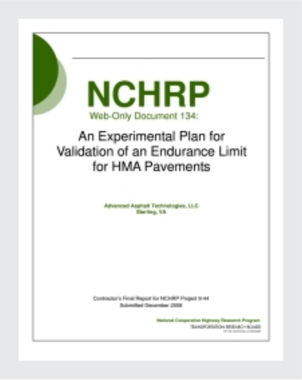

NCHRP

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An Experimental Plan for
Validation of an Endurance Limit
for HMA Pavements

Advanced Asphalt Technologies, LLC
Sterling, VA

Contractor's Final Report for NCHRP Project 9-44
Submitted December 2008

National Cooperative Highway Research Program
TRANSPORTATION RESEARCH BOARD

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NCHRP Project 9-44 included a facilitated workshop to discuss current asphalt concrete fatigue research and to identify alternatives for incorporating an endurance limit for asphalt concrete in mechanistic-empirical pavement design. Mr. Charles Markert, President of Dynamic Leadership Consulting Group, facilitated the workshop. Mrs. Rane Wagner, President of Rane Wagner and Associates, provided logistical support of the workshop. Special thanks are extended to the participants of the HMA Endurance Limit Workshop listed below. These professionals unselfishly presented ideas to the research team that helped shape the planned research.

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Dr. Edward Harrigan	National Cooperative Highway Research Program
Dr. Richard Kim	North Carolina State University
Dr. Dallas Little	Texas A&M University
Dr. Leslie Ann McCarthy	Federal Highway Administration
Dr. Andre Molenaar	Delft University
Professor Carl Monismith	University of California Berkeley
Dr. David Newcomb	National Asphalt Pavement Association
Dr. Michael Nunn	Lane One Limited
Dr. Brian Prowell	Advanced Material Services, LLC
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Ms. Amy Schutzbach	Illinois Department of Transportation
Dr. Jacob Uzan	Technion University
Dr. Linbing Wang	Virginia Polytechnic and State University
Dr. Matthew Witczak	Arizona State University

ABSTRACT

This report documents the work completed in National Cooperative Highway Research Program (NCHRP) Project 9-44. The objective of NCHRP Project 9-44 was to prepare a research plan and associated cost estimate for a future study to validate the endurance limit for HMA and to improve mechanistic-empirical pavement design. The primary product of NCHRP Project 9-44 is the HMA Endurance Limit Validation Study Research Plan.

The planned research is based on the hypothesis that the endurance limit for HMA is the result of a balance of damage caused by loading and healing or damage recovery that occurs during rest periods. Under this hypothesis the primary objective in designing a flexible pavement to resist bottom initiated fatigue cracking will be to make sure that the damage induced by loading remains small enough so that healing occurs and there is no accumulation of damage over the life of the pavement. This is a significant departure from current cumulative or incremental damage models, which assume that no healing occurs and that each load cycle uses up a portion of the finite fatigue life of the HMA.

This research plan includes the framework for a design procedure that is based on layered elastic analysis and compatible with the Mechanistic-Empirical Pavement Design Guide (MEPDG). It uses allowable strains to identify satisfactory conditions for full healing. The allowable strains are a function of the properties of the HMA, the pavement temperature, and the duration of rest periods between traffic loads. Five laboratory experiments that are needed to fully develop the procedure are described. Studies using data from completed accelerated pavement tests and test roads are proposed to verify critical aspects of the design procedure. Finally, an experiment to calibrate the design procedure using selected test sections from the Long Term Pavement Performance Program is presented.

SUMMARY

This report documents the work completed in National Cooperative Highway Research Program (NCHRP) Project 9-44. The objective of NCHRP Project 9-44 was to prepare a research plan and associated cost estimate for a future study to validate the endurance limit for HMA and to improve mechanistic-empirical pavement design. The primary product of NCHRP Project 9-44 is the HMA Endurance Limit Validation Study Research Plan. The research plan was formulated from a review of relevant research and the recommendations from a workshop that included participation by a number of international experts.

Completed laboratory and field investigations clearly show that hot mix asphalt (HMA) exhibits endurance limit behavior. This endurance limit, however, does not reflect an absence of load induced damage in the HMA. It is the result of a balance of damage caused by loading and healing or damage recovery that occurs during rest periods. The endurance limit for HMA is, therefore, not a single value, but will change depending on the loading and environmental conditions applied to the HMA. To properly consider this form of an endurance limit in flexible pavement design requires consideration of the effects of loading, environment and material properties on both damage accumulation and healing. These findings concerning the endurance limit for HMA served as the research hypothesis upon which the HMA Endurance Limit Validation Study Research Plan was formulated.

