermal and rheological properties (DSC, DMA, and DSR). Furthermore, model development will be closely tied to nano-experimental techniques, where free energy expressions pertinent to the various molecular ordering events, (e.g., wax crystallization, Spinodal phase separation, and crazing and crack growth models, etc.) will be investigated. This approach is anticipated to lead to mathematical relations between the various molecular ordering events and the mechanical properties of the material based on fundamental physical and chemical theories of soft condensed matter.

- i. Develop experimental techniques that require the minimum amounts of time and materials to quantify asphalt binder and aggregate surface physico-chemical and nano-mechanical properties based on nanotechnology. (e.g., nano-Thin-Film Chromatography/Composition Analysis, nano-Mechanics nano-indentation nano-surface Tensiometer, AFM solidification analysis, programmable dynamics wetting/Spin-Coating via Lubrication Theory, and programmable combinatorial-automated flocculation titrimetry (PC-AFT).
- ii. Develop approaches (Experimental) based on nanotechnology which lead to data-input computational software (e.g., Virtual Asphaltic Concrete Testing Laboratory (VACTL) to model physico-chemical and chemo-mechanical systems.

Year 2 Work Plan

A detailed work plan will be developed for this subtask at the beginning of Year 2. The work plan will be submitted for review by FHWA and pertinent reviewers.

Subtask F1d-8: Coordinate Form of Healing Parameter with Micromechanics and Continuum Damage Models (Continued in year 2)

This subtask will be conducted in coordination with Work Elements F3b and F3c. The objective of this subtask will be to frame the healing property of asphalt binders and mastics, and if required the fine aggregate matrix, in a form that can be easily incorporated in the micromechanics model as well as the unified continuum fatigue model. This subtask will be critical to ensure that healing is appropriately incorporated along with other material properties as a part of these models.

Major Findings from Year 1 for Work Element F1d

A review of literature related to mechanisms and quantification of self healing properties was conducted (F1d-1). A frame work to model the healing process in asphalt materials was

developed (F1d-1). A new test method that utilizes the DSR to determine the intrinsic healing function was developed. Results from this test method were compared to known values of healing for selected materials determined using the DMA (F1d-4). Key findings from the literature review, details pertaining to the framework to quantify healing, and preliminary results from the DSR based test method to quantify the healing process in asphalt materials were presented in detail in the Quarterly report ending September 2007 and synthesized in recent publications (Little and Bhasin 2007, Bhasin, Little et al. 2008).

Year 2 Milestones for Work Element F1d

- i. Continue the development of test methods to measure material properties related to healing mechanism and extend these test methods to mastics.
- ii. Refine framework to incorporate the net healing in a fatigue model.
- iii. Measure material properties related to healing for select asphalt binders and mastics.

Category F2: Test Method Development

Work Element F2a: Binder Tests and Effect of Composition

Task Lead: Codrin Daranga

Introduction

A successful modification of an asphalt binder with a polymer is intended to improve one or more of the basic asphalt properties such as rigidity, elasticity, brittleness, durability, and compatibility – especially in-blend compatibility. An asphalt-polymer blend is considered compatible if the polymer is soluble in the asphalt cement or if it can be swollen by the asphalt oils without causing flocculation of the asphaltenes. Most polymer modifiers are used to enhance the rutting resistance of asphalt binders. When it comes to the influence of modifiers on fatigue resistance, some have a positive influence, while others can have a negative influence. It is to be expected that by adding more flexibility (increase in toughness) to the binder, fatigue resistance will increase. If, on the other hand, the modifiers will stiffen the material at medium and low temperatures, then a decrease in fatigue resistance is expected. The morphology of the polymers used as modifiers, as well as their chemical structure and affinities, play an important role on how the binder will perform in field applications. The flexibility of rubbers will bring toughness to the asphalt binder, possibly increasing its fatigue resistance. The hardness of waxes will improve rutting resistance properties. On the other hand, crystallinity promoted by rigid wax chains can diminish the fatigue life of asphalt binders and decrease their low temperature cracking resistance. Therefore, a fine balance needs to be maintained between flexibility and stiffness, between elastic and plastic domains within the asphalt binder, between the affinity towards polar compounds (e.g., mineral aggregate) and moisture damage resistance, etc. In addition to modifiers, aging can have a significant impact on fatigue. It is, however, not clear if aging has a negative effect on fatigue under all conditions of loading. For example, aging is expected to increase stiffness and strength but decrease ductility (flexibility). While increasing

stiffness could have a positive effect on stress-controlled fatigue, reduced flexibility and toughness could have a negative effect.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Optimum Pavement Performance: Introducing methods for better characterization of modified asphalts.
- Advanced quality systems: Further development of test methods that are more related to actual pavement performance.

Hypothesis

The hypothesis is that binder modification has a great impact on fatigue resistance of pavements. Aging of both modified and unmodified binders has its own impact on fatigue life. A fundamental understanding of how polymers interact with asphalt, and how aging and chemical modifiers control binder fatigue, can improve modifier selection process.

Objectives

This work element will focus on developing methods to estimate effect of modification and aging on fatigue resistance and provide a framework for selecting binders to reduce potential for inferior fatigue resistance. The framework will include polymer and asphalt chemistry as well as mechanical properties.

Experimental Design

The objective of this subtask will be addressed as follows:

- i. Analyze Existing Fatigue Data on Polymer Modified Asphalts (Year 1 start). Fatigue studies of unmodified, SBS and acid modified binders have been performed by UW-Madison in collaboration with FHWA for the last three years. Testing was performed using the dynamic shear rheometer (DSR), with three types of procedures of particular focus: stress sweep, stress-controlled frequency sweep, and stress-controlled fatigue. In addition, limited strain controlled testing was conducted. The DSR data was analyzed alongside direct tension data using principles of dissipated energy. This data set will be analyzed to identify most dominant trends in effects of polymers and aging on fatigue of binders. Some limited additional testing will be conducted to define the trends and provide a framework for the new testing plan.
- ii. Select Virgin Binders and Modifiers and Prepare Modified Binder (Year 1 start). Based on the results of subtask 1, a complementary work plan will be developed. Modified binders will be prepared using two different “base” virgin binders and four modifiers (SBS rubber, Elvaloy®, Sasobit® wax, and a polyphosphoric acid modifier). In order to better examine the influence of the butadiene moiety along with the variation in ratio

between the lengths of the butadiene and styrene blocks, more than one type of SBS will be tested. Every “base” binder will be modified using each of the chemical additives selected. Sample size to be produced will be determined taking into consideration the testing procedures that the materials will be subjected to.

- iii. Subject Samples of Virgin and Modified Binder to Several Laboratory Aging Procedures. Samples from both the modified and unmodified types of binders will be subjected to lab aging techniques. This is done to enable the study of aging as a determining factor in the fatigue life of binders. Modified and unmodified binder samples will undergo RTFO and one or more PAV treatments.
- iv. Collect Fatigue Test Data for All Samples. This task will concentrate on testing the previously prepared samples according to the work plan in Task 2.
- v. Analyze Data and Propose Mechanisms by Which Aging and Modification Influence Fatigue of Binders. The objective of this task is to analyze all the collected data from the previous task. The focus will be on defining mechanisms by which modifiers and aging control fatigue at various conditions. The outlined mechanisms by which it is believed aging and modification affect fatigue life of binders will be used to develop guidelines for selecting modifiers and the tests required to qualify modifiers for improvement of fatigue life.

Major Findings from Year 1

During year one, the materials and testing conditions for the plan were selected and are shown in table F2a.1.

Table F2a.1. Matrix of materials and conditions.

Binders	Flint Hills PG 58-28	Mineral Fillers	Limestone
	Flint Hills PG 64-22		Sandstone
	Marathon PG 58-28		PG xx-34
	Marathon PG 64-22		D1101 Kraton SBS
Testing Temp	19° C	Modifiers	D1184 Kraton SBS
	25° C		Elvaloy AM
Storage time	0h		Elvaloy 4170
	24h		PPA 115
	72h		PPA105
Storage Temperature	135° C		OPA 85

Three binders (one neat, one SBS modified and one Elvaloy modified) were treated with polyphosphoric acid (PPA). The effect of PPA modification was then studied on storage time and presence of mineral filler. Notable results are as follows:

The starting materials are shown below:

- A1 PG 70-22 SBS Modified
- A5 PG 58-22 Neat
- B9 PG 64-28 Elvaloy Modified
- X 115 PPA (polyphosphoric acid)
- Y 105 PPA
- Z 85 OPA (ortho-phosphoric acid)

Table F2a.2 summarizes the PG properties for the starting asphalt binders included in this study. Note that the polymer modified binders were acquired already modified with unknown concentrations of the respective polymer modifiers.

Table F2a.2. PG grading of starting materials.

	A1 SBS PG 70-22		c.v. %	A5 Neat PG 58-22		c.v. %	B9 Elvaloy PG64-28		c.v. %
Original									
G*/sinδ (kPa)	@70°C	1.26	1.61	@58°C	1.12	1.66	@64°C	1.22	1.23
True Grade (°C)	@1.00 kPa	72.5		@1.00 kPa	59.5		@1.00 kPa	66.3	
RTFO									
G*/sinδ (kPa)	@70°C	2.43	0.20	@58°C	2.44	0.24	@64°C	2.76	0.77
True Grade	@2.20 kPa	71.2		@2.20 kPa	58.9		@2.20 kPa	66.6	
PAV									
G*·sinδ (kPa)	@13°C	4939	6.64	@16°C	3831	3.70	@07°C	4161	7.03
True Grade	@5000 kPa	12.4		@5000 kPa	13.6		@5000 kPa	5.4	
Stiffness (MPa)	@-18°C	267.0	2.12	@-18°C	273.3	10.76	@-24°C	258.3	6.45
True Grade	@300MPa	-29.9		@300MPa	-29.4		@300MPa	-29.6	
m-value	@-12°C	0.358	0.40	@-12°C	0.369	7.26	@-24°C	0.310	0.46
True Grade	@0.300	-26.8		@0.300	-27.8		@0.300	-28.0	
TEMP RANGE	98.0			86.7			94.3		

A small percentage of PPA (between 0.5 and 1%wt) raises the high PG grade of the binder by six degrees (one PG grade); 1.5 to 2% wt PPA will bring an additional PG grade raise. Figure F2a.1 shows the effects of the PPA content on the rheological properties of asphalt binders. The effect of increasing the high end of the PG grade is more pronounced on the polymer modified materials than on the neat binders, as indicated in table F2a.3.

There is also a surprising improvement on the low temperature grade of the binders.

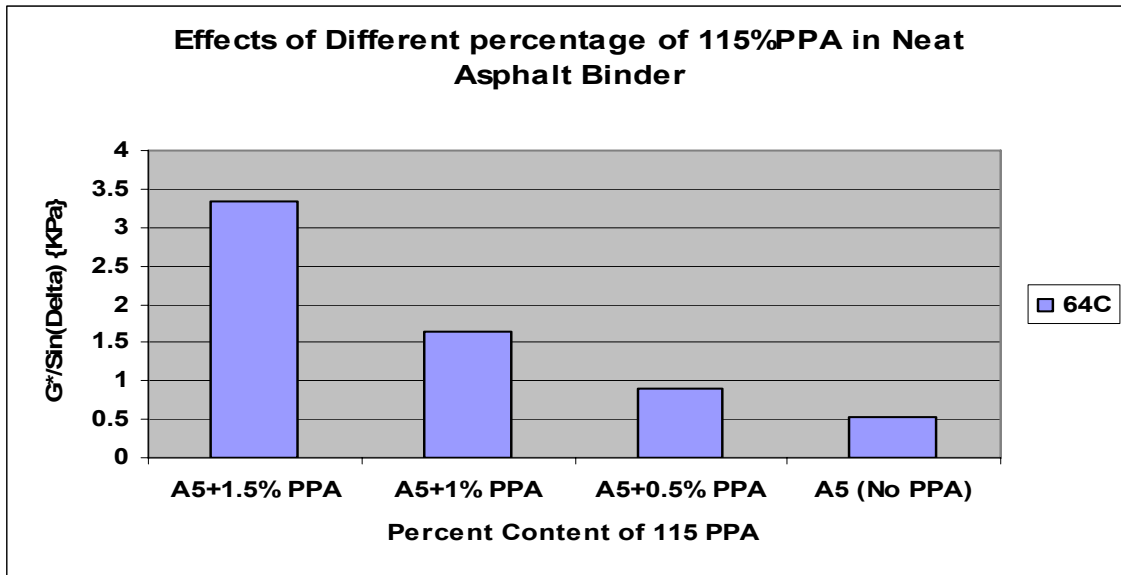


Figure F2a.1. Chart. Effect of PPA concentration on neat asphalt binder.

Table F2a.3. PG grading of binders after modification with 1% 105 PPA.

	A1 SBS PG 70-22			c.v.%	A5 Neat PG 58-22			c.v.%	B9 Elvaloy PG64-28			c.v.%
Original												
G*/sinδ (kPa)	@82°C	1.24	2.87		@64°C	1.25	0.79		@82°C	1.12	5.07	
True Grade (°C)	@1.00 kPa	84.7			@1.00 kPa	66.0			@1.00 kPa	83.3		
RTFO												
G*/sinδ (kPa)	@88°C	2.86	3.73		@64°C	2.76	0.18		@88°C	2.68	8.31	
True Grade	@2.20 kPa	91.5			@2.20 kPa	66.0			@2.20 kPa	91.0		
PAV												
G*·sinδ (kPa)	@13°C	4046	6.71		@13°C	4472	4.02		@07°C	4775	--	
True Grade	@5000 kPa	10.8			@5000 kPa	11.9			@5000 kPa	6.5		
Stiffness (MPa)	@-18°C	200.7	1.39		@-18°C	222.0	3.82		@-24°C	231.0	6.45	
True Grade	@300MPa	-31.5			@300MPa	-30.4			@300MPa	-36.5		
m-value	@-18°C	0.307	0.23		@-18°C	0.311	4.55		@-24°C	0.304	0.46	
True Grade	@0.300	-28.6			@0.300	-29.1			@0.300	-34.7		
GRADE	PG 82-28				PG 64-28				PG 82-34			
TEMP. RANGE	113.3°C				95.1°C				118.0°C			

The storage experiment was performed at 135°C in closed containers for 24 and 72 hours. For all binders there is a definite trend of increased stiffness with increased storage time, as shown in figures F2a.2 and F2a.3.

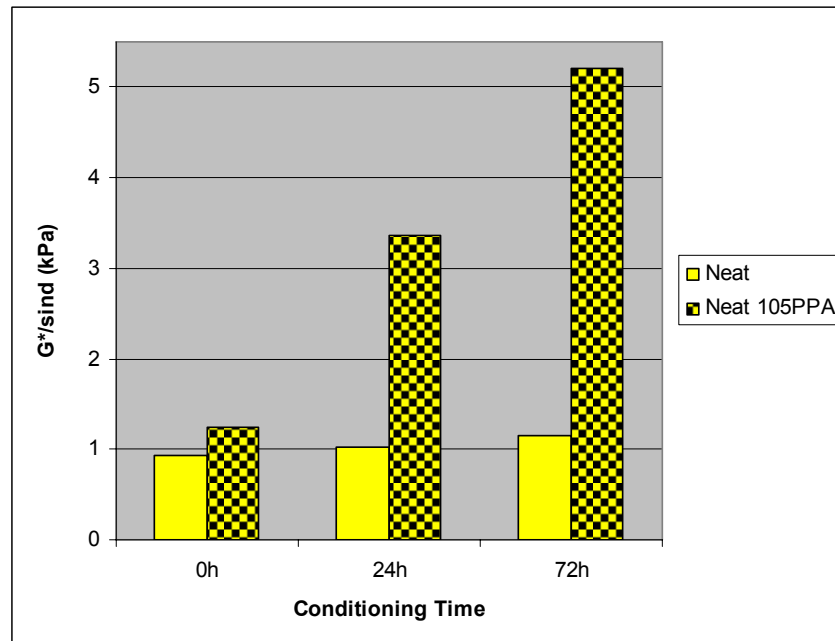


Figure F2a.2. Chart. Effect of conditioning on neat binder @ 135°C.

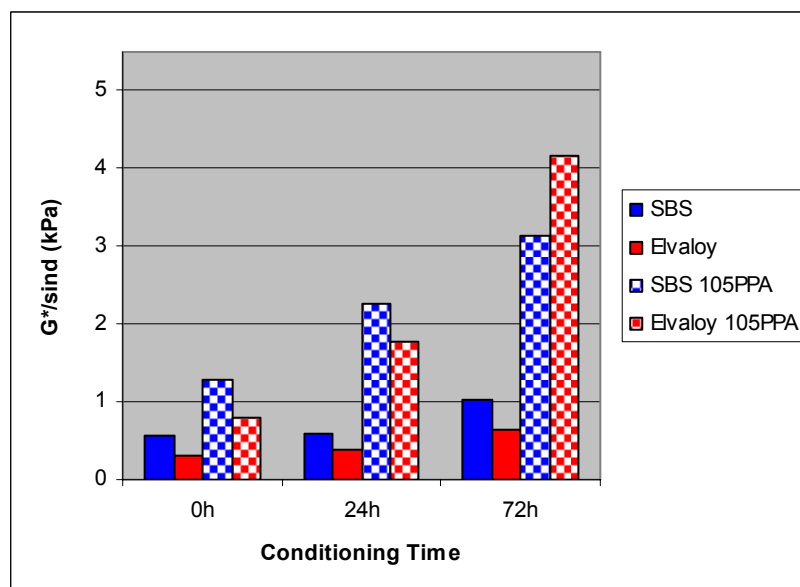


Figure F2a.3. Chart. Effect of conditioning on polymer modified binder @ 135°C.

This trend is valid for both binders and mastics. As in the case of the high PG grade, this trend is more pronounced for the polymer modified binders than for the neat binder, as shown in figure F2a.4.

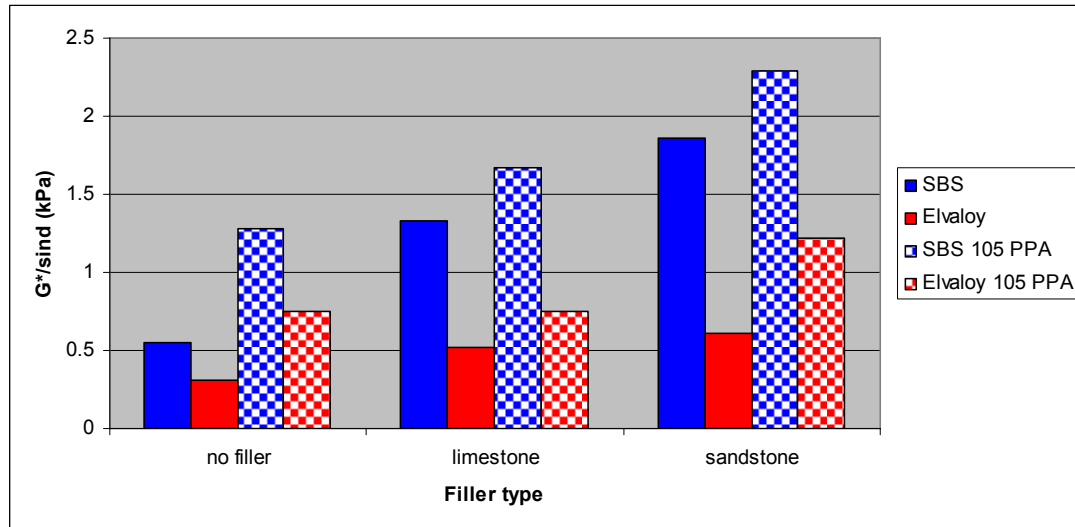


Figure F2a.4. Chart. Effect of filler on polymer modified binders.

In the case of the mastics, the presence of PPA does not seem to have as much of an effect as in the case of binders. However, the trend showing an increase in stiffness when PPA is added is still present.

The increase in stiffness observed in the presence of the PPA is greater than expected. One explanation could be the formation of a gel-like structure in the presence of an acid like PPA. In order to investigate this hypothesis, four samples of binders (two PPA modified and two without PPA) were subjected to stress sweep testing. If a gel-like structure is contributing to the increase in stiffness, then that structure would be expected to collapse under increasing shear stress. As shown in figure F2a.5, no evidence is seen of a gel like structure collapsing, which would indicate the absence of such a structure. However these are just preliminary results and investigation continues into this matter.

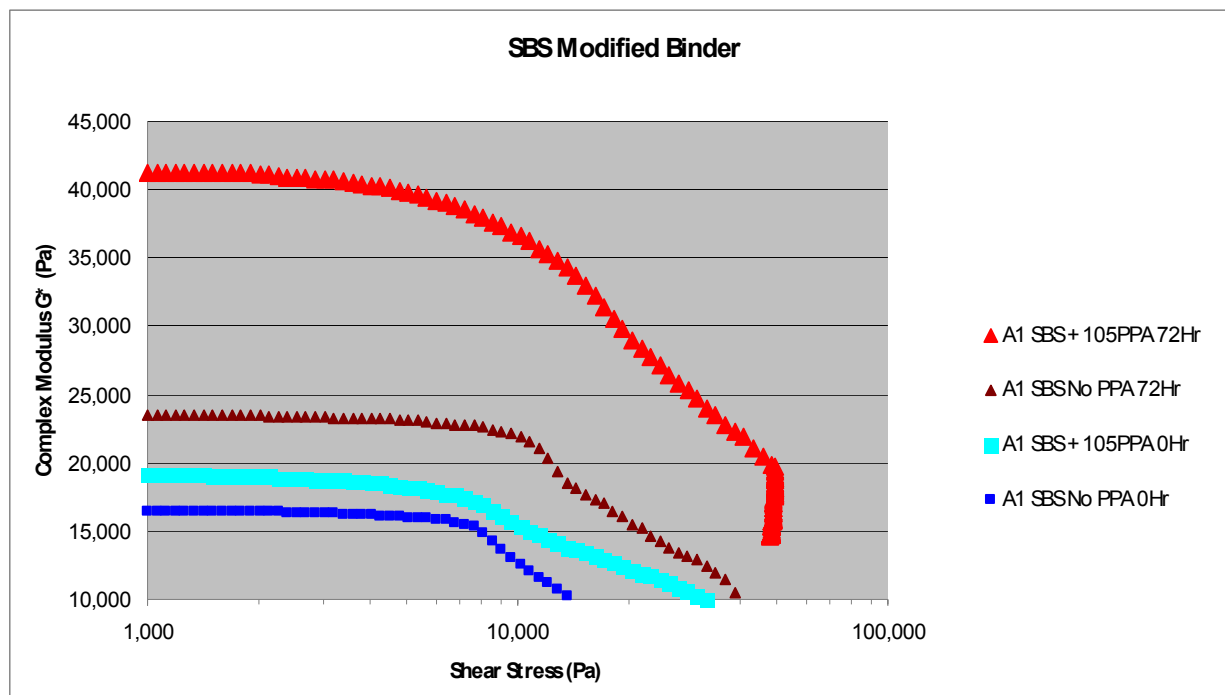


Figure F2a.5. Chart. Stress sweep test results on SBS modified binder with and without PPA, before and after 72 hours of conditioning @135 °C.

Year 2 Work Plan

Stress sweep tests will be performed on these materials in order to assess their fatigue properties. Also the new monotonic test developed at University of Wisconsin-Madison will be performed. This will not only give a better picture of the influence of different modifiers on fatigue properties of binders, but also will help further validate the monotonic test.

The data analysis on this project will be focused on two main areas: rheological properties and damage resistance characterization.

The rheological properties investigation serves as a tool to classify and rank starting materials, as well as a monitoring tool during the modification and conditioning process. This is accomplished by measuring parameters such as $G^*/\sin\delta$, an indication of the rutting resistance of binders, as well as by performing Multiple Stress Creep Recovery tests on the binders. This will provide important information on how the modification of binders affects not only fatigue but also rutting performance of binders. The rheological properties will also be investigated on laboratory aged binders (Rolling Thin Film Oven and Pressure Aging Vessel) in order to cover the entire service temperature range for these materials. This is done knowing that aged binders usually have a shorter fatigue life than un-aged binders.

The damage resistance characterization part of the investigation will focus on classifying and ranking different modifiers and/or modification techniques based on their impact over the

binder's ability to resist damage. This is mainly focused on fatigue damage, but it uses rutting damage control tests to maintain perspective on improving the overall binder properties. Figure F2a.6 depicts the research approach defined for this work element.

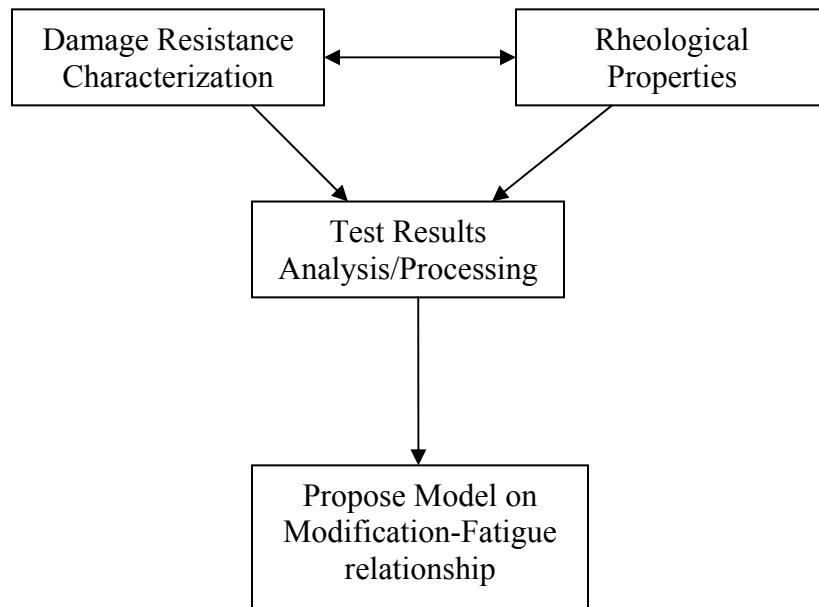


Figure F2a.6. Chart. Flow chart for research approach.

Year 2 Milestones

- Finalize the selection of binders and modifiers
- Subject modified binders to different aging procedures
- Start the fatigue tests on modified binders
- Start analyzing the test results

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Analyze Existing Fatigue Data on PMA	X	X			
ii. Select Virgin Binders and Modifiers and Prepare Modified Binder	X	X			
iii. Laboratory Aging Procedures	X	X	X		
iv. Collect Fatigue Test Data		X	X	X	
v. Analyze Data and Propose Mechanisms		X	X	X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
i. Analyze Existing Fatigue Data on PMA	X			
ii. Select Virgin Binders and Modifiers and Prepare Modified Binder	X	X		
iii. Laboratory Aging Procedures	X	X	X	X
iv. Collect Fatigue Test Data	X	X	X	X
v. Analyze Data and Propose Mechanisms		X	X	X

Budget

The estimated budget for this subtask is \$425,000 over the five years. The work will be conducted by the University of Wisconsin-Madison.

Work Element F2b: Mastic Testing Protocol

This work element will be performed in close coordination with the Technology Development work area of this Consortium. Accordingly, some part of the budget for this work element has been allocated in the Technology Development work area.

The test protocol to determine mechanical properties of asphalt mastics and fine aggregate matrix (FAM) is an important component of the unified fatigue damage model. The test method will serve dual purposes of (i) validating the expected response of asphalt mastic or fine aggregate matrix based on fundamental material properties, and (ii) generating input that will be required for micromechanical or continuum fatigue model. Significant work has been done in the past at the Texas A&M University to develop the use of a Dynamic Mechanical Analyzer (DMA) to accomplish this. The objective of this subtask will be to detailed test protocol to generate parameters that will serve as inputs for the unified fatigue damage model. This objective will be achieved by accomplishing the following sub tasks.

Subtask F2b-1: Develop specimen preparation procedures (Continued in year 2)

The DMA has been used to measure the mechanical properties of asphalt mastic and Fine aggregate matrix (FAM). Different methods have been used for preparing DMA specimens for testing mastics and FAM. The mastic testing relies on preparing specimens with Ottawa sand, filler particles passing sieve # 200, and asphalt binder. An FAM specimen is comprised of asphalt binder and fine aggregates passing the #16 sieve including filler material (passing the #200 sieve). The Fine aggregate portion of the FAM typically follows the same gradation as in the complete asphalt mixture. The binder content for the FAM is determined based on a fixed filler to binder ratio by volume, based on a constant film thickness on aggregate particles, or based on an average film thickness computed using the complete asphalt mixture.

The procedures and relevant assumptions required to design the composition of the mastic and FAM specimens will be evaluated in this sub task. Standard design procedures will be recommended based on considerations that include percent of filler particles in the mixture,

representation of the FAM phase in the complete asphalt mixture, validity of the assumptions used in the procedure, and practicality of compacting and preparing test specimens in the laboratory. The method for preparing and storing test specimens cored out of Superpave Gyrotory Compacted (SGC) samples will also be evaluated and standardized.

In summary, this subtask will accomplish the following:

- i. Compare and standardize the procedure to design the mastic and FAM specimens and ensure that they are representatives of the complete asphalt mixture.
- ii. Evaluate and standardize the procedure to mix, compact, core, and store test specimens. The procedure will also provide for acceptable limits and tolerances in geometry and air voids in the test specimen.
- iii. Assess ruggedness of the test method with reference to variability in specimen preparation and handling procedures.

Objectives (i) and (ii) were virtually completed in year 1 of this project. In year 2 of this project, emphasis will be on objective (iii). Also, joint efforts with Advanced Asphalt Technologies (AAT) will be made in the Technology Development area to accomplish objective (iii).

Subtask F2b-2: Document test and analysis procedures in AASHTO format

In year 2, emphasis will be on the development of a single unified document that describes various test protocols developed in other subtasks. Analytical methods to interpret test data and derive parameters of interest from these test procedures will also be documented along with user friendly software to conduct this analysis. More specifically, this subtask will provide detailed protocols to achieve the following from the test method:

- i. Determine properties of the FAM required as input for micromechanics and continuum fatigue damage models as well as model crack growth in asphalt mastics and mixtures. For example, procedures developed in subtask F1b to determine the linear and non linear viscoelastic properties will be refined for use with FAM and documented in this subtask.
- ii. Determine fatigue cracking life of FAM with and without rest periods. For example, procedures to assess the fatigue and healing characteristics of FAM developed in subtask F1d-5 will be standardized and documented.

Major Findings from Year 1 for Work Element F2b

The procedure for design and preparation of FAM test specimens for use with DMA was further refined. The new design procedure allows the use of a FAM that is an exact representation of the asphalt mixture without the coarse aggregates. The test procedure to prepare and test FAM specimens using the DMA was documented in AASHTO format.

Year 2 Milestones for Work Element F2b

- i. Document the test and analytical procedure in a standard format to obtain specific properties of the FAM using DMA, such as determination of the non linear viscoelastic parameters and fracture parameters.
- ii. Assess ruggedness of the test method with reference to variability in specimen preparation and handling procedures. This task will be conducted in collaboration of with AAT in the technology development area.

Work Element F2c: Mixture Testing Protocol

This work element will be performed in close coordination with the Technology Development work area of this Consortium. Accordingly, some part of the budget for this work element has been allocated in the Technology Development work area.

This work element is intended to develop a mixture testing protocol that will be able to generate mixture parameters of interest for the continuum model with the most optimal level of laboratory testing. The primary characteristics of the comprehensive testing protocol are as follows:

- i. Repeated loading that allows separating the nonlinear viscoelastic, viscoplastic and damage components.
- ii. Different stress levels, temperatures and loading rates in order to determine the linear viscoelastic response, nonlinear viscoelastic response, plastic deformation, and fracture.
- iii. Different stress states (tension and compression) in order to determine the model's parameters under various loading conditions.
- iv. Different confinement levels in order to determine the dependency of model's parameters on confinement.

It is realized that a comprehensive testing protocol might be too elaborate for routine use for mixture design and evaluation. Therefore, we will seek the development of surrogate tests that can potentially lead to determine the necessary model parameters. This, however, can only be done once the comprehensive testing protocol is developed and used to test a variety of mixtures. We will conduct sensitivity analysis using the measurements from the comprehensive testing protocol to determine the parameters that has the significant influence on the mixture performance. It is possible to find that some of the model parameters vary within a small range and they do not have significant influence on performance. These parameters will be assigned fixed values in the model, and reduce the testing steps that are used to determine these parameters.

Year 2 Milestones for Work Element F2c

- i. In the initial phase of this work element, fatigue tests will be conducted using select mixtures in repeated load direct tension mode. The fatigue test will follow protocols similar to those developed for FAM using the DMA with the exception of the mode of loading. The test data will also be analyzed using the similar analytical methods as those

developed and used for the analysis of fatigue data with the DMA. This analysis will provide non linear viscoelastic and fracture parameters for the full mixture, analogous to the parameters for the FAM determined using the DMA.

- ii. In addition, researchers will also develop a protocol for axial testing in both tension and compression of prismatic HMA specimens cut from cores with relatively thin HMA layers. This will facilitate laboratory evaluation of cores from test sections. Three different characterization tests including tensile strength, relaxation modulus in both tension and compression, and repeated tension testing are envisioned.

Work Element F2d: Tomography and Microstructural Characterization

X-ray CT is a nondestructive test to capture the internal structure of materials. Various applications of this method are discussed by Masad (2004). The X-ray CT step up at Texas A&M University includes two separate systems placed in the same shielding cabinet. The mini-focus system has a 350 kV X-ray source, while the micro-focus system has a 225 kV X-ray source. The required X-ray source power increases as the specimen thickness and density increase, while the micro-focus system can achieve a better resolution than the mini-focus system.

The researchers at Texas A&M University have developed methods for identifying of cracks and their dimensions. Also, they developed mathematical functions of the anisotropic distribution of damage, and statistical functions of these cracks based on size and shape characteristics. The X-ray CT will be used to verify the predictions of the developed models by monitoring evolution of damage at various loading conditions. This is valuable in order expand the model's verification beyond the typical macroscopic measurements to detailed microscopic measurements.

X-ray CT imaging will also be used to obtain microscopic images that are needed for the micromechanical models discussed in Category 3. As discussed later, it is possible to use X-ray CT to capture images at high resolution and then use image processing techniques in order to combine these images for detailed micromechanical analysis.

Subtask F2d-1 (new addition): Micro scale physio-chemical and morphological changes in asphalt binders under relaxation, fatigue loading, and healing conditions

In addition to the X-Ray CT imaging, an experimental methodology to evaluate micro scale physio-chemical and morphological changes in asphalt binders in different stress states will be developed. The primary motivation for introducing this subtask is to better understand the physio-chemical and morphological changes associated with the following four processes:

- i. relaxation,
- ii. plastic deformation and fatigue crack initiation,
- iii. fatigue crack propagation, and
- iv. healing

This subtask will assist in understanding the nature of viscoelastic creep, crack nucleation and propagation and healing and the relationship of these phenomena to the physio-chemical properties of asphalt binders. This information can also be used to ensure that the material property measurement and modeling aspects of this research are in line with the physically observed micro scale damage phenomena. The following is a brief description of the methodology that will be used in order to conduct this investigation.

The experimental set up consists of a thin film of asphalt binder on a glass or crystal substrate (figure F2d-1.1). The substrate is clamped onto a mini loading frame that contains a piezoelectric actuator. The piezoelectric actuator is calibrated to apply normal deflection of up to 130 microns on the bottom of the glass or crystal substrate via a hemispherical contact to ensure line loading. Tensile strain on the surface of the asphalt binder film is generated by subjecting the substrate to flexural stresses. The magnitude of tensile strain can easily be computed and controlled by the adjusting the amount of normal deflection applied by the piezoelectric actuator. By varying the applied voltage field, the surface of the binder film can be subjected to a static tensile strain in order to monitor relaxation behavior or a cyclic tensile strain in order to monitor crack nucleation, initiation, and healing behavior. It is also possible to extend the test to a direct tension or shear mode, if required, at a later stage.

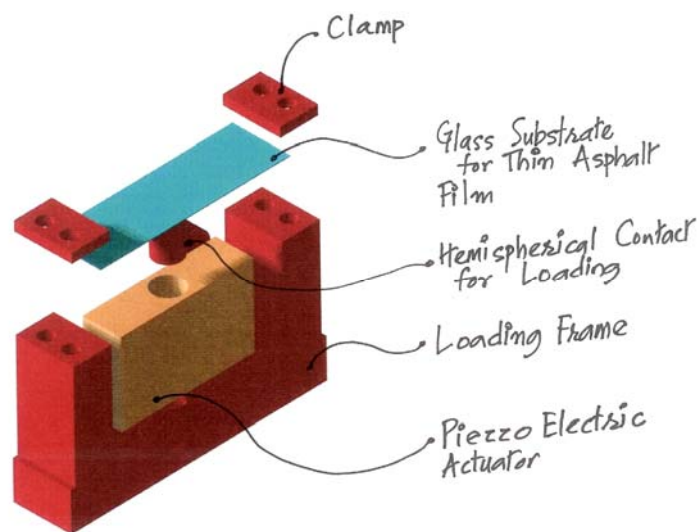


Figure F2d-1.1. Diagram. Isometric representation of the mini loading frame.

The small size of this loading frame (figure F2d-1.2) makes it possible for it to be used in-situ with a variety of microscopic techniques such as optical microscopy, FTIR, and atomic force microscopy. This device is in the design and fabrication stage.

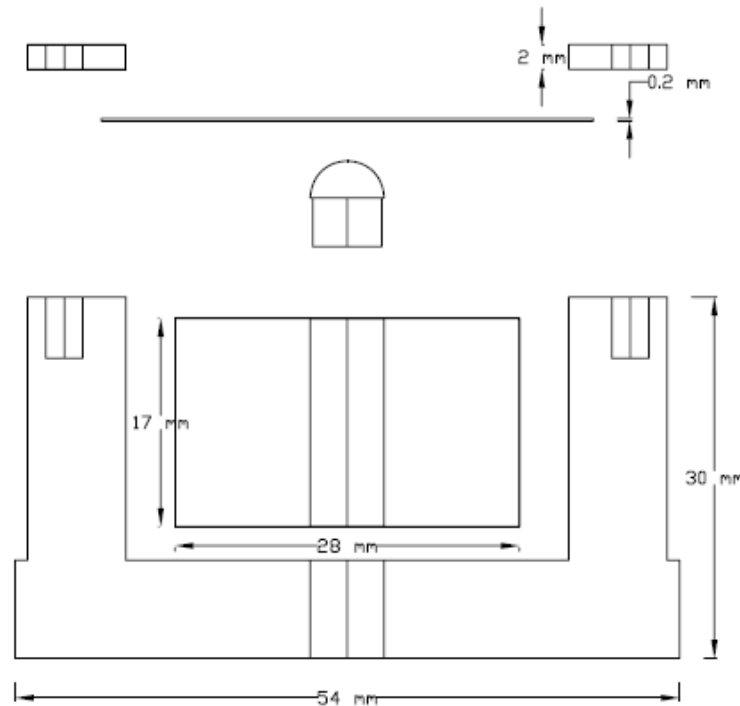


Figure F2d-1.2. Diagram. Front view of mini loading frame with key dimensions.

The micro scale chemical changes and morphological changes in the region of the highest tensile stresses can be recorded using FTIR and atomic force microscopy. In an earlier study, Little et al. (1994) presented the proof of this concept by demonstrating the relaxation behavior of different functional groups in thin films of asphalt binders subjected to shear stresses. It is envisaged that this device and methodology will provide invaluable insight into the understanding of relaxation, crack propagation, and healing in asphalt binders and mastics.

Year 2 Milestones for Work Element F2d

- i. Complete the development of the prototype test apparatus and procedure to evaluate the micro scale physio-chemical and morphological changes in asphalt binders under relaxation, fatigue loading, and healing conditions.
- ii. Conduct preliminary tests on selected asphalt binders.
- iii. X-ray CT will be used to capture damage in mastic specimens at a high resolution (10 microns/voxel) to verify the predictions of the fracture models.

Work Element F2e: Verification of the relationship between DSR Binder Fatigue Tests and mixture fatigue performance

The current Superpave Binder fatigue parameter has been shown to be insufficient as a predictor of pavement fatigue performance. Recent studies have shown that $G^* \sin \delta$ values obtained from binders used in mixes correlate poorly to laboratory mixture fatigue testing. Progress has been made during the last few years to introduce a more meaningful fatigue parameter for binders, but the extent to which the new test and the parameters derived from it relate to mixture and pavement performance is yet to be determined. The lack of correlation between the binder $G^* \sin \delta$ and performance could be attributed to many factors among which the use of the actual conditions of stress and strain experienced by binders in typical mixtures and the reliance on small strain testing are the most important missing factors.

Recent studies have clearly shown that response of binders to repeated cyclic loading show damage accumulation behavior that cannot be predicted by the few initial cycles used to measure $G^* \sin \delta$. Also, modeling of the strain distribution within the mix has shown that the binder can experience strain levels as high as 90 times those experienced by the mix. By testing binders within the linear viscoelastic region, it is likely that the current specification is not addressing the actual behavior within the mix. These high strains may be indicating that fatigue failure of pavements is, in part, due to the non-linear behavior and subsequent stiffness reduction of binders within the mix.

This work element will focus on comparing binder fatigue results to fatigue performance of mixtures measured in the lab and also pavement fatigue of full scale experiments such as the FHWA-ALF results. The work will include imaging of mixtures to estimate ranges in stress and strains, conducting testing under various loading conditions that mimic the mixture testing of the full scale experiments, and development of specification limits and criteria. The work element will be coordinated with other tasks in the Consortium project and also with activities of NCHRP on fatigue. The work is essential for developing an understanding of the role of the binder in fatigue resistance, and in the development of a unified model for fatigue damage. The following tasks will be completed in order to achieve the objectives of this research effort.

Subtask F2e-1: Evaluate Binder Fatigue Correlation to Mixture Fatigue Data (Year 1 start)

Data has already been collected on mixture fatigue performance in the laboratory as part of the Pacific Coast Conference on Asphalt Specifications. In this task, the binders used in that study will be tested at various strains and temperature conditions in order to evaluate the results as indicators to mixture fatigue. This will be done using a standard fatigue procedure in the dynamic shear rheometer. The strain levels used for binder testing will be chosen based on the results of the strain distribution modeling research. Number of cycles to failure for the binders (based on the same failure criterion used for mixture testing) will be compared against the same results for mixtures and evaluated for significance.

Subtask F2e-2: Selection of Testing Protocols

Variables relevant to the binder-mix relation, such as asphalt content in the mix, mixture stiffness, and strain and stress levels in the binder domain will be selected and controlled for the testing. Refined binder fatigue protocols that incorporate these conditions will be integrated into the testing plan. The binder and mixture testing will include controlled strain and controlled stress, adding the surrogate stress sweep test for binder testing. Binder test methods will also include limited use of torsion cylinders consisting of binder-sand mixtures for better representation of thin film behavior tested in the DSR. Utilization of the binders used for the FHWA-ALF study will be incorporated into testing for comparison to the fatigue performance results from that study.

Subtask F2e-3: Binder and Mixture Fatigue Testing

Standard fatigue and surrogate stress-sweep testing will be performed on binders and binder-sand torsion cylinder mixtures. Mixture fatigue testing will be performed using axial cyclic fatigue testing in a servo-hydraulic test frame on gyratory samples prepared in the lab. Images of the cross sections of the mixture samples will be taken for analysis of strain distributions.

Subtask F2e-4: Verification of Surrogate Fatigue Test

Data collected during the stress sweep testing of the binders and binder-sand mixtures will be compared to the traditional fatigue testing as well as results from the FHWA-ALF study to verify the stress sweep as a suitable surrogate test for fatigue.

Subtask F2e-5: Interpretation and Modeling of Data

Results from all binder and binder-sand mixture testing will be correlated to the results from gyratory compacted mixture sample testing to evaluate the contribution of binder fatigue characteristics to the fatigue performance of the mixtures. Results from mixture imaging will verify the ranges of stresses and strains experienced by the binder phase.

A few approaches will be explored to characterize the fatigue behavior of asphalt binder and fundamentally evaluate the effects of asphalt binder on asphaltic mixtures. The hypothesis is that the damage evolution in asphaltic mixture is a function of fatigue performance of asphalt binder, as well as other components of asphaltic mixtures. The team will employ the mechanistic approaches for either asphalt binders or asphaltic mixtures and identify the most effective approach for asphalt binder. The approaches that the team is evaluating are as follows:

- a. Dissipated Energy. The way to characterize the point when fatigue damage occurs is shown by using the concept of change in the dissipated energy per cycle. A binder can be subjected to cyclic loading for a determined number of cycles without showing fatigue damage. During this stage, the energy dissipated per loading cycle remains constant. However, if the binder continues to be loaded and unloaded, a point is reached when it does not dissipate the same amount energy per cycle any longer. This is a sign of fatigue

damage. This behavior can be clearly shown using a parameter called Dissipated Energy Ratio (DER) (Bahia et al. 2001).

- b. Viscoelastic Continuum Damage Mechanics (VECD). VEDC uses the correspondence principle and the concept of pseudo strain to characterize the damage. Without damage, the stress and pseudo strain curve overlaps the line of equality. The curve that deviates from the line of equality indicates damage. The stress and pseudo strain is then regressed to get C and S which are internal damage parameter (Kim et al. 1997). The C and S curve can be used to predict the fatigue life of a material under a specific testing condition.
- c. Dissipated Pseudo-strain Energy (DPSE). Masad et al. derived relationships for the energy dissipated due to damage in viscoelastic materials. These relationships were based on the concept of dissipated pseudo strain energy as pioneered and presented by the works of Little, Kim and Lytton in a number of studies. The derivation relies on calculating the dissipated energy that reflects the change in the apparent phase angle due to damage (W_{R1}), and the dissipated energy due to change in the apparent modulus (W_{R2}). The crack initiation and propagation are obtained based on the change of dissipated pseudo-strain energy.

Subtask F2e-6: Recommendations for Use in Unified Fatigue Damage Model

The results from the previous task will be used to aid in the development of the unified fatigue damage model by providing a more efficient method of evaluating fatigue characteristics of binders, as well as an increased understanding of the behavior of the binder phase within mixtures and its contribution to fatigue performance.

Major Findings from Year 1

During Year 1, the materials and testing conditions for the plan were selected and are shown in table F2e.1. A testing plan was also developed and the proposed tests are shown in table F2e.2.

Table F2e.1. Matrix of materials and conditions.

Neat Binders	PG58-28	Aggregates	Limestone
	PG64-22		Granite
	PG70-22		
Modifiers	SBS	Mix Designs	E-10
	Elvaloy		
	PPA		
	Sasobit		
Mineral Fillers	Limestone	Testing Temp	31 °C
	Granite		25 °C
	Ottawa sand		19 °C

Table F2e.2. Proposed tests on asphalt binders and mixes.

Asphalt Binder	Time Sweep (TS)	Strain level	3%
			5%
			7%
		Frequency	1 Hz
			5 Hz
			10 Hz
	Monotonic Test (MT)	Shear Strain Rate	30%/min.
			45%/min.
			60%/min.
	Stress Sweep (SS)	Strain level	3%
			5%
			7%
		Frequency	1 Hz
			5 Hz
			10 Hz
Mix	Cyclic Test (CT)	Strain level	600 microstrain
			1000 microstrain
			1400 microstrain
		Frequency	1 Hz
			5 Hz
			10 Hz
	Monotonic Test (MT)	Constant Cross-head Rate	12.5 mm/min.
			25.4 mm/min.
			38.1 mm/min.
			50.8 mm/min.

Since the start of Year 1 work plan, the team has extensively evaluated two aspects of fatigue for asphalt binder: (a) a surrogate test for fatigue of asphalt binder, and (b) the application of viscoelastic continuum damage mechanics to asphalt binder. The major findings are briefed here.

a. Surrogate test for fatigue of asphalt binder.

A surrogate test is desired to substitute the time-consuming time sweep test for rapid characterization of fatigue performance of asphalt binder. The team developed a monotonic shear test using the DSR. A constant strain-rate, 45% per minute in this case, was applied to the specimen until the stress reached the peak level and dropped. The fracture energy was calculated under the stress-strain curve up to the peak stress level. It was found that fracture energies of ALF asphalt binders (three replicates for each binder) highly correlated with the field performance of these binders at ALF site, as shown in figure F2e.1.

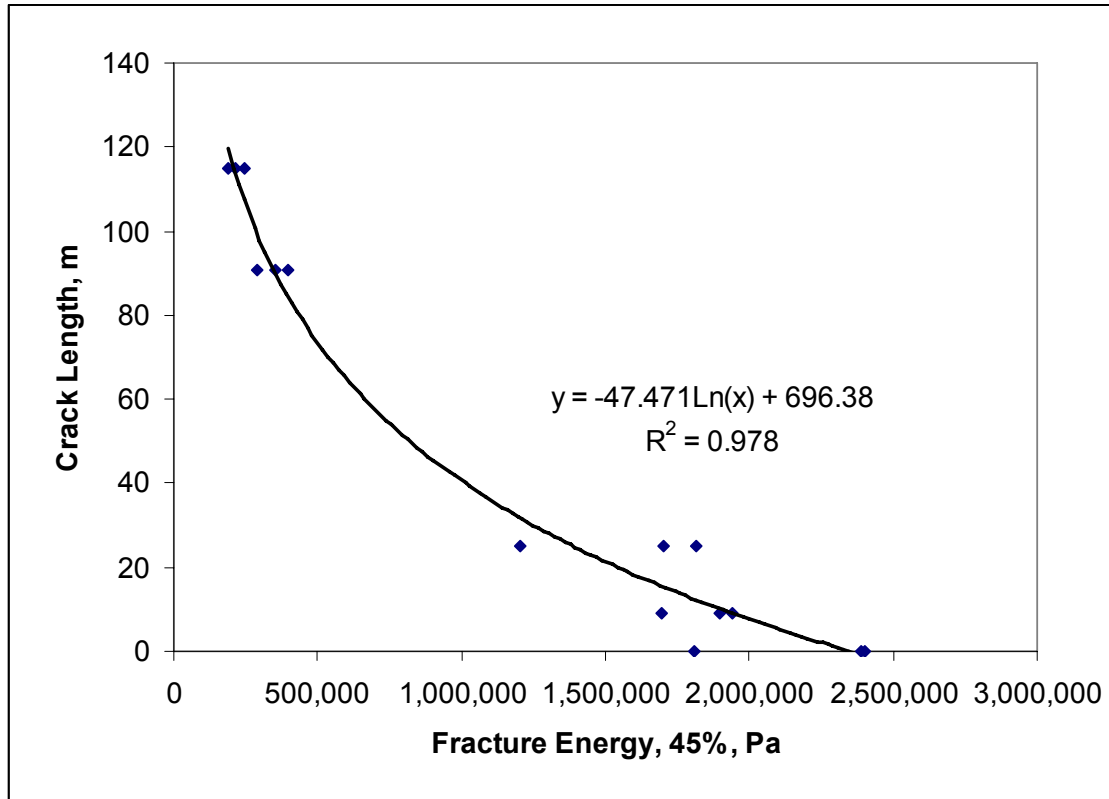


Figure F2e.1. Chart. Correlation of fracture energy and field performance of asphalt binders.

This observation indicates that the constant strain rate test has the potential to be a surrogate test for fatigue of asphalt binder. The fracture energy from the constant strain rate test of asphalt binder could be a good indicator of fatigue performance of asphalt binder. The team will further evaluate the repeatability and ruggedness of this test.

b. Viscoelastic Continuum Damage (VECD) Mechanics

Viscoelastic continuum damage mechanics were employed to characterize the asphalt binders. Frequency sweep and monotonic constant-strain rate tests were conducted using DSR. The complex moduli of asphalt binders were obtained from frequency sweep test and converted into relaxation moduli. The relaxation moduli were fitted into the Prony series and used for pseudo strain calculation. The pseudo strain was then used to obtain pseudo stiffness, C , and damage parameter, S . Three strain rates were used for each asphalt binder. It was found that the VECD approach could eliminate the effects of different strain rate. The C vs. S curves for three strain rates collapsed, as shown in figure F2e.2. The C vs. S relationship can be used to predict the fatigue life of asphalt binders. This demonstrated that VECD has the potential to be used for asphalt binder, as well as asphaltic mixtures which have been reported by Kim et al. (1997). The cyclic fatigue test data for these binders will be analyzed to evaluate of the effectiveness of VECD on the binders.

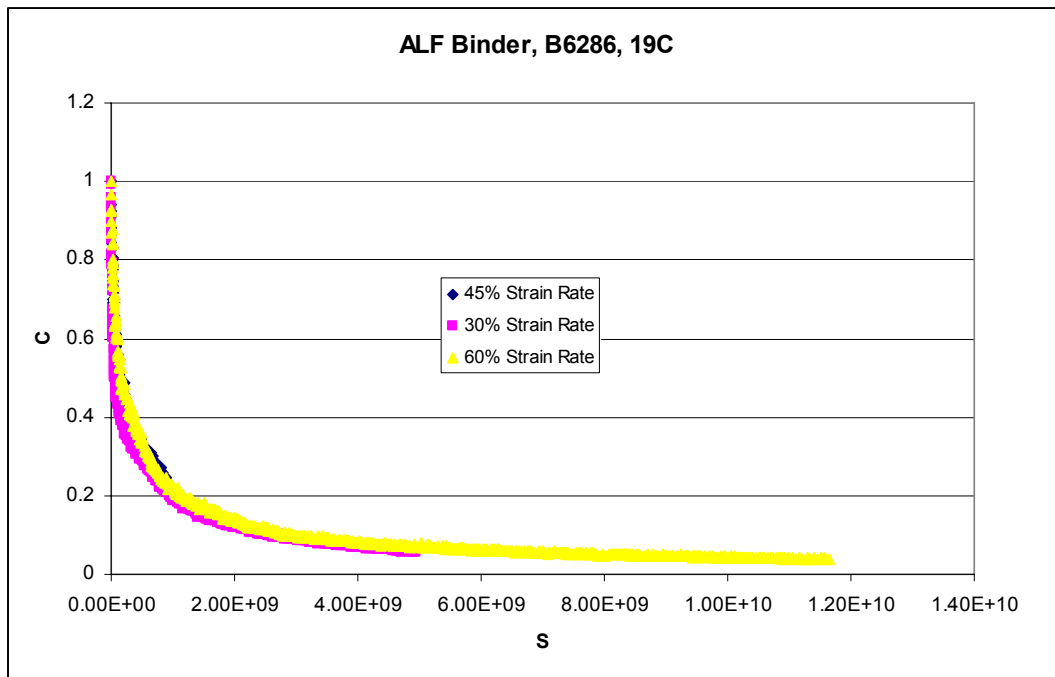


Figure F2e.2. Chart. C vs. S curves for asphalt binder.

Year 2 Work Plan

During Year 2, the team will continue to evaluate different approaches for fatigue performance of asphalt binder, especially the VECD mechanics. The Year 2 work plan consists of two major parts: a detailed experimental plan and an evaluation of the effectiveness of different analytical approaches based on the experimental results.

The test results will be analyzed using different analytical approaches. These analyses will determine the fundamental properties of asphalt binder that govern the damage resistance to fatigue. In addition, the team will strive to quantify the relationship between the damage properties of asphalt binders and those of asphaltic mixes. For instance, the damage parameter of S in VECD can be an input to the fatigue life of asphaltic mixes.

Figure F2e.3 depicts the research approach defined for this work element.

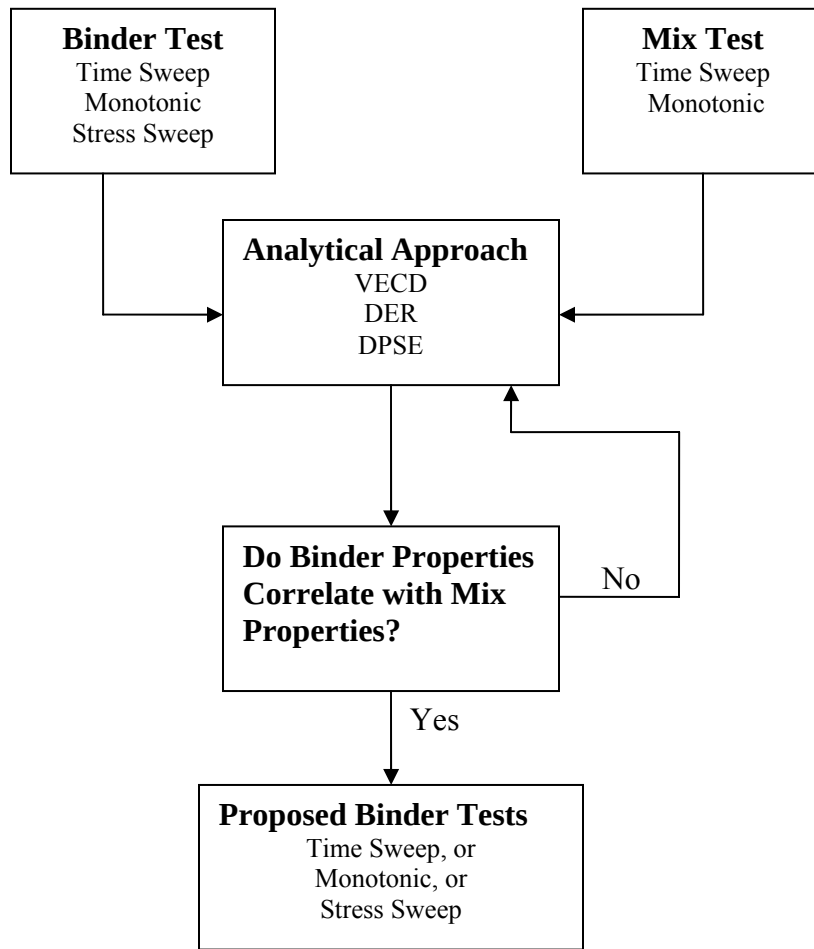


Figure F2e.3. Chart. Flow chart for research approach.

Year 2 Milestones

- Complete report on review of literature for fatigue of asphalt binders and asphaltic mixtures
- Finalize material selection and experimental plan
- Conduct the proposed tests on asphalt binders and prepare for mix tests
- Select the analytical approach for further evaluation

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Evaluate binder fatigue	X	X			
ii. Select testing protocols for binder and mixture fatigue testing	X	X			
iii. Evaluate fatigue performance of binders in both DSR and mixture testing	X	X	X	X	
iv. Evaluate possible surrogate procedures	X	X	X	X	
v. Interpretation and modeling of data		X	X	X	
vi. Recommendation of binder fatigue characteristics for use in unified fatigue model				X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
i. Evaluate binder fatigue	X	X		
ii. Select testing protocols for binder and mixture fatigue testing	X	X		
iii. Evaluate fatigue performance of binders in both DSR and mixture testing	X	X	X	X
iv. Evaluate possible surrogate procedures	X	X	X	X
v. Interpretation and modeling of data	X	X	X	X
vi. Recommendation of binder fatigue characteristics for use in unified fatigue model				

Budget

The estimated budget for this subtask is \$425,000 over the five years. The work will be conducted by the University of Wisconsin-Madison.

Category F3: Modeling

Work Element F3a: Asphalt Microstructural Model (Year 2 start)

For nearly a century, heavy crude oil has been viewed by a majority of investigators as colloidal in nature. Although naturally occurring (Trinidad Lake deposit), asphalt is generally defined as the residuum from the distillation of petroleum. Heavier residua such as asphalt consist of a rather grand number of different “petrol” organic compound types (molecules) comprising their chemical makeup. These compound types vary in a complex manner in terms of their molecular composition; hydrogen-to-carbon ratio, shape, molecular weight or size, polarity, density, surface activity, etc. Asphalt molecules are generally thought to range in molecular character from that of non-polar hydrocarbon, waxy and oily type molecules, to condensed poly-aromatic sheet, heteroatom-containing (graphite-like) molecules. Hence, common logic would dictate that

a concise description of the composition of the molecules present in heavy residua and their associated interactions with each other and with other foreign materials should directly relate to the physico-chemical properties of asphalts and their propensity to bind with aggregate, polymer, fillers, etc., if used as the gluing agent in pavement construction applications.

A logical approach to take to guide studies which will lead to the most accurate and realistic description of the compositional nature of asphalt binder should rely heavily on theoretical modeling of asphalt nano-structure grounded in such fields of study as that of non-equilibrium statistical mechanics. This type of modeling approach assumes that idealized materials such as polymers, or in the present case, complex petrol-organic molecules found in asphalts, tend to undergo such phenomena as phase separation and nucleate, flocculation/dissolution, crystallizing and melting, all contributing to material softening and embitterment, when characterized as a function of time and temperature. One may then attempt to describe irreversible non-equilibrium thermodynamic processes involving phase ordering vis energy dissipation in asphalt molecular moieties leading to such processes as solidification/melting events by assuming the coupling of material (molecular particles) transport and heat flow between “classes” of petro-chemical molecules to describe diffuse interface dynamics. In these kinds of studies asphalt may be described as a continuum nano-emulsion, that is to say, a solution comprised of a molecular distribution (M.W., H/C, density, etc.) of petro-chemicals (much like a complex true solution mixture), when defined specifically at temperatures above the material’s glass transition temperature, or as an amorphous glass specifically defined through and below the material’s glass transition temperature. For an example, past research has demonstrated that the Pal-Rhodes model for concentrated micro-emulsions serves well as a first approximation for quantifying asphalt “micro/nano structuring” events at midrange service temperatures. On the other hand asphalt may be described as an amorphous solid at sub-zero temperatures, but why? This task will attempt to answer this question.

In this task, models of asphalt-binder, coupled with nanotechnology (AFM imaging; friction and morphology, contact-force AFM, nanoindentation AFM, chemical-force AFM, etc.), will continue to be developed or improved that strictly adhere to both quantum mechanical and classical mechanical laws of physics to describe well defined molecular components that accurately represent asphalts as functions of crude source. Phase-field modeling, for example, which may be derived from the theory of extended irreversible thermodynamics (EIT), has been utilized for almost fifty years to describe such phenomena as phase separation in heterogeneous material phases, growth of new phases such as polymer crystals, phase-field modeling has even been utilized to describe brittle fracture in solid materials.

- i. Collaborate with academic and private institutions (Consortium members, NIST, U of RI, TU Delft, etc.) to develop compositional modeling tools. This endeavor may include computational molecular simulations based on *ab initio* calculations, density function theory and Monte Carlo (fluctuation-dissipation theory) simulations, dissipative-structure theory, diffuse interface and phase-field approaches, which stem from the extended irreversible thermodynamics (EIT).
- ii. Collaborate with academic and private institutions to develop physical/rheological modeling tools. These endeavors may include development and utilization of contact and fracture mechanics approaches, strain energy models and other continuum mechanics

models, and phase-field modeling grounded in EIT theories, as previously alluded to. It is anticipated that a chemo mechanical model will emerge from these efforts to target direct relationships between material composition and pavement performance.

Develop approaches (Theoretical) which lead to computational software (e.g., Virtual Asphaltic Concrete Testing Laboratory (VACTL), chemo-metrics, data mining, and neural-networks) to model physico-chemical and chemo-mechanical systems pertinent to continuum mechanics models already in place in current and future asphalt pavement technologies.

Year 2 Work Plan

A detailed work plan will be developed for this work element at the beginning of Year 2. The work plan will be submitted for review by FHWA and pertinent reviewers.

Work Element F3b: Micromechanics Model

Subtask F3b-1: Model Development

Micromechanical models are powerful in accounting for the interactions among the mixture constituents. They are capable of explicitly modeling the mixture microstructure geometry and the properties of each of the constituents. In this task, the researchers will pursue the development of several micromechanical modeling approaches.

The first approach will develop the analytical micromechanics models that yield effective mastic and mixture properties given the properties and distribution of the constituents. These analytical micromechanics models will also be able to account for the influence of damage distribution on the effective properties. The analytical models will be developed at Texas A&M University.

The second approach will advance the micromechanics-based computational model that has been developed by researchers at the University of Nebraska (NU). Past work has demonstrated a number of innovative features of the model including (1) bridging the scales between micro-scale (fundamental mixture component properties) and macro-scale (damage-dependent behavior of whole asphalt concrete mixtures), (2) explicit prediction of nonlinear-inelastic material behavior, (3) realistic simulation of rate-dependent microscale fracture damage based on a cohesive zone approach, and (4) microstructure characterization to represent mixture heterogeneity and anisotropy. This modeling approach is directly incorporated into this project in that it employs fundamental materials and mixture properties (outcomes from Category 1) that are obtained from testing methods (Category F2), and will be implemented into other modeling efforts including the unified continuum model (Category F3). The NU model will eventually be calibrated and/or validated through various laboratory performance data and the FHWA-ALF experimental results. More specifically, the NU model will use the thermodynamic/mechanical cohesive-adhesive properties of mixture components, linear-nonlinear viscoelastic properties, and geometric information such as mixture microstructure and aggregate images provided by TAMU and UWM as basic model inputs. Furthermore, the model will be elaborated by taking into account several key fatigue damage-associated factors such as the effects of binder modification, binder aging, additives, damage healing, and moisture to seamlessly explain the

complex fatigue damage behavior of asphalt mixtures and pavements. As a subcontractor, NU will take the lead in this particular modeling activity by being closely collaborated with TAMU where would lead the experimental-analytical part.

The third approach will further develop the multi-scale lattice micromechanical model. The research group at NCSU will focus on developing, refining, validating, and calibrating the multi-scale lattice micromechanical model and in linking it to nonlocal models for the purpose of carrying out large scale simulations of pavements.

Lattice Model: The lattice modeling technique was developed at NCSU with the ultimate goal of linking micromechanical constituent properties with macroscopic damage behavior of asphalt concrete. Past work in this area showed significant promise of this approach, but highlighted several issues. The most important of these are the scale-dependency of surface energy, the stiffening effect of asphalt binder in thin-film form and the absence of a viscoelastic fracture framework in the lattice model. The extensive experimental program proposed in various work elements of the FHWA DTFH61-07-H-00009 project would provide rich data that could be used to develop a more robust and reliable lattice model. Specifically, the thermodynamic and mechanical, cohesion and adhesion properties as well as data from the aggregate imaging system would provide valuable input to the model. Similarly, any insight gained into asphalt concrete behavior from other microscopic testing by synchrotron and AFM would greatly help refine the lattice model and enhance its predictive capabilities. On the computational side, algorithms to improve the performance of lattice modeling will be developed. During the first year, fundamentals of the aforementioned properties and methods have been studied with the primary objective of improving the current lattice model. A detailed research approach incorporating experimental, analytical, and computational methods will be developed in the beginning of the second year.

Nonlocal Model: While the lattice model provides a micromechanical approach to damage and fracture modeling, the nonlocal models try to achieve the same using a continuum mechanics approach, which is better suited to large scale simulations of pavements. A constitutive model is called nonlocal when the stress (or strain) at a point depends on state variables in a region around the point. Nonlocal models are necessary when the scale of the microstructural features in the material is comparable to the size of the domain being analyzed. In other words, these models try to include the effect of the underlying microstructure on the average material behavior. In the first year, a detailed literature review has been carried out to understand the different forms of nonlocal models and the applicability of these models to asphalt concrete. Since the nonlocal models would require extensive fracture testing for determining the parameters of the model, it seems ideal that the lattice models be used to provide data from virtual testing. During the second year, a nonlocal modeling framework will be developed based on the existing form of the lattice model.

Subtask F3b-2: Account for Material Microstructure and Fundamental Material Properties

Previous research efforts have shown that most micromechanical computational models, irrespective of the numerical implementation, underestimated the stiffness and strength of asphalt mixtures. This was attributed to the lack of realistic representation of the mixture microstructure

and the use of bulk properties of the constituents. This finding motivates us to focus some of the research efforts on the use of detailed representation of the microstructure, which can be achieved by using X-ray CT imaging at multiple resolutions. Also, the research will focus on the use of rigorous upscaling methods that are able to incorporate experimental measurements conducted at a small scale into a micromechanical model at a larger scale. For example, the bond energy per unit area calculated from surface energy measurements should be upscaled prior to its use in a micromechanical model. The upscaling takes into account the fact that the micromechanical model cannot, due to computational limitations, account for the nanostructural details at which the surface energy is acting. In other words, the actual area of the microstructure can be reduced by orders of magnitudes when transferred to the model scale.

In summary, the research efforts will focus on improving the cohesive zone-based computational micromechanics model and the lattice model in order to better account for the microstructure distribution (asphalt film thickness, realistic shape of aggregates, aggregate size distribution) and to incorporate the fundamental properties measured in Category 1 of the work plan.

Major Findings from Year 1 for Work Element F3b

An extensive review of the micromechanics-based computational models to characterize damage-dependent behavior of asphalt materials and mixtures was conducted by ARC researchers at the University of Nebraska. The review efforts mainly focused on (i) investigation of the state of the art of modeling techniques typically based on the micromechanics and computational methods such as the finite element method, (ii) strategy for development of the model that can appropriately account for geometric heterogeneity and nonlinear-inelastic constitutive behavior of the asphalt materials and mixtures, and (iii) strategy for appropriate integration of material properties (as model inputs) obtained from other tasks into the micromechanics-based computational model being developed by the researchers at the University of Nebraska.

The following are some of the findings based on this literature review and revisit to the modeling technique being developed at the University of Nebraska:

- i. For more accurate characterization and modeling of fatigue damage in asphaltic materials and mixtures, inelastic fracture and corresponding energy dissipation must be considered in the process. Asphalt demonstrates a significant complexity of rate-dependent and inelastic damage behavior.
- ii. In order to model heterogeneity of asphalt mixtures, the concept of micromechanics specifically with the aid of computational techniques such as the finite element method is necessary. In addition, damage and failure of asphalt mixtures are associated with the growth of thousands of cracks in multiple scales. Computational techniques can successfully deal with these complex issues.
- iii. The model being developed at the University of Nebraska is based on the cohesive zone concept to simulate initiation and propagation of damage. This appears to be reasonable in that the cohesive zone modeling is a well-established fracture mechanics tool, which removes stress singularities ahead of crack tips and takes into account both brittle and ductile fracture behavior within the same theoretical framework. The cohesive zone

modeling concept has been receiving increasing attention from the asphalt mechanics community due to its useful and powerful modeling capability.

- iv. This micromechanical modeling approach is expected to provide a number of meaningful findings at the final stage of this project, because this effort is directly and strongly incorporated with other key testing-modeling-validation tasks in this project.

Year 2 Milestones for Work Element F3b

- i. Continue the review of literature related to the micromechanics-based computational modeling techniques.
- ii. Modify and/or elaborate the current cohesive zone model to predict fracture and damage characteristics in asphalt mixtures so that the model can be better fit with material and damage properties that will be measured and provided by the TAMU and UWM.
- iii. Determine the representative volume elements (RVE) of various asphalt mixtures to facilitate the computational modeling within the micromechanics concept. This particular milestone will be related to the Work Element F2d: Tomography and Microstructural Characterization led by the TAMU.

In the area of lattice modeling work will primarily focus on:

- i. incorporating new computational methods that can increase the computational efficiency by an order of magnitude,
- ii. streamlining the analysis procedure that facilitates automated analysis of a large number of lattice mesh realizations, and
- iii. investigation of modeling time-dependent fracture in lattice modeling framework.

Work Element F3c: Development of Unified Continuum Model

Subtask F3c-1: Analytical Fatigue Model for Mixture Design

In this task, a fracture model for predicting the resistance of asphalt mixtures to fatigue loading will be finalized. This model is founded based on the principles of the fatigue model developed during the Strategic Highway Research Program (SHRP) at Texas A&M University. The model accounts for the energy dissipated in fracture, energy dissipated in permanent deformation, physio-chemical properties of mixture (adhesive and cohesive bonds), and viscoelastic properties (Masad et al. 2007). This model is capable of unifying the results from stress-controlled and strain-controlled tests. This model can also be used to analyze experimental measurements conducted on the mastic and fine portions of the mix using the dynamic mechanical analysis and on full mixtures using repeated loading.

The model has been used so far to analyze experimental measurements conducted at a limited range of temperatures and loading frequencies. The research will focus on expanding the use of the model to analyze master curves constructed from comprehensive measurements over wide ranges of temperatures, loading rates, stress levels and strain levels. This is necessary to verify

the unified nature of the model for stress controlled and strain controlled tests at all temperatures and loading rates representing different pavement structures.

Subtask F3c-2 Unified Continuum Model

This item constitutes significant part of the research as it will lead to the development of comprehensive viscoelastoplastic continuum damage (VEPCD) model that is applicable for wide ranges of temperatures, different loading rates and complex and realistic mechanical and thermal stresses.

The modeling efforts are based on the following theoretical pillars: (1) the elastic-viscoelastic correspondence principle based on pseudo strain for modeling the viscoelastic behavior of the material; (2) the continuum damage mechanics-based work potential theory for modeling the effects of microcracks on global constitutive behavior; (3) the time-temperature superposition principle with growing damage; (4) the strain hardening viscoplastic model for modeling plastic and viscoplastic behavior; (5) the strain decomposition theory for integrating the nonlinear viscoelastic strain and the viscoplastic strain to describe the total strain; and (6) the anisotropic nature of the aggregates structure.

The VEPCD model's ability to predict the material behavior under complex, realistic mechanical and thermal loading conditions has been demonstrated in previous research at NCSU. The only current limitation is that VEPCD model is robust only till the onset of *macrocrack* formation. Typically, fracture mechanics models are necessary for modeling the propagation of macrocracks. Thus, in order to get a unified model for accurate prediction of fatigue life, it is crucial to bridge the gap between the continuum damage mechanics and fracture mechanics.

The hybrid VEPCD model combining damage mechanics and fracture mechanics will be developed in this research using the four major components of material modeling research, i.e., experimental, analytical, computational, and optical methods. Experimental and optical research will involve continuum damage and fracture mechanics testing with the aid of Digital Image Correlation (DIC) technique. For theoretical robustness and computational stability, it is important to ensure a smooth transition between the distributed damage characteristic of the VEPCD model and the localized damage characteristic of fracture mechanics. Considering the existence of length scales associated with fracture mechanics (i.e., crack length), and the lack of length scales in the current continuum damage models for asphalt concrete, the NCSU research team proposes to generalize the VEPCD model to include the concept of damage length scales. This theoretical study would aid the development of a constitutive framework; experimental studies described in the previous paragraph would facilitate parameter estimation using direct and detailed measurements; and computational modeling would be used to verify the stability and accuracy of the developed models. It is expected that such a synergistic approach would result in a robust material model integrating distributed damage with fracture mechanics.

The hybrid VEPCD model will be implemented to the finite element program FEP++ developed by the NCSU research team. This pavement structural model is currently being expanded to incorporate three-dimensional analysis with multiaxial VEPCD models. The VEPCD-FEP++ has been successfully used to predict the fatigue cracking performance of standard and polymer-

modified asphalt mixtures in the FHWA ALF pavements. The modified FEP++ is expected to perform analysis of pavement structures starting from microcracking, and leading to macrocrack-induced failure in the asphalt pavement under realistic loading conditions with rest periods.

The fundamentals that govern the model's development have already been established by work at NCSU and TAMU. However, there is still significant work that needs to be done as part of this project in order to:

- a. integrate all these components in a comprehensive model,
- b. verify the model predictions under various loading, environmental and boundary conditions,
- c. relate the model's parameters to fundamental material properties as discussed in section F3c-3, and
- d. implement the material model in the a public domain finite element structural model developed at NCSU.

Subtask F3c-3: Multi-Scale Modeling

A draw back of conventional continuum damage models is that the parameters are determined based on fitting the model to experimental macroscopic parameters. Therefore, these parameters could lose to a certain extent their link to the fundamental properties and their values could become dependent on the tests used in fitting the model. A major contribution of the research will be to focus on linking the parameters of the continuum model to the fundamental materials properties measured in Category F1. This will be achieved through developing a multi-scale approach in which the micromechanical models described in work element F3b will be used to calculate effective mixture properties based on properties of the mixture constituents. These effective material properties are used as inputs for the continuum model. The multi-scale approach will assist in formulating damage in the continuum model based on the principles of fracture and healing established in work element F1d.

Development of the multi-scale modeling approach has many benefits, including: (1) a more realistic simulation of pavement cracking phenomena by covering the propagation of both microcracks and macrocracks; (2) simpler testing requirements for state highway agencies; (3) a more accurate prediction of performance of asphalt pavements; and (4) a direct relationship between mixture design, material properties and mixture performance.

As part of the multi-scale modeling approach, the results of the computational micromechanical models will be compared to the continuum model results in order to ensure that the macroscopic predictions by the continuum models are explained by the interactions among the mixture constituents in the micromechanical models.

Major Findings from Year 1 for Work Element F3c

Most of the components of the continuum model have been implemented in finite element. The model includes a nonlinear viscoelastic component and a viscoplastic component.

Year 2 Milestones for Work Element F3c

The model will be fully implemented in finite element during the second year. It will be evaluated using based on its ability to predict experimental measurements conducted at TAMU and NC-State on various mixtures during the past three years. In addition, the researchers will utilize the comprehensive testing database available at the University of Nottingham to validate and calibrate the model. The model verification during the second year will focus on the tests conducted on dry mixtures.

Work Element F3d: Calibration and Validation

Calibration and validation will be conducted using materials selected specifically for each task or work element based on its individual hypothesis. The calibration and validation efforts from different work areas will be optimized by:

- i. ensuring that core materials described at the beginning of this work plan are included in various tasks as applicable
- ii. maximizing the use of materials and mixture designs that are being used in various test sections

SCHEDULE

		2008	2009	2010	2011
Category F1: Material Properties					
F1a	Cohesive and Adhesive Properties	X	X		
	1a-1 Critical review of literature				
	1a-2 Develop experiment design				
	1a-3 Thermodynamic work of adhesion and cohesion	X	X		
	1a-4 Mechanical work of adhesion and cohesion	X	X		
	1a-5 Evaluate acid-base scales for surface energy	X			
F1b	Viscoelastic Properties	X	X	X	
F1c	Aging	X	X	X	X
	1c-1 Review of binder oxidative aging				
	1c-2 Develop experiment design				
	1c-3 Develop transport model for binder oxidation	X	X		
	1c-4 Effect of binder aging on properties and performance	X	X	X	X
	1c-5 Polymer modified binders		X	X	

F1d	Healing	X	X	X	X
	1d-1 Critical review of literature				
	1d-2 Select materials with targeted properties	X			
	1d-3 Develop experiment design				
	1d-4 Test methods to determine properties relevant to healing	x	x		
	1d-5 Validate contribution of healing using DMA	x	x	x	
	1d-6 Determine relationship between healing and endurance limit	x	x	x	x
	1d-7 Coordinate with AFM analysis	x	x		
	1d-8 Develop form for healing parameter to incorporation in models	x	x	x	x
	1d-9 Design experiment on selected binders with synchrotron	x	x		
Category F2: Test Methods					
F2a	Binder Tests and Effect of Composition	X	X	X	X
	2a-1 Analyze existing fatigue data for polymer modified asphalts				
	2a-2 Select virgin binders and modifiers to prepare modified binders	x			
	2a-3 Subject virgin and modified binders to several aging procedures	x	x		
	2a-4 Collect fatigue test data for all samples		x	x	x
	2a-5 Mechanisms for aging & modification effects on binder fatigue				x
F2b	Mastic Testing Protocol				X
	2b-1 Develop specimen preparation procedures				
	2b-2 Document test and analysis procedures in AASHTO format				x
F2c	Mixture Testing Protocol			X	X
F2d	Tomography and microstructure characterization	x	x	x	
F2e	Verification: DSR fatigue & Mixture performance	X	X	X	X
	2e-1 Evaluate binder fatigue correlation to mixture fatigue data				
	2e-2 Selection of mixture testing protocols	x			
	2e-3 Binder and mixture fatigue testing	x	x	x	
	2e-4 Verification of surrogate fatigue test			x	
	2e-5 Interpretation and modeling of data			x	
	2e-6 Recommendations for use in unified model				x
Category F3: Modeling					
F3a	Asphalt Microstructure Model	X	X	X	X
F3b	Micromechanics Model	X	X	X	X
	3b-1 Model development	x	x	x	x
	3b-2 Account for fundamental material properties in model	x	x	x	x
F3c	Unified Continuum Fatigue Model	X	X	X	X
	3c-1 Analytical fatigue model for use during mixture design	x	x	x	x
	3c-2 Unified continuum model	x	x	x	x
	3d-2 Multi-Scale modeling	x	x	x	x
F3d	Calibration and Validation		X	X	X

RELATIONSHIP TO FHWA FOCUS AREAS

The fatigue work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property and pavement performance.

BUDGET

		Year 1	Year 2	Year 3	Year 4	Year 5
Category F1: Material and Mixture Properties						
F1a	Cohesive and Adhesive Properties (TAMU)	60,000	100,000	90,000		
F1b	Viscoelastic Properties (TAMU)	70,000	75,000	30,000	25,000	
F1c	Aging (TAMU)	70,000	100,000	110,000	110,000	75,000
F1d	Healing (TAMU)	60,000	105,000	100,000	100,000	75,000
	Healing (UWM)	75,000	75,000	100,000	100,000	50,000
Category F2: Test Method Development						
F2a	Binder Tests and Effect of Composition (UWM)	75,000	100,000	100,000	100,000	50,000
F2b	Mastic Testing Protocol (TAMU)	20,000				20,000
F2c	Mixture Testing Protocol (TAMU)				20,000	20,000
F2d	Tomography and microstructure characterization (TAMU)		70,000	50,000	50,000	
F2e	Verification: DSR fatigue & Mixture performance (UWM)	75,000	100,000	100,000	100,000	100,000
Category F3: Modeling						
F3a	Asphalt Microstructure Model (WRI)		316,000	321,000	321,000	319,000
F3b	Micromechanics Model (TAMU)	60,000	125,000	125,000	125,000	110,000
F3c	Unified Continuum Fatigue Model (TAMU)	60,000	125,000	125,000	125,000	110,000
F3d	Calibration and Validation*			90,000	95,000	140,000
TOTAL		625,000	1,291,000	1,341,000	1,271,000	1,069,000
		5,597,000				

Note* Tentatively only budget from TAMU is reflected here but this element will involve coordination from all agencies.

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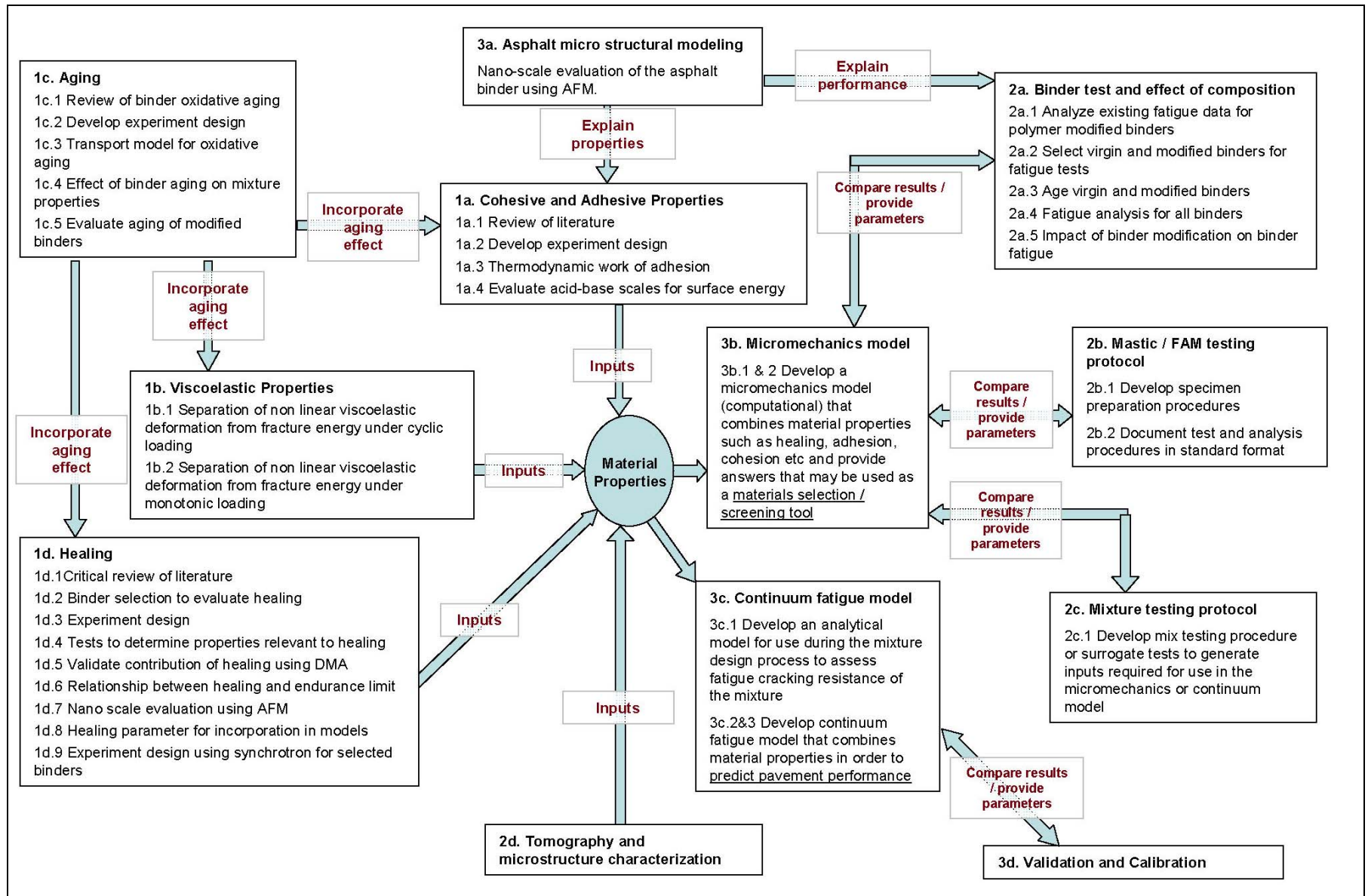
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Appendix F1

**Flow Chart Illustrating Integration of Elements
for
Fatigue Work Area**



PROGRAM AREA: ENGINEERED MATERIALS

INTRODUCTION

The Need for Engineered Paving Materials

Demands on flexible pavements in terms of traffic loadings and service life are rapidly increasing. Recent published transportation statistics indicate that between 1993-2002 truck traffic has increased by more than 33 percent while lane miles have increased by only 2 percent. The total vehicle mile travel in the United States is expected to increase by 50 percent in the next 20 years and, more importantly, freight movement is expected to double by 2025. Figure 1 shows the estimated growth in truck traffic on various sections of the National Highway System between 2000 and 2020.

In addition to increased traffic demands, the escalating increase in crude oil prices as well as cost of energy in general, are expected to result in increased production costs of asphalts. The use of recycled asphalt pavements (RAP) is known to reduce the quantity of required asphalt, resulting in a reduction of the energy required for asphalt production. Currently, the use of RAP is limited by state agencies due to risks involved in using it at higher levels in the mix. It is well recognized that more knowledge is needed to allow for effective use of higher percentage of RAP in HMA mix designs.

Engineered Paving Materials (EPMs) are developed for specific performance-related purposes such as extended fatigue lives, moisture or rut-resistance, or durability against thermal and fatigue cracking, and aging. These materials can be designed for ease of construction, quality control/quality assurance, or of maintenance and rehabilitation activities. They can also be designed for many of the other functional and structural objectives that all pavements must satisfy. The process of engineering of materials requires an understanding of the engineering properties of the constituent materials of HMA and how they contribute to the composite properties of asphalt concrete. The performance of HMA is dependent on the response of the properties of this composite under the varying conditions imposed by traffic and weather including the stiffness under rapidly applied loads and slowly applied thermal stresses, thermal expansion and contraction, permeability, thermal conductivity, time-temperature shift, time-aging shift, anisotropy due to the shape of aggregates used, fracture, healing, and plastic properties. Engineering these properties requires the use of materials property models to provide reliable and accurate estimates of the desired properties of the composite. The selection of the precise set of required composite properties is attained as the result of an optimization process in which all of the properties are considered in a prediction of the pavement performance given specific traffic, weather, drainage and subgrade support conditions at the project site. Thus, the engineering design of the pavement structure is not considered as a separate process from the engineering design of the composite material to be used as its surface.

Materials property models have been developed and used successfully in other engineering disciplines such as mechanical engineering, plastics and polymers, and aerospace composites. Admittedly, the materials used in pavements are recognized as being more difficult to model and

inherently more variable largely because of the huge volumes of materials that are constructed annually. However, recent successful developments in micromechanics and analytical modeling in these other fields and recent success in FHWA-sponsored research in pavement construction materials have demonstrated that it is now possible to engineer materials that are better able to satisfy the multiple performance requirements that are placed on pavement surfacing.

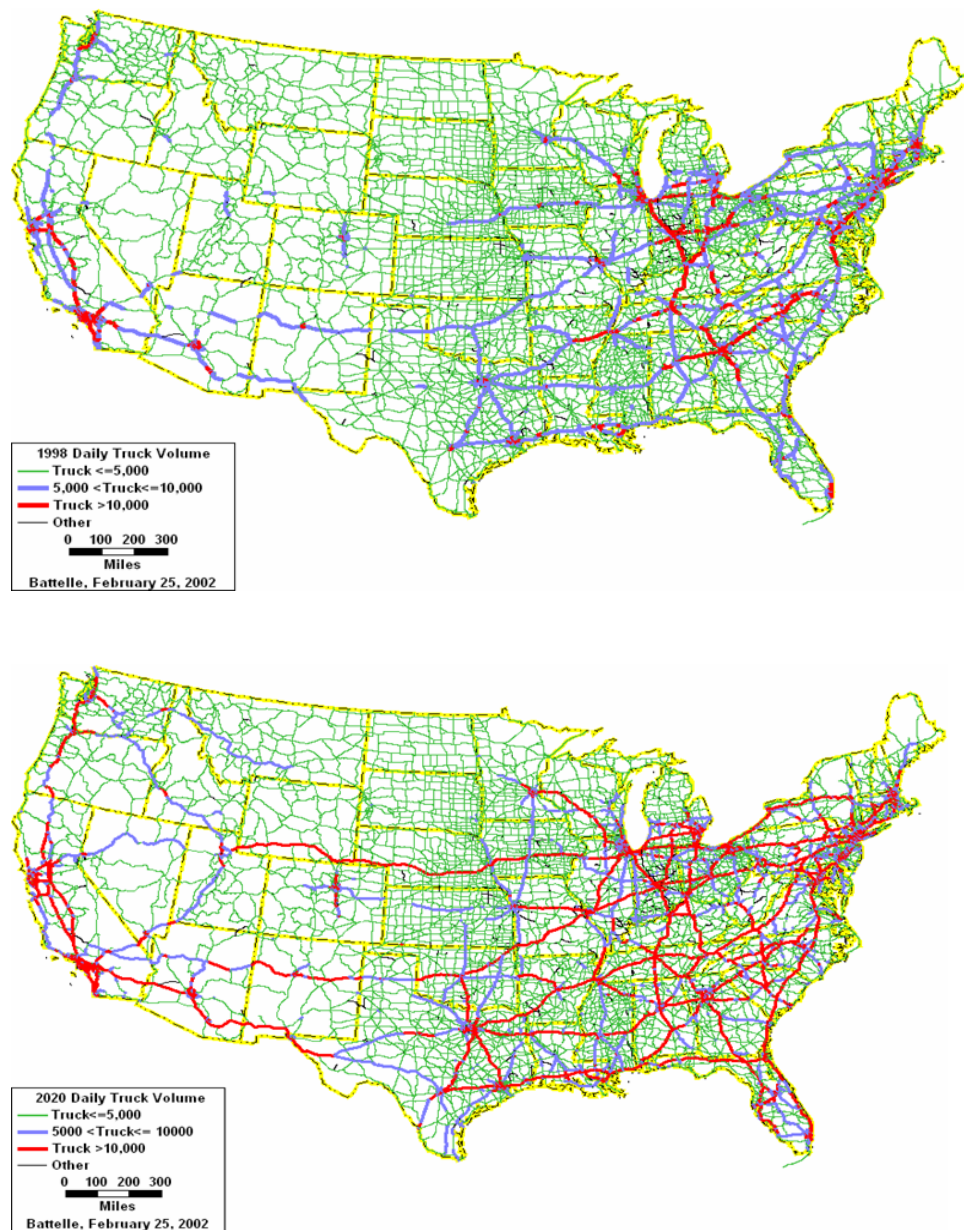


Figure 1. Expected growth of truck traffic on the national highway system.
Source: FHWA office of asset management.

Functional Requirements of Engineered Paving Materials

Since the introduction of Superpave, the types of materials that can satisfy the Superpave performance criteria have changed. The use of modified asphalt, as an example, has increased from 5 percent of the market to more than 15 percent today. The aggregate gradation and characteristics, such as angularity, have also changed significantly. The request for special types of mixtures to deliver specific functions, such as improved friction, less noise, and drainage has increased significantly. All these changes reflect the reaction of the industry to increased traffic and environmental demands. Superpave also introduced more performance-based tests and design systems and enhanced the level of knowledge regarding relationships between material characteristics and pavement performance. These systems have allowed industry to be more effective in choosing materials, have encouraged more innovation in selecting mixtures, and increased the competition on warranted pavements.

Utilizing Engineered Paving Materials (EPMs) is an essential requirement for resistance of damage from increased demands and for reducing cost or increasing reuse of resources. Design and modeling of EPMs for flexible pavements is one of the main focus areas for the research of the Consortium. EPMs for the purpose of this project can be classified into two groups based on their function.

I. High performance to resist damage from the following critical conditions:

- High Traffic Volume
- Extreme Heavy Loads and Slow Traffic Speed
- Extreme Climate
- Increased friction and reduced noise
- Perpetual service life

II. Reduce cost, energy, and use of natural resources by increase use of:

- Recycled Asphalt Pavement (RAP)
- Warm mixture additives
- Emulsions for Cold Mixtures Asphalt (CMA)

What Is Needed to Improve the Process of Engineered Paving Materials?

The engineering of pavement surface materials requires the use of analytical computer models that are both fast and accurate while requiring input data that are generated by simple, rapid, and accurate test methods. The approach that is most amenable to these requirements makes use of the measured response of the input materials and models the behavior using the disciplines of mechanics. The demand for accuracy in the input and the predictions is not academic; instead it is imposed by the need for high degrees of reliability in the predicted service life of the pavement material. The accuracy is determined by proper sampling and monitoring of delivered properties at the time of construction. Thus development of simple, rapid, and accurate methods to measure as constructed materials inputs is essential for improved engineering of pavement materials. Accurate predictions and high reliability are requirements of performance-based specifications

and the use of warranties, as well as for the subsequent management of the maintenance, rehabilitation, and re-construction operations to be conducted by the operating agency. Engineering of materials should include models that can define the end result of this engineering process, which is reliable prediction of materials performance. It is a simple truth that reliability can be assured by almost any method; however, by reducing the variance of the predictions, the risk of spiraling life-cycle costs to the operating agency is reduced, as are the time-delay costs to the traveling public. Reducing the variance requires methods of measuring materials properties that have low coefficients of variation. The goal should be to have methods with measured coefficients of variation of approximately 5-10 percent rather than 35-40 percent. With this level of accuracy, it will be possible to reliably engineer materials for pavement surfaces that will meet all of the site-specific demands for performance.

Required Material Inputs—Components and Scaling

The material properties to be determined must take into account all of the physical, chemical, and thermodynamic processes that are known to have a significant effect on the performance of pavements. The deterioration processes include fracture and plastic deformation, both of which are scale-dependent phenomenon. Therefore, the materials properties that are measured and modeled must be consistent with the scale of the deterioration process. For example, the cracks and plastic zones that eventually coalesce into macroscale distress begin as micro-cracks and micro-plastic zones.

Asphalt concrete is a composite material that begins with the binder that may be altered by a modifier and/or a filler, and further altered by the addition of fine aggregate particles as well as coarse aggregate particles. Each alteration changes the material properties of the composite and the final composite properties are the result of the accumulation and interactions of all of the materials at smaller scales. The disciplines of micromechanics have developed energy-based methods of combining the properties of the constituent materials to produce composite properties that partition, store, release, and dissipate energy in the same manner as the actual composite material.

Research Needed to Better Engineer Paving Materials

While the list of properties needed for ideal mechanics based modeling seems to be impossibly long, this project will focus on finding the importance of these properties and identifying those that play a prominent role in enhancing the reliability of the engineering process. Major progress has been made by the Consortium partners and others in identifying the most critical properties that are needed for modeling of performance. Also progress has been made to reduce testing requirements. For example, it has been found in recent moisture damage work at Texas A&M that when dealing with material properties, it is possible to catalog these fundamental properties and eliminate the need to repeat the measurements. The tests to assure that the materials have not changed or to determine the degree to which they have changed are simple and rapid to perform. Recent efforts at UW-Madison and FHWA have also introduced simple tests that can more accurately model the damage accumulation in asphalt binders. The MSCR test and the fatigue surrogate tests are such examples.

Cataloguing material properties simplifies the task of engineering materials and is one of the major benefits of focusing on analytical methods to model material properties. It is then possible to make use of mechanics-related computer models of pavements and use these catalogued properties and materials models to optimize the materials selection process for a give set of site conditions based on expected performance and resistance to distress. The principle objective of the Engineered Materials work plan is to define tools that allow reliable and cost effective methods (tests and models) to select materials to meet required and specific functional performance.

Engineered Paving Materials (EPMs) are modified mixtures which are designed to deliver specific functions related to increased traffic or environmental demands, to re-use of pavement materials, and to allow less energy intensive and more practical construction methods. EPMs include mixtures with binders of specific modification, aggregates with special characteristics, and void distributions that provide a high level of resistance to damage caused by traffic or environment. Furthermore, they include mixtures with high levels of RAP that is well characterized and introduced by specific production methods. Finally, EPMs include warm mixtures, cold mixtures, or other types of mixtures that are produced and constructed to optimize performance, production, and construction. Such mixtures will be designed using fundamental understanding of mechanisms of interactions between asphalt, mineral surface, and air voids; using micromechanics of viscoelastic materials and granular materials; and the use of damage resistance characterization.

RESEARCH HYPOTHESES

The Consortium working hypotheses for EPMs are:

- i. All materials of which asphalt concrete is composed have mechanical and geometric properties which may be combined, using the energy principles of micromechanics, to obtain the net properties of the composite materials.
- ii. Using additives and or new production processes, modified asphalt binders and mixtures can be designed to deliver superior performance that can tolerate extreme traffic and climatic conditions.
- iii. Using fundamental engineering principles in design of mixtures superior performance can be achieved with using high concentration of recycled asphalt mixtures, emulsions, or warm mixture additives.
- iv. Practical and effective protocols for testing and modeling of such superior materials could be developed. Such protocols would provide guidance for selecting high performance materials with predictable (less risky) performance.

GENERAL RESEARCH OBJECTIVES

1. Develop analytical models of the properties of binders, mastic, and mixtures using the principles of mechanics.

2. Develop guidelines for producing and selecting engineered pavement materials focused on limiting risks of pavement failures.
3. Develop guidelines for high level use of recycled pavement mixtures, warm mixtures, and cold mixtures.
4. Use laboratory damage testing and coordinate with validation activities of the Consortium to verify that these guidelines are useful and implementable.

EXPERIMENTAL DESIGN - WORK ELEMENTS PLANNED

Eight major work elements, organized in two categories are planned. Modeling is considered a basic tool to improve prediction of material performance and thus reduce risk of failures. Design guidelines are the tools to make the best use of modeling in practice. The work elements compose an integrated solution linking materials' mechanics to traffic, climate, and age conditions.

Category E1: Modeling

Work element E1a: Analytical and Micro-mechanics Models for Mechanical behavior of mixtures (Year 1 start)

The FHWA Pavement Distress Manual recognizes 17 different types of distress in asphalt pavements. The materials properties that are realistically needed to predict the appearance of distress include the viscoelastic, viscoplastic, and fracture properties, thermal conductivity and heat capacity, thermal expansion and contraction, time-temperature, and time-aging shift properties, diffusivity of the material to air and water in liquid and vapor form and several electrical properties that are important to non-destructive testing such as conductivity and permittivity. While this seems to be an impossibly long list of properties, it has been found in recent moisture damage work at Texas A&M that when dealing with material properties, it is possible to catalog these fundamental properties and eliminate the need to repeat the measurements. The tests to assure that the materials have not changed or to determine the degree to which they have changed are simple and rapid to perform. Cataloguing material properties makes the task of engineering materials much simpler and is one of the major benefits of focusing on analytical materials models of materials properties. It is then possible to make use of mechanics-related computer models of pavements to use these catalogued properties and materials models to devise the best materials from available components for a given site based upon the expected performance and resistance to distress. This is the principle objective of Engineered Materials.

Hypothesis

The properties of full asphalt mixes can be developed by applying the same broad principles and approaches of micro-mechanics to combine the properties of the mastic with the mechanics and geometric properties of the coarse aggregate portion of the mix. These properties include the relaxation modulus of the mixture including isotropy and anisotropy and non-linearity in both the

response and damage properties, time-temperature-aging shift, viscoplasticity, permeability to both air and water in liquid and vapor form, thermal conductivity, thermal expansion and contraction coefficients, thermal heat capacity, both adhesive and cohesive fracture and healing characteristics, as they are affected by moisture and aging, and dielectric permittivity.

It is these properties of the full mixture that are needed as input to a pavement performance prediction model to anticipate what the expected performance and resistance to the various forms of distress will be. These properties can be estimated using the mechanics principles noted above and the accuracy that can be achieved with these measurements will be verified by the planned testing in this project. The performance prediction must be capable to translate the variance of the input values into the variance of the predicted result and the resulting reliability.

Objectives

1. Develop analytical models of the properties of binder, mastics and mixtures using the principles of mechanics. Relate the properties of the binders to the molecular composition, structure, and energy potentials.
2. Verify with laboratory tests the predicted materials properties of the models from Item 1.
3. Implement the models into a mechanics-based pavement performance prediction model which is capable of taking into account the effect of the traffic, weather, drainage, and subgrade support on the candidate asphalt mixture using the estimated mechanics properties. The model should be capable of predicting fatigue cracking, moisture damage, aging, and permanent deformation.
4. Calibrate the pavement performance model to actual known pavements in the LTPP data base with sufficient materials data to permit the estimation of the mixture properties using the analytical models of Item 1 and verify the predicted distress with pavements that were not used in the calibration process.
5. Incorporate into the model of Item 4 the ability to calculate the variance of the estimated life and the reliability of the designed pavement structure for each of the predicted types of distress.
6. Design and initiate materials properties catalogues including all of the materials properties which are needed for the models of Item 1 and which do not change or have predictable changes.
7. Design and initiate a selection engine which will calculate the best combinations of available materials which will provide acceptable mixture properties or resistance to distress.