To effectively design laboratory and field experiments for the HMA Endurance Limit Validation Study, the framework for a pavement design procedure that incorporates healing and endurance limit behavior was conceived during NCHRP 9-44. The procedure is based on layered elastic analysis and is compatible with the Mechanistic-Empirical Pavement Design Guide (MEPDG). It uses allowable strains to identify satisfactory conditions for full healing. The allowable strains are a function of the properties of the HMA, the pavement temperature, and the duration of rest periods between traffic loads. The underlying principal of the design procedure is to make sure that the damage induced by loading remains small enough so that full healing occurs between traffic loads and there is no accumulation of damage over the life of the pavement. This is a significant departure from current cumulative or incremental damage

models, which assume that no healing occurs and that each load cycle uses up a portion of the finite fatigue life of the HMA.

The HMA Endurance Limit Validation Study is included as a stand-alone appendix to this report. It is a comprehensive plan for research to rationally incorporate the concept of an endurance limit for HMA into a mechanistic-empirical algorithm for bottom initiated fatigue cracking in flexible pavements, and to validate the resulting procedure using performance data from full-scale pavement sections. The plan presents details of five laboratory experiments that are needed to fully develop the procedure. Studies using data from completed accelerated pavement tests and test roads are proposed to verify critical aspects of the design procedure. Finally, an experiment to calibrate the design procedure using selected test sections from the Long Term Pavement Performance Program is presented.

1. INTRODUCTION AND RESEARCH APPROACH

1.1 Introduction

This report documents the research completed in National Cooperative Highway Research Program (NCHRP) Project 9-44, *Developing a Plan for Validating an Endurance Limit for HMA Pavements.* For hot mix asphalt (HMA) pavements, the endurance limit has been defined as *a level of strain below which there is no cumulative damage over an indefinite number of load cycles* (*1*). The endurance limit is an important concept in the design of long life flexible pavements that is gaining increasing acceptance worldwide. Appropriate application of the endurance limit in flexible pavement design will lead to more effective pavement sections with significant benefit and cost savings to the public.

1.2 Problem Statement and Research Objective

1.2.1 Problem Statement

The endurance limit, as applied to HMA and flexible pavement design, is a strain level below which the fatigue life of the HMA is infinite and the pavement will not experience bottom-up fatigue cracking. Current mechanistic-empirical fatigue criteria for HMA, including the field calibrated criterion in the Mechanistic Empirical Pavement Design Guide (MEPDG), assume the fatigue life of HMA to be a power function of the tensile strain at the bottom of the asphalt layer. These criteria do not include the provision for an endurance limit. There is mounting evidence that an endurance limit for asphalt concrete does exist. It has been observed in laboratory studies of fatigue at low strain levels, and several documented cases studies indicate that bottom-up fatigue cracking is almost non-existent in properly constructed, thick asphalt concrete pavements. A concentrated research effort, however, is needed to validate the endurance limit concept, and to devise effective methods for incorporating it in mechanistic-empirical pavement design methods.

1.2.2 Objective

The objective of NCHRP Project 9-44 was to prepare a research plan and associated cost estimate for a future study to validate the endurance limit for HMA and to improve mechanistic-empirical pavement design. To be successful, the research plan must address the following:

1. Validation of the existence of an endurance limit for HMA in pavements through an analysis of laboratory and field data;
2. Potential differences in the endurance limit measured in the laboratory and observed in field performance; and
3. Identification of a recommended methodology for incorporating an asphalt concrete endurance limit in mechanistic-empirical pavement design.

1.3 Research Approach

The research approach taken in NCHRP Project 9-44 was to synthesize information gathered from a review of relevant research and a workshop with invited experts to develop a comprehensive work plan and budget for a future project to validate the endurance limit for HMA and improve mechanistic-empirical pavement. NCHRP Project 9-44 included six major tasks, which are briefly described below.