Attaining these objectives will make it possible to provide the pavement designer with a rapid method of considering all available component materials, and using the materials property catalogues to select the combinations that will provide the greatest likelihood of successful construction and performance. The engineer will also be able to evaluate the likely service lives, variances and reliabilities of each type of distress. With these efficient computerized tools available, it will be possible to engineer pavement surface materials properties as part of the engineering design of an engineered pavement structure.

The properties of the materials to be modeled and used in the models of the binder, mastic, and full mixture will be those for which laboratory characterization protocols will be developed in this research project in coordination with the other team members of the Coalition and with the ongoing binder characterization work in the FHWA.

Experimental Design

The development of the materials property models of the binder, mastic, and mixture will not require an experiment design but will require that the other work elements and subtasks in this project will conduct the necessary tests to provide an evaluation of the accuracy of the models that are developed. This will require coordination with every work element within this project in which characterization work is being accomplished. To the extent that no other work element in this project is focused on developing a needed property, such as thermal coefficient of expansion or contraction, it will be necessary to design a limited experiment within this part of the project to provide the experimental data to verify the model that is developed. In these experiments, the design will be reviewed or developed by the project statistician, Dr. E. S. Park of the Department of Statistics at Texas A&M University.

Subtask E1a-1: Analytical Micro-mechanical Models of Binder Properties

Subtask E1a-2: Analytical Micro-mechanical Models of Modified Mastic Systems

Subtask E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures

Subtask E1a-4: Analytical Model of Asphalt Mixture Response and Damage

This work element will be coordinated with the modeling efforts discussed in the fatigue and moisture damage plans. As discussed in the fatigue plan, multi-scale modeling approach will be followed in order to relate the fundamental material properties to the models' parameters. This will be achieved by developing subroutines that use the micro-mechanical models of binders, mastic and mixture to determine the parameters of the continuum models that will be used for predicting mixture performance.

Major Findings from Year 1

The focus in this first year were twofold: (a) to develop micromechanics methods to determine the mechanical properties of the components of mixes from tests that were made on those mixes and (b) to determine the properties of the mixes from the properties of the constituents, namely, aggregates, bitumen, and air. In part (a), a program has been developed to compute the bulk and shear moduli of aggregates from resilient modulus tests made on mixes using a self-consistent micromechanics model and systems identification to determine the two properties of the aggregates. In part (b), a program has been developed to compute the bulk and shear moduli of mixes from the same properties and volumetric composition of the constituents of the mixes, again using the systems identification approach. The method in part (a) works well and quickly and the computations of the bulk and shear moduli of different types of aggregates from mixture tests is under way.

Year 2 Milestones

The reverse analysis of a variety of mixes and aggregates will be completed and a catalog will be initiated of the properties of a wide range of aggregates will be developed concentrating on gaining knowledge of the characteristic values of aggregates from different geologic origins and mineralogy. It is expected that most of the variability of the results within a given aggregate type will be attributable to the form, angularity, and texture of the aggregate surfaces.

The forward analysis of a variety mixes will be conducted starting with the properties of the aggregates determined in the reverse analysis and determining the bulk, shear and resilient moduli of mixes with a variety of bitumen binders. The results will be compared with measured values.

The forward analysis of a variety of mixes with the properties of the bitumen tested at different temperatures will be used to determine the bulk and shear compliances and relaxation moduli of the mixes at different temperatures.

The forward analysis of a variety of mixes with the properties of bitumen tested at different ages will be used to determine the properties of mixes at different ages. An aging shift function due to Grasley and Lange (2007) will be used with varieties of bitumen to determine the accuracy and robustness of the shift. If successful, the forward analysis of shifted bitumen properties will be used to determine the age-shifted properties of the mixes. Overall, this micromechanics approach will greatly accelerate and simplify the task of making accurate estimates of mixture properties in the field.

Formulation of reverse and forward micromechanics analysis methods will be developed for the following mixture properties: thermal contraction coefficient; adhesive and cohesive bond surface strength; short-term and long-term healing bond surface strength; moisture diffusivity; anisotropic compliance and relaxation moduli; viscoplasticity parameters; dielectrical permittivity and tensile strength.

Reference:

Grasley, Zachary C., and David A. Lange, 2007, "Constitutive Modeling of the Aging Viscoelastic Properties of Portland Cement Paste." *Mechanics of time-Dependent Materials*, Springer Science, accepted for publication.

Work element E1b: Binder Damage Resistance Characterization (DRC)

Subtask E1b-1: Rutting of Asphalt Binders

Subtask Lead: Haifang Wen

Introduction

While linear viscoelastic rheology is considered a major step forward in binder performance modeling, damage resistance characterization is found necessary for low risk selection of high performance materials. Modified binders can be best differentiated and effectively qualified for high performance by using damage resistance testing principles. Binder rutting tests have been performed generally using low stresses. However, it is not clear that testing at a low stress level is the best way to characterize the rutting resistance of an asphalt binder. The stresses and strains in the binder can be very high – much higher than the linear limit for the material. Estimates of the strain in the binder of a typical mixture can vary between 0 and 500 times the overall mixture strain. Due to this fact, when the asphalt mixture is subjected to loading, some of the binder performs in the linear viscoelastic region and some of the binder reaches the region of nonlinear behavior. Current research is being performed at FHWA and also at UW Madison on this topic. A limited number of binders and mixtures are currently being used to find a relationship between the binder nonlinear behavior and the mixture permanent deformation. FHWA results reported at the Binder ETG meetings indicates that stress levels that mimic binder conditions in typical mixtures are not known and are difficult to estimate. The stress levels that are used in the current version of the MSCR test (AASHTO TP 76) are intended to measure stress sensitivity but are not clearly related to mixture behavior. Recent results collected at UW-Madison, as part of a study for the Airfield Asphalt Pavement Technology Program (Project 04-02), indicate that a stress of 3200 Pa, which is recommended in the MSCR AASHTO standard, could be too low and a much higher stress is needed to correlate binder and mixture rutting. The recent results also indicate that the stress level is not the only important parameter in rutting testing, but the accumulated loading time is one as well. It is found that asphalt binders reach a yield point similar to the tertiary flow in mixtures, and thus loading time in a binder rutting test needs to be considered as an important parameter. The results of these recent works will be extended in this study to confirm the validity of the current MSCR procedure or to propose modification to it based on testing a wider number of asphalt binders and mixtures. This work will be coordinated with FHWA staff.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Optimum Pavement Performance: Introducing methods for better characterization of modified asphalts.
- Advanced Quality Systems: Further development of test methods that are more related to actual pavement performance.

Hypothesis

The stress level at which the binder performs and the time of total loading are two parameters that highly influence the permanent deformation of mixtures. Binder needs to be characterized at different stresses and loading times in order to accurately predict the rutting performance of mixtures.

Objectives

The objective of this subtask is to quantify the relationship between binder creep and recovery testing results using the newly proposed procedures and the rutting performance of asphalt mixtures. The binder testing will be done at various stress levels and for various loading times to mimic stress conditions in typical pavements. Based on these relationships, recommendations for binder specification limits will be proposed.

Experimental Design

The objective of this subtask will be addressed as follows:

- vii. Literature Review. A detailed search of existing data and published papers on the subject will be compiled. The review will include worldwide publications and will cover the binder rutting evaluation and also most recent development in mixture rutting evaluation. An attempt will be made to focus on studies in which relationship between binder and mixture behavior is documented. A critical review will be conducted and documented in a report. In addition, a database will be established for available data.
- viii. Selection of Materials and Development of Testing Plan. Based on the findings of the literature review, an experimental plan will be developed. The plan will include testing a set of binders and aggregates to represent the different modification types currently used in the United States. The binder and mixture variables under consideration are as follows:

High temperature PG grades: PG 64-XX, PG 70-XX, and PG76-XX

Modification types: SBS, Elvaloy, SB, EVA, PPA, oxidized

Mixture Gradation: Fine, Coarse, and OGFC

Aggregate shape: Angular and Rounded

Asphalt Content: Design and Design+ 0.5 percent

The plan will also consider the testing methods that are needed. It will include the following binder and mixture tests.

- The binder tests should include creep and recovery testing using the dynamic shear rheometer. Extended creep testing can also be included as a complement.
- Two geometries should be considered: parallel plate and cone and plate. Parallel plate should be included because is the most widely used geometry for testing binders. Cone and plate should be used because it provides a homogeneous

distribution of shear rates which are needed for non linear characterization. The stresses should consider from 100 Pa (linear range) up to 50000 Pa (maximum range for commercial DSR).

- The time of loading (or number of cycles) should be enough to reach the tertiary creep region.
 - The temperature of testing should be the same used in the mixture testing.
 - Mixture rutting test should be performed on samples prepared with the selected binders. Two temperatures would be recommendable: 46 °C and 58 °C.
 - Mixture rutting test using the creep and recovery should be used. At least two stress levels should be considered: 22 psi (standard stress for Flow Number test) and 100 psi (representing high tire pressures).
- ix. Conduct Testing of Binders and Mixtures. Testing of binders and mixtures will be carried out. The data will be organized in a database to allow for statistical correlations and for modeling of behavior using various models found in the literature.
- x. Analysis and Interpretation. The concept will be to explore a few approaches to characterize the non-linearity of asphalt binder and fundamentally evaluate the effects of asphalt binder on asphaltic mixtures. The hypothesis is that the permanent deformation in asphaltic mixture is a function of permanent deformation of asphalt binder, as well as interaction with other components of asphaltic mixtures. The team will employ the mechanistic approaches currently available for either asphalt binders or asphaltic mixtures and identify the most effective approach for the rutting of asphalt binder.

The approaches which the team is evaluating are introduced, as follows:

- Viscoelastoplasticity. This approach has been used to characterize the fatigue of asphaltic mixture. However, in other fields, it is also used for plastic deformation of materials. In addition, the theory of viscoelasticity has been used for rutting study of asphalt binder. The strain consists of linear viscoelastic (including instantaneous elastic), and viscoplastic (including instantaneous plastic) strains. Saadeh et al. (2007) used this concept for repeated creep tests on asphaltic mixtures and characterized the viscoplastic response of materials. The nonlinear viscoelastic response was subtracted from the total strain during loading to calculate the viscoplastic strain as a function of loading time.
- Viscoplastic Damage. This approach has been used in other fields to characterize the creep damage of materials, such as metal (Bellenger and Bussy 2001). The macroscopic modeling of the creep curves with its three stages was based on the irreversible thermodynamics theory with internal variables. A unified viscoplastic model is used to describe primary and secondary creep behaviors, and the tertiary creep description is based on the introduction of a scalar damage variable and the nonlinear effects of changes in geometry. Viscoplastic damage models in nonlinear geometry are defined in order to describe different modes of creep damage development. The numerical properties of the models allow obtainment of a different crack growth development, providing information on the post-critical behavior and the damage development until failure.

- **Power Law Model.** For asphaltic mixture, flow number is defined as the cycle number when the deformation slope starts increasing, which means that tertiary flow is starting. For some mixtures, however, this increase in slope is very gradual and they can resist many cycles of loading after Fn without considerable increases in deformation. To further analyze the influence of the binder characteristics in the rutting performance of mixtures, the deformation results can also be studied using a power law model to include the primary, secondary, and tertiary flow of asphalt binder.

The data collected will be analyzed to identify the relationship between binder rutting and mixture rutting as a function of stress level, aggregate properties, and mixture volumetric properties. The data will also be used to verify the analytical models developed for mechanical behavior of asphalt mixtures. The focus will be on defining the importance of testing variables including stress level (no-linearity), temperature, total time of loading, RTFO aging, and number of cycles used to allow prediction of traffic volume effects. The interpretation will be conducted using statistical correlations and fitting as well as mechanics based phenomenological models.

- xi. **Standard testing Procedure and Recommendations for Specifications.** The results of analysis will be used to evaluate the current MSCR standard protocol and suggest modification if needed. Also, a recommendation for inclusion of the procedure and limits for acceptance in the PG binder specification will be developed. The limits will be based on the correlations to mixture response and on LTPP data of rutting performance.

Major Findings from Year 1

During Year 1, the materials and testing conditions for the plan were selected and are shown in table E1b-1.1. A testing plan was also developed and the proposed tests are shown in table E1b-1.2. Since the start of Year 1 work plan, the team has extensively evaluated two aspects of rutting for asphalt binder: tertiary flow for asphalt binder, and power law modeling of asphalt binders and asphaltic mixtures. The major findings are briefed here.

Table E1b-1.1. Matrix of materials and conditions.

Neat Binders	PG64-22	Aggregates	Limestone
	PG70-22		Granite
	PG76-22		
Modifiers	SBS	Mix Designs	E-10
	Elvaloy		
	PPA		
	Sasobit		
	EVA		
	Oxidized		
Mineral Fillers	Limestone	Testing Temp	46 C
	Granite		58 C
	Ottawa sand		70 C

Table E1b-1.2. Proposed tests on asphalt binders and mixes.

Asphalt Binder	Extended Creep	Stress Level	100Pa
			1000Pa
			10kPa
			20kPa
			30kPa
	MSCR	Stress Level	100Pa
			1000Pa
			10kPa
			20kPa
			30kPa
		Loading/unloading	0.1s/0.9s
			0.2s/0.8s
Mix	Extended Creep	Stress Level	0.69Mpa
			1.035Mpa
			1.38Mpa
	MSCR	Stress Level	0.69Mpa
			1.035Mpa
			1.38Mpa
		Loading/unloading	0.1s/0.9s
			0.2s/0.8s

Tertiary flow of asphalt binder. Repeated creep and recovered tests were conducted on asphalt binders, using parallel plate in Dynamic Shear Rheometer (DSR). Tertiary flow was clearly observed. However, when the parallel plate was replaced with the cone plate, the tertiary flow disappeared. Figure E1b-1.1 shows the tests results on the same binder when parallel plate and cone plate were used, respectively. It can be seen that the creep strains from parallel plate test exhibited tertiary flow and diverted from the strains of cone plate tests in which no tertiary flow occurred. Digital pictures were taken for both parallel plate and cone plate tests, as shown in figure E1b-1.2. It was found that material loss was severe when the parallel plate was used. The opposite was true for cone plate tests. For parallel tests, the cross section of asphalt binder specimens reduced as the material flows away from the plate. It seems that the tertiary flow is partially a result of the change of geometry.

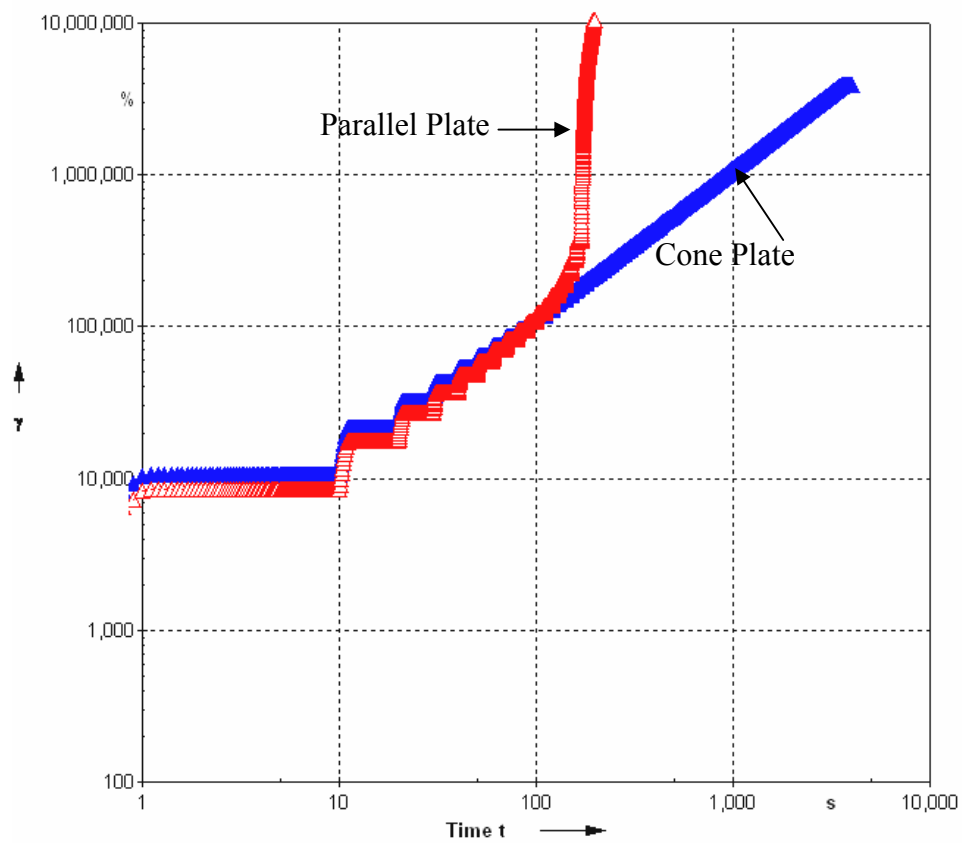


Figure E1b-1.1. Chart. Discrepancy of shear strains between parallel and cone plate under creep test.



Figure E1b-1.2. Photo. Specimen before and after parallel plate tests.

Power Law Modeling of Rutting of Asphalt Binder. Considering the linear shape of the curves in the log-log scale, the nonlinear power representation seems to be the best fit for the behavior of the material. Nonlinear power representation is given by the following equation:

$$\gamma(t, \tau) = \sum_{i=1}^m k_i \cdot t^{n_i} \cdot \tau^{p_i}$$

Where: γ = shear strain
 t = time
 τ = shear stress
 k_i, n_i, p_i = constants

The number of arguments, m , to be used depends on the material. For the polymer modified binder, a value of m equals to two was found to be enough to describe the shape of the curves. This is logical considering that the curves show a linear shape with two different slopes.

Nonlinear fitting using was used to determine the parameters of the model. In order to give the same importance to the low strain/time range than to the high strain/time range, the fitting was weighed using the strain as the weighing variable. The fitting showed to be very good, with an R value of 0.998. The following equation shows the results of the nonlinear power law fitting.

$$\gamma = 2.3668 \cdot 10^{-4} \cdot t^{0.58717} \cdot \tau^{0.99412} + 1.8484 \cdot 10^{-19} \cdot t^{2.0019} \cdot \tau^{4.0265}$$

The first argument on the right side of the equation represents the behavior at low stress levels and shorter times. The power parameter on the stress variable is almost equal to one, which confirms the linear behavior on this region. The second argument on the right side of the equation represents the nonlinear behavior at higher stresses and longer loading times. Figure E1b-1.3 shows the results of the fitting of the shear strain using the power law model.

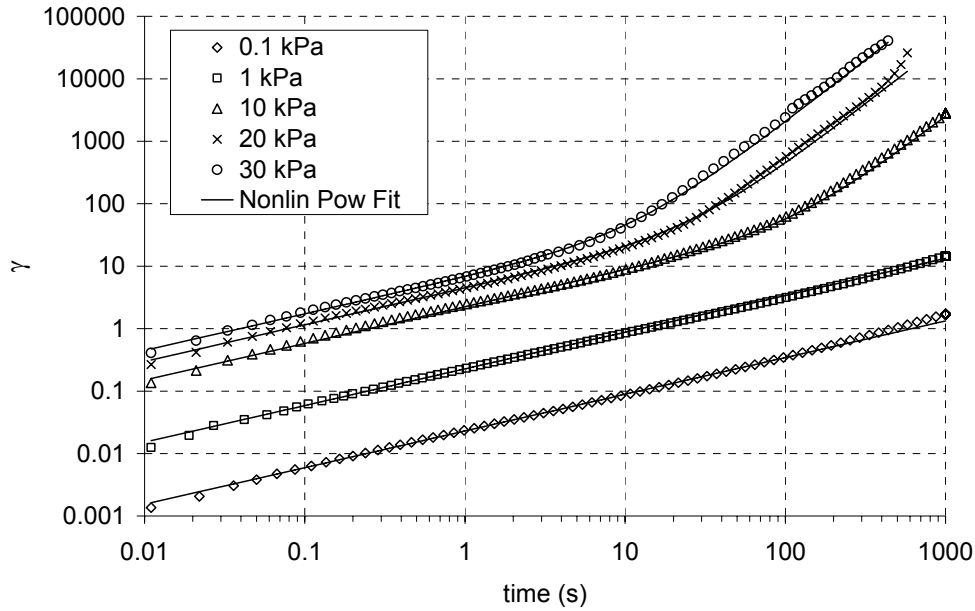


Figure E1b-1.3. Chart. Nonlinear power fitting, creep phase, PG64-34 binder, 1000 seconds loading.

The creep compliance of the material can be obtained by dividing the shear strain by the shear stress, as follows:

$$J(t) = 2.3668 \cdot 10^{-4} \cdot t^{0.58717} \cdot \tau^{0.00588} + 1.8484 \cdot 10^{-19} \cdot t^{2.0019} \cdot \tau^{3.0265}$$

$$J(t) \approx 2.3668 \cdot 10^{-4} \cdot t^{0.58717} + 1.8484 \cdot 10^{-19} \cdot t^{2.0019} \cdot \tau^{3.0265}$$

Year 2 Work Plan

During Year 2, the team will continue to evaluate different approaches for rutting performance of asphalt binder and evaluate the effectiveness of different analytical approaches, based on the experimental results. The experimental plan was designed to evaluate the factors that have potential to influence the rutting performance of asphalt binders, as well as asphaltic mixtures.

The test results will be analyzed using different analytical approaches. These analyses will determine the fundamental properties of asphalt binder that govern the resistance to rutting. In addition, the team will strive to quantify the relationship between the rutting properties of asphalt binders and those of asphaltic mixes.

Figure E1b-1.4 depicts the research approach defined for this work element.

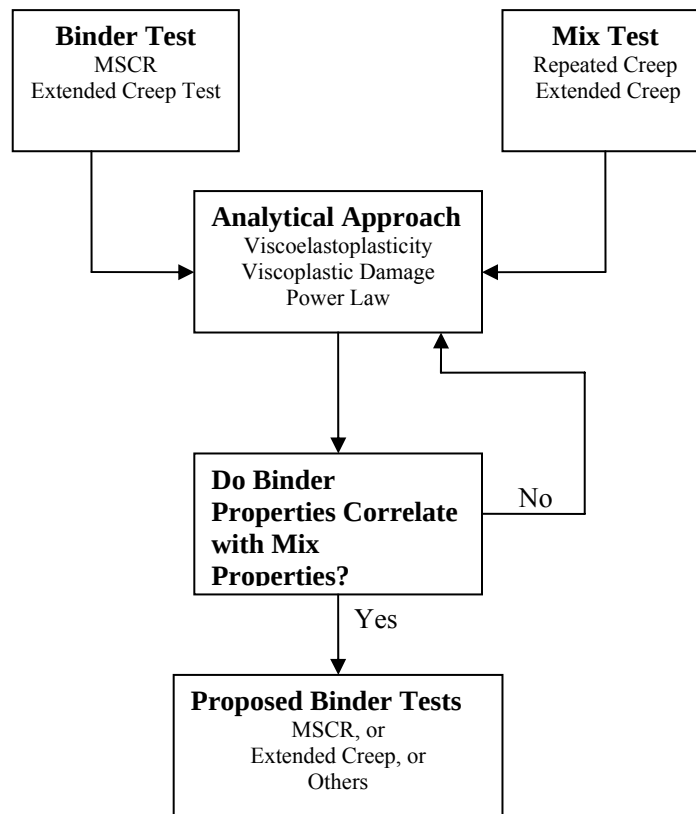


Figure E1b-1.4. Chart. Flow chart for research approach.

Year 2 Milestones

- Complete report on review of literature for rutting of asphalt binders and asphaltic mixtures
- Finalize material selection and experimental plan
- Conduct the proposed tests on asphalt binders and prepare for mix tests
- Develop framework for emulsion selection and design of surface treatments

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Literature Review	X	X			
ii. Select Materials & Develop Work Plan	X	X			
iii. Conduct Testing		X	X	X	
iv. Analysis & Interpretation		X	X	X	
v. Standard Testing Procedure and Recommendation for Specifications		X	X	X	

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
i. Literature Review	X			
ii. Select Materials & Develop Work Plan	X			
iii. Conduct Testing	X	X	X	X
iv. Analysis & Interpretation	X	X	X	X
v. Standard Testing Procedure and Recommendation for Specifications				X

Budget

The estimated budget for this subtask is \$350,000 over the four years. The work will be conducted by the University of Wisconsin-Madison.

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Subtask E1b-2: Feasibility of determining rheological and fracture properties of thin films of asphalt binders and mastics using nanoindentation

Subtask Lead: Dante Fratta

Introduction

The effort in this subtask will be closely coordinated with similar work at WRI in the “Fundamental Properties of Asphalts and Modified Asphalts III” contract with FHWA. If any research is identified here, it will be complementary research. The behavior of asphalt mixtures is highly affected by the rheological and fracture properties of the asphalt mastic, the glue that holds together the aggregate skeleton in the composite asphalt mixture. The current asphalt binder specifications are based on mechanical tests performed on specimens with dimensions that are not representative of the scale of asphalt films found in a typical asphalt mixture, which is in the range of 13.5 μm to 600 μm , with 30 to 50 percent in the range of 13.5 to 17 μm . Currently, there are not any documented research studies that address nondestructive determination of mechanical properties of asphalt thin films in an asphalt mixture. If such technology were developed it could revolutionize the methods of accepting pavement materials after construction is complete. It would greatly simplify the task of monitoring changes in materials due to aging or repeated loading in the field, eliminate the need for the expensive and destructive methods used today, and, perhaps most importantly, allow for rapid and simple quality control for contractors. The purpose of this study is to evaluate the usefulness of nanoindentation devices to measure asphalt binder or mastic properties.

The work will be conducted in collaboration with the University of Minnesota and will focus on utilizing nanoindentation equipment available at the University of Minnesota or other research establishments for exploratory measurements. These measurements will be compared to measurements collected with conventional methods used today in the PG grading such as the DSR, BBR and the Direct Tension.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Optimum Pavement Performance: Introducing methods for better characterization of modified asphalts.
- Advanced Quality Systems: Further development of test methods that are more related to actual pavement performance.

Hypothesis

In-situ properties of asphalt binders in asphalt mixtures can be determined using nanoindentation equipment with or without minor modifications.

Objectives

The proposed study has the following objectives:

- i. Determine the rheological and fracture properties of asphalt binders and mastics using nanoindentation equipment.
- ii. Compare the rheological and fracture properties of asphalt mastics determined with the current PG grading test methods to the similar properties determined using nanoindentation.

Experimental Design

The objectives of this subtask will be addressed as follows:

- i. Literature Review and Identification of Equipment
- ii. Exploratory Use of Nanoindentation Devices
- iii. Conduct of Exploratory Tests on Binder Specimens
- iv. Compare the Binders Responses with the Dynamic Shear Rheometer (DSR) device
- v. Develop & Design Testing Setup for Exploratory Testing on Mixtures
- vi. Conduct Exploratory Tests on Mixture Samples
- vii. Test Binders and Mastics Using PG Grading Test Methods
- viii. Analysis and Report: Develop Recommendation for Possible Implementation

Major Findings from Year 1

During year one, the materials and testing conditions for the plan were selected and are shown in table E1b-2.1. The University of Wisconsin-Madison research team contacted the University of Minnesota to evaluate the potential of nanoindentation measurements to evaluate the rheological and fracture properties of binders. In a set of exploratory tests at 5 and 10 μm indentation, the results show a great amount of creep and stress relaxation (figures E1b-2.1 and E1b-2.2). During testing, the technicians faced the issue of large adhesion between the binder sample and the indenter probe. To reduce/control the effect of adhesion on the probe, a drop of water was added to the surface of the binder sample.

These results seem to show some potential for the use of the technique to evaluate rheological properties of asphalt binder. Several more tests, including a small parametric study, will be run to further the potential of the nanoindentation technique for the evaluation of the viscoelastic and fracture properties of asphalt binders.

Year 2 Work Plan

The binders presented will be tested at 10 and 25°C to evaluate how well the nanoindentation technique can be used to systematically and rapidly evaluate the rheological and fracture behavior of binders. The binders will be tested both with the nanoindenter and the DSR to provide an

independent verification of the material response. Once the research team evaluates the response of the materials, and it establishes meaningful correlations between nanoindentation and DSR results, the methodology for the evaluation of the rheological and fracture behavior of asphalt mixtures will be proposed.

Because the nanoindenter and DSR do not measure the exact same material parameters (e.g., different size scales, different deformation modes, etc.), the research team will evaluate the differences in boundary condition, loading rates, and scales (McGennis et al. 1994; Lin et al. 2006). The Kelvin-Voigt model will be used to evaluate the rheological properties (Ashby and Jones 1996; Roberts et al. 1996; Pichler et al. 2005). Figure E1b-2.3 depicts the research approach defined for this work element.

Table E1b-2.1. Matrix of materials and conditions.

Neat binder	PG 58-28
	PG 64-22
Modified binders with	SBS
	Elvaloy
	PPA
Mineral fillers	Limestone
	Sandstone
	Ottawa Sand

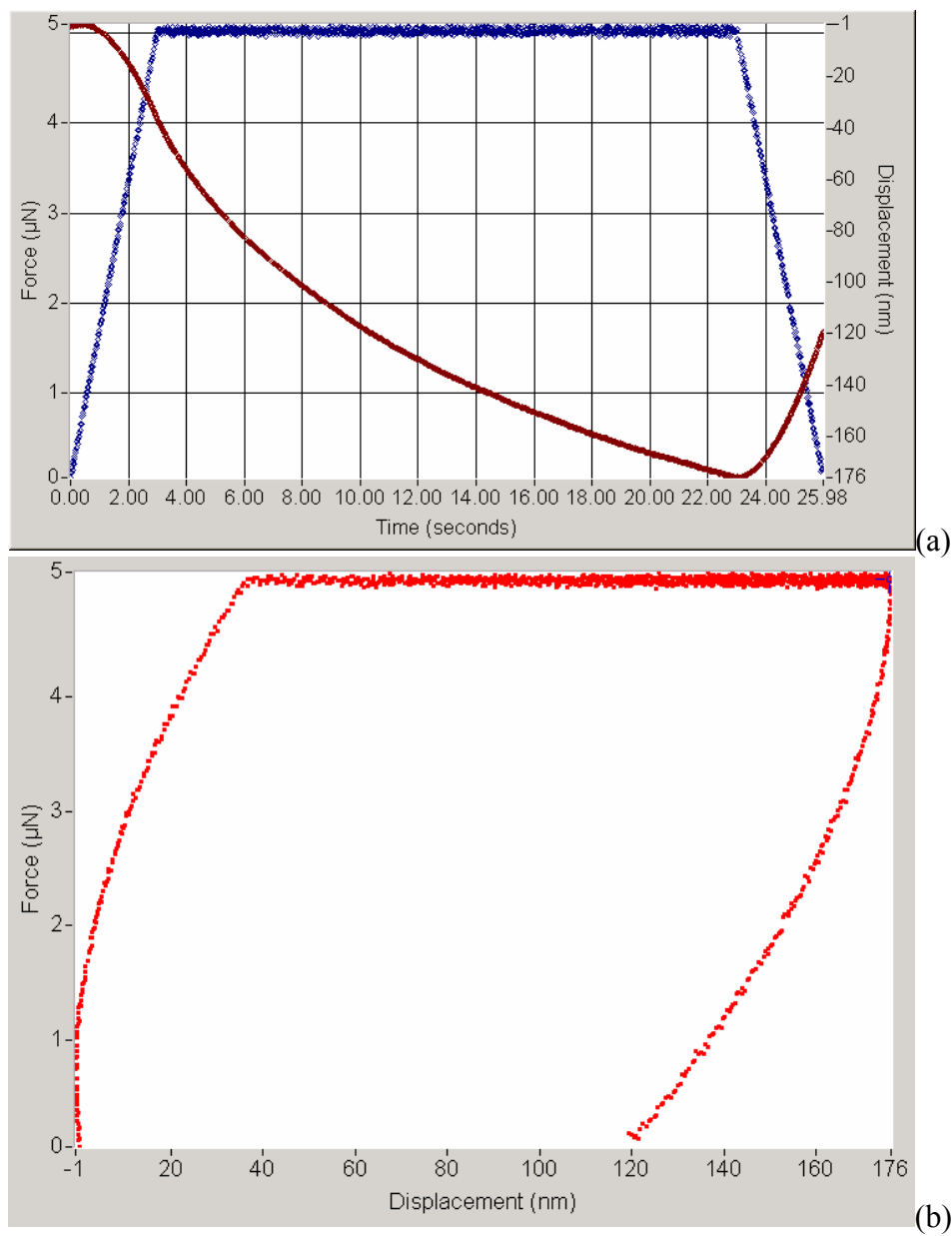


Figure E1b-2.1. Chart. 5 μN indentation results on BAY+filler with a 500 μm flat punch probe. (a) Force and displacement versus time and (b) force versus displacement.

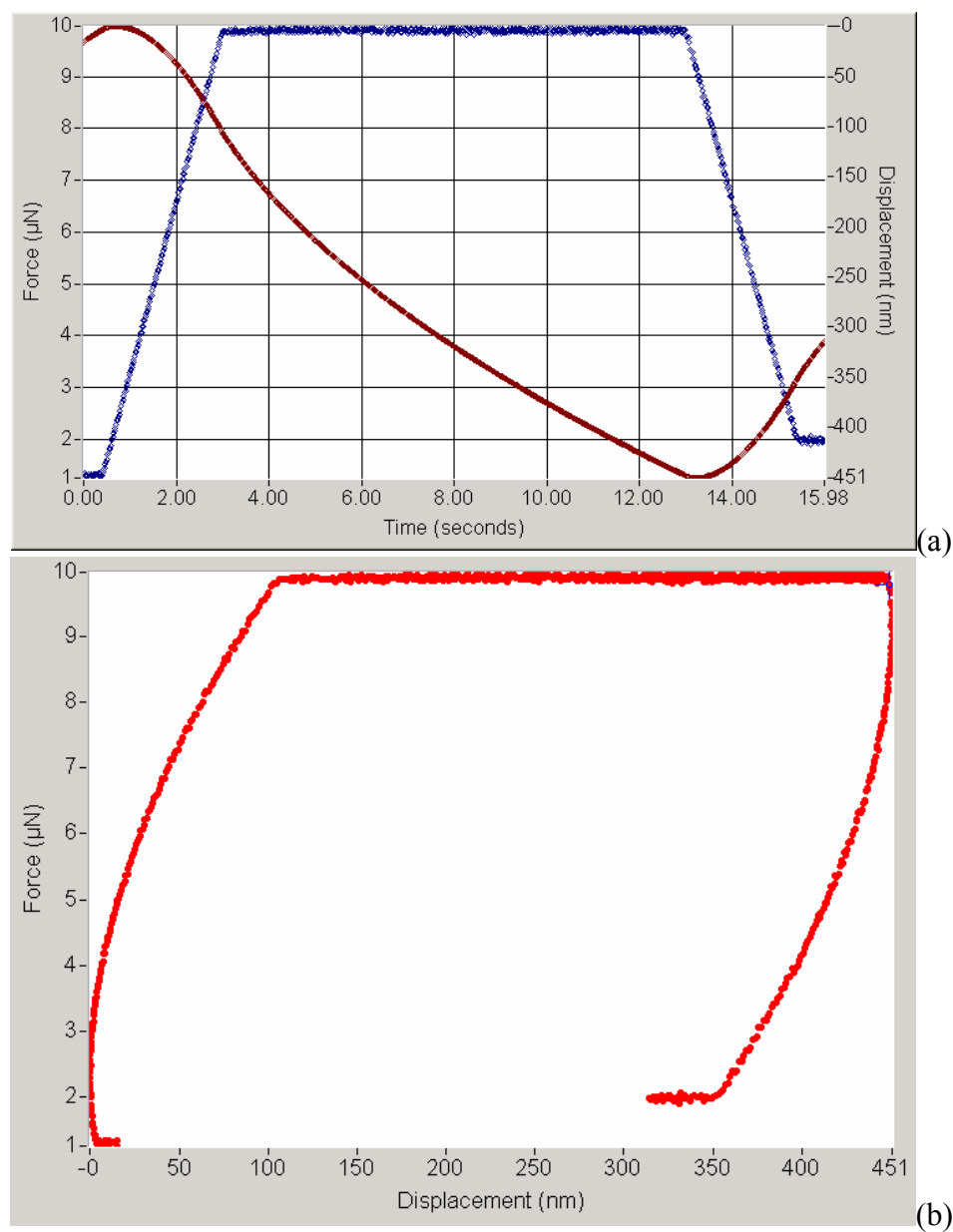


Figure E1b-2.2. Chart. 10 μN indentation results on BAY+filler with a 500 μN flat punch probe. (a) Force and displacement versus time and (b) force versus displacement.

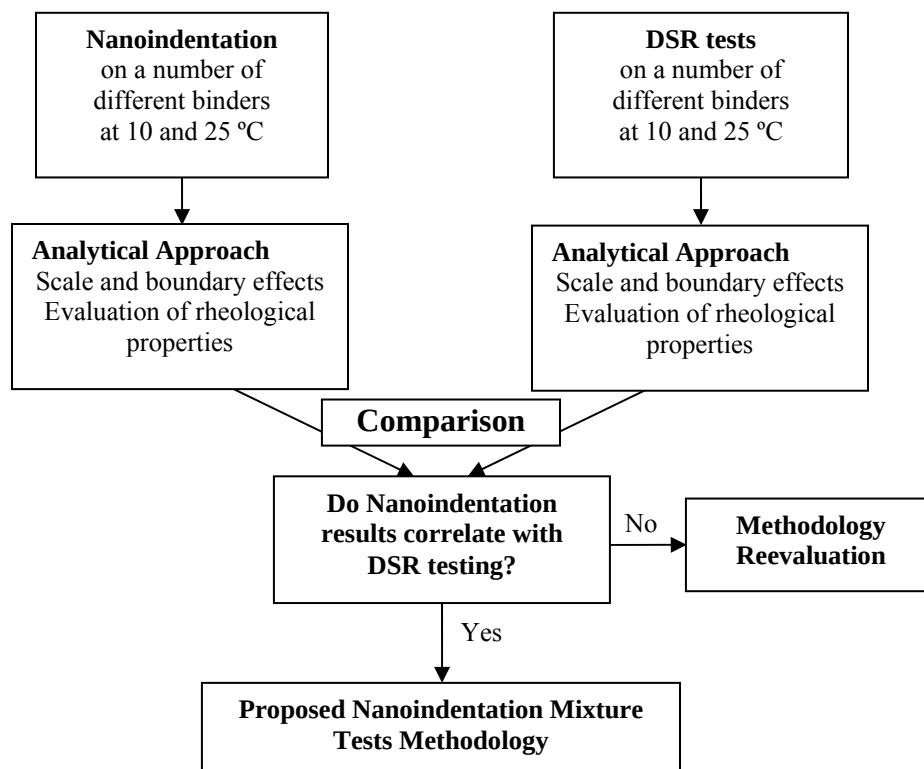


Figure E1b-2.3. Chart. Flow chart for research approach.

Year 2 Milestones

- Complete report on review of literature
- Finalize material selection and experimental plan
- Conduct the proposed tests on asphalt binders and mastics
- Evaluate the boundary conditions, loading rates, and scales
- Compare nanoindentation results with those of DSR

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Literature Review and Identification of Equipment	X	X			
ii. Exploratory Use of Nanoindentation Devices	X	X			
iii. Conduct of Exploratory Tests on Binder Specimens		X	X	X	
iv. Compare the Binders Responses with DSR		X	X	X	
v. Develop & Design Testing Setup		X	X	X	

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
i. Literature Review	X	X	X	
ii. Select Materials & Develop Work Plan	X	X	X	
iii. Conduct Testing	X	X	X	X
iv. Analysis & Interpretation		X	X	X
v. Standard Testing Procedure and Recommendation for Specifications				X

Budget

The estimated budget for this subtask is \$150,000 over the four years. The work will be conducted by the University of Wisconsin-Madison and University of Minnesota.

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Work element E1c: Warm and Cold Mixes

Subtask E1c-1: Warm Mixes

Subtask Lead: Codrin Daranga

Introduction

Rising energy prices and more stringent environmental regulations have resulted in significant interest in warm mix asphalt additives. These additives are means to decrease the energy consumption and emissions associated with conventional hot mix asphalt production by allowing

asphalt mixes to be produced at lower mixing and compaction temperatures, addressing the prominent environmental and economic factors currently faced by industry. Lower production temperatures reduce plant emissions and energy consumption. There is also great technical benefit to the use of warm mixes, namely, extension of the construction season and reduced aging of the asphalt binder. The ability to achieve a suitable in-place density at lower temperatures allows for extension of the construction season. Reduction of the short term aging (oxidation and volatilization) of the asphalt binder during conventional construction would also lead to enhanced pavement performance through reduced thermal and fatigue cracking, thus improving the life cycle cost of the pavement.

The concept behind warm mix technologies is reduction in asphalt binder viscosity, allowing for the asphalt to attain suitable viscosity for coating of the aggregate and compaction of the mix at lower temperatures. Currently there are two commonly used types of warm mix additives in the market: wax-based additives that are added to the asphalt binder through low shear mixing and hydrated mineral compounds that are added to the pugmill during normal batching operations. Each of these additives achieves reduced binder viscosity by different mechanisms.

One of the most widely used wax-based additives currently on the market is Sasobit®. This additive is a “long chain aliphatic hydrocarbon produced by Fischer-Tropsch synthesis of coal or natural gas.” The wax has been engineered such that it is completely soluble at 115 °C, allowing it to be incorporated into the asphalt binder homogeneously. This wax-based additive has been classified as an “asphalt flow improver” due to its ability to reduce viscosity above the previously defined temperature threshold. Below this temperature threshold the wax additive crystallizes, forming a lattice structure in the binder that leads to enhanced binder stiffness at high temperatures while minimizing low temperature performance.

The hydrated mineral compounds reduce asphalt binder viscosity by foaming of the asphalt at mixing and compaction temperatures. Currently there are aluminum-silica and phosphorous based mineral additives available. These additives contain 18-21 percent water by mass and it is expected that the entrapped water is released in the asphalt at temperatures between 85-180 °C. At these temperatures the water is released in the form of vapor, creating a volume expansion of the binder which results in foaming of the asphalt. The foamed asphalt enhances lubrication, allowing for workability and aggregate coating at lower temperatures. In theory, once the asphalt mixture is placed and cooled, the water vapor evaporates from the mix. Therefore, the performance of the mixture is not enhanced.

The implementation of warm mix technology as a viable option for paving operations is a promising concept. However, further investigation of the effects of the aforementioned additives on the constituent materials of asphalt mixtures and pavement performance must first be investigated. Specifically, the effects of the additives on fundamental binder and mixture properties must be defined, the impact of the additives on mixture workability quantified, and the field performance of pavements placed using warm mix technologies evaluated and compared to conventional HMA mixes. Past research has defined rutting, moisture damage, and mix design as key issues that have yet to be fully resolved. Recent work at UW-Madison has shown that Sasobit additives increases the S(60) and decreases m(60) and thus low temperature cracking could be affected negatively. It is imperative that the effects of these additives be fully

understood and evaluated to facilitate development of specifications and construction guidance to allow for wide spread application of this technology.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Promotion of environmental stewardship.
- Development of the use of the gyratory plate as an improved measure of mix workability.
- Clear definition of mix design and construction procedures to provide a basis for modeling of energy savings associated with the use of warm mixes.
- Field investigation quantifying the risk of compromising performance at the expense of energy savings.

Hypothesis

- Detailed investigation of the effects of wax and mineral-based warm-mix asphalt additives on the performance of asphalt binders and mixtures will provide a basis for best practices of incorporating this technology into current practice.
- Laboratory testing of materials during field trials and subsequent monitoring of pavement performance will verify laboratory findings, identify deficiencies in current procedures, and allow for development of best practices for mix design and construction of warm mix asphalt.

Objectives

The overall objective of this research effort is to gain an understanding of the effects of commercially available warm mix additives on the performance of the asphalt binder and mixture and mixture workability. This understanding will allow for optimization of mixture design and construction practices for application of warm mix technology to the field. Optimized practices will be applied in field trials and evaluated/refined through monitoring of pavement performance.

Experimental Design

The following activities will be completed in order to achieve the objectives of this research effort.

- i. Evaluation of the Effects of Warm Mix Additives on the Rheological Properties of Asphalt Binders

Understanding of how the warm mix additives affect binder properties is imperative for further comprehension of mixture and field performance. The current state of industry requires that both polymer modified and neat binders be investigated.

ii. Evaluation of the Effects of Warm Mix Additive on Mixture Workability and Stability

The Gyratory Load Plate developed by UW Madison will be used to measure the resistance of the asphalt mixture to compactive effort. Previous research has used air voids to define increased workability due to reduction in viscosity caused by warm mix additives. The use of the gyratory load plate will provide a more fundamental measure of these effects. Previous work at UW-Madison has defined two indices, the Construction Energy Index (from 88 to 92 percent Gmm) to quantify mix workability and the Traffic Energy Index (92 percent - 98 percent Gmm) to evaluate the stability of the mixture. All mixes will be compacted past Nmax to allow for measurement of both these parameters.

Nine parameters at two to four levels have been defined above, making a full factorial experimental design infeasible. A partial factorial design will be used to design an experiment that will identify significant effects while reducing the number of mixtures required for testing.

iii. Mixture Performance Testing

Effects deemed to be significant through binder and compaction testing will be varied to evaluate the performance of asphalt mixtures.

- Moisture Damage: Previous research has found moisture damage to be a significant mode of distress in warm mixes. The following tests will be used in conjunction with binder cohesion testing to investigate moisture damage in warm mixes and its causes.
 - Mastic: The fine materials (R30 and below) will be used to create torsion cylinders to quantify the effects of moisture on the mastic in aggregate blends tested.
 - Mixture testing: Moisture damage will be defined using TSR testing. If moisture damage is found to be a problem, investigate the use of liquid anti-stripping additives and hydrated lime.
- Simple Performance Tests (E* and FN).
 - Dynamic Modulus (E*) and Flow Number tests will be used to characterize the stiffness and rutting resistance of mixtures using warm mix additives and to compare the results to conventional HMA mixes. Tests will be performed on short and long term aged mixtures.
- Resistance to Fatigue and Thermal Cracking (IDT):
 - Fracture Energy: Literature review has shown that the fracture energy parameter at different testing temperatures is able to predict resistance to fatigue and thermal cracking (Wen and Kim 2002).

iv. Refine Mix Design Procedure with Consideration of the Phase I NCHRP 9-43 Report; Develop Performance Recommendations

Results of binder and compaction testing will be used to identify any necessary revisions to current Superpave mix design procedures. Possible revisions include:

- Binder grade: Define appropriate binder grade adjustments to account for contribution of wax lattice structure or to compensate for reduced rutting resistance.
- Aggregate Moisture Content: The appropriate moisture content of the aggregate blend must be defined to provide consistency between laboratory tests and field application.
- Optimum Asphalt Content: Guidance on whether optimum asphalt content should be based on warm mix compactions or conventional HMA compaction.
- Additive Concentration: Define concentrations of additive that will provide optimum performance.
- Mixing and Compaction Temperatures: Define optimum and mixing and compaction temperatures based on warm mix additive concentration.
- Anti-stripping additives: Specify additives and concentrations to prevent moisture damage.

v. Field Evaluation of Mix Design Procedures and Performance Recommendations

The results of the binder and mixture testing previously discussed will be used to identify key variables for field investigation and define parameters for the design of test sections for field investigation. Furthermore, guidance developed in part iv (above) will be used in the construction of warm mix test sections to evaluate the mix design procedures. The following parameters should be measured in the field during construction:

- Mixing temperature
- Compaction temperature
- In-place density (Nuclear Gauge)
- Number of Passes to Achieve Target density
- Thickness
- Thickness-NMAS ratio

Field mix will also be obtained from each site and evaluated using the test procedures defined in the previous parts of this subtask that indicated potential effects caused by using warm mixes.

Field performance will be monitored through pavement distress surveys and pavement coring and correlated to laboratory testing results. This field evaluation will lead to refined mixture design and construction guidance. (Work will be done with UW Platteville.)

The team will coordinate with other research activities in this area, such as NCAT, NCHRP 9-43 and 9-47.

Major Findings from Year 1

During Year 1, the materials and testing conditions for the plan were selected and are shown in table E1c-1.1. In addition, the preliminary test plan is shown in table E1c-1.2. Activities in Year 1 focused on the effects of both wax-based (Sasobit) and a proprietary mineral based warm mix additives on asphalt binder properties. The preliminary study focused on the effects of both additives on mixing and compaction temperatures as measured in the Brookfield Viscometer. Furthermore, the effects of Sasobit on physical hardening and mineral based additives on binder rutting performance were investigated. The following is summary of the findings of each of these efforts.

Table E1c-1.1. Matrix of materials.

Binder		Mineral Aggregate			Warm Mix Additive		
Neat	Polymer Modified	Granite	Limestone	Gravel	Zeolite (Aspha-min)	Wax (Sasobit)	Emulsion (Evotherm)

Table E1c-1.2. Proposed tests.

Viscosity	Adhesion/Cohesion		Rutting		Fatigue	Low Temperature	
Brookfield RV	Thin Film Rheology	UW-Madison Tack Test	DSR $G^*/\sin\delta$	MSCR	Monotonic Test	BBR	SENB

1. Effects of Sasobit on Binder Viscosity and Mixing and Compaction Temperatures

The effects of Sasobit on binder viscosity were evaluated through assessment of the binder viscosity profiles for two different binder grades (PG 70-22) and concentrations (1 percent and 3 percent). Viscosity profiles were created for three temperatures: 105 °C, 135 °C, and 165 °C. Figures E1c-1.1 and E1c-1.2 provide the viscosity profiles at the aforementioned testing temperatures for PG 70-22 and PG 70-28, respectively.

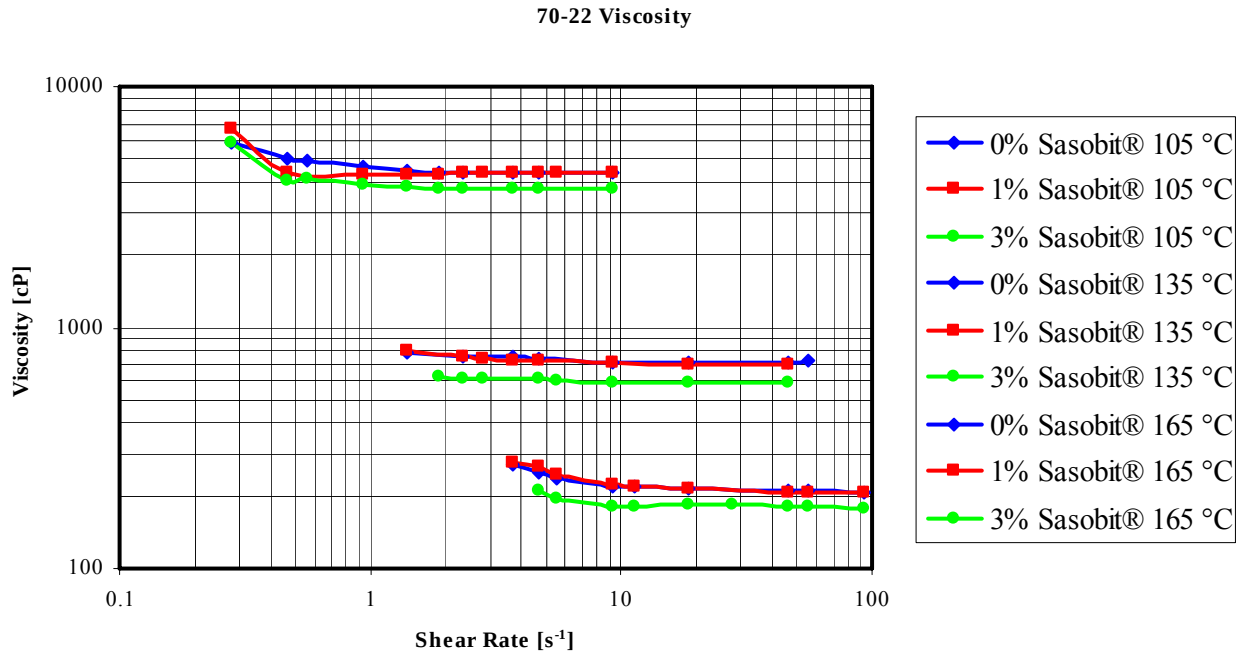


Figure E1c-1.1. Chart. Viscosity profile for PG 70-22.

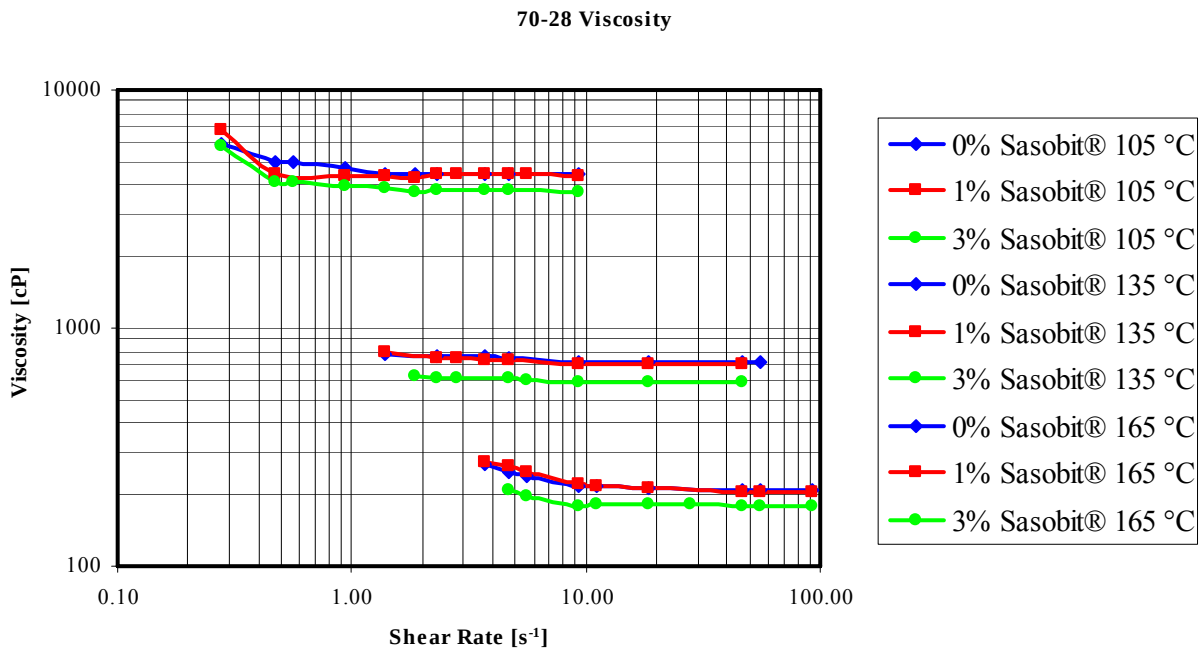


Figure E1c-1.2. Chart. Viscosity profile for PG 70-28 binder.

The viscosity profiles for both binder grades show virtually no effect of the addition of Sasobit on binder viscosity for all shear rates at concentrations lower than 3 percent. To investigate the relationship between the measured viscosity profiles and mixing and compaction temperatures, the methodology developed in NCHRP 9-10, which uses measurements of zero shear viscosity and curve fitting using the Cross Williamson Model, was applied. Table E1c-1.3 provides a summary of the mixing and compaction temperatures determined for a given Sasobit concentration and binder type.

Table E1c-1.3. Summary of estimated mixing and compaction temperatures for Sasobit.

Binder	Temperature (C)	Sasobit Concentration		
		0%	1%	3%
PG 70-22	Mixing	144.3	---	140.4
	Compaction	132	---	128.7
PG 70-28	Mixing	152.3	152.9	145.9
	Compaction	137	137.3	132.4

The data provided in table E1c-1.3 shows only and approximately 4 °C reduction in mixing and compaction temperatures for 3 percent Sasobit. Based on the extra cost of the additive and the potential reduction in low temperature binder performance, this reduction is not significant enough to justify the use of Sasobit. However, further work needs to be done to verify these results and investigate the effect of binder grade on the ability of Sasobit to reduce mixing and compaction temperatures.

Effects of Sasobit on Physical Hardening

The same binders and concentrations of Sasobit previously discussed were used to examine the effects of Sasobit on the physical hardening of asphalts. The conclusions of the study are as follows:

- The addition of Sasobit to the binder produces a significant increase of the stiffness, and a reduction of the m-value. The magnitude of this effect is almost identical for both RTFO and PAV aged samples, thus indicating a minor susceptibility of Sasobit to aging.
- BBR and glass transition tests show that Sasobit has a negligible influence on rate and magnitude of physical hardening. Specifically, the phenomenon is slightly intensified for PAV aged binders, while it is vaguely weaker for RTFO aged ones. This tendency is somehow more marked for the PG 70-22 asphalt.
- For the PG 70-28, the T_g of the Sasobit-modified binder is higher than the one of the original binder. The explanation could be that the addition of the FT-wax (a glasslike

material) the glassy region of the material is extended. On the other hand, the PG 70-22 shows an opposite behavior, proving – besides the non-optimal dispersion of the experimental data – the strong dependency on asphalt.

- Both asphalts exhibit clearly the occurrence of physical hardening through the different T_g measured during cooling and heating processes. Furthermore, the free volume estimated during heating is always bigger than the one during cooling, revealing the free volume fraction which is lost in the isothermal conditioning period of 10 minutes.
- Future research should be focused on the dependency of physical hardening on the PG grade of the binder, the possible interference of Sasobit with previous modifying agents and the occurrence of physical hardening in WMA mixtures.

2. Mineral Based Additives Effects on Binder Viscosity

The effect of a proprietary mineral additive on binder mixing temperatures and the duration for which the effect is realized in the binder was measured through evaluation of binder viscosity at a three prescribed shear rates (0.68, 2.04, and 6.80 /s) at mixing times of 1 and 6 hours. Temperature was also varied (150 °C, 115 °C, and 90 °C) to capture the temperature dependence on the rate of release of the water from the hydrated compound and its effects on reduction in binder viscosity. All tests were conducted using a PG 64-22 binder. Furthermore, anhydrous molecules of the mineral additives investigated were acquired to provide a control. The effect of the WAM additives on binder viscosity is shown in figure E1c-1.3 as a plot of the ratio of viscosity of additive to that of neat binder for a given shear rate.

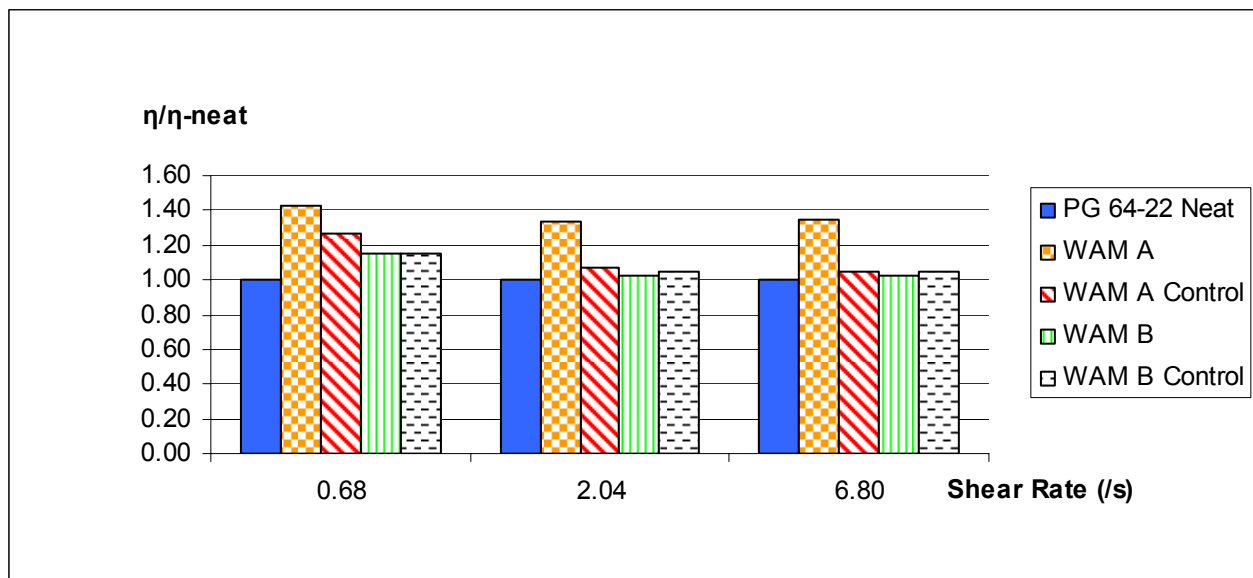


Figure E1c-1.3. Chart. Plot of viscosity ratio for 115 °C mixing temperature and 1 hour conditioning time.

For all shear rates, addition of the warm mix additive did not result in a reduction in viscosity. In fact, in most cases viscosity increased, possibly due to the effect of the mineral filler used as a delivery system for the hydrated compound. As expected, reduction in viscosity was also not realized after 6 hours of conditioning time. The main finding from this investigation is that other test methods for quantifying the effect of water based warm mix additives on mixing and compaction temperatures must be researched as part of this work plan. New potential methods are being developed in NCHRP 9-39; the applicability of these methods to water-based warm mix additives will be developed upon delivery of the final report, which is due June 30, 2008.

3. Mineral Based Additives – Effect on Binder Rutting Performance

The effect of mineral based warm mix additives on binder performance was evaluated through a frequency sweep (0.5-20 Hz) at testing temperatures of 40 °C, 52 °C, 64 °C, and 76 °C using 40 mm parallel plate geometry in the Dynamic Shear Rheometer. The frequency sweep was chosen as an evaluation tool for binder performance over the conventional rutting parameter of $G^*/\sin\delta$ because it allows for more comprehensive characterization of binder performance through development of master curves using time temperature superposition while still allowing for determination of the Superpave rutting parameter. An example of master curves generated using this testing procedure is provided in figure E1c-1.4.

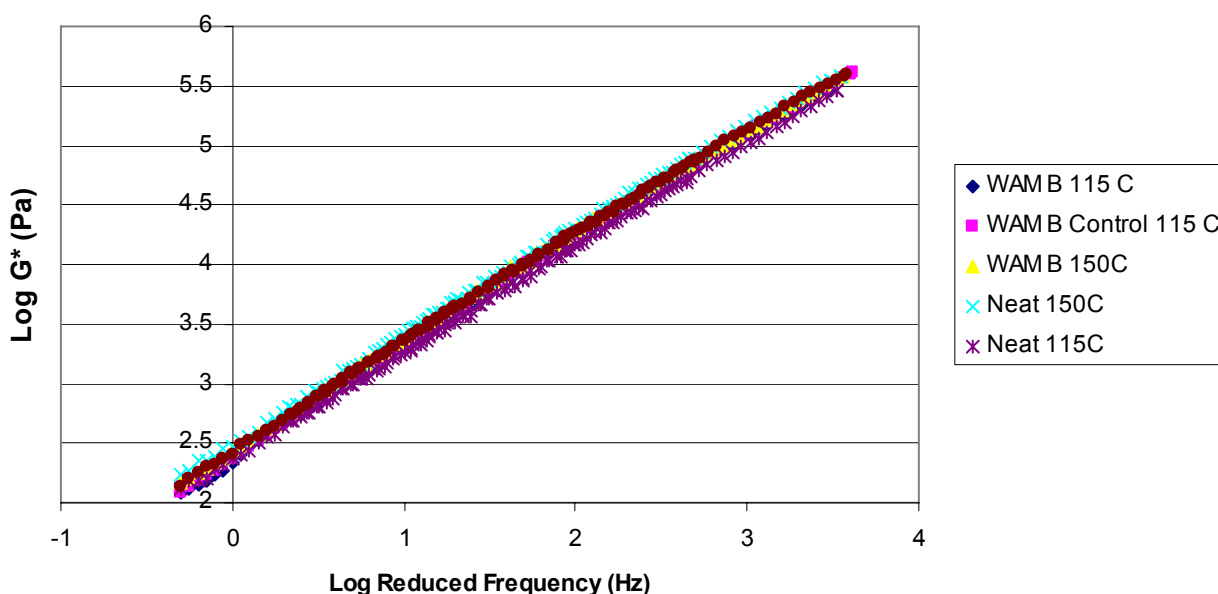


Figure E1c-1.4. Chart. Master curve comparison of neat binder and WAM B at 115 °C and 150 °C mixing temperatures.

Master curve data generated in figure E1c-1.4 shows that the warm mix additive has no significant effect on binder performance. The significant finding from this aspect of the research is the development of a test method that has the ability to characterize binder performance that

can be used to for both wax based and water based warm mix additives as the study moves forward.

Year 2 Work Plan

This work plan will focus on the following items:

1. Wrap up the evaluation of the warm mix additives effect on rheological properties of binders

- Viscosity (Brookfield RV): The reduction in viscosity due to the addition of warm mix additives must be further quantified over a wide range of additive concentration and binder temperatures. Year one work has indicated that reduction of binder may be binder specific. Specifically, the benefit of warm mix additives will not be realized in neat binders, which have inherently low viscosity. Furthermore, the time effect associated with creation and evaporation of the water vapor produced with the mineral additives must be understood.
- Thin Film Rheology Measurements Using the DSR: Effect of film thickness on warm mix behavior will be studied by running DSR measurements at gaps around 25 μm .
- Adhesion and Cohesion Testing (Tack Test developed by University of Wisconsin-Madison): Moisture damage has been identified as a critical distress found in warm mix pavements. TSR testing with the mineral based additives found a premature cohesive mixture failure possibly due to the emulsification of the asphalt in the foaming process. The effects of the release of water vapor over time on cohesion must be investigated further. The wax additive must also be evaluated to understand the contribution of the wax lattice structure to binder cohesion.
- Rutting ($G^*/\sin\delta$ and MSCR)
 - Superpave Rutting Parameter: $G^*/\sin\delta$ will be measured for all binders to evaluate the rutting resistance of warm mix and unmodified binders as defined by Superpave. The use of this parameter will provide a direct link to how warm mix additives affect rutting resistance in terms of a widely accepted specification.
 - Multiple Stress Creep and Recovery: A fundamental understanding of binder rutting will be obtained through evaluation of accumulated strain using the MSCR test. This will further quantify the any contribution to rutting resistance by the crystalline lattice associated with the wax additives or any increase in accumulated strain caused by the inability of the water vapor to completely evaporate from the asphalt binder.
- Fatigue (Monotonic Test): The monotonic test is performed in the DSR using the 8-mm geometry. The binder specimen is prepared the same as for traditional Superpave binder fatigue evaluation. Instead of oscillation, though, the specimen is subjected to a constant shear-rate (twist) loading until the maximum amount of stress is developed in the specimen. Parameters such as strain at maximum stress, yield energy, and the characteristic C(S) curve from viscoelastic continuum damage mechanics can be used to evaluate fatigue performance. Fatigue performance will be measured to identify any effects caused by the wax lattice structure or entrapped water from the mineral additives.

- Low Temperature Properties (BBR): What is the effect of the lattice structure from the wax or any entrapped water from the mineral additive on low temperature properties?
 - Single Edge Notched Beam Test (SENB): This test will provide useful information on the brittleness of the binders before and after warm mix additive addition.
 - Aging (RTFO and PAV): The reduction in short term aging due to lower mixing and compaction temperatures and its effect on the previously mentioned binder properties must be understood in order to predict mixture and field performance.
2. *Continue work on evaluation of the effects of warm mix additives on workability and stability of mixes*
- Compactive Effort: Mixes will be compacted at 600 kPa and 300 kPa. Previous research has found the SGC to be insensitive in terms of mix densification to temperature changes. Measurement of the forces related to compaction will bring resolution to this issue.
 - Temperature: Temperature will be varied to define mixture workability and stability as a function of temperature for the warm mix additives and unmodified mixtures. Variation of temperature will also identify the tender zone for warm mixes.
 - Aggregate Type: Different aggregate types have different properties in terms of aggregate shape and strength, necessitating the investigation on how these properties affect the performance of the warm mix additives. Granite, limestone, and gravel aggregate types will be used.
 - Gradation: Fine and Coarse or S-Shaped aggregate blends will be used.
 - Binder Grade: If viscosity testing reveals an effect on unmodified and modified binders, both neat and polymer modified binders will be evaluated to establish a relationship between binder viscosity and mixture compaction.
 - Asphalt Content: Investigate the effects of asphalt content. Literature review identified a need to investigate if the asphalt content for warm mixes should be defined through normal mix design procedures or volumetrics obtained from warm mix compaction.
 - Additive Type: Three types of warm mix additives will be used; a zeolite (Aspha-Min[®]), a wax (Sasobit[®]), and a non-zeolite water bearing additive (Evotherm[®]) in order to evaluate three different mechanisms. Possible other additives considered are Redi-set Warm Mix Additive by Azko Nobel and Waterless Warm Mix by Gerald Reinke.
 - Additive Concentration: Define high and low levels of warm mix additive concentration.
3. *Start work on mixture performance testing*
- Simple Performance Tests (E* and FN)
 - Dynamic Modulus (E*) and Flow Number tests will be used to characterize the stiffness and rutting resistance of mixtures using warm mix additives and to compare the results to conventional HMA mixes. Tests will be performed on short and long term aged mixtures.

4. *Begin field evaluation of current mix design and construction procedures*

- Dr. Robert Schmitt of UW-Platteville will perform research services in this area, including:
 - Coordinate with WisDOT and contractors to conduct field evaluation of warm mix construction projects in the State of Wisconsin.
 - Arrange traffic control as necessary with county highway departments.
 - Perform nuclear density testing.
 - Obtain loose mix samples and pavement cores for laboratory testing.
 - Perform pavement field distress surveys.

Figure E1c-1.5 depicts the research approach defined for this work element.

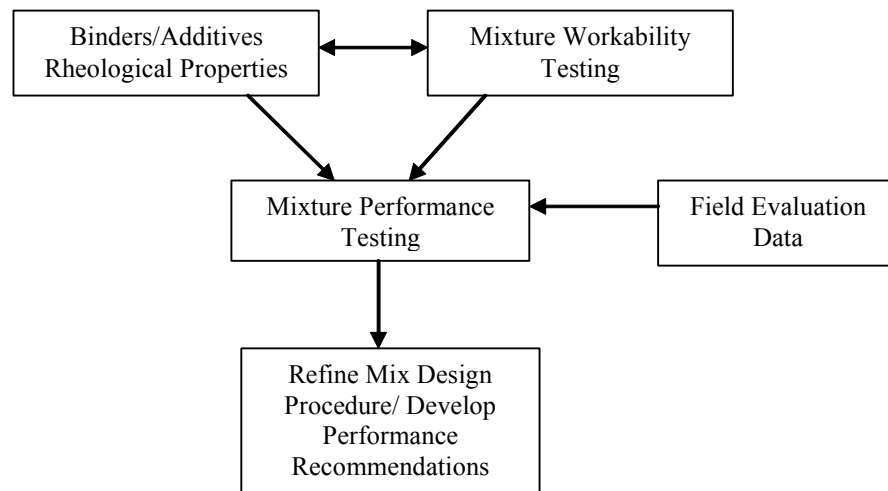


Figure E1c-1.5. Chart. Flow chart for research approach.

Year 2 Milestones

- Complete the evaluation of the effects of warm mix additives on rheological properties of asphalt binders
- Complete the effects of warm mix additives on mixture workability and stability
- Start conducting the proposed tests on asphaltic mix tests
- Start field evaluation and validation of laboratory test results

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Effects of Warm Mix additives on rheological properties	X	X			
ii. Effects of Warm Mix additives on mixture workability and stability	X	X			
iii. Mixture Performance Testing		X	X		
iv. Develop Revised Mix Design Procedures			X	X	X
v. Field Evaluation of Mix Design Procedures and Performance Recommendations			X	X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
i. Effects of Warm Mix additives on Rheological Properties	X			
ii. Effects of Warm Mix additives on Mixture Workability and Stability	X	X	X	X
iii. Mixture Performance Testing		X	X	X
iv. Develop Revised Mix Design Procedures	X	X	X	X
v. Field Evaluation of Mix Design Procedures and Performance Recommendations				

Budget

The estimated budget for this subtask is \$475,000 over the five years. The work will be conducted by the University of Wisconsin-Madison.

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Subtask E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications

Subtask Lead: Hussain Bahia and Peter Sebaaly

Introduction

Rising energy costs and increasing environmental awareness have led to an increased interest in the research and development of surface treatments and cold mix asphalt technologies. Cold asphalt applications and cold mixture technologies allow for coating of aggregates and subsequent compaction of the asphalt mixture at ambient temperatures. As a result, energy requirements and emissions are significantly reduced relative to conventional HMA mixtures (Jenkins et al. 2002). The economic and environmental implications of successful implementation of well-designed surface treatments and cold mixtures for flexible pavements have the potential to provide a sustainable alternative to current HMA practice. However, further research is needed to improve evaluation methods of emulsions and to develop a more rigorous mixture design procedure to ensure that performance of pavements is not significantly compromised at the expense of energy saving or environmental sensitivity.

Surface treatments are the prime candidates for pavement preservation activities. Within the last few years, focus on pavement preservation has increased significantly. The concept of preventive maintenance as a more cost effective alternative to corrective maintenance is widely accepted and practiced. Emulsions are the main component of pavement preservation strategies. However, the test methods used to characterize emulsions are some of the most empirical and the most outdated tests methods used in the asphalt industry in North America. While the hot binder application has seen significant change in sophistication of grading and testing, emulsion technology has lagged behind.

The use of Cold Asphalt Mix (CMA) is a viable option for pavement layer stabilization, particularly for cold in place recycling, and for surface layers under moderate traffic. Although this is widely recognized, a volumetric mixture design procedure consistent, or comparable, to the current HMA practices, such as Superpave specifications, is not yet available. Specifically, CMA design procedures should include guidance on mixing and compaction temperatures, quantify the rate of curing of the mixture, and evaluate test methods to assess the performance of

mixtures under traffic, including moisture susceptibility and aging effects. If cold mixes are expected to serve as surface layers, the mechanical properties of the mix and the performance required for different applications must be established.

In cold asphalt applications, the workability of the material is derived from reduction of viscosity in the asphalt binder through emulsification. The use of these mechanisms allows the coating of aggregates and compaction of the mix to occur at ambient temperatures. In the emulsification process an emulsifying agent is added to the asphalt resulting in the dispersion of asphalt cement in water (Asphalt Institute, 1989). In this mixture the water serves as the continuous phase with the asphalt suspended in discontinuous droplets throughout the medium. After a certain period of time the emulsion sets or “breaks” and cures, leaving behind an asphalt mixture. The curing time of an emulsion is based on the grade of emulsion used, the ambient conditions, and the physical and chemical characteristics of the surface the emulsion is applied to.

Development of a performance-based emulsion selection system and a mixture design process will improve use of emulsions in surface treatments and define potential uses for cold mixes. The development of these technologies will facilitate development of specifications and construction guidance to allow for widespread application of cold asphalt technologies.

Relationship to FHWA Focus Areas

This subtask is related to the following focus areas;

- Promotion of environmental stewardship.
- Development of the use of the gyratory plate as an improved measure of mix workability.
- Clear definition of mix design and construction procedures to provide a basis for modeling of energy savings associated with the use of cold mixes.
- Mixture performance testing to provide insight into the risk of compromising performance at the expense of energy savings.

Hypothesis

- Development of test methods and performance thresholds for emulsions, based on type of application, will provide a more consistent scientific tool for classification of emulsified asphalts. A system similar to the performance grading of conventional asphalts, which is climate, traffic, and application based, could significantly improve emulsion use and acceptance.
- An application-based CMA design procedure that considers handling and performance of mixes will allow a more predictable performance for mixtures used for partial depth recycling, full depth recycling, and surface paving applications. Design procedures should include consideration of curing time and allow for recommendations on the timing of opening constructed cold mixes to further construction activities and/or traffic.
- Mixture performance testing compatible with the requirements of the AASHTO MEPDG procedure will provide basis for considering CMAs as viable options for any pavement

layer. Further understanding of the mechanical properties of cold mixes will allow for better definition of limitations and opportunities for using these materials.

Objectives

The overall objective of this study is to develop a more scientific characterization system of emulsified asphalts, including the residual binder properties. Such system will lead to development of volumetric mixture design procedures and a mixture performance framework based on the application. The feasibility and practical application of the emulsion characterization, mix design procedures, and performance framework will be evaluated through field trials.

Experimental Design

The objectives of this subtask will be addressed by pursuing nine subjects:

- i. Review of National and International Standards for Emulsions, Aggregates, and Performance Evaluation of Cold Asphalt Applications. There are many standard test methods and local specifications that are used all over the world. It is important to collect these standards and analyze similarities and differences in these standards, as a starting point to develop rational methods and standards. Because cold asphalt applications vary in components and intended purpose, the review in this subtask will address three areas:
 - a. Review testing methods, standards, and specifications related to asphalt emulsions.
 - b. Review testing methods, standards, and specifications related to aggregates used in cold asphalt applications such as surface treatments and CMA.
 - c. Review testing methods, standards, and specifications related to performance evaluation of cold mix applications including surface treatments and CMA.
- ii. Create an International Advisory Group for the Project. A significant part of emulsion testing and applications is based on experience of various individuals, contractors, and suppliers. Very little is documented in publications. It is thus necessary to create an advisory group to identify the critical gaps in the knowledge and guide the research to change some of the tests that are specified today but have no real relationship to performance. The advisory group could help simplify testing and focus specifications on important and relevant properties. The advisory group will meet twice a year at convenient location and in coordination with annual conferences to review progress and provide feedback. The group will also serve as the link to AEMA, ISSA, and other organizations that have a stake in this field.
- iii. Identify Potential Performance Related Tests. Based on results of subjects i and ii, a list of tests that show high potential for measuring properties of emulsions, aggregates, and other additives that are related to performance of surface treatments and cold mixtures will be identified. The details of each test including engineering basis, cost, practicality, repeatability, and relevance will be defined. The tests will be ranked and an experimental

plan for evaluating the tests and validating their attributes will be developed. The tests will be divided into three types:

- a. Emulsion tests
 - b. Aggregate and surface condition tests
 - c. Performance test of complete mixture or application
- iv. Establish a Materials Reference Library for Cold Asphalt Applications. To validate tests methods and to derive criteria limits, it is necessary to have reference materials that are used in the field and materials that have gone through rigorous testing in the lab. Samples of emulsions, aggregates, additives and mixtures used in various projects will be collected and stored to validate tests and to establish limits for acceptance. It is recognized that lab-prepared materials could be very different from field-prepared materials. Therefore an attempt will be made to store both finished products as well as components used in production. The following list presents the materials to be sampled in this subtask:
- a. Base asphalts used in emulsion production
 - b. Emulsifiers
 - c. Additives
 - d. Aggregates and fillers
 - e. Polymers
 - f. Field-produced samples for emulsions or mixtures

The properties of the sampled materials will be stored in the ARC Materials Reference Library following the ARC's established procedure for sample tracking and data storage.

- v. Conduct Laboratory Evaluation Plan Developed in subject iii. The plan for evaluating "promising" testing methods developed in subject iii will be conducted in this subtask. The plan will include materials that are representatives of the range in formulations used in practice today and will cover applications that are widely used. The results collected will be analyzed using statistical methods to relate response measured on emulsions and aggregates with performance of mixtures or surface treatments. The relationship derived will be used to propose limits to be used for quality control.
- vi. Develop Performance Guidelines for Emulsion and Aggregates that are Application Specific. Based on the results of subject v, guidelines for material selection and mixture design will be developed. These guidelines will build on the current manuals and design recommendations published by AEMA, Asphalt Institute, ISSA, and other international organizations. The attempt will be to revise and modify existing manuals and guidelines to include new or improved tests and design procedures.
- vii. Field Validation of Guidelines and Criteria Limits. Field validation will start in Year 3 of this project. It will include implementation, on an experimental basis, of the test methods and design procedures that are developed in subjects v and vi.
- viii. Cold Mix Asphalt Design. The many uses of cold mix technologies necessitate development of mix design procedures based on application and location within the

pavement structure. Specifically volumetric mix design procedures will be developed for partial depth recycling, full depth recycling, and cold mix paving applications.

Information gathered in parts i and ii of the study regarding the constructability and in-service performance properties of different emulsions and residual asphalts will be used as a baseline for developing mix design procedures. It is understood that the aggregate properties and how they affect the mixture-emulsion interaction play a significant role in the workability, and performance of the mix and must be considered.

Mix design procedures will be evaluated and refined through practical experience and volumetric mixture analysis. As stated previously, different mixture design procedures could be necessary for full depth recycling, partial depth recycling, and paving applications.

The performance of cold mixes for the previously specified applications will be evaluated in terms of rutting, fatigue, and low temperature cracking using existing test methods or those developed through the other work elements in the ARC. The research team will work closely with the other ARC partners to ensure the state of the art testing procedures will be used. The aim of this project is not to directly compare the performance of cold mixes to conventional HMA. Instead the focus will be on quantifying the functional or structural performance of cold mixtures and suggestion of practical applications based on this performance. A summary of the properties and parameters that could be considered in this subtask is shown in table E1c-2.1. It is recognized that the relevance of these properties and their importance could vary by mixture type and application intended.

- ix. Develop Cold Mix Asphalt (CMA) Guidelines. In this part of the subtask a mixture design manual will be developed. The manual will include different types of mixtures as follows (n.b., this list is from one of the reviewers of the original work plan):
 - a. Micro-surfacing (a mix design method is already being worked on by Caltrans)
 - b. CIR
 - c. FDR
 - d. Stockpile mixes (made with RAP or virgin aggregate)
 - e. Central plant CMA
 - f. Paver-produced CMA

The manual will include information for proportioning, testing of components and completed products, and construction guidelines.

Table E1c-2.1. Mix design evaluation parameters to be considered.

Engineering Property	Parameter(s) Measured	Comments
Emulsion Selection	Breaking Rate as measured by the change in tensile strength over time.	Results of Task 2 and consideration of the aggregate components in the mix and how the mix will be applied (base vs. surface course) will be used to define emulsion selection criteria.
Optimum Emulsified Asphalt Content	Aggregate Coating Workability Air Voids	Optimum emulsified asphalt content will be estimated based on aggregate gradation, absorption, and RAP content in the blend. Estimates will be verified through analysis of air voids and compactive effort as measured by the PDA.
Mixing and Compaction Conditions	Change in mixture workability/compaction over time and how it is effected by conditions.	Appropriate mixing chambers and evaluation parameters must be developed in order to understand the effects of temperature and humidity on mixture curing and how this can be accounted for in the field.
Establishment of Gradation Thresholds	Air Voids	Typical Superpave gradations may not apply to cold mixes due to the increased amount of space required to accommodate the emulsion. Gradation limits will be set through evaluation of mixing and compaction performance.
Definition of Gyration Levels and Density Thresholds	Air Voids	Discussion with industry indicated the Superpave gyration levels are too high for cold mixes. Application based gyration and density levels need to be developed and defined.
Resistance to Raveling	Raveling Test according to ASTM D7196	Proposed test will provide insight to rate of curing of the mix.
Moisture Damage	TSR as specified by ASTM D4867	TSR testing will be conducted on mixtures and compared to moisture damage results of binder and mastics collected in Task 2.
Aging	Laboratory for aging after specimen is cured	A mixture aging protocol must be established to simulate aging in the field after the CMA has cured. This will be used to evaluate inservice mix performance.

Major Findings from Year 1

During year one, the focus was put on collecting information on emulsions, surface treatments and cold mixtures. The process for information gathering involved a comprehensive literature search and review, visits and interview of experts in the United States and abroad, and attending various workshops or meeting related to the subject. These efforts have resulted in a concept paper in which a system of performance grading of emulsions is proposed. Also, a tentative list for performance measures has been established.

Two applications of cold asphalt technologies have been identified: Spray and mixing. Based on this concept two types of emulsion grades can be introduced as shown in table E1c-2.2. The types of application in which each of these two emulsion grades are used are listed as well.

Table E1c-2.2: Grades and applications of emulsified asphalts.

Grade	Application
Spray	Chip Seals
	Microsurfacing
	Crack Sealing
Mixing	Full Depth Recycling
	Partial Depth Recycling
	Asphalt Stabilized Base Course
	Paving Applications as a Binder or Surface Course

Based on the activities of subject i, the definition of physical properties of emulsions that are important to the design and construction of the various applications were developed and a tentative list is shown in table E1c-2.3. The definition of the parameter to be used and the proposed test methods to measure these properties are also summarized. The properties are divided into two categories: (1) construction properties, which cover emulsion characteristics related to the construction process, and (2) in-service properties, which are related to performance during traffic.

Table E1c-2.3: Summary of pertinent construction and in-service properties for surface treatments.

Engineering Property	Parameter(s) Measured	Comments
Construction Properties		
Storage Stability (ASTM D6930)	%Stability defined as the difference in residue at the top and bottom of the storage vessel after 24 hours.	Emulsions must remain homegenous and fluid during the transport and construction. Unstable emulsions will result in difficulties spraying, breaking, and wetting of aggregates.
Breaking Rate	Change in binder stiffness (G^*) at a given temperature and curing time.	Inert, basic (limestone), and acidic (granite) fillers will be used to evaluate the effects of aggregate mineralogy on breaking rate. Temperature sensitivity will also be investigated.
Spray-ability and Drain Out	Viscosity	Binder must have an optimum range of viscosity which is low enough to allow for application and high enough to prevent drain out off the road.
Wetting of Aggregates	Adhesion	PATTI test will be used to evaluate the adhesion of different emulsion/aggregate combinations.
In-Service Properties		
Resistance to Bleeding	Creep Stiffness Early Adhesion	Binder stiffness and adhesion characteristics during emulsion curing may identify potential bleeding problems.
Restistance to Raveling	Residual Binder Cohesion Wet Adhesion of Residual asphalt to aggregate	Raveling is either caused by binder softness (lack of cohesion) or lack of adhesion. Proposed testing addresses both causes.
Fatigue Cracking	Creep Stiffness Estimated Rate of Creep Stiffness Elongation at Break	Excessive cracking will greatly increase the permeability of the surface treatment leading to premature failures.
Aging	Change in rheological properties due to short and long term aging.	The effects of aging on the performance of the residual binder must be understood and applied to design of surface treatments.

Year 2 Work Plan

During Year 2, subjects i, ii, and iii will be completed. The team will continue the literature review and will focus on collecting information on specifications and design practices from various countries for spray seals for cold mixtures. In addition, the international advisory group will be formed in coordination with AEMA. The evaluation of potential performance related tests for emulsions will also start and is expected to result in a short list of tests to be evaluated. Figure E1c-1.1 depicts the research approach defined for this work element.

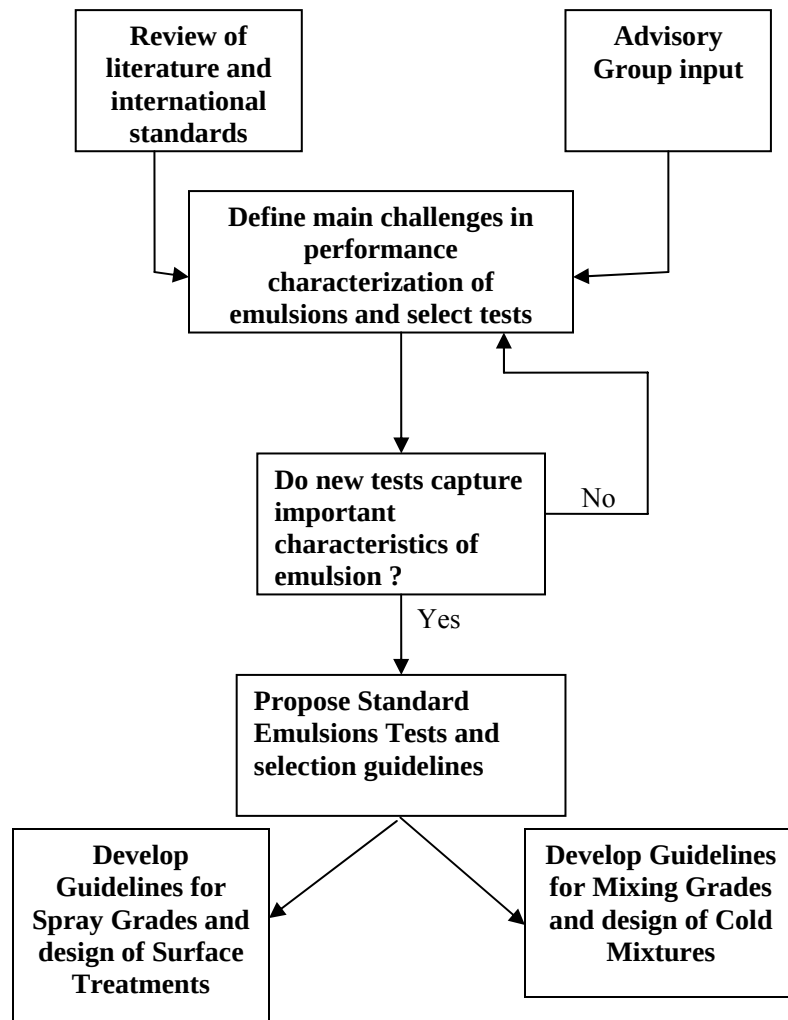


Figure E1c-2.1. Chart. Flow chart for research approach.

The tentative list of variables to be considered for testing of emulsions during year 2 are shown in table E1c-2.4. This list is based on significant discussions with experts in the field and review of many manuals and papers on the subject of emulsions. Initial contacts to secure samples of emulsions already used in the market has already started.

Table E1c-2.4. Variables to be considered in the testing of emulsions for this work plan.

Variables	Ranges
Emulsion - Rate of Setting	Slow
	Medium
	High
Emulsion - Viscosity	High
	Low
Emulsion - Charge	Cationic
	Anionic
	Inert
Asphalt Modification	SBS
	SBR
	Elvaloy
Base Asphalt	Source 1
	Source 2

Year 2 Milestones

- Complete report on review of literature and international practice for cold asphalt applications
- Identify advisory group members and hold the first two meetings
- Develop the short list of best tests for emulsions and generate typical data to evaluate feasibility and practicality of tests
- Develop a framework for emulsion selection and design of surface treatments

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Review of Literature and Standards	X	X			
ii. Creation of Advisory Group	X	X			
iii. Identify Tests and Develop Experimental Plan		X	X	X	
iv. Develop Material Library and Collect Materials		X	X		
v. Conduct Testing Plan		X	X	X	
vi. Develop Performance Selection Guidelines			X	X	
vii. Validate Guidelines			X	X	X
viii. Develop CMA Design Procedure			X	X	
ix. Develop CMA Performance Guidelines			X	X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
i. Review of Literature and Standards	X	X		
ii. Creation of Advisory Group	X	X	X	X
iii. Identify Tests and Develop Experimental Plan		X	X	
iv. Develop Material Library and Collect Materials			X	X
v. Conduct Testing Plan			X	X

Budget

The estimated budget for this subtask is \$350,000 (for UWM) and \$ 255,000 (for UNR) over the five years. The work will be conducted by the University of Wisconsin-Madison and the University of Nevada-Reno.

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Category E2: Design Guidance

Work Element E2a: Comparison of Modification Techniques

Subtask Lead: Codrin Daranga

Introduction

A successful modification of an asphalt binder with a polymer is intended to improve one or more of the basic asphalt properties, such as rigidity, elasticity, brittleness, durability, adhesion, and compatibility. Modification can be classified into three types: (1) chemical modification,

such as oxidation and acid reaction; (2) additive modification, such as with polymers, crumb rubber, or other materials; and (3) a combination of chemical and additive modification. In all modification techniques, compatibility of additives and base asphalt is very important. An asphalt-polymer blend is considered compatible if the polymer is soluble in the asphalt cement or if it can be swollen by the asphalt oils without causing flocculation of the asphaltenes. Most polymer modifiers are used to enhance the rutting resistance of asphalt binders. When it comes to the influence of modifiers on fatigue resistance and Low Temperature Cracking (LTC) resistance, some have a positive influence, while others can have a negative influence. It is to be expected that by adding more flexibility (increase in toughness) to the binder, fatigue and LTC resistance will increase. If, on the other hand, the modifiers will stiffen the material at medium and low temperatures, then a decrease in fatigue and LTC resistance is expected. The morphology of the polymers used as modifiers, as well as their chemical structure and affinities, play an important role on how the binder will perform in field applications. The flexibility of rubbers will bring toughness to the asphalt binder, possibly increasing its fatigue resistance. The hardness of waxes will improve rutting resistance properties. On the other hand, crystallinity promoted by rigid wax chains can diminish the fatigue life of asphalt binders and decrease their low temperature cracking resistance. Therefore a fine balance needs to be maintained between flexibility and stiffness, between elastic and plastic domains within the asphalt binder, between the affinity towards polar compounds (e.g., mineral aggregate) and moisture damage resistance, etc. In addition to initial properties, aging can have a significant impact on properties of binders. It is, however, not clear if aging has a negative effect on fatigue and LTC under all conditions of loading. For example, aging is expected to increase stiffness and strength but decrease ductility (flexibility).

In the current market, there is significant (30-100 percent) increase in cost of binders when they are modified. There are also significant implications in terms of handling and storage of modified binders. There are many concerns regarding the quality control methods, the level of improvements achieved and the alternatives available to meet the required performance. These concerns have intensified recently as acid modification is being used by many suppliers as a cost effective and extremely practical approach to meet some of the grades. There are also many suppliers that are using combined modification with polymers and acid and there are many claims regarding the benefits of such modifications. It is therefore necessary to provide realistic picture of what can be expected from modification in terms of better performance, the risks associated with some modifiers, the cost implications, and the necessary handling precautions, if any, that need to be considered.

Every modification technique and every modifier has its own set of advantages and disadvantages. Acid and air-blowing modification is cheap and requires very little or no modification to the crude refining installation that provides the binder. Polymer modification can be more expensive, but the higher modification cost is usually balanced by better performance and longer service life. Non-reactive modifiers tend to be easier to incorporate, while reactive modifiers, especially reactive polymer modifiers, can add a reaction time needed to achieve its full potential. Acids, on the other hand, can act either as stand-alone modifiers or in conjunction with other modifiers. In short, the modification of asphalt binders can be as simple and inexpensive as air-blowing or as complicated as highly engineered reactive polymer

modification in the presence of acids that can act as catalysts and/or take active part and change/influence the overall modification process.

This work element will focus on developing guidelines for best practice of selecting and handling modified asphalts. The selection criteria will include models to consider cost of modification, risks of handling problems, and performance improvements. The handling criteria will be based on short and long term stability of modified asphalts and their effect on the overall construction process.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Optimum Pavement Performance: Introducing methods for better characterization of modified asphalts.
- Advanced Quality Systems: Further development of test methods that are more related to actual pavement performance.

Hypothesis

The hypothesis is that binder modification has a great impact on damage resistance properties of pavements. They also have significant cost and handling consequences when used. A fundamental understanding of how polymers interact with asphalt, and how aging and chemical modifiers control binder properties, can result in development of models and guidelines to improve modifier selection process and to reduce risk of negatively impacting construction and performance of asphalt pavements.

Objectives

The four-year study will focus on the following objectives:

- Identify the possible binder modification targets and the additives and processes that can be used to achieve each of the targets.
- Develop a new system for classification of modifiers that is based on end results rather than generic material type.
- Develop models that allow estimation of level of modification and a costing index.
- Write an asphalt modification manual that lists the possible modifiers, best methods to blend them with asphalts, handling techniques, construction and performance risks.
- Create a model for a performance database that allows continues recording of modified asphalt usage, cost, technical publications, and performance of field pavements where modified asphalts are used.

Experimental Design

The objectives of this work element will be addressed as follows:

- i. Literature Review Report: A detailed search of types of additives used for modification and what properties are improved by them.
- ii. Develop a new system for classification of additives and a costing index.
- iii. Conduct testing and propose models for estimating level of modification based on modifiers, base asphalt, and concentration of modifier.
- iv. Write an asphalt modification manual.
- v. Develop a structure for database on effect of asphalt modification on performance.

Major Findings from Year 1

No work has been performed during Year 1. This work-plan starts during Year 2.

Year 2 Work Plan

In order to obtain a better understanding of the influence different modifiers have on binder properties, a comprehensive list of binders and modifiers has been compiled. This list contains a nonreactive polymer (SBS) in two different steric forms (linear and radial), a reactive polymer (Elvaloy) in two different co-monomer ratios, a pair of plastomeric polymers (EVA and PE), a crosslinked elastomer (Crumb Rubber) in two particle sizes (200 Mesh and 30 Mesh), and an acid modifier (PPA) in two commercially available forms (different concentrations). The selected neat binders will be modified with all the above mentioned additives, according to the detailed work-plan provided below. After modification, the resulting material's high temperature, low temperature, and intermediate temperature properties will be investigated. This will allow for classification and comparison of the different binder modifiers, the goal being to map the effect of modification on binders.

The base polymers will be altered using a wide selection of modifiers depicted in table E2a.1. Variations on time, temperature, and rate of blending will be used to characterize the storage stability of the resulting materials. The modified binders will be subjected to storage stability test like the Cigar Tube Test and the Laboratory Asphalt Stability Test (LAST) in order to evaluate their homogeneity and storage capability.

The data analysis on this project will be focused on two main areas: rheological properties and damage resistance characterization.

The rheological properties investigation serves as a tool to classify and rank starting materials, as well as a monitoring tool during the modification and conditioning process. This is accomplished by measuring parameters like $G^*/\sin\delta$, an indication of the rutting resistance of binders, as well as performing Multiple Stress Creep Recovery tests on the binders. Time sweep tests at different frequencies will provide the necessary information to build Master Curves, highlighting the impact of modification over a broader range of properties. Bending Beam

Rheometer testing will shed light on the effect of modification on behavior in low temperature conditions. Important information will be provided this way on how the modification of binders affects their properties.

The damage resistance characterization part of the investigation will focus on classifying and ranking different modifiers and/or modification techniques based on their impact over the binder's ability to resist damage. This is focused on fatigue damage (Monotonic Test), rutting damage (MSCR Test), and low temperature (Single Edge Notched Beam Test) damage control tests to maintain perspective on monitoring the overall binder properties.

The experimental test matrix is shown in table E2a.1.

Table E2a.1. Proposed experimental matrix.

Modifiers	D1101 Kraton SBS			Binders	Flint Hills PG 58-28
	D1184 Kraton SBS				Flint Hills PG 64-22
	Elvaloy AM				Marathon PG 58-28
	Elvaloy 4170				Marathon PG 64-22
	PPA 115			Testing Temperatures	70 °C
	PPA105				58 °C
	Crumb Rubber 30 Mesh				25 °C
	Crumb Rubber 200 Mesh				19 °C
	EVA Polymer				-12 °C
	Polyethylene				-24 °C
Storage Time	0 hour	24 hours	72 hours	Storage Temperature	135 °C

Year 2 Milestones

- Complete the list of possible binder modification targets and the additives and processes that can be used to achieve each of the targets based on existing literature and interviews with experts in industry and in the user community.
- Develop a Consortium for research and education on modified asphalts and invite suppliers to contribute to a center at the University of Wisconsin-Madison. This will be at no cost to the project and will be presented as a cost-share activity.
- As part of the center develop a user friendly database model for publications and ongoing research on modified asphalts.
- Develop a materials library for modifiers and invite suppliers of additive to add to share materials intended for this market.
- Start the testing of modified asphalts to mimic the most widely used additives and practices.

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Literature Review Report		X	X		
ii. Develop a New System for Classification of Additives		X	X		
iii. Conduct Testing and Propose Models		X	X	X	
iv. Write an Asphalt Modification Manual			X	X	X
v. Develop Database for Effect of Additives			X	X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
i. Literature Review Report	X	X	X	X
ii. Develop a New System for Classification of Additives	X	X	X	X
iii. Conduct Testing and Propose Models	X	X	X	X

Budget

The estimated budget for this subtask is \$450,000 over the four years. The work will be conducted by the University of Wisconsin-Madison.

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Work element E2b: Design System for HMA Containing a High Percentage of RAP Material

Work Element Lead: Peter Sebaaly (UNR), Scot Schwandt (UW-M)

Introduction

Reclaimed asphalt pavement (RAP) is produced either by cold planning (CP) or by heating/softening and removal of the existing aged asphalt pavement. Recycling of the aged pavement has become more popular since the late 1970's although it had been practiced as early as 1915. The escalation of crude oil prices as well as cost of energy in general are expected to result in increased prices of asphalts which in turn raises the interest in the use of RAP in pavements. Furthermore, several studies showed that asphalt mixtures containing RAP can have equivalent performance to virgin mixtures. Hence, many agencies and contractors have made extensive use of RAP in constructing highway.

The overall goal of the mix design process of hot mixed asphalt (HMA) is to recommend a mix that can withstand the combined actions of traffic and environment. Therefore, it is critical to assess the impact of the various mix components on the performance of the constructed pavement (i.e. resistance to rutting, fatigue, and thermal cracking). The existence of RAP in the mix presents a challenge to the design engineer due to the complex interaction among the new and recycled components of the mix. The inclusion of RAP materials in the HMA mix can improve its resistance to rutting while it may greatly jeopardize its resistance to fatigue and thermal cracking. The key to successfully include RAP in the HMA mix is to be able to assess its impact on pavement's performance while recognizing the uniqueness of each project with respect to both materials and loading conditions.

One of the main concerns in RAP HMA mixtures is the effect of the RAP material on the mixture durability. Moisture susceptibility is regarded as the main cause of poor mixture durability. Moisture susceptibility can be evaluated by performing laboratory tests on unconditioned and moisture conditioned specimens. However, two recent research studies did not support the concerns over the durability of RAP containing HMA mixtures. Stroup-Gardner and Wagner (1999) showed that the inclusion of coarse RAP decreased the moisture susceptibility of HMA mixtures. In 2000, Sondag used the tensile strength ratio to evaluate the moisture sensitivity of 18 different mix designs incorporating three different asphalt binders, two sources of RAP and varying amounts of RAP. Sondag concluded that the addition of RAP to a mixture had no positive or negative influence on the mixture moisture susceptibility. In 2007, Hajj et al. concluded that if the appropriate virgin binder grade and anti-strip additive are used, the moisture sensitivity of the RAP containing HMA mixtures can be greatly reduced.

The properties of RAP are largely dependent on the properties of the constituent materials (i.e. aggregate type, quality and size, extracted binder grade, etc.). The RAP composition is also affected by the previous maintenance and preservation activities that were applied to the existing

pavement. Additionally, sometimes RAPs from several projects are mixed in a single stockpile where deleterious materials or lower quality materials are also present. Consequently, a high variability is introduced in the RAP materials affecting the RAP properties and most likely resulting in a variable HMA mixture. Using low quality and/or highly variable RAP materials will definitely lead to premature failure of the HMA pavement.