1.3.1 Task 1. Review Relevant Research.

In this task, published research associated with the endurance limit and the design of flexible pavements and HMA mixtures to resist fatigue cracking was reviewed. Information obtained in Task 1 was used to select topics for the facilitated workshop that was conducted in Task 2 and to develop the overall approach for incorporating the endurance limit in mechanistic-empirical pavement design. This review focused on the following key topics:

- Laboratory endurance limit studies,
- Alternative forms for fatigue testing,
- Approaches for incremental damage analysis,
- Laboratory studies on healing and damage tolerance,
- Field studies of measured strains in thick flexible pavements,
- Case studies of long life flexible pavements.

1.3.2 Task 2. Conduct Facilitated Workshop.

Task 2 included the planning, execution, and documentation of a facilitated workshop directed at evaluating various methodologies for HMA fatigue characterization, and strategies for incorporating an endurance limit in mechanistic-empirical design. Recommendations from the workshop shaped the research plan produced in NCHRP Project 9-44.

The HMA Endurance Limit Workshop was held in Washington, D.C. on August 1 and 2, 2007. Participants included members of the NCHRP Project 9-44 panel and research team, key researchers and consultants with extensive experience in HMA fatigue analysis, and engineers from highway agencies who are responsible for designing, constructing, and maintaining flexible pavements. Thirty-four individuals were invited to attend, including four members of the research team, the NCHRP Project 9-44 panel members and Project Manager, and 22 invited experts. There was a high degree of interest in the workshop with 82 percent of the invitees participating. Table 1 presents summary information about the participants.

The HMA Endurance Limit Workshop was facilitated by Mr. Charles Markert, a Certified Professional Facilitator. The agenda for the workshop was developed jointly by Mr. Markert and Dr. Ramon Bonaquist, Principal Investigator for NCHRP Project 9-44. A copy of the agenda is reproduced as Figure 1. The key element of the workshop was a series of discussion sessions focusing on four major topics considered important to validating an endurance limit for HMA pavements:

- Endurance limit and other important fatigue effects,
- Methodologies for HMA fatigue characterization,
- Strategies for incorporating an endurance limit in flexible pavement damage analysis, and
- Approaches for calibrating and validating pavement analysis methods that include an endurance limit.

A summary report documenting the HMA Endurance Limit Workshop was prepared. This report in included as Appendix A.

Table 1. HMA Endurance Limit Workshop Invitees and Attendees.

No	Name	Affiliation	Role	Attend
1	Dr. David Anderson	Consultant	Panel Member	Y
2	Dr. Ramon Bonaquist	Advanced Asphalt Technologies, LLC	Research Team	Y
3	Dr. Stephen Brown	University of Nottingham	Invited Expert	N
4	Dr. William Buttlar	University of Illinois	Invited Expert	N
5	Dr. Samuel Carpenter	University of Illinois	Invited Expert	Y
6	Dr. Donald Christensen	Advanced Asphalt Technologies, LLC	Research Team	Y
7	Mr. Danny Dawood	Pennsylvania Department of Transportation	Panel Member	N
8	Dr. Herve Di Benedetto	Ecole Nat. des TPE	Invited Expert	Y
9	Mr. Bruce Dietrich	Florida Department of Transportation	Panel Member	Y
10	Dr. Jon Epps	Granite Construction Company, Inc.	Invited Expert	N
11	Mr. Kenneth Fults	KWF Pavement Consulting	Invited Expert	Y
12	Mr. Roger Green	Ohio Department of Transportation	Panel Member	Y
13	Dr. Kevin Hall	University of Arkansas	Invited Expert	Y
14	Dr. Edward Harrigan	National Cooperative Highway Research Program	Panel Member	Y
15	Mr. Frederick Hejl	Transportation Research Board	TRB Liaison	N
16	Dr. Richard Kim	North Carolina State University	Invited Expert	Y
17	Dr. Dallas Little	Texas A&M University	Invited Expert	Y
18	Dr. Robert Lytton	Texas A&M University	Invited Expert	N
19	Dr. Leslie Ann McCarthy	Federal Highway Administration	Panel Member	Y
20	Mr. Charles Markert	Dynamic Leadership Consulting Group	Research Team	Y
21	Dr. Andre Molenaar	Delft University	Invited Expert	Y
22	Professor Carl Monismith	University of California Berkeley	Invited Expert	Y
23	Dr. David Newcomb	National Asphalt Pavement Association	Invited Expert	Y
24	Dr. Michael Nunn	Lane One Limited	Invited Expert	Y
25	Ms. Linda Pierce	Washington Department of Transportation	Invited Expert	N
26	Dr. Brian Prowell	Advanced Material Services, LLC	Invited Expert	Y
27	Dr. Rey Roque	University of Florida	Invited Expert	Y
28	Ms. Amy Schutzbach	Illinois Department of Transportation	Panel Member	Y
29	Mr. Darin Tedford	Nevada Department of Transportation	Panel Member	N
30	Dr. Jacob Uzan	Technion University	Invited Expert	Y
31	Mr. Harold Von Quintus	Applied Research Associates	Invited Expert	Y
32	Dr. Linbing Wang	Virginia Polytechnic and State University	Panel Member	Y
33	Ms. Rane Wagner	Rane Wagner and Associates	Research Team	Y
34	Dr. Matthew Witczak	Arizona State University	Invited Expert	Y