The RAP percentage in the mixture significantly affects the properties of the HMA mixture. Several highway agencies have their own specifications on RAP usage in HMA mixtures. Currently, a total of 35 highway agencies allow the use of RAP with the majority allowing in excess of 30 percent RAP in HMA mixes (Sebaaly & Shrestha 2004). Some highway agencies do not specify a maximum limit on the percentage of RAP but leave it up to the mix design process to identify the maximum allowable percentage of RAP. Several highway agencies restrict the use of RAP to the layer underneath the wearing course.

Relationship to FHWA Focus Areas

This research effort fits under the FHWA Focus Areas of Optimize Pavement Performance and Environmental Stewardship.

Hypothesis

The use of RAP materials in HMA can be highly beneficial from both the economical and long-term performance aspects if the appropriate testing and analysis procedures are used to design the final mixtures.

Objectives

The overall objective of this research effort is to develop testing and analysis procedures that can be effectively used to evaluate RAP materials and optimize the performance of HMA mixtures containing RAP materials. The research effort will cover the various aspects of the design process starting with the evaluation of the RAP materials (binders and aggregates) through the mix design process and the performance evaluation of the final HMA mixture containing RAP materials.

Experimental Design

The following subtasks will be completed in order to achieve the objectives of this research effort.

Subtask E2b-1: Develop a System to Evaluate the Properties of RAP Materials

Evaluating the RAP materials consists of measuring the properties of the binder and aggregates of the reclaimed mix. Several research studies have been conducted to identify the best methods for separating and testing the binder and aggregates of the RAP materials but there have not been any standard procedures that agencies can use on a routine basis.

In the case of the binder in the RAP, the two critical properties are: binder content and binder properties. The binder content of the RAP can be easily identified through the extraction process. However, measuring the properties of the binder is still a complex process. Extracting and recovering the asphalt binder from the RAP materials faces the fundamental issues of the impact of the extraction/recovery process on the properties of the recovered binder and the health/environmental impact of the chemicals used in the process. These issues become very difficult to resolve when polymer-modified or crumb rubber modified binders are present in the RAP materials.

This subtask will review the previous research work on the development of an effective system to test the properties of asphalt binders from RAP materials. The review will focus on considering one or more of the following alternatives:

1. If a binder extraction/recovery system that is feasible, environmentally safe, and practical exists, or could be developed, it will be developed and standardized.
2. If such a system does not exist and the potential of developing it is not likely, a separation technique of the mortar from the RAP, without using solvents, will be pursued. A method for estimating RAP binder properties from the mortar deploying the technology currently used in binder testing will be developed.
3. If mortar separation and testing is too complex and not likely to be successful, a RAP mixture testing system will be developed instead.

In the case of the aggregates in the RAP, the two critical properties are: gradation and specific gravity. The gradation of the aggregates in the RAP materials can be easily evaluated through the extraction process. Determining the specific gravity of the RAP aggregates represents a challenge. Several techniques have been used in the past but there is not an accepted standard procedure. This subtask will identify a standard method for measuring the specific gravity of RAP aggregate and develop a standard procedure.

An experimental plan was developed to cover the activities to be conducted under Subtask E2b-1. The objective of this subtask is to develop systems to evaluate the properties of the aggregates and binders in the RAP materials. Two experiments will be conducted: one experiment to recommend a system to evaluate the properties of the RAP aggregates and one experiment to recommend a system to evaluate the properties of the RAP binder.

E2b-1.a: Develop a System to Evaluate the Properties of RAP Aggregates: The objective of this experiment is to recommend a system to evaluate the properties of the RAP aggregates. In order to recommend the most effective system, it is critical to evaluate the impact of the current extraction techniques on the properties of the extracted RAP aggregates. This objective will be achieved by producing RAP mixtures in the laboratory and extracting the aggregates using different extraction techniques. The physical properties of the aggregates before mixing with the asphalt binder and after the extraction process will be evaluated and compared.

Three existing extraction methods will be evaluated under this experiment: centrifuge, reflux, and ignition oven. It is believed that the reflux method had the least impact on the properties of

the aggregates after extraction however this was never verified. The proposed experimental plan consists of the following:

- Identify four aggregate sources with different mineralogy (i.e., soft limestone, hard limestone, granite, andesite). Select two sources from the east and two sources from the west of the U.S.
- UNR will identify and evaluate the aggregate sources from the west and NCAT will identify and evaluate the aggregate sources from the east.
- UNR will identify one binder to be used with the two aggregate sources from the west and NCAT will identify one binder to be used with the two aggregate sources from the east. Both binders will be graded following the PG system.
- For each combination of aggregate source and binder, conduct the experiment listed below. UNR will evaluate the two west sources and NCAT will evaluate the two east sources.
 - Develop an intermediate Superpave gradation for each of the aggregate sources.
 - Measure the physical properties of the blend aggregates: gradation, LA abrasion, soundness, absorption, specific gravity, fine aggregate angularity (FAA), coarse aggregate angularity (CAA), fractured faces, sand equivalent, and durability index.
 - Conduct a Superpave mix design for each combination of aggregate source and binder based on 6 millions ESALs for a top lift.
 - For each mixture, subject loose samples to the short-term aging as recommended by Superpave followed by long-term aging as recommended by the Superpave for compacted samples with the exception that the loose samples should be stirred once a day.
 - Extract the aggregates from the aged loose specimens using the centrifuge, reflux, and ignition oven following the most current standard procedures. Use an 85 percent TCE+15 percent Ethanol solution for the reflux and centrifuge methods.
 - Measure the same physical properties of the extracted aggregates that were measured on the virgin aggregates.
 - Evaluate the impact of the extraction method on the physical properties of the aggregates by comparing the measured properties of the aggregates before and after extraction.
 - Conduct the following experiment to evaluate the impact of reflux and centrifuge on the properties of the recovered binder.
 - Prepare two replicate samples from each mix without any aging.
 - Recover the asphalt binder from the centrifuge and the reflux methods using the Rotovap method.

- Grade the recovered asphalt binders according to the Superpave grading system and the guidelines provided by the NCHRP Research Results Digest No. 253.
- Compare the properties of the recovered binders from the two extraction methods to their original properties.

E2b-1.b: Develop a System to Evaluate the Properties of the RAP Binder: The amount and properties of the aged binder in the RAP material determines the amount and grade of the virgin asphalt that needs to be added to the new mixture containing the RAP. The researchers strongly believe that the process of extracting and recovering the RAP binder followed by determining its PG grade and using it in the blending chart to identify the required grade of the virgin binder is not a very reliable/practical method for the design of HMA mixtures containing RAP materials.

The objective of this subtask is to identify an innovative system that can evaluate the impact of the RAP binder on the required properties of the virgin binder without resorting to the extraction-recovery process. The proposed research approach is based on the assumption that evaluating the mortar portion of the RAP material can lead to valuable information on the properties of the RAP binder and on the interaction between the RAP binder and the virgin binder in the final blended mix. Fractionating the RAP material at the #8 sieve and using the passing #8 fraction (i.e. mortar) to evaluate the properties of the RAP binder provides an accurate asphalt blending analysis. It also allows a more accurate representation of the blending that occurs between aged and virgin binders. The amount of virgin asphalt that needs to be added to RAP containing mixes without affecting grade requirements could also be estimated.

The properties of the RAP binder can be evaluated at high and low temperatures using voidless asphalt mortar samples that includes passing #8 RAP and virgin binders. The objective is to develop a testing protocol that evaluates the high and low temperature properties of the RAP mortar by using a modified Bending Beam Rheometer (BBR) test method and/or Dynamic Shear Rheometer (DSR). This testing protocol will be used to determine the affect that the RAP aggregate has on the RAP mortar properties, and will also determine the linear relationship between virgin binder grade and measured property compared to various RAP mortar mixtures and their measured property.

The following experimental plan will be followed:

Materials

- Identify four different RAP sources:
 - Modified-Stiff: AAT from the DC area
 - Modified-Very Stiff: UNR from Nevada
 - Unmodified-Stiff: NCAT from the Southeast
 - Unmodified-Very Stiff: UNR from Palm Springs California
- Extract and recover the binders from the RAP mixtures (UNR).
- Grade the recovered RAP binders according to the Superpave grading system and the guidelines provided by the NCHRP Research Results Digest No. 253 (UNR).

- Select three virgin binders grades:
PG64-22: UNR from Paramount
PG64-28: NCAT unmodified from CITGO
PG58-34: UWM from Wisconsin
- Verify the grade of all three selected binders.
- Sieve the RAP mixtures on the #8 sieve. The material passing #8 sieve will be referred to as RAP(-#8) or mortar and will be used for further testing.

Evaluation 1: Evaluate the Mortar with 100 percent Virgin Binders

- For each source, extract the RAP aggregates from the RAP(-#8) mortar according to the procedure identified in E2b-1.a with the least impact on the aggregate properties.
- Determine the RAP(-#8) mortar binder content for each RAP source material.
- Mix the extracted RAP aggregates with each of the three selected virgin binders to produce a virgin mortar material at a 10 percent twm binder content.
- Measure the high temperature and low temperature properties of the virgin mortar mixtures in the BBR and/or DSR (actual tests to be recommended by UNR and UWM).

Evaluation 2: Evaluate the Mortar with Blended Binders

- Mix the RAP(-#8) mortar with each of the three selected virgin binders at a 10 percent twm binder content.
- Measure the high temperature and low temperature properties of the virgin mortar mixtures in the BBR and/or DSR (actual tests to be recommended by UNR and UWM).
- Extract and recover the RAP+virgin binders from the mortar materials.
- Grade the recovered asphalt binder according to the Superpave grading system.

Evaluation 3: Evaluate the Binder Grade of the RAP Mixtures

- Compact replicate samples from each of the four RAP sources in the Superpave Gyratory Compactor (SGC) to 4 percent air-voids.
- Measure the volumetric properties of the samples compacted in the SGC.
- Measure the E* Master curves for all mixtures and use the Hirsch model to estimate the properties of the RAP binder.

Subtask E2b-2: Compatibility of RAP and Virgin Binders

The compatibility between the RAP and virgin binders is a significant factor for the long-term performance and durability of the HMA mixture containing the RAP materials. There are chemical as well as rheological tests that can estimate the compatibility of binders. One of the possible simple compatibility tests is the measurement of viscosity of the blended binder. Also evaluation of G* and Phase angle could be used to measure compatibility. The expectation is

that G^* of blended binders should be in between the values of the virgin and the RAP binders. In most cases a linear relationship between $\log G^*$ and percent virgin binder is found for compatible binders. A significant deviation from the linear relationship could be an indication of incompatibility. These ideas and others could be used in this subtask to develop a simple and practical test for compatibility.

The compatibility of RAP binders and virgin binders can also be measured by using Automated Flocculation Titrimetry (AFT) and Atomic Force Microscopy (AFM). The AFT measurements can be made on various blends of RAP binder and virgin binder and basically evaluate the solubility characteristics of the materials. The AFT measurements will be coordinated and correlated with the rheological measurements. The AFM can be used to investigate the compatibility of the blended binders on a nanoscale. Recent developments in AFM research have revealed important aspects of asphalt behavior upon thermal cycling that can be applied to RAP and virgin blended binders.

The compatibility of RAP and virgin binders, both rheological and chemical, will consider the actual blending of the binders that takes place in hot-mix plants by comparing laboratory blending samples with samples of RAP mix obtained from hot-mix plants. WRI will work on evaluation of a chemical-based test while UNR and UW will share responsibility of developing a rheology-based test for compatibility.

An experimental plan was developed to cover the activities to be conducted under Subtask E2b-2. The objective of this subtask is to develop a test that is capable of evaluating the degree of compatibility between the RAP binder and the virgin binder.

- Three levels of compatibility might be present in HMA mixtures with RAP material:
 - Chemical and physical compatibility between RAP binder and virgin binder: use always.
 - Chemical and physical incompatibility between RAP binder and virgin binder: do not use at anytime.
 - Chemical incompatibility but physical compatibility between RAP binder and virgin binder: use with caution on long-term durability.
- WRI researchers will work with a team of industry experts to identify materials that fit the three classes of compatibility identified above.
- WRI researchers will obtain samples from the identified sources.
- WRI researchers will develop a chemical test that is capable of identifying the three types of compatibility/incompatibility of HMA mixtures containing RAP.

Subtask E2b-3: Develop a Mix Design Procedure

This subtask will concentrate on developing a mix design procedure for HMA mixtures containing RAP materials. The mix design procedure will follow the Superpave Volumetric Mix Design Method. It is anticipated that some changes will have to be made to the Superpave method to account for factors such as: mixing and compaction temperatures and the number of

gyrations, etc. This subtask will obtain RAP materials from 10 different sources to cover a wide range of pavement age, environmental conditions, and material sources. These sources will be used to develop a standard mix design method that is applicable to HMA mixtures containing RAP materials at various levels of 15, 30 and 45 percent.

The mix design method will use the recommendations of Subtasks E2b-1 and E2b-2 in terms of the appropriate methods to evaluate the binder and aggregates in the RAP materials and assessing the compatibility between the virgin and RAP binders. The final product of this subtask will be a complete mix design system for HMA mixtures containing RAP materials that includes the following components:

- A process to evaluate the properties of the RAP binder
- A process to measure the specific gravity of the RAP aggregate
- A process to identify the appropriate mixing and compaction temperatures
- Recommendations for the number of gyrations
- Mix design criteria

Subtask E2b-4: Impact of RAP Materials on Performance of Mixtures

This subtask will evaluate the impact of RAP materials on the performance of the final mix in terms of fundamental properties and resistance to distresses. In order for HMA mixtures containing RAP materials to be widely accepted, the agencies should be able to evaluate their fundamental properties and their potential long-term performance. In other words the agencies need to be able to input the fundamental properties of the RAP mixtures into the AASHTO MEPDG and use the appropriate performance models to conduct the final structural design.

This subtask will conduct an experimental program to evaluate the fundamental properties and resistance to distresses of the RAP mixtures that were used and designed in Subtask E2b-3 using the following technologies:

- Evaluate the dynamic modulus master curves of short-term and long-term aged mixtures
- Evaluate the resistance of the short-term and long-term aged mixtures using the tests recommended by the Consortium research on moisture damage
- Evaluate the resistance to rutting using the repeated load triaxial test on short-term aged mixtures
- Evaluate the resistance to fatigue using the flexural beam fatigue test on long-term aged mixtures and/or the tests recommended by the Consortium research on fatigue
- Evaluate the resistance to thermal cracking using the thermal stress restrained specimen test on long-term aged mixtures and/or the tests recommended by the Consortium research on thermal cracking

The final product of this subtask will be a database of the fundamental properties and performance characteristics of HMA mixtures containing RAP materials from 10 different sources at four levels of RAP contents of 0, 15, 30, and 45 percent.

Subtask E2b-5: Field Trials

This subtask will conduct field trials of the developed system. In cooperation with Granite Construction Inc. and state highway agencies, field test sections will be produced and constructed following the system developed in this research. During the construction of the field test sections, the plant produced HMA mixtures containing RAP materials will be evaluated in terms of their properties and performance characteristics (i.e. rutting, fatigue, and thermal cracking) following the systems developed in the previous subtasks.

The long-term performance of the field test sections will be monitored in cooperation with the state highway agencies and the data will be used to validate the design and evaluation systems developed in this research.

During the construction of the field trials, data will also be collected to achieve two additional goals: RAP source acceptance and RAP source variability. It will be unrealistic to expect the agencies to conduct rutting, fatigue, and thermal cracking tests on each RAP source. This subtask will attempt to develop an acceptance guideline based on simple tests either on the entire RAP mix or on RAP components. This subtask will also identify the tests to be used to assess the variability of the RAP stockpiles. The potential tests for measuring the variability of the RAP stockpiles will have to be practical and reliable.

An experimental plan was developed to cover the activities to be conducted under Subtask E2b-5. The objective of this subtask is to early evaluate the field performance of HMA mixtures with 40 percent RAP material designed without changing the binder grade and with the appropriately changed binder grade.

- Construct field test sections at five different locations in the U.S.
 - Palm Springs, CA: Granite Construction
 - West Texas, TX: Granite Construction
 - Alabama or Florida: NCAT
 - Wisconsin or Minnesota: UWM
- It is desired to have field projects at the above locations that include 40 percent RAP materials in two test sections:
 - One test section with 40 percent RAP using the same binder grade for the project
 - One test section with 40 percent RAP using the appropriately changed binder grade
 - Each test section will consist of 500 tons of mix (i.e. one transport of 20 tons binder).

- o UNR and NCAT will provide support for the design and evaluation of the mixtures.

Major Findings from Year 1

The Year 1 activities of this work element concentrated on the following areas:

- Conduct a literature review on the evaluation and performance of RAP mixtures
- Develop experimental plans
- Identify and obtain materials for the various experiments
- Conduct laboratory evaluations

Literature Review: The literature review covered the evaluation and performance of RAP mixtures throughout the U.S. It covered the various efforts that have been conducted to evaluate the properties of RAP materials (i.e. aggregates and binders) and the various laboratory tests that have been used to evaluate the properties of the RAP containing mixtures. The literature review is still in progress and it is planned to be completed toward the middle of Year 2.

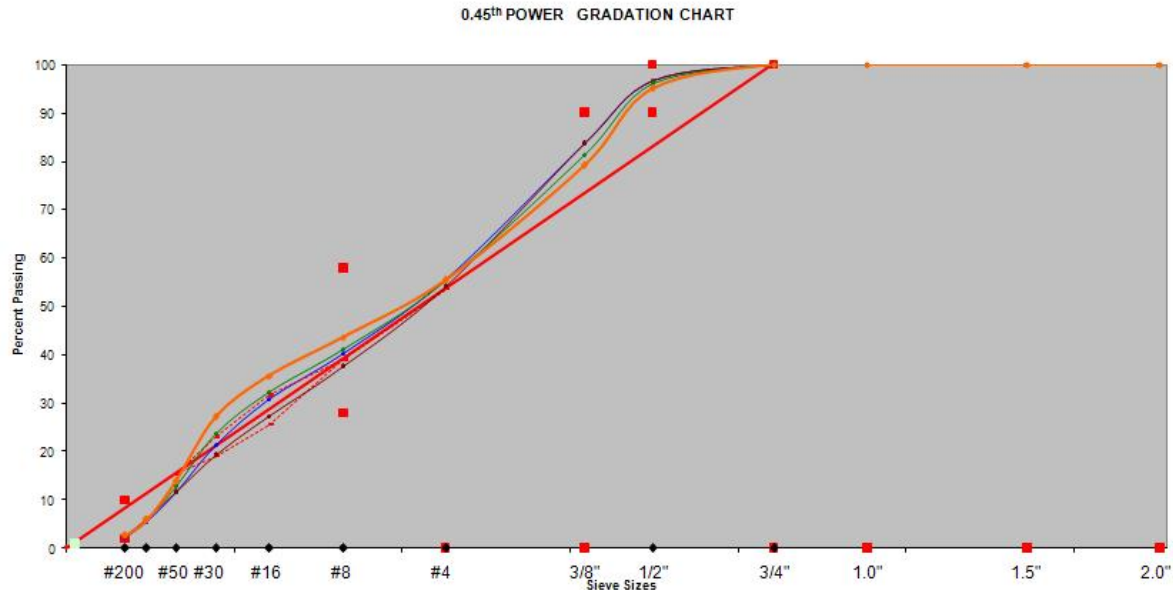
Experimental Plans: Experimental plans were developed to cover the activities to be conducted under Subtasks E2b-1, E2b-2, and E2b-5. The plans have been described under the individual subtasks in the previous sections.

Identify Materials: The following RAP sources were identified and sampled in Year 1.

- One RAP source from South Carolina that fits the category of unmodified-stiff.
- One RAP source from Southern California that fits the category of unmodified-very stiff.

Conduct Laboratory Evaluations: Two laboratory evaluations were conducted during Year 1: Evaluation 1 assessed the feasibility of using the BBR for testing passing #8 RAP mortar and Evaluation 2 assessed the feasibility of using 40 percent RAP without changing the binder grade.

Evaluation 1: In an effort to identify the feasibility of using the BBR for testing RAP mortars, samples were prepared composed of RAP (-#8) material and virgin binder. BBR beam specimens were a challenge to make using the RAP mortar. The -#8 aggregate in the mortar was too large for the standard BBR beam specimen dimensions. Modification of the BBR beam specimen dimensions were made by reconfiguring the standard BBR mold pieces to create a specimen with end cross-sectional dimensions of ~12.7mm x 12.7mm. This configuration involved using 3 of the standard bottom mold pieces and 4 standard mold end pieces. BBR beam specimens were successfully produced using this mold arrangement, which led to the development of a modified BBR beam specimen mold. The following is the mold shop drawings and also a picture of the finished product.

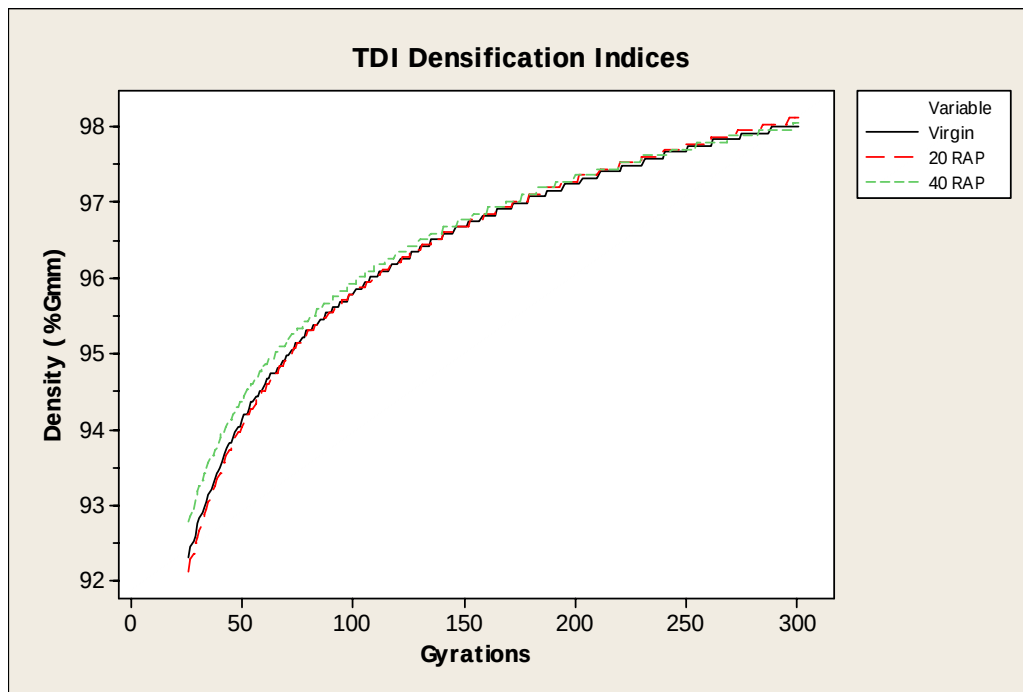
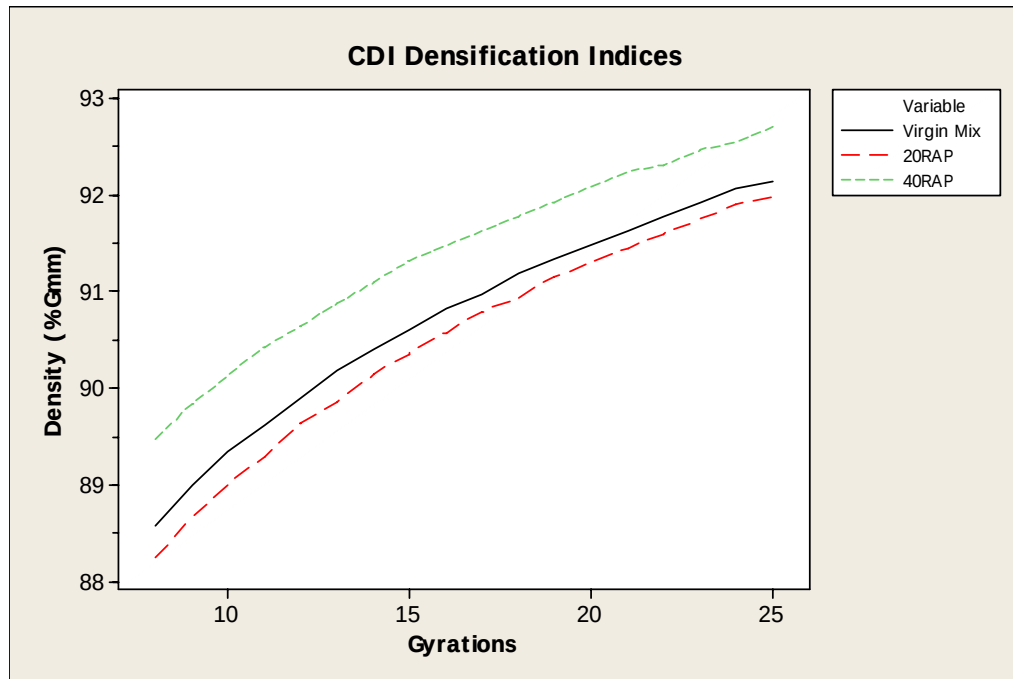


All of the mixtures met WisDOT specifications for an E-3 Superpave mix, showing that it is possible to make a HMA mixture with 40 percent RAP content. The same virgin binder (PG58-28) was used for all three mixes, e.g. no binder grade adjustments for the RAP mixes. After completion of the mix designs, test specimens were made so that the three mixtures could be evaluated based upon moisture damage testing (AASHTO T-283), Superpave gyratory compactor (SGC) compaction data analysis (CDI and TDI), and a low temperature indirect tension testing. The following are the results from the moisture damage testing:

Moisture Damage Analysis						
Specimen	Condition	t	D	P	S _t	TSR
Virgin 1	wet	4.83	6	8350	183	
Virgin 2	wet	4.82	6	8900	196	
Virgin 3	dry	4.79	6	8700	193	
Virgin 4	dry	4.79	6	9300	206	95.14
20% RAP a	wet	4.67	6	9600	218	
20% RAP b	wet	4.79	6	8800	195	
20% RAP c	dry	4.72	6	9900	223	
20% RAP d	dry	4.75	6	9350	209	95.74
40% RAP a	wet	4.64	6	8800	201	
40% RAP b	wet	4.66	6	8800	200	
40% RAP c	dry	4.74	6	9200	206	
40% RAP d	dry	4.72	6	9300	209	96.77

This testing shows that all of the mixes pass the moisture damage specification requirements, but also that there is no significant difference between the mixtures.

The next set of testing utilized the SGC compaction data by analyzing it to compute the compaction densification index (CDI) and the traffic densification index (TDI). This analysis can be done graphically by comparing the SGC compaction curves over the appropriate gyration intervals. The following graphics show the results of the CDI and TDI analysis respectively.



The CDI graphic shows that the area under the 40 percent RAP curve is the largest, indicating that it would be the most difficult to compact and work with during the paving process. The 20 percent RAP and Virgin mixtures are fairly similar, indicating that it would probably be difficult to distinguish between the two mixes in the field. The TDI graphic shows that the area under the 40 percent RAP curve is slightly larger, indicating that it would be the most resistant to traffic rutting. The SGC compaction data analysis indicates that HMA mixtures with higher amounts of RAP tend to be stiffer than comparable virgin mixes.

A final mixture performance test was conducted on the three mixes. The test involved freezing the test specimens to 0°C for 12 hours and testing their tensile strength using an indirect tension test. The results of the testing are as follows:

Low Temperature IDT Analysis					
Specimen	t	D	P	S _t	Avg S _t
Virgin 1	4.65	6	6700	153	
Virgin 2	4.68	6	8100	184	168
20% RAP 1	4.67	6	8300	189	
20% RAP 2	4.64	6	7300	167	178
40% RAP 1	4.54	6	8300	194	
40% RAP 2	4.6	6	7900	182	188

These testing results indicate that all three mixtures exhibit statistically similar tensile strength properties at 0°C temperature.

In summary, the findings from the initial mix design and mixture performance testing that was done indicate that the use of high percentages (up to 40%) of RAP without changing the PG grade of the virgin binder does not appear to have detrimental effects on the performance of the HMA mixture in resisting moisture damage and thermal cracking. However, two facts must be noted on this evaluation: (1) the RAP is from Wisconsin which may not be highly aged, and (2) the fatigue resistance of these mixtures will have to be evaluated.

A cost analysis using these mix designs was also done to identify potential HMA mix material cost savings by utilizing RAP. The costs used in this analysis are representative for Wisconsin at the time of the analysis and are summarized below:

Mixture	Rock	Man Sand	Natural Sand	RAP	Mixture Aggregate	Mixture	Virgin	Total
					Cost	%AC	%AC Added	Mixture Cost
Virgin	25%	65%	10%	0%	\$6.85	4.8%	4.8%	\$23.65
20% RAP	25%	50%	5%	20%	\$6.35	4.7%	3.9%	\$20.00
40% RAP	25%	30%	5%	40%	\$5.65	3.8%	2.2%	\$13.35

As the table indicates, there is ~15 percent cost savings between the 20 percent RAP and the Virgin mixture mainly due to a 0.9 percent reduction in virgin asphalt usage. However, a 40 percent RAP mixture was able to be designed with similar mixture volumetrics as the virgin mix by using 2.6 percent less virgin asphalt than the virgin mix. This results in an overall savings of ~43 percent per ton of mixture produced using a virgin asphalt price of \$350 per ton. The aggregate savings accounts for ~12 percent of the total ~43 percent cost savings.

Year 2 Work Plan

During Year 2, the research team will continue the literature review, continue the laboratory evaluation of the RAP materials, and obtain materials from the various RAP sources. UNR, UW-M, and AAT researchers will work on developing a laboratory test method to evaluate the properties of RAP binder without resorting to the extraction and recovery process of the asphalt binder from the RAP materials. As indicated in the experimental plan, this objective will be achieved by evaluating the properties of the mortar portion or the full RAP material and using these properties to identify the properties of the RAP binder.

During Year 2, the UNR and NCAT researchers will identify the most reliable method of evaluating the properties of RAP aggregates. The three commonly used techniques of extracting the aggregates from the RAP materials will be evaluated and the one that induces the least impact to the properties of the aggregates will be recommended.

WRI researchers will work on developing a system to identify the compatibility between the virgin and RAP binders. Also in Year 2, the field trial projects will be identified.

The work on the mix design procedure for HMA mixtures containing high RAP contents will start in the third quarter of Year 2.

The ARC research on RAP mixtures will be coordinated with the NCHRP project: 09-46: Improved Mix design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content. The ARC lead researcher (P.E. Sebaaly) is an observing member of the NCHRP Project Panel D09-46 and will share the findings of the ARC research activities.

Year 2 Milestones

The following milestones will be realized in Year 2:

- Identify a system to evaluate the properties of RAP binder
- Identify a system to evaluate the properties of RAP aggregates
- Identify a system to assess the compatibility between virgin and RAP binders

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
E2b-1: Develop a System to Evaluate the Properties of RAP Materials	X	X			
E2b-2: Compatibility of RAP and Virgin Binders	X	X			
E2b-3: Develop a Mix Design Procedure		X	X		
E2b-4: Impact of RAP Materials on Performance of Mixtures			X	X	X
E2b-5: Field Trials	X	X	X	X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
E2b-1: Develop a System to Evaluate the Properties of RAP Materials	X	X	X	X
E2b-2: Compatibility of RAP and Virgin Binders	X	X	X	X
E2b-3: Develop a Mix Design Procedure			X	X
E2b-4: Impact of RAP Materials on Performance of Mixtures				
E2b-5: Field Trials	X	X	X	X

Budget

The estimated budget for this work element is \$1,730,000 over the five years. The work will be conducted by the University of Nevada, University of Wisconsin-Madison, Western Research Institute, Advanced Asphalt Technologies, Granite Construction (Cost Share), National Center for Asphalt Technology, and the Wisconsin Asphalt Pavement Association (Cost Share).

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Work Element E2c: Critically Designed HMA Mixtures

Work Element Lead: Peter Sebaaly and Elie Hajj

Introduction

Field performance data from the Westrack project and other pavements indicate that every HMA mix has a critical temperature and a critical loading rate beyond which the mixture will become highly unstable. Therefore, it is recommended that the critical temperature and critical loading rate be identified for every HMA mixture. Once these two critical conditions are identified, they must be checked against the expected field conditions where the HMA mix will be placed. An HMA mix should not be placed at locations where its critical conditions are expected to be violated.

Furthermore, it is believed that the critical conditions of an HMA mix can be significantly influenced through changes in binder content, binder properties, and aggregates gradation. This process will allow the mix design engineer to design excellent performing HMA mixtures for mainline traffic and traffic on off-ramps and at intersections with changes that can be accommodated in the production process without major interruptions, such as slightly modify the binder properties or slightly reduce the binder content as the construction approaches the intersection.

Relationship to FHWA Focus Areas

This research effort fits under the FHWA Focus Areas of Optimize Pavement Performance and Advanced Quality Systems.

Hypothesis

The strength and performance of HMA mixtures can be optimized by loading them below their critical conditions as depicted by the combination of temperature and loading rate.

Objectives

The objective of this research effort is to establish a practical test method to identify the critical temperature and critical loading rate of HMA mixtures. The test will be based on fundamental properties of the HMA mixture and consistent with the Superpave mix design method. The

developed test method should be simple enough to be implemented as part of the mix design process.

Experimental Design

The following subtasks will be completed in order to achieve the objective of this research effort.

Subtask E2c-1: Identify the Critical Conditions

As the HMA mix is placed at a given project location, it will be simultaneously subjected to the local environmental conditions and traffic loading. Due to the viscoelastic nature of the HMA mix, its behavior is highly dependent on both temperature and rate of loading. The pavement temperature is related to the air temperature through a relationship that has been established and verified based on the data from the Long Term Pavement Performance (LTPP) studies. This relationship has been accepted in the Superpave system. The loading rate of the HMA mix depends on the speed of the traffic using the facility. The loading rate varies from short under freeway traffic to long under urban traffic.

Low temperature coupled with a short loading rate is the best condition for an HMA mixture while high temperature coupled with a long loading rate represents the worst condition. In reality the combination of temperature and loading rate varies over a wide range. Identifying the temperature of the HMA mix is relatively simple since it only depends on the location of the pavement and the air temperature. However, identifying a loading rate represents a more difficult challenge since the mixed nature of traffic loading has to be included. This subtask will use dynamic mechanistic analysis of flexible pavements subjected to various traffic speeds to identify the loading rates that are applicable to the various road facilities (i.e. freeways, urban streets, intersections, and off ramps).

An experimental plan was developed to cover the activities to be conducted under Subtask E2c-1. The objective of this subtask is to define the critical loading conditions under a moving truck load. This objective will be met through a mechanistic analysis of the HMA pavement as it is subjected to moving loads at various speeds and under braking and non-braking conditions.

- Use the 3D-Move software to evaluate the stress conditions under dynamic loads within the HMA layer.
- Analyze the following pavement structures:
 - 4" HMA over 6" base
 - 6" HMA over 8" base
 - 8" HMA over 10" base
- Analyze the following geometries:
 - Level road
 - 4 percent grade road
- Analyze the following speeds:
 - 60 mph without braking

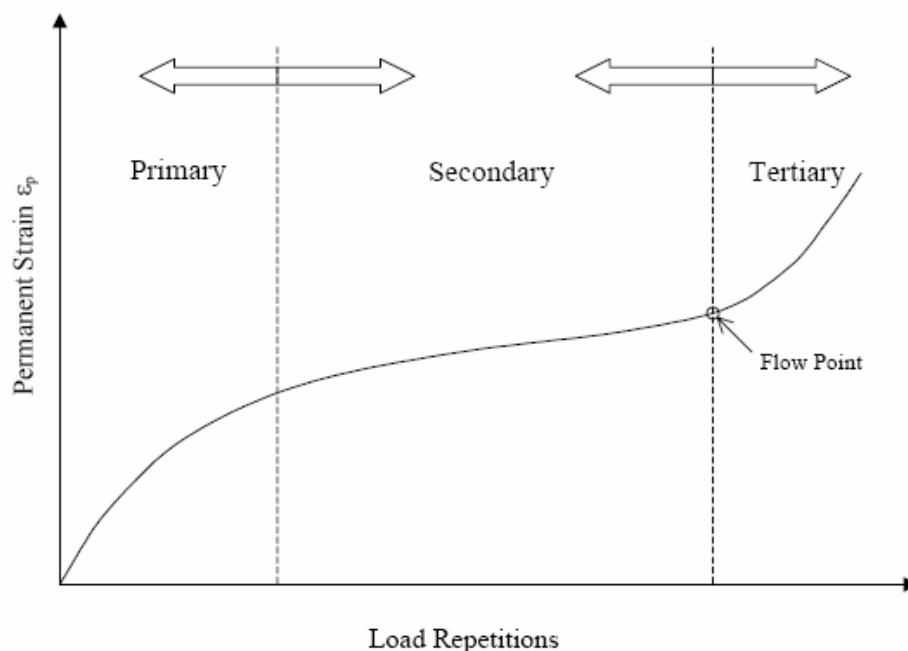
- o 40 mph without braking
 - o 20 mph with and without braking
 - o 2 mph with braking
- Tire-Pavement Pressure Distribution
 - o Uniform
 - o Non-uniform
- Analyze the following HMA mixtures:
 - o One aggregate source: Lockwood (andesite)
 - o Intermediate Superpave gradation with 1/2" nominal max size
 - o Three binders: PG52-22, PG58-22, PG64-22
- Analyze the following HMA layer temperature
 - o 40°C
 - o 50°C
 - o 60°C
 - o 70°C
- Conduct Superpave mix designs for the three mixtures for 6 millions ESALs and for a top lift.
- Subject the mixture to Superpave short-term aging.
- Measure the E* Master Curves for all three mixtures.
- Use the measured properties of the HMA mixtures in the 3D-Move analyses.
- Use a modulus of 35,000 psi and 15,000 psi for the base and subgrade, respectively.
- Use the 18-wheeler truck configuration at 125 psi inflation pressure.
- Evaluate the distributions of vertical displacements, vertical and lateral stresses within the HMA at the surface and 1/2" depth increments for the top 2" of the HMA layer and at 1" increment thereafter within the influence zone of the loaded tires.
- Analyze the data to identify the following:
 - o Time of loading throughout the HMA
 - o Magnitude of the confining and deviator pressures throughout the HMA layer

Subtask E2c-2: Conduct Mixtures Evaluations

The objective of this subtask is to determine the critical combination of temperature and loading rate for HMA mixtures. The critical combination is defined as the one that creates an unstable HMA mix exhibiting excessive permanent deformation. Figure E2c.1 shows the development of permanent strain in an HMA sample tested under the repeated load triaxial (RLT) test. It can be seen that the permanent deformation goes through three phases: initial phase with a high rate of permanent deformation but short duration, a secondary phase where the permanent deformation is linear with a long duration, and tertiary phase where the permanent strain is increased

exponentially. It is believed that the formation of the tertiary phase is an indication of an unstable HMA mix.

The repeated load triaxial test is the most representative test of actual field conditions. The deviator and confining stresses can be varied to simulate the actual state of stresses within the HMA layer while simultaneously changing the temperature and the rate of loading. It is proposed that the RLT test be used to evaluate a variety of HMA mixtures ranging from weak to strong mixtures to identify their critical temperatures and rates of loading. The permanent deformation curves similar to the one shown in figure E2c.1 will be developed for each mixture under the various combinations of temperature and rate of loading as determined in Subtask E2c-1.



- Figure E2c.1. Typical repeated load permanent deformation behavior of pavement materials.

An experimental plan was developed to cover the activities to be conducted under Subtask E2c-2. The objective of this subtask is to evaluate the critical conditions of HMA mixtures defined as the critical combination of testing temperature and loading rate under the repeated load triaxial (RLT) testing conditions.

- Use the same three mixtures that were designed under Subtask E2c-1.
- Test the mixtures in the RLT at various temperatures of 40, 50, 60, and 70°C and at the state of stresses and loading times that were determined in subtask E2c-1.
- Analyze the RLT of the various mixtures in terms of the relationship between the permanent axial strain as a function of number of load cycles.

Subtask E2c-3: Develop a Simple Test

One disadvantage of the RLT test is its complexity since it requires accurate control of the deviator and confining stresses for the duration of the test which makes it an impractical test for routine applications.

This subtask will use the evaluation data from the RLT tests conducted in subtask E2c-2 to investigate the possibility of developing a simpler version of the test. At this point, the researchers believe that a test that can be conducted in the Simple Performance Tester (SPT) may be feasible with some adjustments. This will have the advantage of conducting the critical conditions test in the same equipment used for the dynamic modulus test which will make it easier to implement as part of the mix design process. If the SPT proves unfeasible, then other tests will be investigated.

A detailed experimental plan will be developed prior to beginning this subtask.

Subtask E2c-4: Develop Standard Test Procedure

The objective of this subtask will be to develop a standard test procedure to be used for the identification of the critical conditions of HMA mixtures. The standard procedure will be developed in AASHTO format and submitted to AASHTO for approval.

A detailed experimental plan will be developed prior to beginning this subtask.

Subtask E2c-5: Evaluate the Impact of Mix Characteristics

The objective of this subtask is to identify the mix characteristics that impact the critical temperature and loading rate of HMA mixtures. This subtask will use the test procedure developed in Subtask E2c-4 to assess the impact of the various mix properties on the critical conditions.

It is anticipated that mix properties such as binder grade and content and aggregate properties and gradation may play a major role on the critical temperature and loading rate of HMA mixtures. The work conducted under this subtask will identify the various mix properties and their corresponding levels that have significant impact on the critical conditions of the HMA mix. Through this effort, it will be feasible to recommend changes in the mix properties that will improve their critical behaviors.

For example if an HMA mix is performing well under mainline traffic but it is experiencing severe rutting at the intersection, then it is possible that it is reaching its critical loading rate under slow-stop traffic for the given location (i.e. temperature). The data generated in this subtask will help identify the necessary changes in mix properties that will improve its resistance to rutting at the intersection.

It is anticipated that this research effort will identify some mix properties that can be easily modified during production and that will lead to significant improvement in the response of the HMA mix under critical conditions. The research under this subtask will also cover other failure modes of the HMA mix in order to avoid improving the resistance of the mix to one mode of failure while at the same time jeopardizing its resistance to the other failure modes.

A detailed experimental plan will be developed prior to beginning this subtask.

Major Findings from Year 1

The Year 1 activities of this work element concentrated on the following areas:

- Developed experimental plans for subtasks E2c-1 and E2c-2. The plans have been presented in the Experimental Design section.
- Conducted theoretical modeling as described in the experimental plan for subtask E2c-1.

Year 2 Work Plan

During Year 2, the researchers will continue the development of the critical loading times and loading rates for the various combinations of HMA mixtures and pavement structures according to the experimental plan for subtask E2c-1. The data will be summarized in tables and charts that are simple to use by practicing engineers.

In subtask E2c-2, the researchers will conduct laboratory testing of the three HMA mixtures under the stress conditions of the various loading times and loading rates as determined from the mechanistic analyses. The laboratory testing will be conducted in the repeated load triaxial test. Additional HMA mixtures will also be evaluated.

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
E2c-1: Identify the Critical Conditions	X	X			
E2c-2: Conduct Mixtures Evaluations		X	X		
E2c-3: Develop a Simple Test			X	X	
E2c-4: Develop Standard Test Procedure			X	X	
E2c-5: Evaluate the Impact of Mix Characteristics				X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
E2c-1: Identify the Critical Conditions	X	X		
E2c-2: Conduct Mixtures Evaluations	X	X	X	X
E2c-3: Develop a Simple Test				
E2c-4: Develop Standard Test Procedure				
E2c-5: Evaluate the Impact of Mix Characteristics				

Budget

The estimated budget for this work element is \$600,000 over the five years. The work will be conducted by the University of Nevada.

Work element E2d: Thermal Cracking Resistant Mixes for Intermountain States

Work Element Lead: Peter Sebaaly (UNR) and Codrin Daranga (UW-M)

Introduction

Thermal cracking in asphalt pavements is caused when internal tension stresses during restrained thermal deformations are greater than the tensile strength of the asphalt binder. The thermal cracking phenomenon is hastened when temperatures become lower than the binder glass transition temperature. Glass transition occurs when the liquid component of the asphalt binder freezes to a solid, restricting segmental motion within the material's molecule (Brandrup and Immergut 1975; Odian 1991; Bonemazi et al. 1996). Any attempt to deform the frozen structure results in brittle fracture.

Oxidation raises the glass transition temperature of the binder, and therefore, decreases its resistance to thermal cracking. The impact of oxidation is two fold: the introduction of polar groups and the decrease in the amount of oily fractions. However, there is a big question whether oxidation only occurs within the top one inch of the pavement surface or it actually progresses throughout the depth of the HMA layer. The two common sources of information on this issue provide contradicting recommendations. Coons and Wright (1968) concluded that binder oxidation occurs only in the top inch of the pavement below which the binder is left virtually unaffected by years of use and environmental exposure. However, Glover et al. (2005) indicated that binders can in fact age well below the pavement surface and that the hardening of the binder is virtually unabated over time. Recent SHRP program studies on binder glass transitions and subsequently University of Wisconsin-Madison studies on glass transitions of binders and mixtures have shown that sources of asphalt binders, modification, aging, and aggregate properties can alter the glass transition behavior significantly. In addition, recent University of Wisconsin-Madison studies (pooled fund program TPF-05) showed that thermal cycling has an important effect on the thermal cracking behavior of pavement mixtures. Results indicate that the coefficient of contraction for mixtures could be significantly different from

coefficients of expansion and thus thermal cycling needs to be modeled carefully for more accurate prediction of thermal stresses and cracking.

These recent results on aging and glass transition behavior merit a fresh look at the prediction of thermal cracking models. In addition, the increasing use of modified binders, particularly polymer and acid modified binders, require a more in depth evaluation of these factors for better understanding of thermal behavior and cracking prediction of pavement mixtures.

Relationship to FHWA Focus Areas

This research effort supports the FHWA Focus Areas of Optimize Pavement Performance and Advanced Quality Systems.

Hypothesis

Field performance data indicate that HMA mixtures in the intermountain region of the U.S. experience severe thermal cracking distresses that are not well covered by the current technology. The intermountain region experiences significant hardening of the asphalt binder coupled with extreme thermal cycling, and highly absorptive aggregate leading to thermal cracks that are six inches wide.

Objectives

The objective of this research effort is to develop a binder/mix evaluation and testing system that can effectively simulate the long term properties of HMA mixtures in the intermountain region and to assess the impact of such properties on the resistance of HMA mixtures to thermal cracking.

Experimental Design

The objective of this work element is to develop a system that simulates the field aging and thermal cracking process of HMA mixtures in the intermountain region. First the binder aging kinetics when there is free access to atmospheric oxygen will be evaluated, followed by an evaluation of the impact of aggregate and mixture properties on the aging of the binder in the mix. The findings of both evaluations, together with intermountain region data on pavement temperature variations with time and depth will be used in a mixture aging model, developed in Work Element Subtask F1c-3, to simulate the aging of asphalt binders in HMA mixtures placed in the intermountain region of the U.S.

The intermountain region of the U.S. was defined as covering the following states: West Texas, New Mexico, Colorado, Wyoming, Montana, Idaho, Utah, Arizona, California, and Nevada.

The intermountain region represents a unique environment that impacts HMA mixtures in a manner that is different than the other regions of the U.S. This unique environment is defined as follows:

- Large daily temperature changes (low-high)
- High rate of daily temperature changes
- Wide range of seasonal temperatures
- Low humidity
- High number of freeze-thaw cycles

In addition, the aggregates available in the intermountain region exhibit unique properties that may have large impact on the aging characteristics of HMA mixtures. These include:

- Highly absorptive aggregates
- Siliceous aggregates

As a result of the combined impacts of the unique environment and properties of available aggregates, HMA mixtures in the intermountain region are subjected to some unique conditions that can be summarized as follows:

- Unique temperature profile throughout the depth of the HMA layer
- Significantly more aging of the asphalt binder
- Higher thermal stresses within the HMA layer

It is believed that the combinations of the above listed conditions and factors result in severe thermal cracking of HMA mixtures in the intermountain region of the U.S. As a result it became common to identify HMA pavements in the intermountain region experiencing thermal cracks that are in excess of 6 inches wide and continue to widen as the pavement ages.

In order to achieve the objectives of this research effort, the following subtasks will be completed.

Subtask E2d-1: Identify Field Sections

This subtask will identify the extent of thermal cracking in HMA pavements located within the intermountain region of the U.S. Several HMA pavements will be identified at various locations within the intermountain region and their performance for the past 10-15 years will be collected and analyzed. A concerted effort will be made to select pavement sections that coincide with the LTPP SPS sections in the intermountain region. The research team will consult with FHWA and Nichols Consulting Engineers to select the appropriate LTPP SPS sites in the intermountain region. The performance of the selected pavement sections will be collected from the pavement management systems (PMS) of the corresponding owner agencies and the LTPP databases. The selected pavements will cover a wide range of pavement age, environmental conditions, and traffic loadings. Since thermal cracking develops in the form of transverse cracks which highly resembles reflective cracking, special efforts will be made to separate the two modes of distress.

An Experimental plan was developed to cover the activities to be conducted under Subtask E2d-1. The objective of this subtask is to collect and report actual temperature history and profile throughout the depth of HMA pavements within the intermountain region of the U.S. This objective will be achieved by identifying HMA pavements throughout the intermountain region with measured temperature hourly histories and profiles throughout the depth of the HMA layer. The following steps will be completed.

- Identify HMA pavements at various locations within the intermountain region of the U.S. that have information regarding the HMA temperature histories and profile. This will be achieved by contacting:
 - Nichols Consulting Engineers for LTPP SPS sites in the intermountain region
 - Nevada Automotive Test Center (NATC) for the Westrack project
- Collect mixture and binder properties for the various sites that offers the temperature histories and profiles, if available

Subtask E2d-2: Identify the Causes of the Thermal Cracking

This subtask will obtain samples from the various pavement sites that are experiencing thermal cracking and conduct laboratory testing to identify the causes of the thermal cracking failure. The following tests will be conducted on the samples obtained from the various sites.

- Compare the environmental conditions at the site with the critical temperatures of the binder used during construction as specified by the Superpave PG system.
- Measure the temperature profile throughout the depth of the HMA.
- Measure the volumetric properties of the samples from the various sites.
- Measure the fracture temperature of the mix using the thermal stress restrained specimen test (TSRST) conducted on field samples.
- Extract and recover the binder from the samples at 1.0" depth increments and measure their rheological properties following the Superpave PG system and the master curves of G' , G'' , and G^* .
- Test the recovered binders for oxidation, solvent removal, and low shear rate limiting viscosity.
- Evaluate the extent of binder oxidation as a function of depth of the HMA layer.
- Measure the glass transition behavior of extracted binders and of mixtures at cooling and heating rates that resemble the conditions of the pavement sections that are sampled.

The activities of this subtask will be closely coordinated with the activities of other Consortium partners on aging of HMA mixtures that will be conducted under the fatigue and moisture damage areas.

Subtask E2d-3: Identify an Evaluation and Testing System

The objective of this subtask is to identify a system to evaluate and test HMA mixture's resistance to thermal cracking in the intermountain region. It is anticipated that HMA pavements in the intermountain region are subjected to significant hardening of the asphalt binder coupled with extreme thermal cycling, and highly absorptive aggregate leading to thermal cracks.

Based on the data generated from Subtasks E2d-1 and E2d-2, the researchers will work on developing an evaluation and testing system to simulate the actual conditions in the intermountain region. At this point the researchers anticipate that the work under this subtask will cover the following parameters:

- A binder aging system that simulates the field aging process of HMA mixtures in the intermountain region.
- The impact of fillers on the aging characteristics of the HMA mix.
- The impact of air voids on the aging characteristics of the HMA mix.
- The impact of highly absorptive aggregates on the aging characteristics of the HMA mix.

Using the data from the above experiments, a thermal cracking test will be developed that simulates the actual tensile mode of loading that is experienced by the HMA layer. Attention will be paid to the following aspects.

Thermal Expansion Coefficient Measurements

There are two values for the thermal expansion coefficient: one below and one above the glass transition temperature. This is valid for both binders and mixes. The evaluation of thermal expansion coefficients are conducted using an apparatus developed at University of Wisconsin-Madison. The apparatus monitors the dilatometric properties of mixes and binders while the samples are subjected to a prescribed temperature program. By plotting the length (for mix samples) or volume (for binder samples) vs. temperature, the thermal coefficients of expansion are given by the two slopes in the bilinear function.

Low Temperature Mix Strength Properties Measurements

This testing is performed exclusively on mix samples and it is referred to as: "Thermal Stress Restrained Specimen Test (TSRST)." A mixture bar is fixed mounted using a solid steel frame so as to restrict thermal contraction. When the sample is cooled, the restricted deformation by the solid steel frame triggers the generation of tensile stresses. These stresses are measured using a load cell. The temperature will continue to drop until the sample is driven to failure. The tensile stresses are plotted against the temperature to allow the evaluation of the mixture behavior prior to and at failure. If the test described in the previous paragraph does not impose any moving restrictions on the sample, this test imposes maximum moving restriction. In this way, the two tests complement each other, allowing the complete characterization of the pavement mixture thermal behavior.

Monitoring of Carbonyl Growth

In order to better gauge the oxidative aging in asphalt binders, the carbonyl peak growth must be monitored. This is usually done using Fourier Transformed Infrared Spectroscopy (FTIR) technique. Currently we do not own or have ready access to such instrument, but we are in the process of developing a working relationship with the chemistry department at the University of Wisconsin-Madison, in order to gain access to FTIR testing. Even though we do not foresee any problems in developing such a relationship, in the event that we will not be able to gain access to FTIR testing, this work will be carried out by subcontracting it to WRI.

The activities of this subtask will be closely coordinated with the activities of other Consortium partners on aging of HMA mixtures that will be conducted under the fatigue and moisture damage areas.

An Experimental plan was developed to cover the activities to be conducted under Subtask E2d-3. Three experiments will be conducted: the first experiment to evaluate the aging of binders in the intermountain region, the second experiment to evaluate the impact of aggregates properties on aging of binders, and the third experiment to evaluate the impact of mixtures properties on the aging of binders.

E2d-3.a: Evaluate Long-Term Aging of Asphalt Binders Subjected to Free Atmospheric Oxygen: The objective of this experiment is to evaluate the aging characteristics (oxidation and hardening kinetics) of intermountain region asphalt binders when they have full access to atmospheric oxygen. The following steps will be conducted:

- Obtain the following asphalt binders:
 - Neat PG64-22
 - Neat PG64-22 + 3 percent SBS polymer (using the same PG64-22)
 - Polymer modified PG64-28 (using the same PG 64-22) that meets the grades of NV, CA and UT.
- Blend the PG64-22 with hydrated lime at 10 percent and 20 percent by weight.
- Subject a 1 mm film of each of the asphalt binders to long-term oven aging at 50°C, 60°C, 80°C, and 100°C for a various time periods. Prior to aging the matrix, check for potential volatile loss during aging. Weigh samples to the nearest 0.001gram before and after aging to determine weight gain or loss. Individual samples at each temperature will be removed from the aging oven according to the following schedule:
 - 50°C: Remove samples after 60, 120, 200 and 320 days
 - 60°C: Remove samples after 30, 60, 100 and 160 days
 - 80°C: Remove samples after 7.5, 15, 25 and 40 days
 - 100°C: Remove samples after 44, 90, 150 and 240 hours
- Measure the following properties for the aged binders at each of the 50°C, 60°C, 80°C, and 100°C (the aging temperatures should be precise to within 0.1 °C):
 - Carbonyl growth (UWM) to determine binder reaction rates and activation energies.

- Rheological properties following the Superpave PG system and the master curves of G' , G'' , and G^* (UNR), measurements of the low shear rate viscosity, and multiple stress creep recovery (MSCR) (UWM).
- Strength properties at low temperature using the single edge notch bending (SENB) (UWM).
- Thermal expansion coefficient (UWM).

E2d.3.b: Evaluate the Impact of Aggregate Absorption on the Aging of the Asphalt Binder: The objective of this experiment is to evaluate the impact of aggregate absorption on the long-term aging properties of the binder in the HMA mix. This subtask will assess the impact of the unique characteristics of the intermountain aggregates on the aging characteristics of asphalt binders in the HMA mix. The following steps will be conducted:

- Select aggregates with different mineralogy from four different sources within the intermountain region.
- Develop an intermediate Superpave gradation for each of the aggregate sources.
- Measure the specific gravity and absorption of the blend aggregates.
- Calculate the surface area of each blend aggregates.
- For each of the blend gradations conduct the following:
 - Mix each of the blend aggregates with each of the two extreme asphalt binders identified in E2d-1.a at a constant binder content (i.e. variable film thickness).
 - Mix each of the blend aggregates with each of the two extreme asphalt binders identified in E2d-1.a at the required binder content to achieve a constant film thickness (i.e. variable binder content).
- Measure the E^* master curve and TSRST fracture properties of compacted mixtures before aging and after 3, 6, and 9 months of long-term oven aging at 60°C. This aging does not need to be as precise as the binder aging kinetics ovens because the state of aging will be determined by recovering the binder. Age the loose mixture following AASHTO R30, 4hr aging.
- Compare the mechanical properties of HMA mixtures before and after long-term oven aging.
- Extract and recover the binder from the tested mixture at each aging level and determine the binder's level of oxidation and hardening (carbonyl and DSR properties). The extraction and recovery process will be done using a solvent system maximize binder recovery and in a way that minimizes changes to the binder and assures virtually complete solvent removal.

E2d-3.c: Evaluate the Impact of HMA Mix Characteristics on the Aging of the Asphalt Binder: The objective of this experiment is to evaluate the impact of intermountain region mixture characteristics on the long-term aging characteristics of the asphalt binder. As the asphalt binder is placed in the HMA mix, it will have a limited access to oxygen. Therefore, the binder aging

kinetics that is based on free access to atmospheric oxygen will have to be modified to simulate real field conditions of HMA pavements. The following steps will be conducted:

- Aggregate Sources: select two aggregate sources based on the recommendations of E2d-3.b.
- Gradation: develop an intermediate and fine Superpave gradations for each of the aggregate sources.
- Measure surface area and specific gravity.
- Binders: Select three binders – two extremes and one intermediate as identified in subtask 1.a.
- Mineral Fillers: none, Lime, and regular limestone.
- Conduct Superpave mix designs for all combinations of mixtures based on 6 millions ESALs for a top lift: 36 mixtures (2 agg. x 2 grad. x 3 binders x 3 fillers).
- Air-Voids: prepare compacted samples from each mixture at three levels of air-voids – 4, 8 and 11 percent. Age the loose mixture following AASHTO R30, 4hr aging.
- Measure the E* master curve and TSRST fracture properties for three replicate samples of the compacted mixtures before aging and after 3, 6, and 9 months of long-term oven aging at 60°C. This aging does not need to be as precise as the binder aging kinetics ovens because the state of aging will be determined by recovering the binder).
- Loose mix: prepare a loose mix and subject it to the various long term aging periods prior to compaction. Measure the E* master curve of the aged loose mix after compaction.
- Compare the mechanical properties of HMA mixtures before and after long-term oven aging.
- Extract and recover the binder from the tested mixture at each aging level and determine the binder's level of oxidation and hardening (carbonyl and DSR properties). The extraction and recovery process will be done in a way that maximizes binder recovery and minimizes changes to the binder and assures virtually complete solvent removal.

Subtask E2d-4: Modeling and Validation of the Developed System

This subtask will develop a software program for prediction of critical cracking temperatures using the input variables measured in subtask E2d-3. The software will include variables that are found to be important in subtask E2d-3 and that have shown clear role in predicting the performance observed in the field.

The subtask will also include validation of the testing and modeling system. The validation process will be conducted in the laboratory based on the use of the TSRST. Although the SHRP research concluded that the TSRST is too complex to become a production test, it is clear that the test can be used effectively to evaluate stress build up and cracking under well controlled variables. In addition, this subtask will make a concentrated effort to validate the developed

system on a national basis. Some national pavement sites will be identified and used for this validation effort.

Subtask E2d-5: Develop a Standard

This subtask will develop a standard testing procedure for the system developed in Subtask E2d-3 and validated in Subtask E2d-4. The standard will be prepared in AASHTO format.

Major Findings from Year 1

The Year 1 activities of this work element concentrated on the following areas:

- Develop experimental plans
- Identify and obtain materials for the various experiments
- Identify field sections in the intermountain region
- Conduct laboratory evaluations

Experimental Plans: Experimental plans were developed to cover the activities to be conducted under Subtasks E2d-1, E2d-2, and E2d-3. The plans have been described under the individual subtasks in the previous sections.

Identify Materials: During Year 1, the materials and testing conditions for the experimental plans were selected as described under the individual subtasks. The aggregates and asphalt binders have been obtained.

Field Sections: During Year 1, the researchers worked with the western region LTPP contractor (Nichols Consulting Engineers) to identify LTPP field sections that are located in the intermountain region and that can be used in this research. The criteria for selecting the LTPP sites included: located within the intermountain region, availability of hourly temperature profiles throughout the depth of the HMA layer, availability of materials properties, and availability of long-term performance data. The following LTPP sites have been identified for this work element:

- Arizona: 041024, 04(0113, 01114)
- New Mexico: 351112
- Colorado: 081053
- Utah: 491001
- Nevada: 320101
- Wyoming: 561007
- Idaho: 161010
- Montana: 300114, 308129
- Texas: 481122

The temperature profiles throughout the HMA layer have been extracted from the LTPP database and were analyzed to calculate the rate of temperature changes at various depths in the HMA

layer as a function of time of day and year. Figure E2d.1 shows a typical temperature rates data for an LTPP section in Arizona.

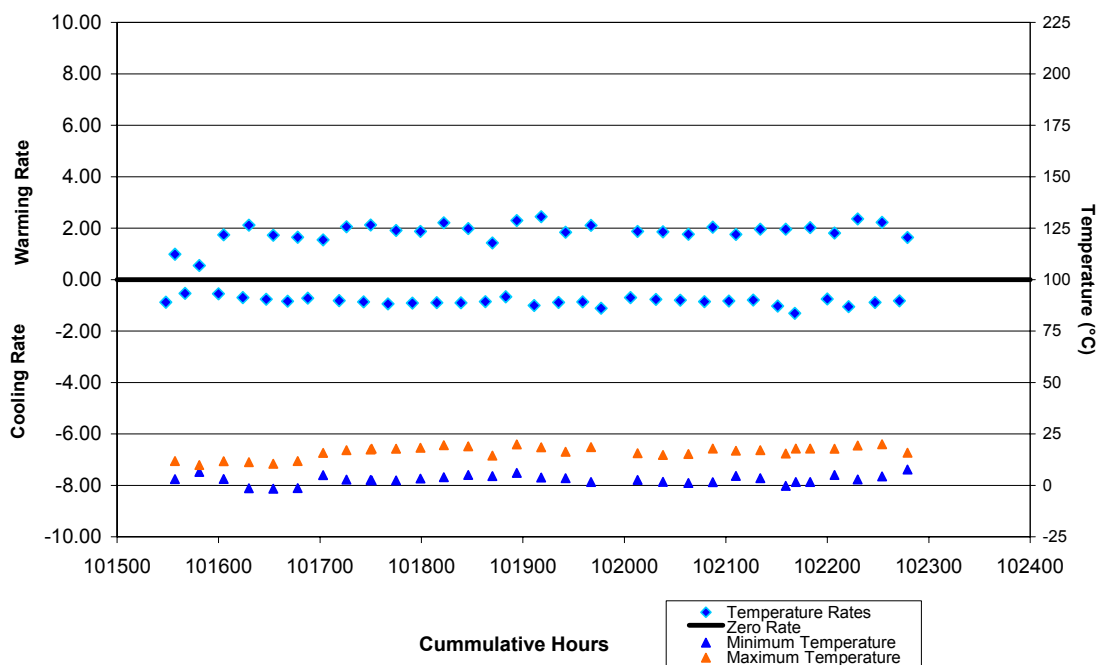


Figure E2d.1. Pavement temperature rates along with the maximum and minimum daily temperatures for section 040113 in Arizona at sensor 1 (depth = 1.7 inches) for January of 2004.

Conduct Laboratory Evaluations: The glass transition behavior of asphalt binders and mixtures is an essential component for the prediction of thermal cracking of pavements. For many decades this subject has been studied, however published results are very limited. Measuring thermo-volumetric properties of asphalt paving materials is not simple and there are no standard methods for conducting such measurements. During Year 1, a dilatometric system for measuring binder properties was used to study the glass transition of ten binders and a length change measuring system was used to measure the glass transition of asphalt mixtures. Results show a variation in the glass transition behavior as function of the binder grade and modification. Furthermore, the glass transition temperature T_g of the mixtures does not correlate with binder glass transition properties, which highlights the importance of aggregate characteristics and mixture compaction data in defining mixture thermo-volumetric properties. It is also found that the contraction and dilation behavior of mixtures shows a hysteretic response. These findings hint at a need for fundamental understanding of the effect of aggregate interaction in the thermal behavior of asphalt mixtures and they also shed some light on the important aspect of thermal cracking of pavements and the measurements needed for better modeling.

We have developed a finite difference model that simulates the temperature gradient and strain distribution in 2.5-in by 2.5-in cross-section mix specimen during thermal cycling. This finite difference model solves the heat diffusion equation:

$$\frac{\partial T(x, z, t)}{\partial t} = k \cdot \left(\frac{\partial^2 T(x, z, t)}{\partial x^2} + \frac{\partial^2 T(x, z, t)}{\partial z^2} \right)$$

by discretizing it both in the space and time:

$$\frac{T(x_i, z_i, t_{i+1}) - T(x_i, z_i, t_i)}{\Delta t} = k \cdot \left(\frac{T(x_{i+1}, z_i, t_i) - 2T(x_i, z_i, t_i) + T(x_{i-1}, z_i, t_i))}{\Delta x^2} + \frac{T(x_i, z_{i+1}, t_i) - 2T(x_i, z_i, t_i) + T(x_i, z_{i-1}, t_i))}{\Delta z^2} \right)$$

where $T(x, z, t)$ is the temperature specimen in space and time, k is the thermal diffusivity, and Δx , Δz , and Δt are the space and time discretization intervals. By applying the chamber temperature as the time-varying boundary condition, the distribution of temperature throughout the specimen during heating and cooling cycles can be calculated (figure E2d.2). Furthermore, the combination of local temperatures with thermal expansion coefficients (including different thermal expansion coefficients above and below the glass transition temperatures) permit calculating both local and global thermal strains for any asphalt mixture specimens.

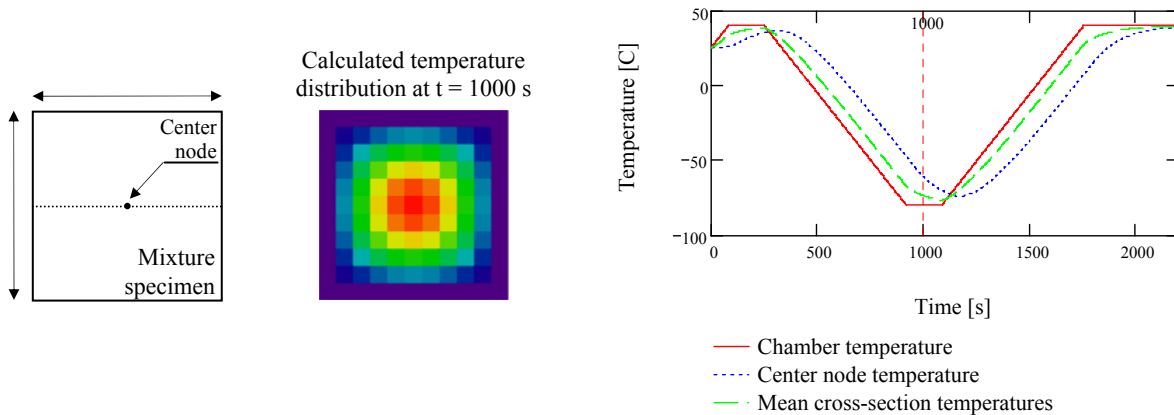


Figure E2d.2. Finite difference model of temperature distribution on asphalt mixture specimens.

The ability to evaluate the temperature node by node across the specimen cross-section shows that using a single thermocouple to characterize the thermal behavior a whole specimen could mask the true response of the asphalt mixture. For example, figure E2d.3a shows how local measurements cannot be used to match the average temperature distribution in the specimen. This is important as the average temperature distribution controls the overall thermal deformation. For example, figure E2d.3b shows the calculated thermal strain of a specimen plotted using thermal expansion for temperatures above and below the glass transitions temperature (Mamlouk et al. 2005; Ojo et al. 2008). Plotting these results versus local temperatures (either inside or outside the specimen, or the average of the two measurements), yield a loop response while the cross-sectional average represents the true diving mechanism and

it eliminates the looping in the response. That is, experimental measurements must be combined with numerical modeling to properly evaluate the response the asphalt mixture system.

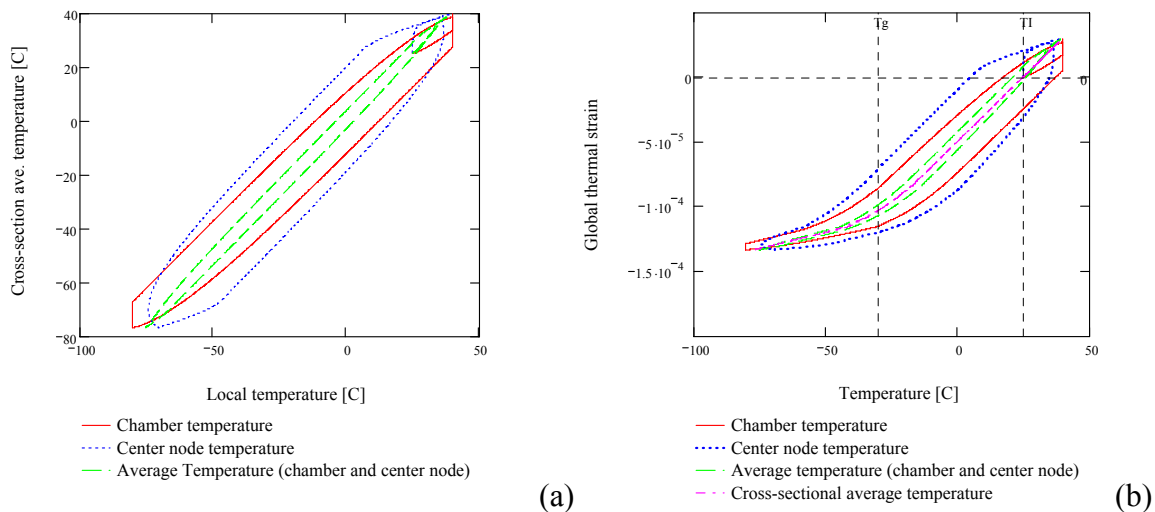


Figure E2d.3. Modeled (a) thermal temperatures and (b) strain. The selection of local or global temperatures for the evaluation of system response may control the data interpretation.

Year 2 Work Plan

During Year 2, the research team will continue working on the various experimental plans.

- The data from the LTTP sites will be analyzed and used in the development of the temperature profile algorithm for the intermountain region.
- The long-term oven aging of the binders will continue.
- The impact of aggregate properties on the aging of the binder will be completed.
- The impact of mixtures properties on the aging of the binders will start.
- The UW-M will improve the testing apparatus as shown in figure E2d.4. Efforts will be placed on securing access to a FTIR machine and run preliminary FTIR testing in order to evaluate the quality of the results obtained. Depending on these findings, a decision will be made whether to continue with the FTIR testing at the University of Wisconsin-Madison or contract it out to WRI. As part of the Year 2 work plan, the testing methodology for this instrument will be improved.

Year 2 Milestones

The following milestones will be realized in Year 2:

- Complete the analyzes of the LTTP data

- Analysis of the available data on the long-term aging of binders
- Evaluate the impact of aggregate properties on the aging of binders
- Develop an effective thermal test system for HMA

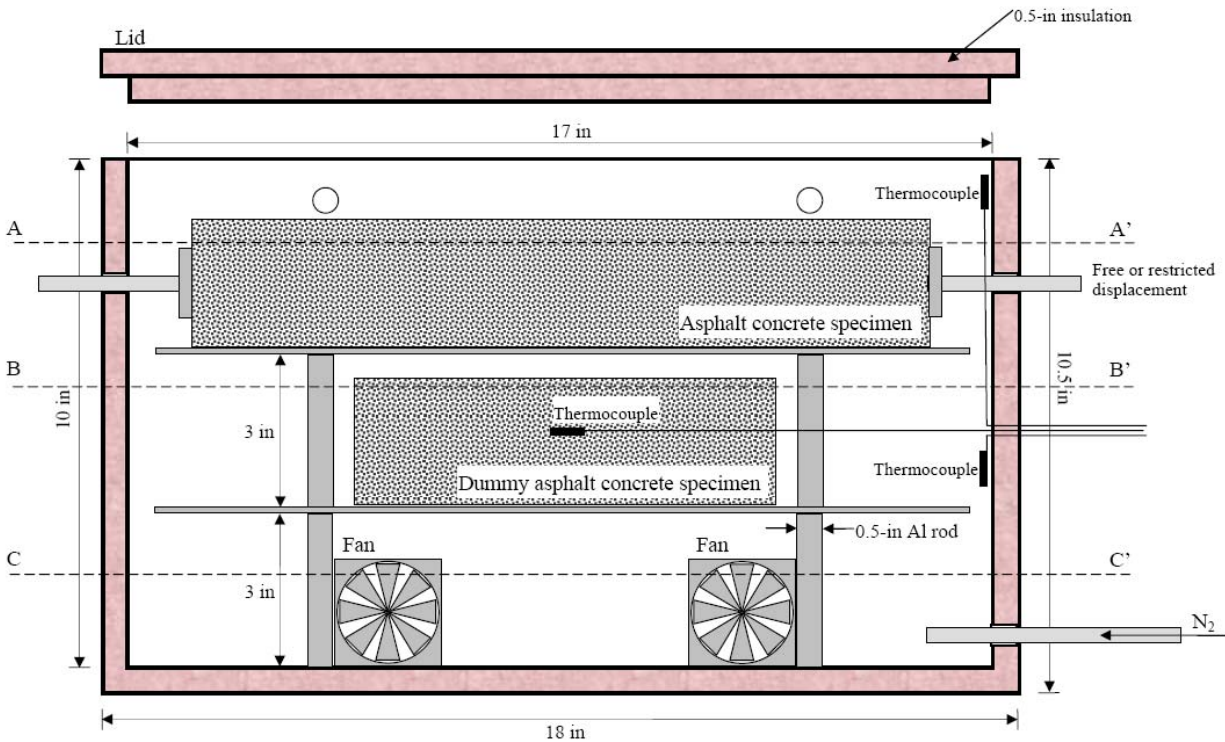


Figure E2d.4. View of the proposed improved thermal testing apparatus

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
E2d-1. Identify Field Sections	X	X			
E2d-2. Identify the Causes of the Thermal Cracking		X	X		
E2d-3. Identify an Evaluation and Testing System		X	X	X	
E2d-4. Modeling and Validation of the Developed System			X	X	X
E2d-5. Develop a Standard				X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
E2d-1. Identify Field Sections	X	X		
E2d-2. Identify the Causes of the Thermal Cracking	X	X	X	X
E2d-3. Identify an Evaluation and Testing System	X	X	X	X
E2d-4. Modeling and Validation of the Developed System				
E2d-5. Develop a Standard				

Budget

The estimated budget for this work element is \$750,000 for the University of Nevada and \$355,000 for the University of Wisconsin-Madison over the five years. Drs. C. Petersen and C. Glover will work as consultants for the University of Nevada and Drs. J. Epps and A. Hand from Granite Construction Inc. will provide a cost share contribution.

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Work element E2e: Design Guidance for Fatigue and Rut Resistance Mixtures

Subtask Lead: Dr. Donald W. Christensen, P.E.

Introduction

There is an urgent need to provide additional guidance to engineers concerning the design of fatigue and rut resistant mixtures. Excellent progress in understanding the relationship between mixture volumetric factors and pavement performance was made in National Cooperative Highway Research Program (NCRHP) Projects 9-25 and 9-31. In these projects, models based on volumetric composition and binder properties were developed for:

- Dynamic modulus
- Rutting resistance
- Fatigue cracking resistance
- Permeability

These models have been used to establish the general design criteria that are incorporated in the new Mix Design Manual for HMA that is being produced in NCHRP Project 9-33.

Further improvement of some of these models is needed to address specific shortcomings that were identified in subsequent validation efforts, and to expand the range of mixtures (nominal maximum aggregate size, compaction level, aggregate type, binder grade, modifier type etc.) used in the model development.

Relationship to FHWA Focus Area

This research effort supports the FHWA Focus Area of Optimize Pavement Performance.

Hypothesis

Models relating mixture composition and binder properties to performance can be used to design and evaluate HMA mixtures for high traffic levels.

Objective

The objective of this research is to develop a document containing supplemental design guidance for HMA mixtures for high traffic levels where a high resistance to rutting and fatigue cracking is needed. This document would supplement the general design guidance included in AASHTO M323 and the new Mix Design Manual for HMA being prepared in NCHRP 9-33. The design guidance will be based on improved models relating mixture composition and binder properties to pavement performance.

Experimental Design

The following subtasks will be completed in order to achieve the objective of this research effort.

Subtask E2e-1: Identify Model Improvements

The models that were developed in NCHRP Projects 9-25 and 9-31 were validated by AAT in NCHRP Project 9-33 using available data from test roads and accelerated loading facilities including: the FHWA ALF, MinnRoad, NCAT, and Westrack. Additionally some of the models have been independently evaluated by other researchers. In this subtask, the results from these validation and evaluation efforts will be reviewed to identify a prioritized list of model improvements that should be considered in this project.

Subtask E2e-2. Design and Execute Laboratory Testing Program

Based on the results of Subtask E2e-1 and the available budget, specific laboratory experiments will be designed to improve the existing model. These experiments will consider a range binders, modifiers, aggregates, mixture gradations, etc so that the resulting data can be used to develop robust models. Sufficient replication will be included to allow estimates of the precision of the resulting models to be made.

Materials for each experiment will be procured. The necessary laboratory testing will be performed and the results of the testing will be assembled into databases for subsequent statistical analysis.

Subtask E2e-3. Perform Engineering and Statistical Analysis to Refine Models

In this subtask engineering and statistical analyses will be performed to refine the models developed in NCHRP Projects 9-25 and 9-31. The primary analysis technique will be regression with the model parameters selected based on engineering principles so that the parameters have specific physical significance and are factors that can be controlled in HMA mixture design.

Subtask E2e-4. Validate Refined Models

The refined models will be validated using laboratory data from other sources and pavement performance data from various accelerated loading facilities, test roads, and the LTPP program.

Subtask E2e-5. Prepare Design Guidance

In this subtask a report providing guidance for the design of mixtures for high traffic applications will be developed. This report will be prepared as a supplement to the Mix Design Manual for HMA that is being developed in NCHRP 9-33. If appropriate, a Standard Recommended Practice for Design of Mixtures for High Traffic Levels will be prepared based on the report and submitted to the Mixtures and Construction Expert Task Group for consideration as an AASHTO Recommended Practice.

Major Findings from Year 1

Subtask E2e-1, Identify Model Improvement, is essentially complete and the findings from this Subtask have been used to prepare preliminary laboratory experiments addressing needed improvements for each of the models. The recommended improvements are summarized in table E2e.1 and described in greater detail in the following sections.

Table E2e.1. Summary of recommended improvements to the NCHRP Project 9-25 and 9-31 Composition to Engineering Property Models.

Model	Recommended Improvement
Hirsch Model for Dynamic Modulus	Curing time
	Low stiffness stress dependency
	Limiting maximum modulus
Resistivity Model for Rutting Resistance	Incorporate MSCR binder characterization
Continuum Damage Fatigue Model	Healing
	Damage tolerance
Permeability	Expand data set
	Aggregate size effect

Hirsch Model for Dynamic Modulus

Estimating the modulus of HMA is useful for a variety of purposes. It can serve as an aid during HMA testing, so that stress and strain levels can be properly set at the beginning of test procedures, including dynamic modulus, creep and fatigue testing. Estimates of $|E^*|$ values can be used in preliminary pavement designs, or for non-critical, low-volume pavement designs. Modulus estimates are also potentially useful in a variety of research situations, since many other HMA properties, such as fatigue resistance and rut resistance, are related to modulus.

The Hirsch model for estimating the modulus of hot-mix asphalt (HMA) was developed by engineers at Advanced Asphalt Technologies, LLC (AAT) as part of NCHRP Projects 9-25 and 9-31. It has been evaluated by several researchers independent of AAT and found to be more accurate and more rational than other similar models. There are however a number of improvements that can be made to the Hirsch model to improve its accuracy:

1. The modulus values of HMA specimens appear to gradually increase with time after specimen compaction. This is similar to curing of Portland cement concrete specimens, although not nearly as pronounced. This increase is probably due to a number of effects, including steric hardening of the asphalt binder, and continued, slow absorption of binder by the aggregate. The accuracy of the Hirsch model—and most other models for estimating HMA modulus values—could be significantly improved if the effect of curing time on HMA modulus could be at least approximately quantified.

2. Although it is generally assumed that the modulus of HMA is independent of stress level at relatively low stress levels, in reality, it is likely that some stress dependency exists even at very low stress levels at high temperatures and/or low loading frequencies/long loading times. The lower equilibrium modulus in the Hirsch model (and other similar models, such as the Witczak model) is assumed to be constant, but in fact probably varies slightly with stress level. The structure of the Hirsch model is such that this non-linearity can easily be accounted for if adequate data is collected to characterize typical stress dependency in HMA.
3. An important feature of the Hirsch model is the upper equilibrium modulus, or glassy modulus value. This is the maximum modulus value reached by an HMA at high frequencies/short loading times and/or low temperatures. The value of this limiting modulus is approximately 4 million psi. It is assumed constant in the Hirsch model, but as explained in item 1 above, probably varies somewhat with curing time. Another important factor affecting the glassy modulus of an HMA mix is the aggregate type used in the mixture. Theoretically, the maximum modulus for most HMA mixtures should be directly related to the modulus of the aggregate. Unfortunately, the data set used to develop the Hirsch model was not well suited for evaluating this effect. Being able to estimate the relationship between aggregate type and the glassy modulus of a mixture would significantly improve the accuracy of the Hirsch model.

Resistivity Model for Rutting Resistance

The resistivity/rutting model was developed during NCHRP Projects 9-25/9-31 as a way of relating HMA composition to rut resistance. The model predicts that rutting resistance increases with decreasing VMA, increasing aggregate surface area, decreasing in-place (or as tested) air voids), increasing design air voids, and increasing asphalt binder modulus or viscosity. The nature of the model is consistent with the results of other studies relating HMA composition and properties to rut resistance. The model is promising, with in-place rutting predictions within about a factor of two of observed values. However, the model does not deal well with modified binders; in order to obtain reasonable accuracy, an indicator value must be used to allow for significantly greater rut resistance for polymer-modified binders as compared to non-modified binders. Recently, the multiple-stress creep and recovery (MSCR) test has been proposed as an alternative to the standard dynamic shear rheometer (DSR) test for evaluating and specifying the properties of binders at the critical temperature for rutting, T_c . The MSCR test directly measures permanent and non-permanent deformation in a binder at two different stress levels, and potentially is much more useful in characterizing the flow properties of modified binders as they relate to HMA rut resistance.

Continuum Damage Fatigue Model

During NCHRP Projects 9-25, 9-31 and 9-33, a model for estimating the fatigue resistance of HMA mixtures was developed based upon continuum damage theory (CDT). The model related certain fundamental constants in the CDT fatigue model to various aspects of HMA composition,

including effective binder content, design and in-place/as tested air voids, and binder properties. The model was verified by independently predicting the results of flexural fatigue tests, with a degree of accuracy approaching that of typical fatigue tests. The CDT model is potentially very useful, and also can be applied in rapid laboratory fatigue testing of HMA mixtures. There are however two improvements needed in the CDT fatigue model in order to make it useful in predicting the performance of HMA mixtures in situ. These two improvements involve a better understanding of damage tolerance and healing. CDT does a very good job of predicting how the modulus of an HMA mixture degrades under continued loading. This is certainly important in understanding fatigue damage in flexible pavements, but it is not sufficient for a thorough understanding of this failure mode. CDT predicts the way modulus decreases due to micro-cracking and other forms of micro-damage. It does not address crack propagation, or even the point at which micro-cracks coalesce into a major flaw and crack propagation begins to occur. Damage tolerance refers to the amount of damage an HMA mixture can withstand before macro-cracking, or crack propagation occurs; this is often referred to as “localization” in CDT terminology. Healing is equally important to understanding the manner in which fatigue damage occurs in real flexible pavement systems. CDT tests are generally performed by applying a continuous sinusoidal load to a specimen. In real pavement system, loading is not continuous, but sporadic, with numerous opportunities for healing to occur in the HMA. Although some preliminary work with promising results has been performed on developing a practical model for modeling healing within the context of CDT, additional work is needed to verify the principle concepts of this model and to refine it.

Permeability

A model to estimate mixture permeability was also developed in NCHRP Projects 9-25/9-31. This model relates the coefficient of permeability to the air void content and surface area of the mixture. Since this model was developed, a substantial amount of additional permeability data has been published by other researchers. This additional data will be compiled and the model will be fit to the expanded database. Emphasis will be placed on quantifying the nominal size effect reported by other researchers.

Year 2 Work Plan

The laboratory testing program, Subtask E2e-2, will be initiated in Year 2 of the project and continue through Year 3. Preliminary experimental designs for each of the model improvements have been designed as described below.

Research To Improve the Hirsch Model for Dynamic Modulus

The objective of this work is to refine the Hirsch model by addressing three items: (1) curing time, (2) limiting modulus, and (3) stress dependency. The curing time experiment will involve $|E^*|$ measurements on a variety of HMA mixtures, over a range of temperatures and frequencies, at specific times—ranging from 1 day to several months. The limiting modulus experiment will involve testing a similarly broad range of mixtures, made with a wide range of aggregate types, but at high frequencies and low temperatures. The stress dependency experiment will also

involve testing a wide range of HMA mixtures, but in this case, the testing will focus on high temperatures and low frequencies, and will be done using a range of applied stress levels.

Hirsch Model Experiment 1: Curing Time Experiment

In this experiment, the change in $|E^*|$ values over time will be monitored for 6 to 10 different HMA mixtures. Dynamic modulus measurements will be made at temperatures of 4, 20 and 40°C, using a frequency sweep from 0.01 through 10 Hz. Three specimens from each mixture will be tested. Specimens will be stored at a temperature of $25 \pm 3^\circ\text{C}$, and tested at curing times of 1, 3, 7, 28 and 90 days. Potential aggregates to be included in this experiment include Pennsylvania limestone, Pennsylvania gravel, Pennsylvania greywacke/sandstone, Virginia limestone, Virginia diabase, and Virginia granite. Two different binder grades will be included in the experiment, a PG 64-22, and a polymer-modified PG 76-22. Data will be analyzed by plotting $|E^*|$ values as a function of curing time and developing simple mathematical models to characterize the change in modulus with time. Statistical methods will be applied to determine if observed differences in $|E^*|$ values with curing time, temperature, frequency, aggregate, etc., are statistically significant. Ultimately, the goal of this experiment is to develop a simple mathematical model that can be used in conjunction with the Hirsch model to account for the effect of curing time on modulus values of HMA concrete.

As discussed below, specimens prepared and tested during this experiment will also be used in the stress sensitivity experiment. A total of six specimens for each mixture will be prepared—three will be initially used in this experiment; once this is complete, they will be subjected to stress sensitivity testing. The other three will be tested after 7 days curing in the stress sensitivity experiment.

Hirsch Model Experiment 2: Limiting Modulus Experiment

The purpose of this experiment is to determine if the limiting (“glassy”) modulus of HMA is related to the modulus of the aggregate used, and if a simple approach can be developed to account for this variation in the Hirsch model. The working hypothesis of this experiment is that aggregate modulus can be related reasonably well to specific gravity and/or absorption values. To establish this relationship, a focused literature search will be performed using the internet and the library facilities at The Pennsylvania State University. The goal of this literature search will be to establish a reasonably good predictive model relating aggregate specific gravity and/or absorption to modulus. If such a relationship can be established, this experiment will move forward to laboratory testing. Laboratory testing will involve making dynamic modulus ($|E^*|$) measurements at the lowest possible temperatures and highest possible frequencies, while maintaining reasonable accuracy. Six to 10 mixes will be tested. The aggregates selected will exhibit a range of modulus values, as predicted using the relationship developed during the literature search. In order to ensure that the HMA modulus values are as high as possible, a single binder will be selected which exhibits unusually high low-temperature stiffness. Potential binder grades, for example, include PG 70-16 and PG 76-10. The objective of the data analysis will be to confirm the relationship determined in the literature search between aggregate specific gravity and/or absorption and aggregate modulus—aggregate modulus, in this case, being directly related to the observed limiting modulus of the HMA mixtures. Limiting modulus value

will be determined using a variety of approaches. One technique will involve plotting $|E^*|$ values vs. phase angle; the limiting $|E^*|$ value is then the value when the phase angle is zero. Another approach would be to fit the resulting $|E^*|$ data as a function of frequency to a function with a horizontal asymptote at high frequencies; the limiting modulus value is then the value of the horizontal asymptote. The final goal of the data analysis for this experiment is a simple mathematical function which can be used to estimate the aggregate modulus (as used in the Hirsch model) from the aggregate specific gravity and/or absorption. Specimens prepared for this experiment, once it is complete, will then be used in the stress sensitivity testing described below.

Hirsch Model Experiment 3: Stress Dependency Experiment

The objective of this experiment is to determine the effect of increased stress on the value of $|E^*|$ at high temperatures and/or low frequencies for a variety of mixtures. Tests will be performed at 40 °C using a frequency sweep of from 0.01 to 10.0 Hz, at three different stress levels, centered about the typical stress used for dynamic modulus tests at high temperature. As described above, the mixes tested will be those tested during Hirsch Model Experiments 1 and 2. Specimens from Experiment 2 will include (for each mixture) 3 specimens not used in the curing time experiment, tested for stress dependency at 7 days curing time, and 3 specimens tested after conclusion of the curing time experiment, after 90 to 120 days curing time. Specimens from each mix included in Experiment 3 will be tested for stress dependency after the conclusion of the low-temperature testing, at a curing time of 7 to 14 days. Data analysis will involve various mathematical and/or statistical techniques to determine the value of the lower limiting modulus, as a function of mix composition and applied stress level.

Research to Improve the Resistivity Model for Rutting Resistance

The purpose of this work is to determine if using data from the MSCR test in the resistivity/rutting model will improve its accuracy for all asphalt binders, modified and non-modified. The original resistivity/rutting model was formulated using viscosity as the binder input property, but the current model has been formulated to use $|G^*|/\sin \delta$ as the input property, in part to try to improve the effectiveness of the model in estimating the rut resistance of HMA made with polymer-modified binders. In this work, viscosity values calculated from the MSCR test at two applied stress levels (100 and 3,200 Pa) will be used as input in the resistivity/rutting model in predicting the rut resistance of various HMA mixtures, as characterized using the simple performance test/flow number test.

Six to 6 to 10 different binders will be characterized using the MSCR test. The majority of the binders tested will be modified, using a variety of different polymer types. Then HMA specimens made with these binders will be tested using the SPT/flow number test. For each binder, specimens will be prepared using two different aggregates; however, all binders will not necessarily be combined with the same two aggregates, so that a wide range of aggregate types can be included in the study. Testing will be done on three replicate specimens for each binder/aggregate combination.

Resistivity Model Experiment 1: MSCR Tests

In this experiment MSCR tests will be performed on 6 to 10 different asphalt binders. The majority of these binders will be modified, using various types of polymer, including SBS, Elvaloy, and PE. The standard protocol for the MSCR test, as promoted by the Federal Highway Administration (FHWA) will be followed. Standard PG grading will also be performed on the binders.

Resistivity Model Experiment 2: SPT/Flow Number Tests

In this experiment, SPT/flow number tests will be performed on various HMA mixtures made using the binders tested in Resistivity Model Experiment 1. Two different aggregates will be combined with each binder to produce two different HMA mixtures. A variety of aggregates will be used, including limestone, diabase and gravel. A total of 12 to 20 different HMA mixtures will be tested; three specimens will be tested for each mixture. Current standard protocols for the SPT/flow number test will be followed.

Data analysis will be performed as part of this experiment. This analysis will include calculation of viscosity values from the MSCR data and using this as input for the rutting/resistivity model to calculate estimated rutting rates. Flow numbers will then be compared to these estimated rutting rates, using graphical and statistical (regression) techniques. As a comparison, rutting rate predications will also be made using $|G^*|/\sin \delta$ values. The objective of the data analysis will be to determine if using the MSCR test data significantly improves the accuracy of the resistivity/rutting model for polymer-modified binders.

Research to Improve the Continuum Damage Fatigue Model

The purpose of this work is to refine the CDT fatigue model by addressing damage tolerance and healing. The proposed effort can be broken down into experiments: (1) Literature Review, (2) Uniaxial Fatigue Tests with Rest Periods, (3) Uniaxial Fatigue Tests to Localization, and (4) Data Analysis.

Experiment 1 will involve a review of research results of NCHRP 9-25, 9-31 and 9-33 pertaining to the CDT fatigue model. Other recent research publications pertaining to CDT, damage tolerance and healing will also be reviewed. Experiment 2 will involve uniaxial fatigue testing of 4 to 6 HMA mixtures with rest periods, to evaluate the effect of healing on damage accumulation. Experiment 3 will involve uniaxial fatigue testing carried out until localization occurs, so that the damage tolerance of each mixture can be characterized. Experiment 4 will consist of data analysis, which will focus on evaluating the current preliminary models for damage tolerance and healing, and refining them as needed.

Literature Review

In this experiment, Dr. Christensen will review various reports and publications dealing with the CDT fatigue model as developed during NCHRP Projects 9-25, 9-31 and 9-33. He will also review other recent publications dealing with CDT, damage tolerance and fatigue. The results of

this literature review will be summarized in a short report, approximately 10 to 20 pages in length, and including recommendations concerning revisions and/or refinements in this work plan.

Uniaxial Fatigue Tests with Rest Periods

In this experiment, uniaxial fatigue tests will be performed using different ratios of loading:rest periods. Tests will be performed at two temperatures, typically, 20°C and 4°C, although this may vary depending on the asphalt binder grade used in the HMA being tested. Three sets of tests will be performed: no rest periods, and with 1:2 and 1:4 loading:rest periods. Tests will also be performed at high and low strain levels. A total of four to six mixtures will be tested; these will each consist of a different aggregate and binder; a range of aggregate types and binder grades (including two polymer-modified binders) will be included in the mixtures tested. The specific test conditions will be determined based upon estimates of the fatigue properties of the HMA mixtures, once they are selected and designed.

Uniaxial Fatigue Testing to Localization

In this experiment, the same HMA mixtures tested in the rest period experiment will be subjected to fatigue loading until failure. Testing will be done at high and low temperatures (typically, 20°C and 4°C, although this may vary with binder grade). The strain level will start at a low level, and gradually increase, to ensure that damage will accumulate gradually and that localization will occur within a reasonable time. Specific test conditions will be determined on the basis of the results of the rest period experiment; this will ensure that test conditions are optimal for ensuring gradual accumulation of damage leading to localization within a reasonable time.

Data Analysis

This experiment will involve analysis of the data generated during the laboratory testing. CDT techniques will be used in analyzing data. The general concept will be to develop an effective model of damage rate as a function of the load:rest period ratio and other pertinent factors, such as binder rheological characteristics. Additionally, the observed damage tolerance, as indicated by the damage ratio at localization, will be related to various characteristics, such as modulus and phase angle for the binder and mix. The objective in both cases will be to develop simple models that can be used to predict the behavior of HMA both in the laboratory and in situ.

Research to Improve the Permeability Model

The objective of this work will be to improve the permeability model developed in NCHRP Projects 9-25/9-31 using published permeability test data from other studies. Since the permeability model was developed other research studies have reported permeability data on a wide range of mixtures. These data will be added to the current data base and the permeability model will be reformulated using the expanded data set. Particular attention will be placed on quantifying the effect of nominal maximum aggregate size on permeability. The work will

consist of two experiments: (1) compile permeability data from various publications, and (2) statistical analysis.

Compile Permeability Data

Several researchers have recently reported results from permeability testing. In this experiment, published permeability data will be located and added to the database originally developed in NCHRP Projects 9-25/9-31.

Statistical Analysis

A variety of statistical and graphical techniques will be used to analyze the expanded permeability data set and develop an improved model for predicting HMA permeability from mixture composition and mixture volumetric data.

Year 2 Milestones

No.	Description	Planned Date
1.	Complete Continuum Damage Literature Review	5/31/08
2.	Finalize Experimental Designs and Select Materials	6/30/08
3.	Collect Materials for Laboratory Testing	8/31/08
4.	Initiate Laboratory Testing	9/1/08
5.	Compile Additional Permeability Data	12/31/08
6.	Complete Permeability Model Development	3/20/09

Overall Schedule

Subtask	Year 1	Year 2	Year 3	Year 4	Year 5
E2e-1. Identify Model Improvements	X				
E2e-2. Design and Execute Laboratory Testing Program	X	X	X		
E2e-3. Perform Engineering and Statistical Analysis to Refine Models			X	X	
E2e-4. Validate Refined Models				X	
E2e-5. Prepare Design Guidance					X

Year 2 Schedule

Subtask	Qtr 1	Qtr 2	Qtr 3	Qtr 4
E2e-1. Identify Model Improvements	This was completed in Year 1			
E2e-2. Design and Execute Laboratory Testing Program	X	X	X	X
E2e-3. Perform Engineering and Statistical Analysis to Refine Models				X
E2e-4. Validate Refined Models				
E2e-5. Prepare Design Guidance				

Budget

The estimated budget for this work element is \$371,500 over the five years. The work will be conducted by Advanced Asphalt Technologies, LLC.

PROGRAM AREA: VEHICLE-PAVEMENT INTERACTION

The interaction between pavement surface and the loading vehicle plays a significant role in both the structural performance (i.e. resistance to fatigue, rutting, and moisture damage) and functional performance (i.e. resistance to skid, noise, and roughness) of pavements. The interaction at the tire-pavement interface represents the final link in the vehicle pavement interaction system, and it controls the distributions of both normal and shear stresses that are transferred to the pavement structure. The loads generated by the moving vehicle are dynamic in nature, and they invoke a dynamic response from the pavement structure which is greatly impacted by the inertia of the pavement structure and the viscoelastic behavior of the hot mix asphalt (HMA) layer.

The more accurate and more realistic predictions of the stresses at the tire-pavement interface and pavement responses under dynamic vehicle loads offer numerous advantages to the FHWA Strategic Roadmap and to the entire pavements/materials engineering community.

The Consortium will work on three elements of vehicle pavement interaction: (a) Workshop on Super-Single Tires, (b) Pavement Response Model Based on Dynamic Analyses, and (c) Mix design to enhance safety. The Workshop on Super-Single Tires will be conducted in the first year while the other two elements will start in year 2.

Category VP1: Workshop

Work element VP1a: Workshop on Super-Single Tires

This effort will organize and hold a workshop on super-single tires usage and their impact on highway pavements. The University of Nevada will work with FHWA to organize the workshop. The following guidelines will be followed:

- The workshop will be held in October, 2007 in the U.S.A.
- The total number of workshop participants will be 12.
- FHWA will supply a list of potential participants.
- UNR and FHWA will identify the final list of participants.
- UNR will invite the workshop participants.
- Participants will make their own travel arrangements.
- UNR will cover travel expenses for the invited participants.
- UNR will prepare a summary of the workshop.

Major Findings from Year 1

The workshop was held at the FHWA Turner-Fairbank Highway Research Center (TFHRC) in McLean, VA on October 25 and 26, 2007. The minutes of the meeting will be published on the Consortium website, www.ARC.unr.edu, after they are forwarded from FHWA.

Year 2 Work Plan

There is no activity planned for year 2.

Budget

The cost for the workshop will be covered by the UNR budget and will be no more than \$50,000.00.

Category VP2: Design Guidance

Work element VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA

Task Lead: Dante Fratta

Introduction

One important emphasis of the new transportation bill is safety. Although safety, comfort, and noise control are known to be direct functions of macro- and micro-texture, there are no significant efforts on integrating these design parameters into asphalt pavement mixtures (Bernhard and Wayson 2005; Guisik and Bahia 2006). It is also not well known if binders and mastics can change friction characteristics and pavement sound generation and absorption. University of Wisconsin-Madison researchers have been working with a number of DOTs in the Midwest to look at new procedures for measuring macro- and micro-texture and enhancing the methods for estimating micro-texture.

Micro-texture is the fine-scale (≤ 1 mm depth) grittiness on the surface of the coarse aggregates. The micro-texture makes direct tire-pavement contact and thus provides the resistance to skidding on the prevailing road surface. Macro-texture is the large-scale roughness that is present on the pavement surface due to aggregate arrangements and provides the drainage ability of the pavement. The combination of macro- and micro-textures, and their changes with traffic and climate factors, make up the overall resistance to skidding. Furthermore, the proper macro-texture contributes to the reduction of roadway noise. Quiet pavement-tire systems have been implemented in Japan and many European countries because of the strong regulatory framework created by the European Community (EU). Several innovative techniques employed in Denmark, the Netherlands, France, Italy, and the United Kingdom have been able to reduce noise level in ranges that vary from 3 to 17 dB (Danish Road Institute 2005; Gibbs et al. 2007). Promising noise-reduction techniques include the use of porous elastic pavements (e.g., single and double layers porous asphalt, stone mastic asphalt, silent block pavements, etc.), recycled

porous layers, emulsified asphalt concrete surfacing, use of a dense or semi-dense gradation in low-to-medium speed traffic roadways, and texturing of newly constructed concrete pavements for enhanced skid resistance and reduced pavement-tire noise.

This work element will focus on evaluating and modifying mixture design procedures to enhance safety and noise-reduction properties of asphalt mixtures for flexible pavements. In particular, this work element will develop a laboratory test procedure or a prediction model for the evaluation of macro- and micro-textures of asphalt pavements. It will also focus on comparing these measurements with field measurements of skid resistance and pavement-tire noise. Results from this work will evolve into the development of pavement mixture design protocols that will not only include structural strength and durability, but also traffic safety, comfort and reduced pavement-tire noise.

Relationship to FHWA Focus Areas

This research effort supports the following FHWA Focus Areas:

- Advanced Quality Systems: Further development of test methods and design procedures that are more related to actual pavement performance.
- Environmental Stewardship: Reducing noise of pavements is an environmental issue.