AGENDA Item	Questions to be answered
Sponsor Welcome, Facilitator Opening, Introductions	
Personal Expectations	What are your expectations for this session?
Briefing 1 Fatigue in the MEDPG	How are fatigue and the endurance limit addressed in the MEPDG?
Briefing 2 NCHRP 9-38 Laboratory Evaluation of Endurance Limit	What was found about the endurance limit in NCHRP Project 9-38?
Briefing 3 A Review of UK Pavement Design	What approach is taken in the UK?
Purpose Discussion	What is the purpose of this session?
Discussion: Existence of Fatigue Endurance Limit	Does a Fatigue Endurance- Limit Exist?
Continue Discussion	Does a Fatigue Endurance- Limit Exist?
Issues Related to Fatigue -Endurance- Limit	"What are the other issues?"
Identify Major Issues	Which of these possibilities go on the Short List? Place your dots – one per card.
What is the Meaning of Each Major Issues?	Discussion on the top few.
Discussion: Alternative Methodologies for Characterizing Fatigue	Do we need alternative to Beam Fatigue? Can they address endurance limit? Are they implementable?
Flexible Pavement Damage Analysis	How can we improve flexible pavement damage analysis? What important issues are not currently addressed?
Plus/Delta	
Adjourn	
DAY TWO	
Review Agenda/Progress/Issues	
Strategies for Incorporating Endurance Limit in Flexible Pavement Damage Analysis	What are the possible strategies for incorporating Endurance Limit?
Identify Barriers to Success?	What are the barriers to success in this effort?
Identify Countermeasures?	What are some countermeasures?
Identify Simplifying Assumptions	Can we identify some simplifying assumptions that will help?
Calibration/Verification	Is calibration necessary? How should it be done? Field sections, accelerated pavement testing, etc?
Suggest Data Evaluation Approaches	What are your suggestions for calibration/verification?
Identify Potential Action for NCHRP 9-44	What should be included in the workplan for future research developed in NCHRP 9-44?
Silver Bullet Actions	Which suggestions from Potential Actions can be addressed in a 3-year project?
Recommendations, Findings & Conclusions	What are your recommendations, findings & conclusions as a group?
Closing	
ADJOURN	

Figure 1. HMA Endurance Limit Workshop Agenda.

1.3.3 Task 3. Identify Data Requirements

A major part of Task 3 was the development of a framework for designing pavements to resist bottom initiated fatigue cracking that considers the effects of an endurance limit. The framework was developed to identify specific laboratory studies needed to fully develop the design procedure and the types of pavement test section data needed for the validation.

The framework of the design procedure that was developed is based on the following research hypothesis that emanated from the HMA Endurance Limit Workshop. *The endurance limit for HMA does not reflect an absence of load induced damage in the HMA. It is the result of a balance of damage caused by loading and healing or damage recovery that occurs during rest periods.* Under this hypothesis the primary objective in designing a flexible pavement to resist bottom initiated fatigue cracking is to make sure that the damage induced by loading remains small enough so that healing occurs and there is no accumulation of damage over the life of the pavement. This is a significant departure from current cumulative or incremental damage models, which assume that no healing occurs and that each load cycle uses up a portion of the finite fatigue life of the HMA.