Hypothesis

The mixture design of asphalt mixtures (including binder types and aggregates) can be revised to include procedures to enhance driving safety and comfort while reducing noise generation. A holistic pavement mixture design protocol can incorporate mechanical strength, durability, safety, and improved roadway environment (noise) properties of asphalt mixtures.

Objectives

The overall objectives of this work element are:

- To study the state of the art on pavement-tire friction coefficient and quiet pavement-tire design techniques.
- To develop a surrogate laboratory test to measure pavement macro- and micro-texture and predict safety and noise related properties.
- To establish criteria for the holistic mixture design protocol that optimizes mechanical properties, durability, skid resistance, and noise generation.

The final result of this work element will be the development of a mixture design protocol that will incorporate macro- and micro-structure of mixtures that produce pavement surface layers with enhanced frictional response while reducing pavement-tire noise levels.

Experimental Design

In order to achieve the objectives this work element the following subtasks will be completed.

Subtask VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics

A literature review of the salient physical and mechanical characteristics of the pavement mixtures with improved skid characteristics will be collected to document the overall properties of asphalt pavements designs. Emphasis will be placed on aggregate properties and binder requirements for mixture types that improve not only frictional skid properties but also reduce cost and improve durability and comfort. Examples are Open Graded, Porous Asphalts, and Pavement Friction Courses. The most recent NCHRP reports and worldwide literature will be covered.

Subtask VP2a-2: Evaluate pavement macro- and micro-textures and their relation to tire and pavement noise-generation mechanisms

There are a number of tire-pavement noise generation (e.g., thread vibration, air pumping, slip stick, and stick snap) and noise enhancement mechanisms (Bernhard and Wayson 2005). Quiet noise designs typically address these two issues and include surface textures of less than 10 mm, below surface textures, greater porosity (to reduce high frequency noise), and elastic surfaces. A complete literature review will be performed on both traffic noise generation mechanisms and noise reducing designs. Emphasis will be placed in technologies that reduce traffic noise in more than 5 dB and have a durability of more than 15 years. The results of this task will be compiled and evaluated along with the results from Task 1 to select best practices for pavement mixtures with enhanced skid friction behavior and reduced noise generation.

Subtask VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macro- and micro-texture of pavements

Currently there is no system capable of measuring texture profiles for a laboratory-prepared sample. Because of the difficulty in measuring micro-texture profiles, a surrogate for measuring micro-texture is required. The development of such a procedure would enable researchers and engineers to estimate macro- and micro-texture of pavements in order to predict both the dry and wet frictional skid and/or noise reduction designs of pavements. The developed laboratory testing protocol will be correlated to traditional texture tests.

Subtask VP2a-4: Run parametric studies on tire-pavement noise and skid response

Using the data collected in Subtasks VP2a-1 and VP2a-2 and the laboratory testing protocol developed in Subtask VP2a-3, a set of parametric studies for different pavement mixtures will be performed to evaluate the correlation between measured macro- and micro-textures and the skid resistance and pavement-tire noise levels. The pavement mixtures to be tested in this task will be selected in coordination with consortium research activities performed parallel to this work element. This will be done not only to evaluate noise-reducing pavement mixture design, but

also to incorporate construction cost and durability in the pavement system design and help create a more holistic pavement mixture design protocol.

Subtask VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis

To complement the capabilities of the consortium with other expertise available in the country, the University of Wisconsin-Madison researchers will reach to nationally recognized laboratories and centers. A leading example is Purdue University's Institute for Safe, Quiet and Durable Highways. This institute's expertise on measurement and analysis will be leveraged to enhance the development of quiet pavement mixture designs. The University of Wisconsin-Madison researchers will establish collaboration initiatives to allow measuring the pavement-noise levels obtained with proposed holistic pavement mixture designs.

Subtask VP2a-6: Model and correlate acoustic response of tested tire-pavement systems

Results obtained in Subtasks VP2a-4 and VP2a-5 will be correlated to pavement mixture design parameters (e.g., gradation, maximum aggregate size, angularity, binder type, etc.). The obtained physical/engineering correlations will be used to constrain numerical models for the evaluation of frictional skid, noise generation mechanisms and pavement/tire noise-reduction designs. These results will be incorporated into a new asphalt mixture design protocol.

Subtask VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs

The parametric studies performed and the correlations and models obtained from previous tasks will be analyzed in combination with other work items in the consortium to maximize research resources and the use of the developed data and expertise. These parametric studies and designs will help in the development of improved frictional and noise-reducing mixture designs while maintaining/increasing comfort and reducing construction costs. State DOTs and nationally recognized laboratories and centers will be contacted to collect feedback about the practicality and the merits of the holistic pavement mixture designs.

Major Findings from Year 1

During Year 1, the materials and testing conditions for the plan were selected and are shown in table VP2a.1. In addition, the proposed tests on these materials are shown in table VP2a.2.

The University of Wisconsin-Madison research team performed an extensive literature review of the state of the art in the areas of skid resistance and quiet pavement. Emphasis was placed on evaluating commonality of parameters that have shown in practice to enhance skid resistance. The evaluation of parameters has helped not only in establishing the commonality of interacting factors, but it also helped in developing areas of research needs. A preliminary summary table is presented in table VP2a.3.

The research team has also evaluated different testing methodology for the characterization of surface parameters and acoustic properties of pavement mixtures.

Table VP2a.1. Matrix of materials and conditions.

Neat Binders	PG 58-28	Maximum Aggregate Size	19 mm
	PG 64-22		12.5 mm
Modifiers	SBS		9 mm
	Crumb Rubber		4.75 mm
Mineral Aggregates	Limestone	Aggregate Angularity	Cubical
	Sandstone		Rounded
Aggregate Gradation	Coarse		
	Fine		
	Gap-graded		

Table VP2a.2. Proposed tests on asphalt binders and mixes.

Skid resistance	Skid friction: Modified British Pendulum (dry and wet surfaces)	Noise Absorption	Noise absorption: Waveguide (dry and wet surfaces)
	Surface characterization: Surface profiling		
	Surface characterization: Sand Patch (index tests)		

Acoustic properties of asphalt mixtures: The established parameter for laboratory measurement of acoustic properties is the sound absorption behavior pavement mixtures.

To evaluate the sound absorption behavior of pavement surfaces, the research team is evaluating and designing an impedance tube (waveguide device) that will allow the testing of different asphalt mixture specimen geometries (6-in diameter specimens and slab specimen). The geometry and testing geometry that is being favored is the one proposed by NCAT (Sound absorption setup) (Hanson et al. 2004; Crocker et al. 2004), as this geometry allows testing of both specimen types.

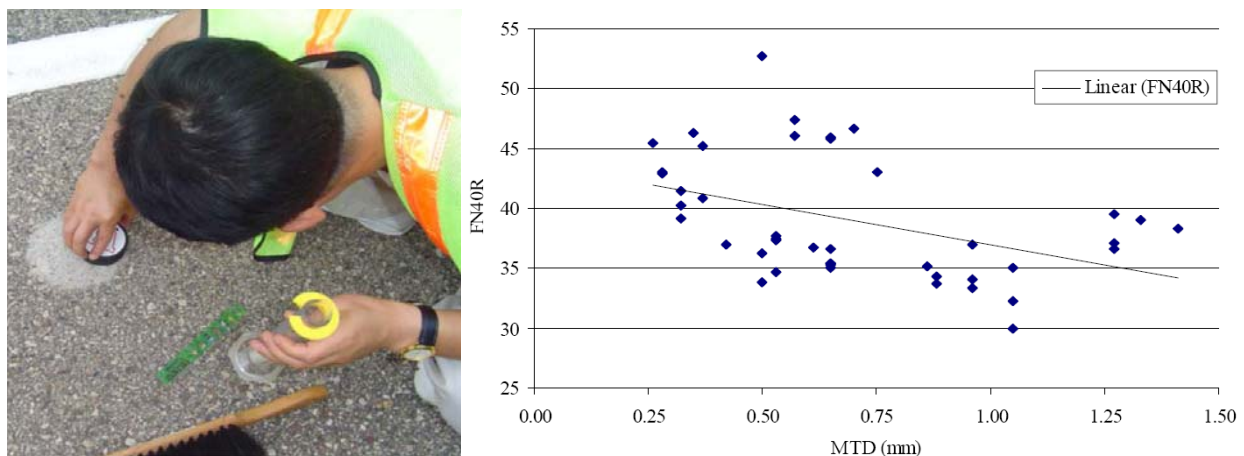
This test will allow the evaluation of the acoustic properties of a large number of pavements mixtures, specially those mixtures that have the desirable strength and dynamic properties of pavements. Finally, to indirectly evaluate the sound absorption properties of asphalt pavements, permeability tests should be run to determine not only the acoustic absorption but also the drainage properties of the pavement. Drainage properties are important in the evaluation of skid friction and the aquaplaning susceptibility of the pavement surface.

Table VP2a.3. Asphalt mixture parameters and performance factors (taken from various sources shown in the References section of this document).

	Rutting Resistance	Fatigue Resistance	Moisture Damage Resistance	Thermal Cracking Resistance	Economy	Skid Resistance	Noise Reduction
Gradation (fine/coarse)	High number of contact points within the mix provide high internal friction that resists permanent deformation.	Gradations that have greater resistance to deformation distribute stresses more evenly and results in less damage from bottom-up cracking.			Fine aggregates are typically more cost effective. However, gradation affects aggregate structure in the pavement, controlling the compactive effort needed.	Coarse gradation increases skid resistance	Higher proportion of fines makes for smoother and quieter surfaces.
Aggregate angularity	High aggregate interlock provides a more structurally stable material that results in stiffer mixes	High aggregate interlock provides a more structurally stable material that results in stiffer mixes			Crushed aggregates are typically more expensive due to processing costs.	Increase angularity increases skid resistance	Smoother aggregates create less tire vibration from adhesive effects.
Aggregate mineralogy			Mineralogy controls hydrophilic (moisture susceptible) or hydrophobic (moisture resistance) of aggregates		Softer aggregates are cheaper to process. Availability of the type of aggregate ultimately drives price, however.		
Maximum aggregate size						Uniform gradation distribution may lead to denser structures and smoother surfaces that may yield lower drainage and reduced skid friction.	Smaller aggregates provide quieter characteristics due to smoother surfaces.
Binder properties	Superpave binder specifications are in place in order to ensure the binder is stiff enough at operating temperatures to resist permanent deformation	Binder can be highly susceptible to fatigue damage. Binders that have a combination of high damage resistance and high healing potential typically lead to good fatigue resistance.		Binder should be ductile at low temperatures in order to relax the stresses induced from thermal restraint. Also, aggregates themselves have no tensile strength, so the tensile strength added by the binder is mostly responsible for resistance to tensile thermal cracking.	Stiffer binders increase compactive effort at similar temperatures, so increased heating is needed to achieve the correct viscosity.		
Asphalt content	Low asphalt contents, known as "dry" mixes, are typically thought of to be more rutting resistant due to less lubrication between the aggregates due to the binder.			The asphalt content should control the expansion and contraction thermal coefficients.	Higher asphalt content increases cost of mix.		
Additives	Many additives are available to stiffen the binder at operating temps, which adds strength to the pavement.	Some polymer additives can add fatigue resistance to materials		Polymers that add ductility to the asphalt can help prevent brittle failure.		Unclear	High damping additives, such as elastic polymers and crumb rubber, have been used to aid in the dissipation of vibration energy. Also, polymers may be used in high void mixes to help increase structural stability.

Skid resistance characteristics. There are a number of both direct and indirect testing techniques to evaluate the skid friction properties of pavements. The direct testing techniques measure the friction coefficient (or a related parameter) of the pavement surfaces. These testing methodologies include the British pendulum (BP) (Liu et al. 2003; Noyce et al. 2007) and dynamic friction tester (DFT) (Brown et al. 2001). The research team will most likely favor the use of the British pendulum as it has simpler geometry for the monitoring of skid resistance on different asphalt mixtures. The instrument will be modified to accept the standard 150 mm-diameter geometry produced by the Superpave gyratory compactor, allowing the research team to evaluate the skid resistance characteristics of standardized asphalt mixture specimens.

Indirect methods include, for example, the sand patch method (SPM) (ASTM E965), circular texture meter (CTM) (Hanson and Prowell 2004), and Ames texture scanner (ATS) (Ames Engineering 2007). The SPM is an indirect and inexpensive measurement technique of the asphalt pavement surface macrostructure. The biggest problem with this methodology is that SPM yields an index parameter (mean texture depth – MTD) that may or may not be able to describe the complexity of the skid friction and noise generation and absorption (figure VP2a.1). Alternatively, the circular texture scanner and the Ames texture scanner use laser profilometry to completely profile the surface of the pavement. These profiling methodologies yield a number of surface measurement parameters that can be used to better correlated noise and skid friction behavior of asphalt pavements but at a greater cost. These portable instruments cost more than \$12,000 per unit.



defined, the research team will develop a testing matrix to evaluate how binder and texture contribute to the design of skid resistant and quiet pavement surface.

The evaluation of the data will be separated by skid resistance and quiet pavement characteristics. For the skid resistance, surface of asphalt pavements will be characterized with both a comprehensive (e.g., surface profiling parameter) and an index test (e.g., sand patch test), and these results will be correlated with direct skid resistance-measured parameters such as British pendulum tests. For quiet pavement behavior, the frequency analysis of noise generated and acoustic absorption will be evaluated by trying to match surface characteristics and mixture microstructures to be able to establish characteristics to reduce noise generation at the source. One of the surface parameters to be analyzed is the effect of negative and positive surface textures on both skid friction and quiet pavement behavior (e.g., noise generation and absorption – Newcomb and Scofield 2004).

Figure VP2a.2 depicts the research approach defined for this work element.

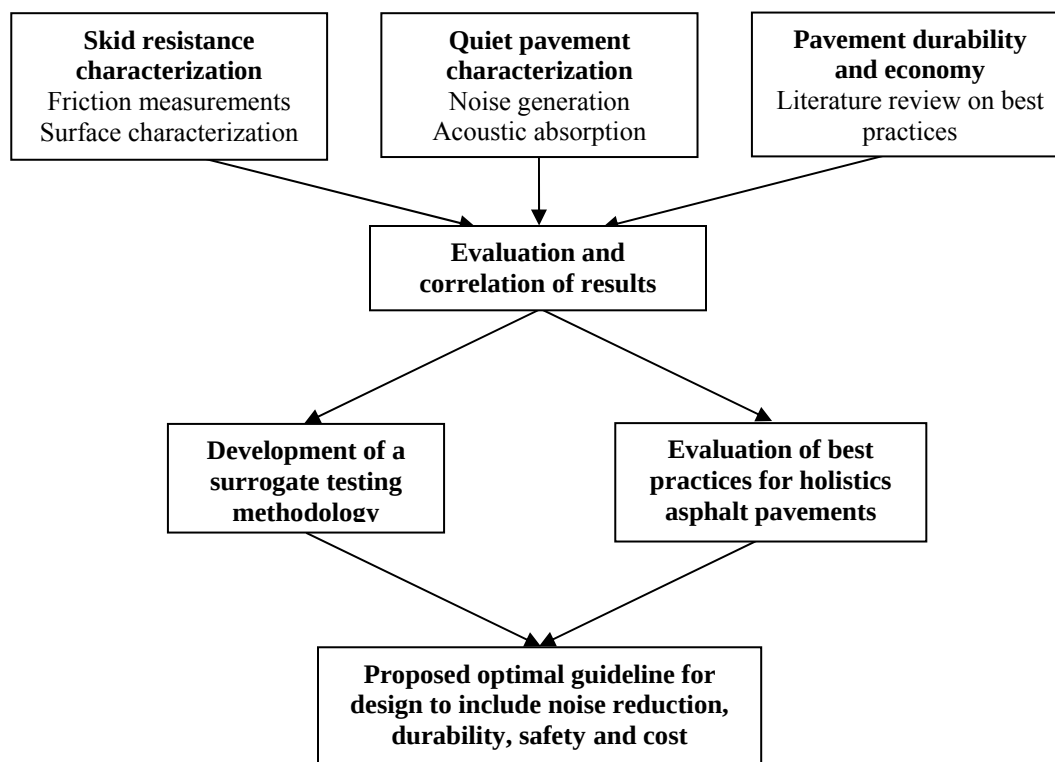


Figure VP2a.2. Chart. Flow chart for research approach.

Year 2 Milestones

- Complete report on review of literature
- Start tests on textures of materials
- Establish a lab test protocol
- Start running parametric studies on tire-pavement noise and skid response

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Evaluate common physical and mechanical properties	X	X			
ii. Evaluate pavement macro- and micro-textures	X	X			
iii. Develop a laboratory testing protocol		X	X		
iv. Run parametric studies		X	X		
v. Gather expertise on measurements and analysis		X	X		
vi. Model and correlate acoustic response			X	X	
vii. Proposed optimal guideline for design				X	

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
i. Evaluate common physical and mechanical properties	X	X	X	
ii. Evaluate pavement macro- and micro-textures	X	X	X	
iii. Develop a laboratory testing protocol	X	X	X	X
iv. Run parametric studies	X	X	X	X
v. Gather expertise on measurements and analysis				X
vi. Model and correlate acoustic response				
vii. Proposed optimal guideline for design				

Budget

The estimated budget for this subtask is \$200,000 over the four years. The work will be conducted by the University of Wisconsin-Madison.

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Work Element VP3a: Pavement Response Model to Dynamic Loads

Work element Lead: Peter Sebaaly

Introduction

The interaction between pavement surface and the loading vehicle plays a significant role in both the structural performance (i.e. resistance to fatigue, rutting, and moisture damage) and functional performance (i.e. resistance to skid, noise, and roughness) of pavements. The interaction at the tire-pavement interface represents the final link in the vehicle pavement interaction system, and it controls the distributions of both normal and shear stresses that are transferred to the pavement structure. The loads generated by the moving vehicle are dynamic in nature, and they invoke a dynamic response from the pavement structure which is greatly impacted by the inertia of the pavement structure and the viscoelastic behavior of the hot mix asphalt (HMA) layer.

The normal and shear dynamic stresses that are generated at the tire-pavement interface control the pavement response in terms of the stresses, strains, and deformations that are generated throughout the pavement structure. The tensile strains generated at the bottom of the HMA layer control the fatigue performance of the HMA pavement. The compressive stresses and strains generated throughout the various pavement layers (i.e. HMA, base, and subgrade) greatly influence the rutting performance of the HMA pavement. The shear stresses and strains generated within the HMA layer greatly control the shoving performance of the HMA pavement at intersections, on off-ramps, and at facilities that service slow moving heavy loads such as seaports and airports. The shear stresses at the tire-pavement interface play a major role in the friction resistance of the HMA pavement. In fact, the higher the shear stress the more friction will be developed at the tire-pavement interface, however, the higher shear stress will require an HMA mix that is more resistant to shear.

Relationship to FHWA Focus Areas

This research effort supports the FHWA Focus Areas of Pavement Surface Characteristics and Optimize Pavement Performance.

Hypothesis

The dynamic nature of the traffic loads coupled with the viscoelastic nature of the HMA mixture have significant impact on the performance of flexible pavements and must be properly considered in the analysis and design of such pavements.

Objectives

The objective of this effort is to develop a model to predict dynamic loads of moving vehicles and their effect on the response of flexible pavements. The proposed model will be used to conduct pavement analyses under special loading conditions such as: intersections and off-ramps, heavy loads at ports, and off-road equipment on highway pavements.

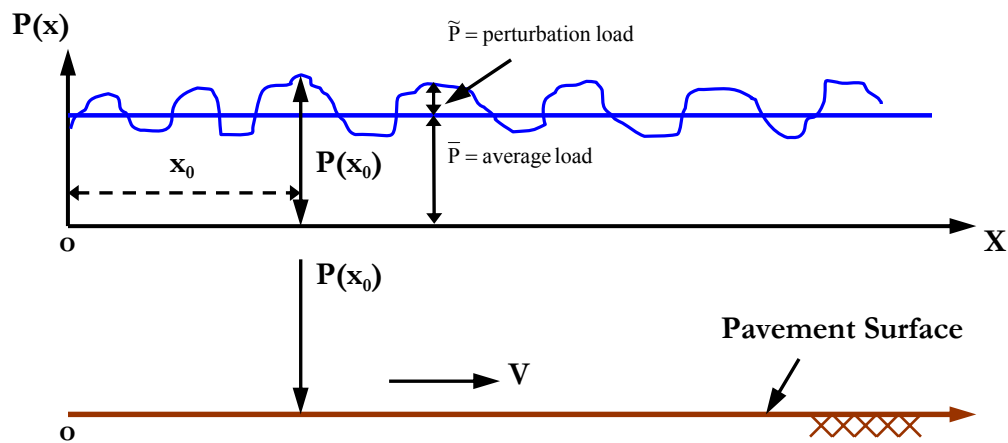
Experimental Design

The proposed model has three major components: dynamic loads, tire-pavement interface, and pavement response. The following subtasks describe the work to be conducted under each of the components.

Subtask VP3a-1: Dynamic Loads

The dynamic loads generated by truck traffic moving at certain speed are impacted by the following factors: truck suspension, road roughness, and speed. The combination of all four factors controls the magnitude of the dynamic loads that are delivered by a moving truck to the pavement surface.

Previous research efforts by FHWA and others showed that the dynamic load can be fully described by two components: nominal static wheel load and the standard deviation of perturbation load as described in figure VP3a-1.1. The dynamic load coefficient (DLC) is defined as the ratio of the standard deviation of the perturbation load over the nominal static load. Previous research efforts by FHWA and others had measured the DLC for various combinations of suspension, speed, and road roughness as shown in table VP3a-1.1.



Perturbation load in terms of dynamic load coefficient (DLC)
(Leblanc & Woodrooffe, 1995)

$$DLC = \frac{\text{Standard deviation of perturbation load}}{\text{Average or nominal static wheel load}}$$

Figure VP3a-1.1. Distribution of dynamic loads along a pavement section.

Table VP3a-1.1. DLC for different tractor suspension (Woodrooffe & LeBlanc).

Vehicle Speed km/h	Tractor Suspension Type								
	Air Bag			Four Spring (Leaf Spring)			Rubber Spring Walking Beam		
	S*	A*	R*	S	A	R	S	A	R
40	0.03	0.04	0.05	0.04	0.05	0.08	0.04	0.08	0.08
60	0.04	0.06	0.08	0.04	0.08	0.09	0.04	0.08	0.11
80	0.05	0.09	0.10	0.07	0.13	NA	0.07	0.22	0.25
40	0.03	0.04	0.05	0.04	0.05	0.08	0.04	0.08	0.08
60	0.04	0.06	0.08	0.04	0.08	0.09	0.04	0.08	0.11
80	0.05	0.09	0.10	0.07	0.13	NA	0.07	0.22	0.25
40	0.03	0.04	0.05	0.04	0.05	0.08	0.04	0.08	0.08
60	0.04	0.06	0.08	0.04	0.08	0.09	0.04	0.08	0.11
80	0.05	0.09	0.10	0.07	0.13	NA	0.07	0.22	0.25

* S = Smooth road; A = Average road; R = Rough road

Using the DLC data, the dynamic load at the tire-pavement interface can be estimated for any combination of suspension, speed, and road roughness. The next step will be to evaluate the impact of braking on the dynamic load at the tire-pavement interface. This is done by imposing the equilibrium dynamic equations of a truck moving at a constant speed and approaching a stopping condition over a pavement surface having a certain downward or upward slope. Solving the dynamic equilibrium equations will result in the distribution of dynamic loads on the various tires.

The objective of this subtask is to develop a system by which the pavement engineer can estimate the dynamic loads at the tire-pavement interface under any of the following combinations of conditions:

- Truck suspension type
- Truck speed
- Road roughness
- Braking conditions
- Pavement slope
- Truck type (single vs multi units)

Not all combinations of the above factors will be applicable for every situation. For example the dynamic loads generated by a truck traveling on a freeway will only be impacted by the suspension, speed, and roughness. On the other, the dynamic loads generated by a truck approaching a stopping condition on an off-ramp will be impacted by the pavement slope and the characteristics of the brake system.

This subtask will use all the available data from previous research conducted by FHWA and others to build a database that includes all available information on the impact of the various

factors on the dynamic loads at the tire-pavement interface. The database will then be incorporated into the overall Pavement Response Model.

Subtask VP3a- 2: Stress Distribution at the Tire-Pavement Interface

The objective of this subtask is to define the distribution of normal and shear stresses at the tire-pavement interface. The distributions of the stresses at the tire-pavement interface are influenced by the following factors: load, tire type, and tire inflation pressure.

Previous research activities by FHWA and others have measured the distributions of the stresses at the tire-pavement interface for various tire types under multiple levels of loads and tire inflation pressure. This task will develop a database of all the available information on the distributions of stresses at the tire-pavement interface.

Subtask VP3a-3: Pavement Response Model

In order to properly simulate the impact of dynamic loads generated and delivered by traffic vehicles moving at various speeds on the response of the HMA pavement structure, a dynamic model of the multi-layer pavement structure must be used. The existing static multi-layer elastic solutions suffer from a multitude of limitations which make their ability to predict pavement responses very limited and less accurate. Some of these limitations include: the use of static uniform circular loads at the tire-pavement interface, the use of static elastic properties of the HMA layer, and ignoring the influence of vehicle speed and the inertia of the pavement structure. The finite-element and finite-layer theories are the two commonly used methods to simulate the dynamic behavior of the pavement structure. Such methods incorporate the non-uniform and non-circular normal and shear stresses at the tire-pavement interface, pavement inertia, and the viscoelastic properties of the HMA layer along with the dynamic nature of the moving loads to estimate the stresses, strains, and deformations generated throughout the pavement structure.

The proposed model is based on continuum-based “finite-layer” theory. The HMA layer is characterized as a viscoelastic material, while the base and subgrade layers are characterized as elastic materials. The normal and shear stresses at the tire-pavement interface can be modeled with any shape and any distribution. The vehicle loads are simulated as moving loads at a constant speed. The analytical model treats each pavement layer as a continuum and uses Fourier transform techniques to handle the complex normal and shear stresses at the tire-pavement interface.

Subtask VP3a-4: Overall Model

The objective of this subtask is to combine the three major components (i.e. dynamic loads, stress distributions at the tire-pavement interface, and the pavement response model) into an overall model that is capable to predict pavement responses to dynamic loads with the following characteristics: public domain, time efficient, user-friendly, and applicable to a wide range of problems.

The magnitude of vehicle dynamic loads will be provided by the database developed under Subtask VP3a-1. The stress distributions at the tire-pavement interface will be provided by the database developed under Subtask VP3a-2. And the pavement response model will use the theory developed under Subtask VP3a-3. This subtask will deliver a menu-driven computer software that combines all the components that have been described in the Subtasks along with the appropriate user manuals and training materials.

Major Findings from year 1

This work element did not start in Year 1.

Year 2 Work Plan

During Year 2, the research team will start on developing the electronic databases for the pressure distributions at the tire-pavement interface and the dynamic load coefficients.

Year 2 Milestones

The following milestones will be realized in Year 2:

- Identify the available data on the pressure distribution at the tire-pavement interface
- Identify the available data on the dynamic loads coefficients

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
Subtask VP3a-1: Dynamic Loads		X	X		
Subtask VP3a- 2: Stress Distribution at the Tire-Pavement Interface		X	X		
Subtask VP3a-3: Pavement Response Model			X	X	
Subtask VP3a-4: Overall Model			X	X	

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
Subtask VP3a-1: Dynamic Loads	X	X	X	X
Subtask VP3a- 2: Stress Distribution at the Tire-Pavement Interface	X	X	X	X
Subtask VP3a-3: Pavement Response Model				
Subtask VP3a-4: Overall Model				

Budget

The estimated budget for this work element is \$300,000 over the five years. The work will be conducted by the University of Nevada.

PROGRAM AREA: VALIDATION

INTRODUCTION

The concept of Validation may encompass several different areas. In the process of taking a fundamental scientific or engineering principle from theory to general use, there are many steps involved. Initially, the experimental process has to be developed and refined such that the experimental method can distinguish between different materials and provide useful information. As the method progresses toward development, the sample set to which the method is exposed generally expands to a much more diverse set. This expansion of the tested sample set is a form of validation. In this project, the application of a test method or procedure to a larger, more diverse sample set is considered to be development, rather than validation, although either label may be appropriate to describe this type of research activity.

Another type of Validation is the use of larger scale test facilities that incorporate a variety of materials in an accelerated loading environment. The accelerated loading is often accomplished using a large-scale load frame such as the ALF (Accelerated Load Facility) at the FHWA Turner-Fairbank Highway Research Center. Accelerated loading at larger scale facilities may also be accomplished by using full or partial scale load vehicles such as the third-scale model mobile loading simulator at Texas Transportation Institute. Some of the advantages of using larger scale accelerated facilities are that the testing is more representative of actual pavement loading compared with laboratory loading devices. The pavement materials used in larger scale loading facilities are generally produced with standard construction equipment using standard construction techniques, and the test sections may be highly instrumented in order to acquire the necessary data. As might be expected though, temperature control during testing is less precise than a laboratory setting, but the data are valuable because they are closer to real-life pavement conditions and are used to evaluate pavement performance. These sites provide a source of original materials collected at the time of construction from which physical property data and any other acquired data can be compared and used for performance prediction, a source of pavement core samples that can be tested as the pavement ages in service (although usually a short time period), a comparative assessment of the performance of different materials under accelerated loading that can be correlated with predicted performance, and sites where instrumentation devices, both new and existing, can be used to acquire pavement performance information. The Asphalt Research Consortium research team intends to use any available materials and data from larger-scale accelerated-loading test facilities in several work elements and also investigate the possibility of constructing new validation sites at accelerated loading facilities such as the Pecos (Texas) test site, a collaboration between Texas Transportation Institute and industry.

Validation can also be accomplished using full-scale validation sections constructed in coordination with State Departments of Transportation (DOT's) where specification-grade materials from different sources are compared. Five of these types of sites were constructed to date as part of the recently completed FHWA-sponsored project "Fundamental Properties of Asphalts and Modified-Asphalts II" by Western Research Institute. These sites provide exposure of the pavement to actual traffic loading and environmental conditions while being monitored

annually using standard-format LTPP monitoring procedures. These sites have available a source of original materials collected at the time of construction from which physical property data can be compared and used for performance prediction, pavement core samples that can be tested as the pavement ages in service, a comparative assessment of the actual field performance of different materials that can be correlated with predicted performance, and sites where instrumentation devices, both new and existing, can be used to acquire pavement performance information. The Asphalt Research Consortium research team intends to use the existing WRI validation sites and also construct new sites in coordination with State DOT's to validate the research findings from this project.

Two additional areas of Validation are the continual assessment of the current SuperPave[®] specifications (M320, M323, and MP8) for appropriate updates/improvements, and the implementation of the Mechanistic-Empirical Pavement Design Guide (MEPDG). The advent of the multitude of "SHRP Plus" specifications in many states that are used to measure properties that State DOT's believe are important is the impetus that is behind the need to continually assess the current specification tests. As new methods of testing are developed by the Consortium and others to measure binder and mixture properties, the need exists to implement the best methods in a timely manner. The Consortium intends to work closely with FHWA, AASHTO, and others to keep the SuperPave[®] PG grading system up to date with the best methods. The Consortium also intends to use State DOT sites where they have implemented the Mechanistic-Empirical Pavement Design Guide (MEPDG) to validate the asphalt materials models.

HYPOTHESES

The Consortium working hypotheses for Validation are:

- Field validation sites built on public highways in cooperation with state DOT's that have a stored supply of original materials, documented location, and monitored performance are useful and necessary for validation of methods, models, and theories developed in research programs intended to improve asphalt pavement performance.
- Field validation using accelerated loading facilities to compare performance of compositionally different materials are also useful for validation of methods, models, and theories developed in research programs intended to improve asphalt pavement performance and offer the advantage of acquiring performance data in a shorter period of time.

OBJECTIVES

- Construct comparative pavement validation sites on public highways in cooperation with State DOT's or at accelerated loading facilities using compositionally different asphalts and perhaps different additives such as RAP, polyphosphoric acid, lime, or liquid anti-strip.

- Collect and store sufficient material from the construction of comparative pavement sites in order to support the research activities of the Consortium and other researchers as approved by the Consortium Program Manager and the AOTR.
- Monitor the comparative validation sites annually, or more often if necessary, to document pavement performance.
- Assist State DOT's with the implementation of the MEPDG. Validation through MEPDG Sites and Revisions of the MEPDG Asphalt Materials Models
- Continually assess the SuperPave® PG specifications for improvements derived from Consortium or other research.

EXPERIMENTAL DESIGN

Category V1: Field Validation

Work element V1a: Use and Monitoring of Warm Mix Asphalt Sections (Year 1 start)

The FHWA and FHWA Western Federal Lands is planning to construct two warm-mix asphalt sections and a hot-mix asphalt control section in a project on the road just inside the east gate of Yellowstone National Park in August 2007. It is planned for Consortium personnel to collect samples of the paving materials at the time of construction for use in the Engineered Paving Materials area and possibly other areas of research. The FHWA was not planning on annual monitoring of the sections; therefore, it is planned for the Consortium to establish two 500-foot performance monitoring sections within each different material that will be monitored using LTPP established procedures on an annual basis.

Major Findings from Year 1

Construction of two warm-mix asphalt sections and a control hot-mix asphalt section were completed in early September 2007 near the East Entrance to Yellowstone National Park (YNP) on U. S. Highway 14-16-20. After construction was completed, three 500-foot monitoring sections were established in each of the three different materials and initial monitoring data was obtained on each section. Samples of all construction materials were obtained during construction. The layout of the project is shown in figure V1a.1.

Year 2 Work Plan

It is planned to continue to monitor the sections for performance on an annual schedule. It is not planned to obtain core samples because the YNP officials are very sensitive to the appearance of the road. If distress starts to become moderate to severe, YNP officials may be asked if core samples can be obtained.

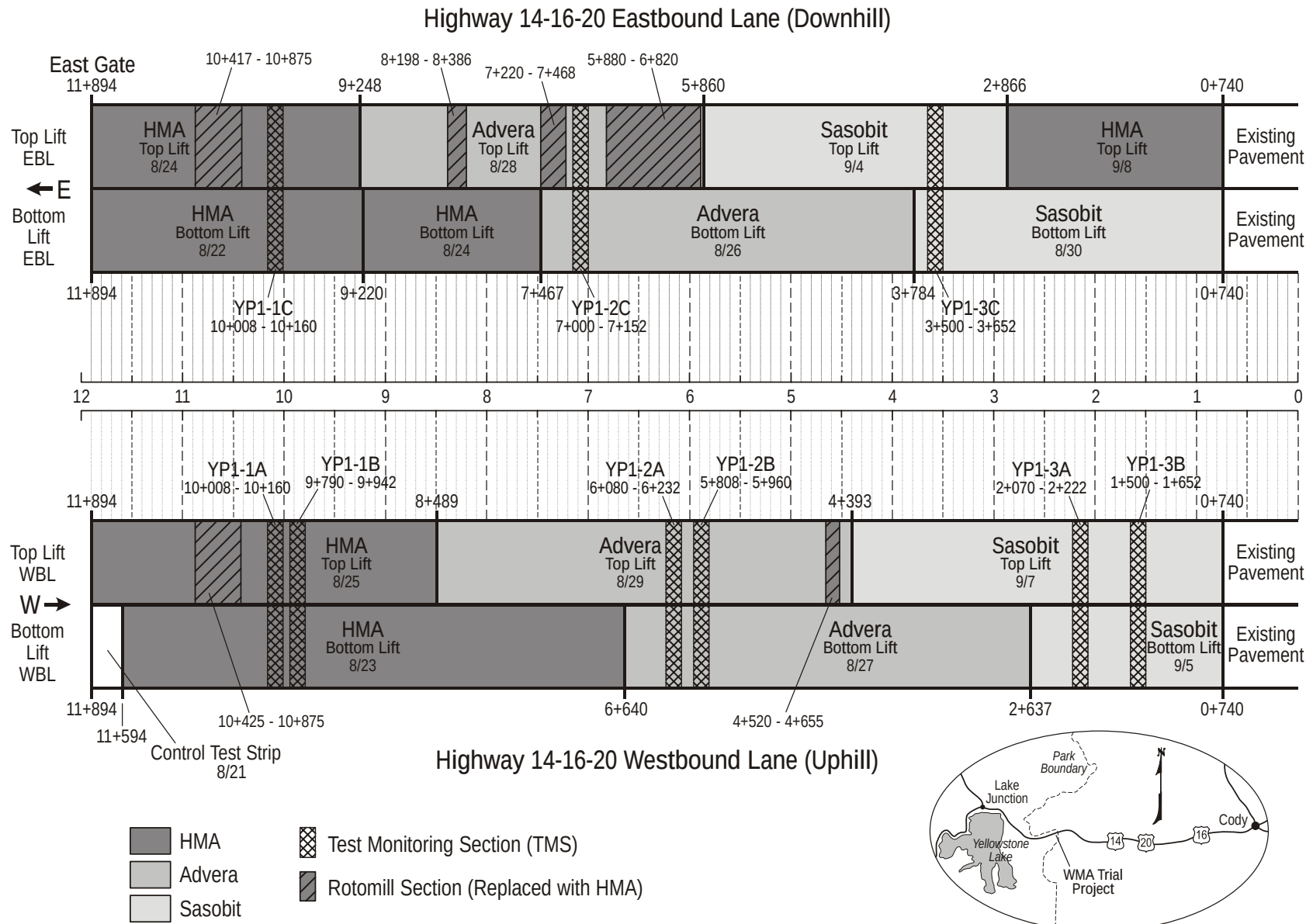


Figure VIa.1. Layout of the Yellowstone National Park Warm-Mix Asphalt project.

Work element V1b: Construction and Monitoring of additional Comparative Pavement Validation sites (Year 1 start)

Western Research Institute has constructed five comparative pavement validation sites in five states where different asphalt sources (different crude sources or different blends) are compared. The five sites were built in cooperation with state DOT's under a previous contract with FHWA entitled "Fundamental Properties of Asphalts and Modified Asphalts II". The sites are located in climate areas that can be labeled cold-dry, hot-dry, and cold-wet. These sites provide a source of original materials that were collected during construction, documented performance that is recorded on an annual basis, and serve as a mechanism to validate methods, models, and procedures that are developed as part of the Consortium research.

Construction of additional sites is desirable to have a more robust variation in environmental exposure, materials, and loading. It will be most advantageous to have the new validation sites constructed as early as possible to maximize service and monitoring during the period of this contract. This effort involves planning and coordination efforts with State DOT's and contractors. Substantially different asphalt sources also need to be identified at each new site to provide the most variability. The focus will be on projects where the different asphalt sources can be used throughout the full-depth of the asphalt pavement construction, especially on the surface. However, other types of construction, such as "mill and fill" can be acceptable provided the different asphalt sources are used on the surface. Each asphalt source will have two 500-foot performance monitoring sections that will be monitored throughout the pavement life. The 500-foot sections will be permanently marked and identified so future monitoring can provide meaningful data and samples. Sampling of all materials including: aggregate, asphalt, loose mix, and as-constructed cores will provide materials from which data can be obtained that can be used to predict pavement performance. The objective is the placement of field validation sites that are constructed using consistent engineering practices. Ideally, each site will contain four pavement sections that are constructed using asphalt binders obtained from different sources. The performance of the sites will be documented over many years of service and core samples will be obtained to evaluate the chemical, rheological, and mechanical properties as a function of service. The sites will also provide core samples that represent the changes the pavement undergoes during actual service with traffic loading and environmental exposure.

Major Findings from Year 1

Additional comparative validation sites were pursued with several state DOT's. WRI participated in sampling materials from four sections constructed at MnRoad using polyphosphoric acid (PPA). The sections were asphalt + PPA with a phosphate ester antistrip additive; asphalt + SBS polymer + PPA with a phosphate ester antistrip additive; asphalt + SBS polymer; and asphalt + Elvaloy polymer + PPA with a phosphate ester antistrip additive. Minnesota DOT performs performance monitoring and can take core samples if needed.

Year 2 Work Plan

Continue pursuit of additional comparative pavement sites with state DOT's or other agencies.

Category V2: Accelerated Pavement Testing

Work element V2a: Scale Model Load Simulation on small test track (Later start)

The Third-Scale Model Mobile Loading Simulator (MMLS3) has been successfully used by the TTI and NCSU research team to evaluate the fatigue and rutting performance of asphalt pavements under moving loads. The accurate control of temperature and loading provided by the MMLS3 and an instrumented pavement slab provides an excellent framework from which pavement response and performance models can be validated. In a recently completed research project funded by the NCDOT, the NCSU research team has demonstrated that the pavement performance under MMLS3 loading can be predicted using a set of mechanistic material and pavement models within a reasonable accuracy. In this research, the micromechanics model and the VEPCD-FEP++ model will be validated using the MMLS3. Both fatigue cracking and rutting performance will be evaluated.

Major Findings from Year 1

No activity during year one.

Year 2 Work Plan

This work element is included in the work plan because it is available at Texas A&M/TTI and it may be possible to get collaborative support from industry to obtain accelerated testing on materials that would be beneficial to the Consortium and FHWA. This work element is not going to be vigorously pursued in the work plan but will remain as a distinct possibility that is available for validation of tests, methods, or models from the Consortium research.

Work element V2b: Construction of validation sections at the Pecos Research & Testing Center (Later start)

The Pecos Research & Testing Center (RTC) is a collaboration between Texas A&M / Texas Transportation Institute and industry. The Consortium will investigate the possibility of constructing comparative pavement validation sections at the Pecos RTC. The Pecos RTC is suitable for applied research testing under controlled conditions. The 5,800-acre facility has nine distinct test tracks and a full range of support facilities.

Major Findings from Year 1

No activity during year one.

Year 2 Work Plan

This work element is included in the work plan because it is available at Texas A&M/TTI and it may be possible to get collaborative support from industry to obtain accelerated testing on materials that would be beneficial to the Consortium and FHWA. This work element is not

going to be vigorously pursued in the work plan but will remain as a distinct possibility that is available for validation of tests, methods, or models from the Consortium research.

Category V3: R&D Validation

Work element V3a: Continual Assessment of Specification

Work Element Lead: Hussain Bahia

Introduction

For the past several years, the spread of the PG-Plus specifications has resulted in a concern about the future of the PG system. In the Consortium research, there will be several new procedures that will be developed to measure rutting of binders, fatigue of binders, cohesion, adhesion, and other possible tests. This work element will review and evaluate concepts and test methods resulting from Consortium and other efforts and evaluate their potential for future revisions of the performance graded binder specifications (AASHTO M320), the Superpave mixture specifications (AASHTO M 323), and the SMA mixture specification (AASHTO MP8).

This work element will focus on recommendations and building consensus for a sequence of gradual changes to improve the PG system and minimize, if not eliminate, the empirical tests that are being used today. This work element will include visits to various state highway agencies and coordination with FHWA, the Asphalt Institute, NAPA, and other stakeholders. This work item will also include close monitoring of the development of specifications in Europe and leveraging the evaluation and reviews done by the technical teams of the European Specification Harmonization project.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Optimum Pavement Performance: Introducing methods for better characterization of modified asphalts.
- Advanced Quality Systems: Further development of test methods that are more related to actual pavement performance.

Hypothesis

The main reason for the evolution of the Superpave plus specifications is the lack of better options for filling the gaps in the current specifications. Understanding the tests used in the (plus) specifications and their scientific basis can help reduce the proliferation of such specifications. In addition, proactive response to the perceived gaps and building consensus on more scientific tests could keep the national standards more usable.

The implementation of new tests that have been developed since the introduction of PG grading can be significantly expedited if there is a proactive evaluation of gaps and proposals for new scientific tests.

Objectives

The objective of this work element is to recommend and build consensus for a sequence of gradual changes to improve the PG system and minimize the empirical tests that are being used today. This will result in better prediction of performance of asphaltic materials and pavements.

Experimental Design

The objective of this work element will be addressed by pursuing the following subtasks:

Subtask V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the “plus” tests.

Subtask V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests

Subtask V3a-3: Development of protocols for new binder tests and database for properties measured

Subtask V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance

Subtask V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications

Major Findings from Year 1

During Year 1, a review of the PG-Plus practices and a literature review were conducted to look at the most commonly used specifications. The work was done in three areas:

1. PG Rutting Parameter. The work on rutting was conducted in coordination with project on PG grading for airfield pavements sponsored by AAPTP (Project 04-02). Tables V3a.1 and V3a.2, taken from that study, gives a summary of the Plus specifications for the different states. Figures V3a.1 and V3a.2, also from the same study, compare elastic recovery and recovery from the MSCR test. It can be seen that the testing at various stresses (100 and 3200 Pa) does not make a significant difference in correlations with ER from ductility test. A higher stress level is required to show significant differences for the binders tested in this study.

Table V3a.1. Superpave-Plus specification details by state (Part I) (after project AAPT 04-02).

State	Superpave Plus Specifications
Alabama	Polymer type (Elastomer), Quantity (%) and Quality (Measured with Infrared Trace)
Alaska	Softening point. Toughness & Tenacity at 25 °C (Alaska DOT test method)
Arizona	Polymer type (SBS or CRA) Quantity (%) plus the following requirements: - For SBS modified: solubility in TCE, phase angle, elastic recovery at 10 °C and softening point - For CRA modified: rotational viscosity, penetration ant 4°C, softening point and resilience
Arkansas	Polymer type (Elastomer) and Elongation Recovery at 25 °C
California	NO
Colorado	Ductility, Toughness & Tenacity at 25 °C, Elastic Recovery at 25 °C
Connecticut	NO
Delaware	Rotational viscosity at 165°C
Florida	Spot Test, Smoke test, Phase Angle, Solubility in TCE, Absolute Viscosity at 60 °C
Georgia	Phase Angle, Separation, Solubility in TCE
Hawai	NO
Idazo	Elastic Recovery at 25 °C
Illinois	Separation, Force Ratio at 4 °C, Toughness & Tenacity at 25 °C, Elastic Recovery at 25 °C
Indiana	NO
Iowa	NO
Kansas	Separation, Elastic Recovery at 25 °C
Kentucky	Solubility in TCE, Elastic Recovery at 25 °C
Louisiana	Solubility, Separation, Force Ductility Ratio, Force Ductility, Elastic Recovery at 25 °C, Ductility at 2 5°C
Maine	NO
Maryland	Critical cracking temperature
Massachusetts	Polymer type (SBR)
Michigan	Polymer type (SBS or SBR, others need approval), Solubility in TCE, separation, Elastic Recovery at 25 °C, plus the following requirements: - For SBS modified: Force Ratio - For SBR modified: Toughness & Tenacity at 25 °C
Minnesota	NO
Mississippi	Polymer type (SBS or SBR, others need approval), Quantity (%), Temperature - Viscosity Curve
Missouri	Separation, Elastic Recovery at 25 °C
Montana	Ductility at 25 °C

Table V3a.2. Superpave Plus specification details by state (Part II)

State	Superpave Plus Specifications
Nebraska	Phase Angle, Elastic Recovery at 25 °C
Nevada	Ductility, Sieve, Toughness & Tenacity at 25 °C, Polymer Content
New Hampshire	NO
New Jersey	Elastic Recovery at 25 °C
New Mexico	NO
New York	Elastic Recovery at 25 °C
North Carolina	Polymer type (Elastomer)
North Dakota	To implement in 2005
Ohio	Penetration at 25 °C, Phase Angle, Separation, Homogeneity, Elastic Recovery at 25 °C
Oklahoma	Separation, Solubility in TCE, Spot Test, Elastic Recovery at 25 °C
Oregon	Only for Chip Seal Asphalt
Pennsylvania	Separation, Softening Point, Elastic Recovery at 25 °C
Puerto Rico	
Rhode Island	NO
South Carolina	Polymer type (Elastomer)
South Dakota	Elastic Recovery at 25 °C
Tennessee	Polymer type (Elastomer), Viscosity at 135 °C (Contractor Plant Testing), Softening Point, Elastic Recovery at 10 °C, Screen Test.
Texas	Elastic Recovery at 10°C
Utah	Phase Angle, Elastic Recovery at 25 °C
Vermont	NO
Virginia	Elastic Recovery at 25 °C
Washington	NO
West Virginia	Elastic Recovery at 25 °C
Wisconsin	To be implemented in 2005
Wyoming	Elastic Recovery at 25 °C

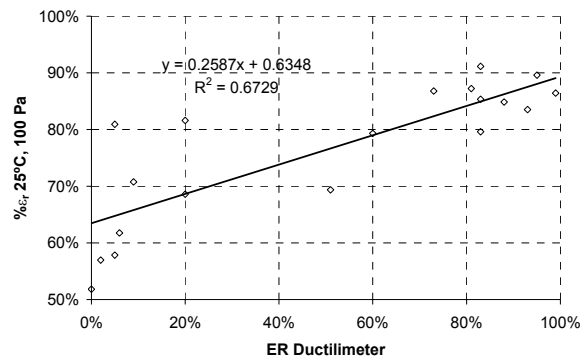


Figure V3a.1. Chart. $\epsilon_r\%$ at 25 °C and 100 Pa vs. ER (after project 04-02).

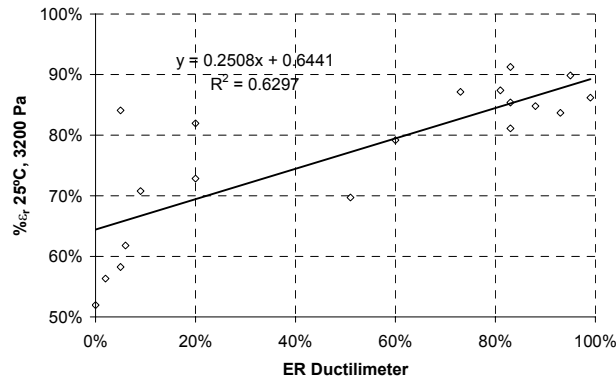


Figure V3a.2. Chart. $\epsilon_r\%$ at 25 °C and 3200 Pa vs. ER (after project 04-02).

2. PG Fatigue Parameter. There is little doubt that the current fatigue parameter $G^* \cdot \sin \delta$ is not a good choice for measuring contribution of binder to fatigue resistance. In collaboration with FHWA, a set of binders was tested for binder fatigue and also for mixture fatigue. Results are shown in figure V3a.3. The binder fatigue testing was done using the time sweep in the DSR. It was observed that minor variation in the time setting of the time sweep could change fatigue behavior significantly. Figure V3a.4 shows the change in correlation when the testing sequence for the same binders, using the same DSR, was changed very slightly. Figure V3a.5 shows the results of the strain-controlled time sweep with various setting on the DSR. The results showed that any binder fatigue test that includes a time weep should consider the possible variation in load history.

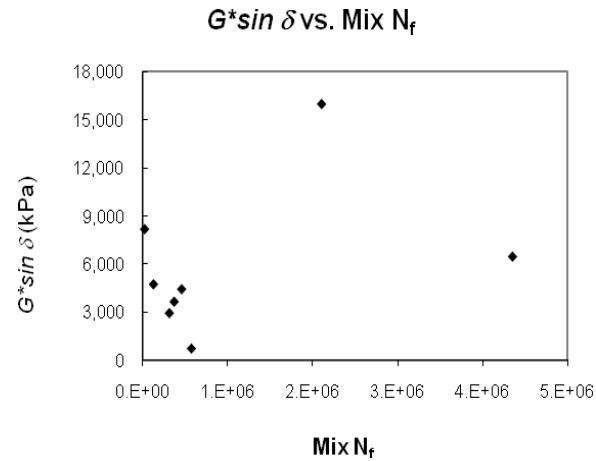
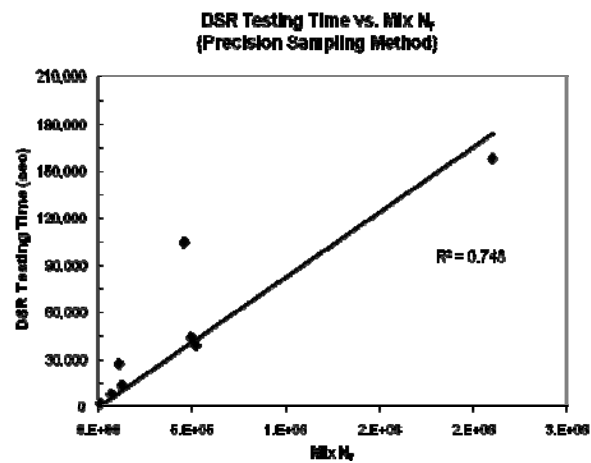
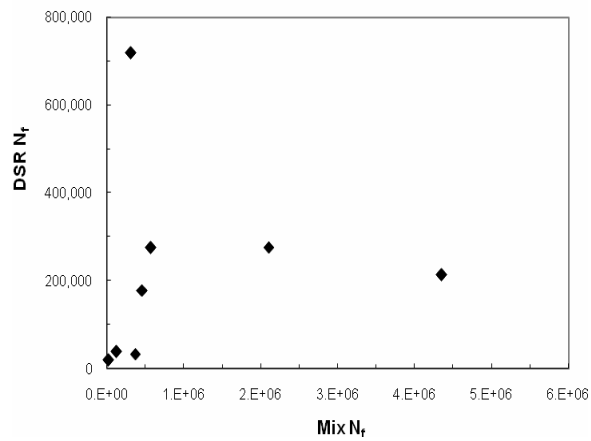


Figure V3a.3. Chart. Plot of $G^* \sin \delta$ values against mixture fatigue life.



(a)

DSR N_f vs. Mix N_f
(Continuous Oscillation)



(b)

Figure V3a-4. Chart. Plot of DSR testing time-to-failure against mixture cycles until failure for (a) the precision sampling method, (b) continuous oscillation.

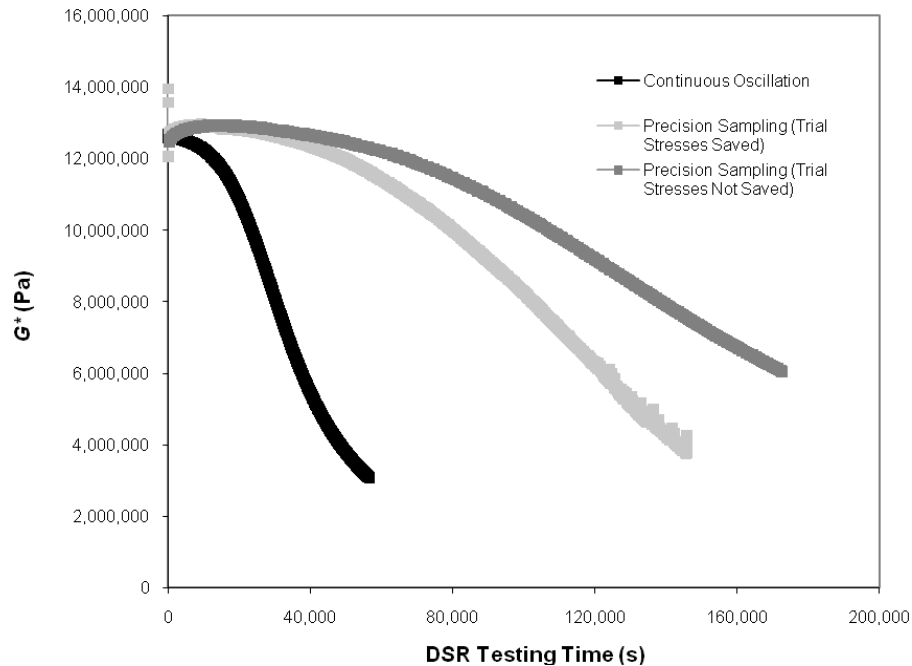


Figure V3a.5. Chart. Plot of binder stiffness against testing time for different types of fatigue tests

3. PG Low Temperature Parameters. There is no doubt that the majority of agencies are not using – and do not plan on using – the Direct Tension Test (DTT). It also appears that the equipment manufacturers are not selling the DTT, and it is almost impossible to get the existing machines serviced by the manufacturers. Therefore, here is a critical need for a failure test to replace the Direct Tension Test. There are two tests that were evaluated in Year 1 of the project: The Single Edge Notched Beam (SENB) test that is used in Canada and the ABCD test developed by Dr. S. Kim of Ohio University. The SENB test could be tested in a modified BBR machine. During Year 1 a plan for adding a stepped motor to the BBR to conduct a constant deformation test was developed. A look at the notched beam geometry and consideration of various steps for conducting the test was taken. It is clear that there is a great potential for simple modification of the BBR to conduct a version of the test while using a modified mold and notch procedure.

Year 2 Work Plan

During Year 2, the team will continue to evaluate the PG plus practices and conduct a thorough review of whether the new tests can replace the empirical tests used today to complement the PG specifications. The following specific tasks will be pursued:

1. Evaluate the MSCR test results and evaluate if they can be used to replace the elastic recovery. Continue to follow up with the criteria being proposed by FHWA and provide input to the binder ETG. Collect information about initial use of the MSCR tests by various state DOTs.

2. Coordinate work with the fatigue studies to propose a surrogate test using the DSR. The stress sweep and the binder monotonic tests are both promising and could yield a solution.
3. Work on further development of the SENB test and the modification of the BBR.
4. Evaluate the new aging procedure and the new procedure for estimating the mixing and compaction temperatures.

Figure V3a.6 depicts the research approach defined for this work element.

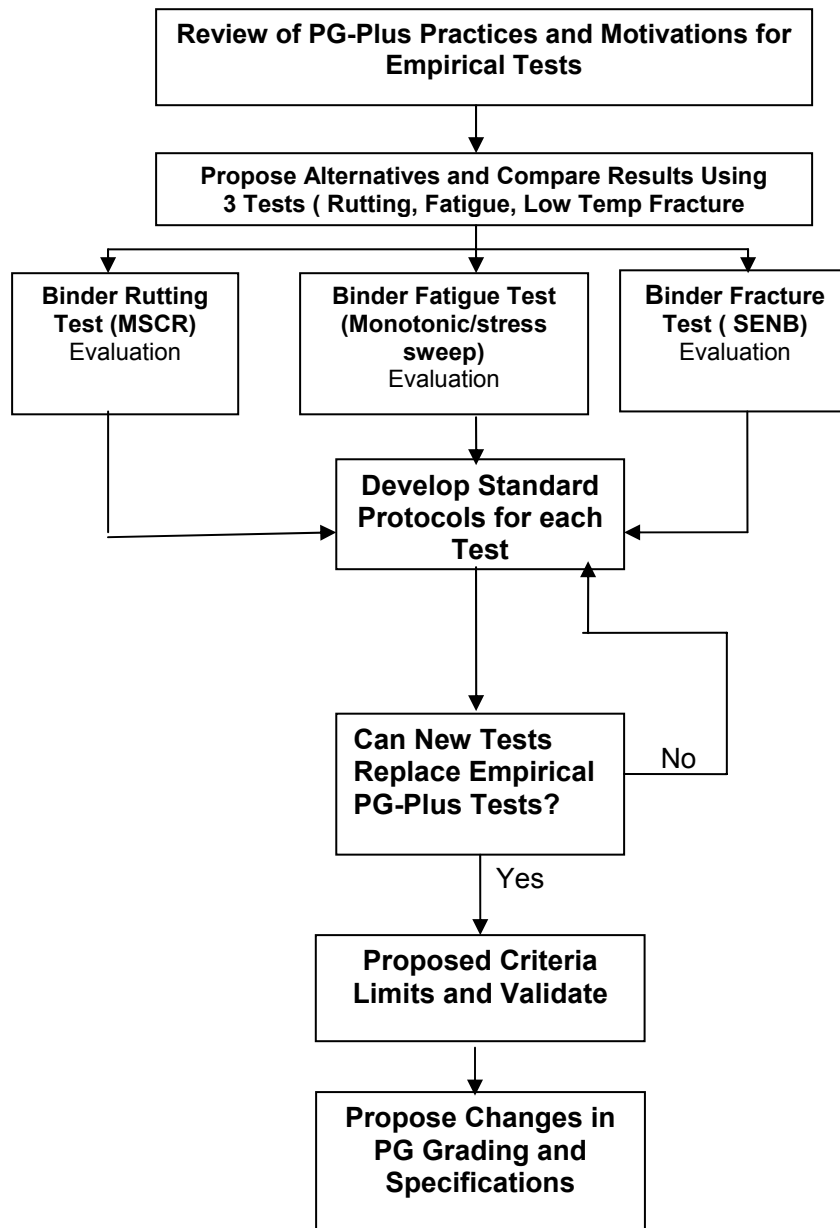


Figure V3a.6. Chart. Flow chart for research approach.

Year 2 Milestones

- Develop standard protocols for each of the three tests (rutting, fatigue, and LT cracking)
- Collect data using PG-Plus empirical data and new tests and provide technical and practical comparisons
- Contact DOTs using PG-Plus and collect feedback regarding the new tests

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
V3a-1. Evaluation of the current PG-Plus practices	X	X			
V3a-2. Detailed analysis of all PG-Plus tests and comparison with new tests	X	X			
V3a-3. Development of protocols for new binder tests		X	X	X	
V3a-4. Development of specification criteria for new tests			X	X	X
V3a-5. Interviews and surveys for soliciting feedback		X	X	X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
V3a-1. Evaluation of the current PG -Plus practices	X	X	X	
V3a-2. Detailed analysis of all PG-Plus tests and comparison with new tests		X	X	X
V3a-3. Development of protocols for new binder tests		X	X	X
V3a-4. Development of specification criteria for new tests				
V3a-5. Interviews and surveys for soliciting feedback			X	X

Budget

The estimated budget for this subtask is \$400,000 over the next four years. The work will be conducted by the University of Wisconsin-Madison in collaboration with Advanced Asphalt Technologies (AAT).

Cited and Related References

Bahia, H. U., D. I. Hanson, M. Zeng, H. Zhai, M. A. Khatri, and R. M. Anderson, 2001, Characterization of Modified Asphalt Binders in Superpave Mix Design. Publication NCHRP 459, National Academy Press, Washington, D.C.

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Work Element V3b: Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP sites

Work Element Lead: Peter Sebaaly (UNR) and Hussain Bahia (UW-M)

Introduction

The mechanistic-empirical pavement design guide (MEPDG) has been recently developed to conduct structural designs for flexible and rigid pavements. The MEPDG uses a mechanistic approach that is empirically calibrated using field performance data to establish the required structural section for a given set of loading, materials, and environmental conditions.

The structural design for flexible pavements conducted through the MEPDG is based on the long-term performance of such pavements in rutting, fatigue, and thermal cracking. The constructed pavement is supposed to perform according to the design criteria established during the structural design process.

Several state highway agencies are currently in the process of implementing the MEPDG. These implementation efforts necessitate the design of flexible pavements using the guide and monitoring their long term performance to calibrate the mechanistic models based on the localized conditions. The MEPDG-designed and monitored flexible pavements represent an excellent opportunity for the Consortium to cooperate with the state agencies at two distinct

levels: validation of the Consortium's research activities and updating of the fundamental models used by the MEPDG based on the Consortium's research activities. When coordination is done at the design stage the validation of current models, and the revisions for these models that could come out of the Consortium research, would be more effective.

In addition to the new sites, the LTPP program has a large number of sites that could be used for early verification of the technologies that are in advanced stages of development by the Consortium research members – or by other researchers – for improvement of specifications and design guidelines. Examples include binder tests that are being proposed for modified binders, the methods for measuring adhesion and cohesion, the binder fatigue tests, and others. These technologies are either already ready for validation or are very close to being ready. Using selected sites from the LTPP program for which excellent performance or premature failures have been observed could expedite the process of technology development and provide means for deriving specification limits or guidelines. The LTPP database can serve as basis for early validation because sections included in the database have had several years of traffic and aging.

Relationship to FHWA Focus Areas

The Validation work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property variation and pavement material performance in order to validate laboratory tests, performance models, and methods.

Hypothesis

The performance of the MEPDG designed flexible pavements coupled with the data generated by the Consortium research activities from LTPP sites can be effectively used to validate the research findings of the Consortium and to update the models used in the MEPDG. In addition, some of the existing LTPP sections can be used for early validation of the recently developed tests and properties.

Objectives

The objectives of this task are to cooperate with state highway agencies to design and construct flexible pavements using the AASHTO MEPDG. Also, to cooperate with the LTPP program to make use of selected performance and materials of selected sections. The constructed sections and the LTPP selected sections will be used to validate the findings of the research activities of the Consortium and to evaluate the models used in the MEPDG for possible revisions. The recommended revisions, if needed, will be based on new testing procedures proposed by the Consortium research.

Experimental Design

In order to achieve the objectives of this research effort, the following subtasks will be completed.

Subtask V3b-1: Design and Build Sections

This subtask will solicit state highway agencies that are willing to cooperate on designing and constructing flexible pavement sections using the AASHTO MEPDG. The solicited agencies will cover the various regions of the U.S.

This subtask will cooperate with the selected state agencies to design and build MEPDG sections. UNR will assist the agencies with the design of the sections using the MEPDG and will conduct the necessary testing for strength properties, fatigue, rutting, and thermal cracking. The agencies will construct the sections as designed. The sources and properties of the materials will be incorporated into the Materials Database.

It is well recognized that the 5 year period of the ARC contract is not long enough to develop sufficient long-term performance from the MEPDG sections. As part of this subtask, the ARC researchers will develop a long-term performance monitoring and implementation plan for the owner agency to follow after the completion of the ARC contract.

Subtask V3b-2: Additional Testing

This subtask will sample materials during the construction of the sections and will conduct additional testing on the field mixtures that will be used to validate the models generated from the Consortium research activities. This subtask will be conducted by researchers from UNR and UWM. Each member will conduct the necessary tests to validate their research efforts. The long-term performance data of the sections will be collected in cooperation with the owner agencies and used to validate the models/tests that will be developed throughout the research.

Subtask V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures

(Note: Subtasks V3b-3 and V3b-4 were combined from the Year 1 plan)

This subtask will be focused on screening the available sections for which noticeable good or poor performance has been recorded, as well as for sections for which sufficient materials have been saved to allow binder and mixture testing. The sections will cover various climatic and traffic conditions and preferably include modified binder grades and variety of mixture types. The scope of the subtask cannot be estimated at this stage but an attempt will be made to have a significant number of sections for each type of pavement failure and in particular rutting, fatigue, and moisture damage. A work plan will be developed based on the test methods and the models that need to be validated. The main focus will be on models or test methods that are intended for filling some gaps in the specifications or the MEPDG models. The screening activity, if not covered by the LTPP program, will be conducted by individual Consortium partners based on the specific tests or models that they intend to validate. UNR will focus on low-temperature thermal cracking and UWM will focus on binder rutting and fatigue testing. Every effort will be made to coordinate the activities among Consortium members and with LTPP. The binder rutting and fatigue validation will start in Year 2.

Subtask V3b-4: Testing of Extracted Binders from LTPP Sections

Major Findings from Year 1

ARC team members reviewed the plans for the extracted binder testing that were recommended by the LTPP Materials Expert Task Group and LTPP Protocols P27 (DSR) and P28 (BBR). The recommended testing includes standard DSR and BBR testing of extracted binders at a single temperature selected based on the location of the LTPP project site. ARC team members believe that adding this data to the LTPP database will be of minimal value. Additionally ARC team members are having difficulty securing the necessary cost share to perform this testing.

Year 2 Work Plan

Considering recent efforts within the LTPP program to provide estimated dynamic modulus measurements for the LTPP sections, the ARC team recommends that the extracted binder testing plan recommended by the LTPP Materials Expert Task Group be reconsidered. The LTPP program currently has a project with Nichols Consulting Engineers to review various models and recommend an approach for estimating mixture dynamic modulus values for the LTPP database. Dr. Richard Kim, A ARC subcontractor, has a key role in this LTPP effort. If a model other than the original Witczak equation is used, it will likely require characterization of binder modulus master curves. To develop a binder modulus master curve requires testing at multiple temperatures and frequencies using the DSR and multiple temperatures using the BBR. This will require more material and effort than originally considered in the extracted binder testing plan recommended by the LTPP Materials Expert Task Group.

ARC team members will work with the FHWA LTPP Division and its contractors to develop an appropriate extracted binder testing plan and associated cost estimate. At this time consideration should be given to performing master curve testing and possibly MSCR testing on selected sections. ARC team members will then work with the FHWA to assess the potential for securing the 20 percent cost share necessary to perform this testing.

Subtask V3b-5: Review and Revisions of Materials Models

The first part of this subtask will review all past and current activities on the revisions and modifications of the materials models that are included in the MEPDG. Also, the proposed changes in binder specifications, the Superpave plus specifications, and mixture design practices will be reviewed and a report for defining the “gaps” will be issued. Based on these reviews, the researchers will identify any additional modifications or revisions that maybe needed.

For example, the equations used to determine the dynamic modulus (E^*) from the binder properties will be validated for polymer-modified binders. The perceived shape of the E^* Master Curve may vary significantly when it comes to polymer-modified mixtures. Using the testing data from Subtasks V3b-1 and V3b-2, the research team will evaluate the prediction equations and E^* Master curves and modify them to accommodate polymer-modified binders and mixtures.

Subtask V3b-6: Evaluate the Impact of Moisture and Aging

This subtask will evaluate the effects of moisture and aging on material properties used in the MEPDG and the LTPP sections. This will lead to recommendations for revisions of models if needed based on our fundamental research results. The revised models could include cohesion, adhesion, trends in aging with effect of mineral surface, etc.

The current MEPDG does not incorporate the impact of moisture damage on the properties of the HMA materials. Also it has a good aging model that is based on changes in viscosity and could be modified to include some more fundamental properties. Also, the existing binder and mixture specifications have aging models based on the RTFO, which is not useful for many modified asphalts. In this subtask, researchers from UNR, AAT, UWM, and WRI will assess the gaps in the models and specifications and the need for revisions to the aging models and the need to incorporate the impact of moisture damage on the properties and behavior of HMA mixtures in the models of the MEPDG and in material specifications.

Major Findings from Year 1

During year 1, in Subtask V3b-1, the researchers initiated contacts with the MEPDG Lead States Team and several other state highway agencies to solicit their cooperation on this work element. At this point the following states have indicated their willingness to further consider their cooperation on this effort: New Jersey, Virginia, Texas, Nevada, Wisconsin, Idaho, Montana, and South Dakota. Other states that have been contacted but not responded yet include: New Mexico and Washington.

In Subtask V3b-3, the UWM team looked into the LTPP database for possible data retrieval. Some of the preliminary findings in the area of fatigue are ready to be validated. For instance, the fracture energy from the constant strain-rate tests has the potential to be used as an indicator to fatigue performance of asphalt binder. Fracture energy correlated well with the performance of asphalt binders at the FHWA ALF pavements, and validation of this finding is planned. LTPP SPS9 sections were designed to validate the Superpave mix design and materials. These sections could be good candidates for validation. A list of the sections is shown in table V3b-3.1.

The UWM team will coordinate with FHWA LTPP to procure the asphalt binder samples. A series of tests will be conducted (e.g. constant strain-rate tests). The parameters from these tests will be correlated with the field performance of these materials. It is noted that there are many variables affecting the field performance, such as climate, aggregate, traffic, thickness, base and soil conditions. To take into account the impact of these factors, as many samples as possible should be included for meaningful statistical analysis.

Table V3b-3.1. Possible LTPP sites for validation of findings.

SHRP_ID	PG_HIGH_TEMP	PG_LOW_TEMP	SOURCE_OTHER
0902	64	-28	Hudson Oil Company, Providence, RI
0903	64	-22	Hudson Oil Company, Providence, RI
0961	58	-34	Hudson Oil Company, Providence, RI
0962	58	-28	Hudson Oil Company, Providence, RI
0902	58	-28	Ultramar, St. Rumuald, QE
0902	52	-40	Bitumar, Montreal, QE
0903	58	-28	Ultramar, St. Rumuald, QE
0903	52	-34	Petro Canada, Montreal, QE
0901	64	-22	Citgo, Perth Amboy, NJ
0902	64	-22	Citgo, Perth Amboy, NJ
0902	58	-28	Suit-Kote, Cortland, NY
0903	64	-22	Citgo, Perth Amboy, NJ
0903	52	-28	Suit-Kote, Cortland, NY
0960	64	-22	Citgo, Perth Amboy, NJ
0960	64	-22	Citgo, Paulsboro, NJ
0961	64	-22	Citgo, Perth Amboy, NJ
0961	76	-28	Suit-Kote, Cortland, NY
0962	64	-22	Citgo, Perth Amboy, NJ
0902	64	-22	Citgo
0902	64	-22	Citgo
0902	64	-22	Citgo
0903	70	-22	Citgo
0903	70	-22	Citgo
0903	70	-22	Citgo
A902	58	-22	Shell Canada, Montreal
A902	52	-40	Bitumar, Montreal
A903	58	-22	Shell Canada, Montreal
A903	52	-34	Petro Canada, Montreal
0902	58	-40	McAsphalt ON
0903	58	-34	McAsphalt ON
0960	58	-28	McAsphalt ON
0961	58	-34	McAsphalt ON
0962	58	-40	McAsphalt ON
0902	58	-40	McAsphalt ON
0903	58	-34	McAsphalt ON
0960	58	-28	McAsphalt ON
0961	58	-34	McAsphalt ON
0962	58	-40	McAsphalt ON
0901	64	-22	Amoco, St.Louis
0901	64	-22	Amoco, St.Louis
0902	64	-28	Polymer Asphalt, St.Louis

SHRP_ID	PG_HIGH_TEMP	PG_LOW_TEMP	SOURCE_OTHER
0902	64	-28	Polymer Asphalt, St.Louis
0903	64	-28	Polymer Asphalt, St.Louis
0903	58	-28	Polymer Asphalt, St.Louis
0959	64	-22	Amoco, St.Louis
0959	64	-22	Amoco, St.Louis
0960	64	-22	Amoco, St.Louis
0960	64	-28	Polymer Asphalt, St.Louis
0961	64	-22	Amoco, St.Louis
0961	64	-22	Amoco, St.Louis
0962	64	-28	Polymer Asphalt, St.Louis
0962	70	-28	Polymer Asphalt, St.Louis
0963	64	-28	Polymer Asphalt, St.Louis
0963	64	-16	Polymer Asphalt, St.Louis
0964	64	-28	Polymer Asphalt, St.Louis
0964	64	-28	Polymer Asphalt, St.Louis
A901	64	-22	Polymer Asphalt, St.Louis
A901	64	-22	Polymer Asphalt, St.Louis
A902	64	-28	Polymer Asphalt, St.Louis
A902	64	-28	Polymer Asphalt, St.Louis
A959	64	-28	Polymer Asphalt, St.Louis
A959	64	-28	Polymer Asphalt, St.Louis
A903	58	-28	Polymer Asphalt, St.Louis
A903	58	-28	Polymer Asphalt, St.Louis
A960	70	-28	Polymer Asphalt, St.Louis
A960	70	-28	Polymer Asphalt, St.Louis
A961	64	-16	Polymer Asphalt, St.Louis
A961	64	-16	Polymer Asphalt, St.Louis
0902	64	-22	Marathon Oil; Memphis, TN
0903	58	-22	Marathon Oil, Memphis, TN
0903	70	-22	
0903	58	-22	
0902	64	-22	
0959	64	-10	
0901	64	-16	Citgo Savannah, GA
0902	64	-16	Citgo, Savannah, GA
0903	58	-16	Citgo, Savannah, GA
0959	76	-16	Citgo, Savannah, GA
0902	64	-16	
0903	64	-16	
A902	64	-16	
A903	64	-16	
B902	76	-10	EOTI / Neste Oil
B903	70	-10	Koch Asphalt

SHRP_ID	PG_HIGH_TEMP	PG_LOW_TEMP	SOURCE_OTHER
0902	64	-34	Montana Refining Company
0903	64	-22	Montana Refining Company
A902	52	-34	Husky Oil
A903	46	-34	Husky Oil

Year 2 Work Plan

During Year 2, in Subtask V3b-1, the research team will continue communicating with state highway agencies about their cooperation in this effort. Field projects will be identified in the states that indicated their willingness to participate and the process of design and materials testing and evaluations will start.

In Subtask V3b-3 in Year 2, the UWM team will procure the LTPP materials to validate the findings. The Year 2 work plan consists of two major parts: (a) a detailed experimental plan, and (b) an evaluation of the effectiveness of different analytical approaches based on the experimental results.

a. Detailed Experimental Plan of Materials and Tests.

The experimental plan was designed to evaluate the factors that have potential to evaluate the performance of asphalt binders as well as asphaltic mixtures. The proposed tests are shown in table V3b-3.2.

b. Analytical Characterization of Behavior of Asphalt Binders and Mixes.

The performance of the asphalt binders and asphaltic mixtures in the lab will be correlated with that of the materials in the field at LTPP sites. The lab test results will be analyzed using different analytical approaches. These analyses will determine the fundamental properties of asphalt binder that govern the damage resistance to fatigue. The tests that can provide indicators to field performance will be selected for possible implementation.

Figure V3b-3.1 depicts the research approach defined for this work element.

Table V3b-3.2. Proposed tests on asphalt binders and mixes.

Asphalt Binder	Time Sweep (TS)	Strain level	3%
			5%
			7%
		Frequency	1 Hz
			5 Hz
			10 Hz
	Monotonic Test (MT)	Shear Strain Rate	30%/min.
			45%/min.
			60%/min.
	Stress Sweep (SS)	Strain level	3%
			5%
			7%
		Frequency	1 Hz
			5 Hz
			10 Hz
Mix	Cyclic Test (CT)	Strain level	600 microstrain
			1000 microstrain
			1400 microstrain
		Frequency	1 Hz
			5 Hz
			10 Hz
	Monotonic Test (MT)	Constant Cross-head Rate	12.5 mm/min.
			25.4 mm/min.
			38.1 mm/min.
			50.8 mm/min.

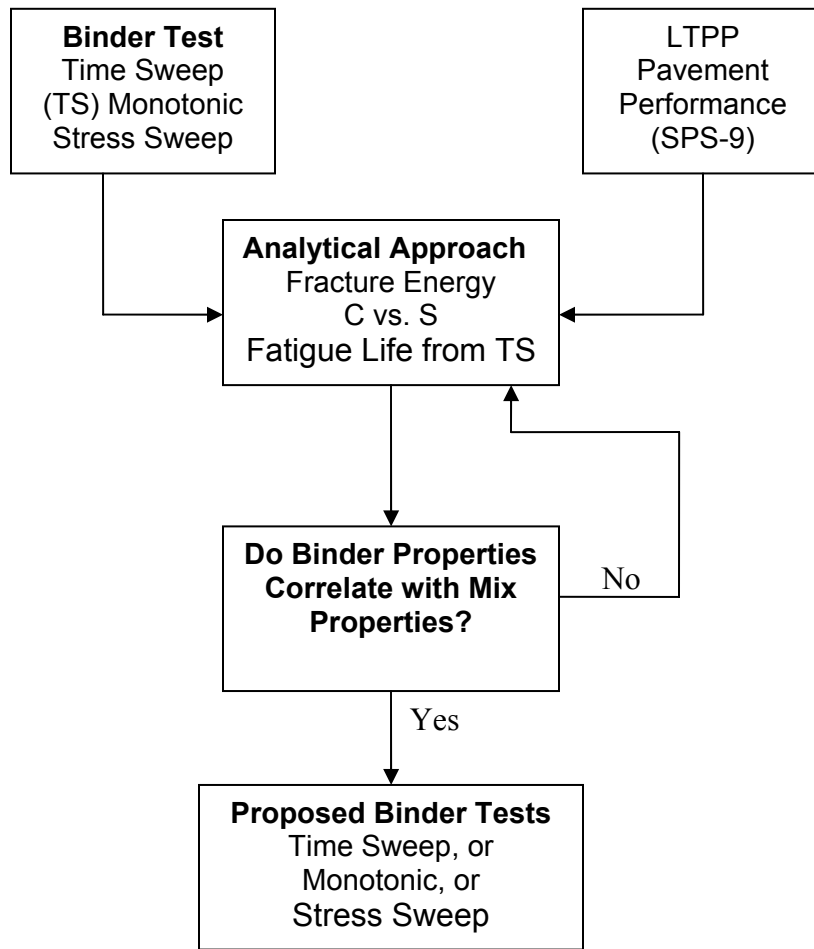


Figure V3b-3.1. Chart. Flow chart for research approach.

Year 2 Milestones

Year 2 milestones for UNR will include the design and construction of MEPDG field projects during the summer 2008. For Subtask V3b-3, to be conducted by UW-M team, the milestones will include the following:

- Finalize the site selections for validation of findings
- Procure the LTPP binders for validation of the fracture energies concept
- Conduct the proposed tests on asphalt binders
- Validate the preliminary findings

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
V3b-1: Design and Build Sections	X	X	X		
V3b-2: Additional Testing		X	X	X	
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures	X	X	X	X	
V3b-4: Review and Revisions of Materials Models		X	X	X	
V3b-5: Evaluate the Impact of Moisture and Aging		X	X	X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
V3b-1: Design and Build Sections	X	X	X	X
V3b-2: Additional Testing		X	X	X
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures	X	X	X	X
V3b-4: Review and Revisions of Materials Models				X
V3b-5: Evaluate the Impact of Moisture and Aging			X	X

Budget

The budget for all the work elements in the Validation area is estimated to be \$5.0M over the five years of the project but is subject to the number of projects identified and completed.

PROGRAM AREA: TECHNOLOGY DEVELOPMENT

Program Area Lead: Dr. Ramon Bonaquist, P.E.

Introduction

A major criticism of past fundamental research efforts in flexible pavements and asphalt materials is they did not produce products that were directly useable by practicing engineers and technologists. Historically, fundamental research studies have produced promising, new approaches that require substantial follow-on research, development, and training efforts before useable products are available to the profession. Even the products from the highly focused, goal oriented Strategic Highway Research Program required substantial additional effort for further development and training before being successfully implemented into design and construction practice.

The Technology Development program area has been included in the research program of the Asphalt Research Consortium to address this concern. The purpose of this program is to begin the process of refining selected products from the Fatigue, Moisture Damage, Engineered Pavement Materials, and Vehicle Pavement Interaction research programs into useful tools for engineers and technologists involved in the design, construction, and maintenance of flexible pavement systems. These tools may take the form of new or improved standard test methods, improved specifications, improved performance models, or specific design guidance for improving the performance of flexible pavements. The Technology Development program area will be closely coordinated with the Technology Transfer program area.

Relationship to FHWA Focus Area

The Technology Development Program Area supports the FHWA Focus Areas of Optimizing Pavement Performance, Advanced Quality Systems, and Technical Capability Building.

Hypothesis

Early identification of implementable research products and further development of those products by Consortium partners will lead to more rapid acceptance of these products by practicing engineers and technicians.

Objective

The objective of this program is to begin the process of refining selected products from the Consortium research programs into useful tools for engineers and technologists involved in the design, construction, and maintenance of flexible pavement systems

Approach

The work in the Technology Development Program Area has been organized to provide early, mid-term, and long-term products. Early efforts will focus on products developed in past FHWA research studies completed by WRI. Promising products from this past work will be developed into useable tools within the first two years of the Agreement. Mid-term and long-term efforts will focus on research being performed in the Fatigue, Moisture Damage, Engineered Pavement Materials, and Vehicle Pavement Interaction program areas and in the current FHWA/WRI Fundamental Asphalt Research contract. Mid-term products will be available in Years 3 and 4, and long-term products will be available at the end of the contract or later.

Work element TD1: Prioritize and Select Products for Early Development

A number of test procedures, analysis methods, and models were developed by Consortium partners using funding provided by previous FHWA/WRI Fundamental Asphalt Research contracts or other federal sources. This work element will consist of prioritizing and selecting the most promising of these for development into early Asphalt Research Consortium products. For each potential early product, the developing Consortium member will prepare a brief summary of the product. This summary will describe the product, the potential user of the product, and how the product can be used to improve asphalt pavement technology. As agreed to at the July, 2007 ETG meeting, these product descriptions will be submitted to the FHWA, then to the ETG chairs, and finally to the appropriate ETG membership for rating. Products receiving the highest ratings from the ETG membership will be recommended for further development.

Work element TD2: Develop Early Products

It is envisioned that several early products will be identified by Work Element TD1. In Work Element TD2, these products will be further developed as needed. The general approach will be for the Consortium to prepare a detailed product development plan and budget for review by the FHWA AOTR. Once agreement is reached on the scope and budget, the assigned Consortium partner will undertake the development effort. It is envisioned that these early product development efforts will require one year or less to complete.

Work element TD3: Identify Products for Mid-Term and Long-Term Development

As research by the Consortium progresses, it is envisioned that potential mid-term and long-term products will emerge. These potential products will be identified in the Quarterly Progress Reports submitted to the AOTR. When the AOTR concurs that a viable mid-term or long-term product has been identified, the potential product will be presented to the appropriate ETG (s) for consideration. The ETG membership may recommend one of the following specific actions for the potential product:

1. Proceed to development.
2. Reassess after completion of additional research.
3. Eliminate from further consideration.

Work element TD4: Develop Mid-Term and Long-Term Products

It is envisioned that several products will be identified by Work Element TD3. In Work Element TD4, these products will be further developed as needed. The general approach will be for the Consortium to prepare a detailed product development plan and budget for review by the FHWA AOTR. Once agreement is reached on the scope and budget, the assigned Consortium partner will undertake the development effort.

Major Findings from Year 1

Six potential early technology delivery projects were identified by the members of the Asphalt Research Consortium (ARC) in Work Element TD1. Table TD1.1 presents a summary listing of the projects, the anticipated product, and the Expert Task Group(s) (ETG) that would have major interest in the project. All of these projects deal with further development of test methods that were conceived during research under Federal Highway Administration (FHWA) project “Fundamental Properties of Asphalt and Modified Asphalts.” Each of these projects will provide a product that addressed a current need of the highway industry.

Table TD1.1. Summary Listing of Early Technology Delivery Projects.

Project	Product	ETG
Automated Flocculation Titrimetric Analysis	Draft AASHTO Standard Test Method for evaluation the propensity of an asphalt or mixture of asphalts to exhibit phase separation	Binder
Determination of Polymer in Asphalt	Draft AASHTO Standard Test Method to determine the quantity of polymer and the nature of the polymer(s) in asphalt	Binder Mixture and Construction
Dynamic Mechanical Analysis	Draft AASHTO Standard Test Method for torsional fatigue testing of the fine aggregate matrix of asphalt concrete	Mixture and Construction Binder Fundamental Properties and Advanced Modeling
Simplified Continuum Damage Fatigue Test	Draft AASHTO Standard Method of Test for fatigue testing of asphalt concrete that can be used with the Simple Performance Test System	Mixture and Construction Fundamental Properties and Advanced Modeling
Universal Sorption Device	Draft AASHTO Standard Method of Test for measuring the surface free energy components of aggregates	Binder Mixture and Construction Fundamental Properties and Advanced Modeling
Wilhelmy Plate Test	Draft AASHTO Standard Method of Test for measuring the surface free energy components of the asphalt binder	Binder Mixture and Construction Fundamental Properties and Advanced Modeling

The project descriptions will be circulated to the ETG Chairs then the appropriate ETG membership in January, 2008 to determine if there is sufficient interest within highway industry for the proposed product. Those projects receiving the support of the ETG membership will proceed to develop in Year 2.

Year 2 Work Plan

It is anticipated that all six projects listed in table TD1.1 will receive sufficient support to warrant development. This development work will be initiated in Year 2 in Work Element TD2. Table TD2.1 lists the Consortium partner that will undertake the development effort for each project in Work Element TD2. For each project, the responsible Consortium partner will prepare a detailed product development plan and budget for review and approval by the FHWA AOTR. The specific tasks that will be included in the development plan will vary depending on the current state of development, but may include the following:

1. Prepare a Draft AASHTO Standard Method of Test.
2. Encourage equipment manufacturers to develop commercial equipment.
3. Perform additional testing to provide characterization of a additional materials.
4. Perform ruggedness testing and revise the Draft AASHTO Standard as needed.
5. Provide technical support for adoption of the procedure as a Provisional Standard.

Upon approval of the product development plan by the FHWA AOTR, development work will be initiated in accordance with the approved product development plan.

Table TD2.1. Responsible Consortium partner for the early technology development projects.

Project	Responsible Consortium Partner
Automated Flocculation Titrimetric Analysis	WRI
Determination of Polymer in Asphalt	WRI
Dynamic Mechanical Analysis	TTI
Simplified Continuum Damage Fatigue Test	AAT
Universal Sorption Device	TTI
Wilhelmy Plate Test	TTI

Year 2 Milestones

No.	Description	Planned Date
1.	Submit Detailed Product Development Plans	6/30/08
2.	AOTR Approval of Product Development Plans	7/31/08
3.	Initiate Early Development Projects	8/1/08

Overall Schedule

Work Element	Year 1	Year 2	Year 3	Year 4	Year 5
TD1: Prioritize and Select Products for Early Development	X				
TD2: Develop Early Products		X	X		
TD3: Identify Products for Mid-Term and Long-Term Development		X	X	X	
TD4: Develop Mid-Term and Long-Term Products			X	X	X

Year 2 Schedule

Work Element	Qtr 1	Qtr 2	Qtr 3	Qtr 4
TD1: Prioritize and Select Products for Early Development	This task was completed in Year 1			
TD2: Develop Early Products	X	X	X	X
TD3: Identify Products for Mid-Term and Long-Term Development				
TD4: Develop Mid-Term and Long-Term Products				

Budget

The budget for the Technology Development Program area is estimated to initially be \$1.12M over the five years of the project. However, it is expected that as procedures, methods, and models are developed, the Technology Development area will be increased.

PROGRAM AREA: TECHNOLOGY TRANSFER

Technology transfer is a very critical step in the overall process of research-technology development-implementation. The ultimate goal of research is to develop sound techniques that can be implemented by the industry to design and build more durable and long-lasting pavements. If the research can not be transferred to the industry in the form of implementable material selection, design, analysis, and construction techniques, then its overall value will be highly questionable. The technology transfer task is a crucial part of every research and development program that is aimed at improving the state of the practice of the asphalt pavements/materials engineering community. This has been highly recognized by the FHWA through its technology transfer centers throughout the country as part of the national Local Technology Assistance Program (LTAP).

The overall objective of the technology transfer effort is to transfer the technology from the various research activities into practical applications for the asphalt pavement community, including both public agencies and private industry. The research findings will be communicated to the highway community using presentations at conferences, publication of results in a variety of journals, presentations at Expert Task Group (ETG) meetings, development and frequent updates of a website, development of training materials, and conducting of workshops. The technology transfer effort will attempt to close the loop between research and practice by translating research findings into standard test methods (some of which may be useful as specification tests), training materials, and training workshops and courses.

The Consortium will work on two areas of technology transfer: (1) Outreach and Databases and (2) Training. The Outreach and Databases effort will start in the first year of the Consortium while the training effort will start in the later years of the Consortium.

Category TT1: Outreach and Databases

BACKGROUND

The two critical aspects of outreach are: communication and accessibility. There is a great need to keep the stakeholders informed of the various Consortium activities. The stakeholders should also be able to have unobstructed and easy access to the various components of the research and development. They should be able to view and follow the progress of the various activities of the Consortium on their own time schedule. The stakeholders should also be kept informed of all the locations, dates, and deadlines for any training activities.

Accessibility is defined as the ability of the stakeholders to access valuable materials and research data that may help their programs. There may be some intermediate findings that the industry will use to improve a certain aspect of their operations. Accessibility to such information will be provided through electronic databases that incorporate the technical information on the various materials that are being researched by the Consortium.

HYPOTHESIS

All activities of the Consortium should be communicated and accessible to the stakeholders in a timely manner.

OBJECTIVES

The objectives of this effort are to provide venues for the transfer of the various activities of the Consortium to the asphalt pavement community in a highly effective and organized manner.

EXPERIMENTAL DESIGN

The following work elements will be completed in order to achieve the objectives of this research effort.

Work Element TT1a: Development and Maintenance of Consortium Website

Work Element lead: Elie Hajj (UNR)

Introduction

There is a great need to keep the stakeholders informed of the various Consortium activities. The stakeholders should also be able to have unobstructed and easy access to the various components of the research and development. They should be able to view and follow the progress of the various activities of the Consortium on their own time schedule. The stakeholders should also be kept informed of all the locations, dates, and deadlines for any training activities.

Relationship to FHWA Focus Areas

This effort supports the FHWA Focus Area of Technical Capabilities Building.

Hypothesis

All activities of the Consortium should be communicated and accessible to the stakeholders in a timely manner.

Objectives

The objective of this effort is to provide venues for the transfer of the various activities of the Consortium to the asphalt pavement community in a highly effective and organized manner.

Experimental Design

A Consortium Website will be developed using Micromedia Dreamweaver. The Website will announce workshops and training courses, provide links to partners research activities, federal and asphalt paving related association websites. The Consortium website will have a comment submission page. The Website will be developed within the first six-month of the contract and will be routinely updated to stay current with the various activities.

Major Findings from Year 1

During Year 1, the Consortium website was developed. It can be accessed on www.ARC.unr.edu

Year 2 Work Plan

During Year 2, the team will continue to maintain and update the Consortium Website.

Work Element TT1b: Communications

Work Element lead: Peter Sebaaly (UNR)

Introduction

Communication is a very important part of the Asphalt Research Consortium (ARC). The ARC team will make every effort to provide open communications with the entire asphalt industry including stakeholders and producers. Timely updates on the ARC activities will be provided in written electronic formats that will be distributed to all interested parties.

Relationship to FHWA Focus Areas

This effort supports the FHWA Focus Area of Technical Capabilities Building.

Hypothesis

All activities of the Consortium should communicated and accessible to the stakeholders in a timely manner.

Objectives

The objective of this effort is to provide venues for the transfer of the various activities of the Consortium to the asphalt pavement community in a highly effective and organized manner.

Experimental Design

The Consortium will produce and distribute flyers and newsletters on the progress of the various research activities. Brochures of the scheduled workshops and training courses will be produced and distributed to the industry. Newsletters will be produced three times annually which will

highlight the activities of the Consortium with technical write-ups on the various research activities.

Major Findings from Year 1

During Year 1, the first Consortium newsletter was produced and delivered to the asphalt industry. It can be accessed from: www.ARC.unr.edu

Year 2 Work Plan

During Year 2, the team will produce three Newsletters.

Work Element TT1c: Prepare presentations and publications

The Consortium members will prepare presentations and publications on the results and progress of the research. The presentations may be made at forums such as, but not limited to, Expert Task Group (ETG) meetings, Association of Asphalt Paving Technologists (AAPT), Transportation Research Board (TRB), Petersen Asphalt Research Conference, Association of Modified Asphalt Producers, Regional Asphalt User-Producer Groups, and many others.

Work Element TT1d: Development of Materials Database

Work Element Lead: Elie Hajj (UNR)

Introduction

Accessibility is defined as the ability of the stakeholders to access valuable materials and research data that may help their programs. There may be some intermediate findings that the industry will use to improve a certain aspect of their operations. Accessibility to such information will be provided through an electronic database that incorporates the technical information on the various materials that are being researched by the Consortium.

Relationship to FHWA Focus Areas

This effort supports the FHWA Focus Area of Technical Capabilities Building.

Hypothesis

All activities of the Consortium should be communicated and accessible to the stakeholders in a timely manner.

Objectives

The objective of this effort is to provide venues for the transfer of the various activities of the Consortium to the asphalt pavement community in a highly effective and organized manner.

Experimental Design

A materials database will be developed and designed to store information related to the sources and properties of the materials that are being used in the various research activities of the Consortium. The overall structure of the database will be defined based on the type of the data collected and the information that needs to be stored. The Consortium website developed in Subtask TT1a will serve as a means to access the database. A dynamic database-driven web application will be developed allowing data users to present information retrieved from the database on the web pages. Additionally, authorized personnel of the Consortium partners will have a secured access to populate the database with information pertinent to their activities. The subsequent steps will be followed to design the materials database system.

Subtask TT1d-1: Identify the overall Features of the Web Application

Under this subtask, UNR will identify and list the aspects of the web application. The list of the identified features will be sent to the Consortium partners for inputs and modifications. It is anticipated at this point that the web application will include the following features:

- Allow any user to request and retrieve information from the Consortium materials database through an electronic format.
- Allow authorized users to add, delete, and edit materials information through an electronic format.
- Allow authorized users to create a new category of materials.

Subtask TT1d-2: Identify Materials Properties to Include in the Materials Database

This subtask will use the information from the Materials Management Plan that has been developed by the Consortium to identify the specific materials information that needs to be included in the materials database.

Subtask TT1d-3: Define the Structure of the Database

After identifying the features of the web application, the type of information requested by users will be the basic step for defining the structure of the database. This task will define how the database should be structured to best answer users' needs. All data will be stored in a simple row/column format in tables (rows referred as records and columns referred to as fields). The first step consists of choosing the tables in the database. A relational database format will most probably be used. A relational database is a database containing separate tables, with the tables sharing data. Each table will describe a collection of related entities. The next step will be choosing, in each table, the columns describing the properties of each entity in the table and the *primary key* column(s). Each row of data will be uniquely identified by the values in a *primary key* column or a combination of columns allowing users to zero in on the exact row requested when searching the database. After defining the basic columns and *primary keys* in the tables, relationships between the various tables will be defined. Once the relationships are defined, Structured Query Language (SQL) statements to combine data from two tables will be written in

Micromedia Dreamweaver. SQL is the standard language for controlling and interacting with relational databases. SQL allows retrieving, adding, and deleting data to and from a database.

Subtask TT1d-4: Create and Populate the Database

The final design step is to create the database using a database system like Microsoft Access, SQL Server, or Oracle9i. A quality control (QC) system for data checks during acquisition and prior to database loading will be developed. QC checks on the information consist of validity of the provided information. Range checks on the validity and reasonableness of values entered in a field will be conducted. Additionally, relational checks between data stored in other fields will be conducted.

Major Findings from Year 1

This work element will start in year 2.

Year 2 Work Plan

During Year 2, the researchers will work on Subtasks TT1d-1, TT1d-2, and TT1d-3.

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
TT1d-1: Identify the overall Features of the Web Application		X			
TT1d-2: Identify Materials Properties to Include in the Materials Database		X			
TT1d-3: Define the Structure of the Database		X	X		
TT1d-4: Create and Populate the Database			X	X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
TT1d-1: Identify the overall Features of the Web Application	X	X		
TT1d-2: Identify Materials Properties to Include in the Materials Database	X	X		
TT1d-3: Define the Structure of the Database			X	X
TT1d-4: Create and Populate the Database				

Work Element TT1e: Development of Research Database

Work Element Lead: Elie Hajj (UNR)

Introduction

Accessibility is defined as the ability of the stakeholders to access valuable materials and research data that may help their programs. There may be some intermediate findings that the industry will use to improve a certain aspect of their operations. Accessibility to such information will be provided through an electronic database that incorporates the technical information on the various materials that are being researched by the Consortium.

Relationship to FHWA Focus Areas

This effort supports the FHWA Focus Area of Technical Capabilities Building.

Hypothesis

All activities of the Consortium should be communicated and accessible to the stakeholders in a timely manner.

Objectives

The objective of this effort is to provide venues for the transfer of the various activities of the Consortium to the asphalt pavement community in a highly effective and organized manner.

Experimental Design

A research database is important to keep Consortium partners and the asphalt pavement community current with the on-going and completed researches. The research database will cover the Consortium's recent, ongoing, and planned research studies. The Consortium website developed in Task 1.0 will serve as a medium to access the research database. It is anticipated that the University of Nevada will develop and maintain the Research Database and the other Consortium partners will populate the databases through a secured access with information pertinent to their activities. A dynamic database-driven web application will be developed allowing data users to present information retrieved from the research database on the web pages. The subsequent steps will be followed to design the materials database system.

Subtask TT1e-1: Identify the Information to Include in the Research Database

This subtask will identify the information in the research database that needs to be included. It is anticipated at this point the research database will include the following information for each research task: problem statement, budget, timeline of activities, results update in form of reports, white papers or any other type of documents, contacts information, and relationship to other studies.

UNR will send the Consortium partners a list of the anticipated information that needs to be included in the research database for inputs and modifications.

Subtask TT1e-2: Define the Structure of the Database

After defining the type of information that needs to go into the research database the structure of the database will be defined. All data will be stored in a simple row/column format in tables (rows referred as records and columns referred to as fields). The first step consists of choosing the tables in the database. A relational database format will most probably be used. A relational database is a database containing separate tables, with the tables sharing data. Each table will describe a collection of related entities. The next step will be choosing, in each table, the columns describing the properties of each entity in the table and the *primary key* column(s). Each row of data will be uniquely identified by the values in a *primary key* column or a combination of columns allowing users to zero in on the exact row requested when searching the database. After defining the basic columns and *primary keys* in the tables, relationships between the various tables will be defined. Once the relationships are defined, Structured Query Language (SQL) statements to combine data from two tables will be written in Dreamweaver. SQL is the standard language for controlling and interacting with relational databases. SQL allows retrieving, adding, and deleting data to and from a database.

Subtask TT1e-3: Create and Populate the Database

The final design step is to create the database using a database system like Microsoft Access, SQL Server, or Oracle9i.

Major Findings from Year 1

This work element will start in year 2.

Year 2 Work Plan

During Year 2, the researchers will work on Subtasks TT1e-1 and TT1e-2.

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
TT1e-1: Identify the Information to Include in the Research Database		X			
TT1e-2: Define the Structure of the Database		X			
TT1e-3: Create and Populate the Database			X	X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
TT1e-1: Identify the Information to Include in the Research Database	X	X		
TT1e-2: Define the Structure of the Database	X	X		
TT1e-3: Create and Populate the Database				

Budget

The initial estimated budget for the website and database portion of the Technology Transfer area is \$650,000 for the five year period. The budget may be revised as the project progresses.

Work Element TT1f: Workshops and Training

Work Element lead: Peter Sebaaly (UNR)

Introduction

Technology transfer is a very critical step in the overall process of research-technology development-implementation. The task of workshops development and training is a crucial part of every research and development program that is aimed at improving the state of the practice of the asphalt pavements/materials engineering community. This has been highly recognized by the FHWA through its technology transfer centers throughout the country as part of the national Local Technology Assistance Program (LTAP).

Relationship to FHWA Focus Areas

This effort fits under the FHWA Focus Area of Technical Capabilities Building.

Hypothesis

The findings of the research and development activities of the Consortium should be transferred to the asphalt pavements/materials engineering community through workshop developments and hands-on training.

Objectives

The objective of this effort is to develop workshop and training materials that can be delivered to the pavements/materials engineering community at various locations and time intervals throughout the country.

Experimental Design

As the research and development activities of the Consortium progresses, workshops and training materials maybe developed and delivered to the pavements/materials engineering

community at various locations and time intervals throughout the country. The subjects of the workshops and training materials will be submitted for approval by the AOTR prior to their development. Appropriate budgets will be developed for each individual workshop and training activity.

Budget

Specific budgets for workshop and training activities will be developed as they occur.