A number of approaches for designing pavements to resist bottom initiated fatigue cracking were identified in Task 1. Table 2 briefly summarizes the approaches that were considered. These range from relatively simple modifications of traditional mechanistic-empirical fatigue algorithms to sophisticated finite element models based on damage mechanics and fracture mechanics. The major deficiency of the more practical approaches is that they do not account for the beneficial effects of healing. In the HMA Endurance Limit Workshop, healing was identified as a significant factor affecting the endurance limit in HMA (*1*). The sophisticated approaches can account for healing, but are not practical at this time for use in routine pavement design. Since an acceptable existing design procedure could not be identified, the framework for a new design procedure was developed. It is based on limiting strains at the bottom of the lowest asphalt bound layer to those that will permit full healing to occur between traffic loads. This approach results in lower allowable strains for conditions that result in less healing: higher traffic volumes and colder temperatures. Chapter 2 includes a description of the framework for the new design procedure.

Table 2. Summary of Existing Pavement Analysis Approaches Considered.

Approach	**Key Elements**	**Selected References**	**Advantages**	**Disadvantages**
Strain Limit	Assume fatigue life is infinite at damage levels below the endurance limit. Use Miner's law for strain levels above the endurance limit.	Timm and Young (2) Witczak (3) Thompson and Carpenter (4)	Easy to implement in existing M-E design. Compatible with layered elastic analysis used in MEPDG.	Does not consider the beneficial effect of rest periods. Relies on Miners law for strains above the endurance limit. Above endurance limit fatigue life of HMA is predefined.
Crack Initiation	Limit strain level to that causing crack initiation in laboratory fatigue tests.	Sidess and Uzan (5)	Easy to implement in existing M-E design. Compatible with layered elastic analysis used in MEPDG. Rational basis for design.	Does not consider the beneficial effect of rest periods. Relies on Miners law. Cycles to crack initiation are predefined.
Strain Limit-Crack Initiation	Assume fatigue life is infinite at damage levels below the endurance limit. Use Miner's law for strain levels above the endurance limit. The endurance limit is estimated from the indirect tensile strength test and is dependent on the modulus of the mixture.	Von Quintus (6, 7)	Relatively easy to implement in existing M-E based methods. Compatible with layered elastic analysis used in the MEPDG. Value is dependent on the temperature (modulus), and volumetric properties of the mixture.	Does not consider the beneficial effect of rest periods. Relies on Miner's law for strains above the endurance limit. Key property used to estimate endurance limit is highly variable.
Recursive Miner's Law	Modify fatigue life of HMA to account for the strength loss of a pavement structure as a function of traffic loading.	Tsai, et al., (8)	Easy to implement in existing M-E design. Compatible with layered elastic analysis used in MEPDG. Accounts for changes in fatigue life of HMA with traffic.	Assumes that HMA fatigue life deteriorates with traffic loading. Does not consider the beneficial effect of rest periods.
Visco-Elastic Continuum Damage	Model the evolution of damage in a viscoelastic continuum.	Mun, et al., (9)	Can be used to predict crack initiation. Directly accounts for damage accumulation and healing.	Computationally intensive. Not compatible with layered elastic analysis used in MEPDG.
Fracture Mechanics	Model responses at the crack tip and the propagation of cracks.	Roque, et al. (10)	Predict crack growth.	Requires crack initiation model. Computationally intensive. Not compatible with layered elastic analysis used in MEPDG.

Five experiments were identified to full develop the design procedure incorporating an HMA endurance limit. Table 3 summarizes the laboratory experiments that are needed. The experiments are briefly described below. Details of these experiments are included in the HMA Endurance Limit Validation Study Research Plan that is presented in Appendix B.

Table 3. Summary of Proposed Laboratory Experiments.

Experiment	Topic	Factors
1	Mixture Compositional Factors Affecting Healing in HMA	• Binder Type • Binder Age • Effective Binder Content • Air Voids • Design Compaction • Gradation • Filler Content
2	Effect of Applied Strain on Healing	• Strain Level • Healing Rate From Experiment 1
3	Effect of Temperature and Rest Period Duration on Healing	• Temperature • Rest Period Duration
4	Development of Testing and Analysis Procedures to Determine Allowable Strain Levels	• Healing Rate From Experiment 1 • Mixtures From NCHRP 9-38
5	Estimation of Allowable Strain Levels from Mixture Composition	• Mix Compositional Factors Affecting Damage Accumulation • Significant Factors From Experiment 1 • Temperature • Rest Period Duration

Experiment 1 is a screening study to identify the mixture compositional factors that affect healing and therefore, the allowable strain levels in HMA. The results from this experiment will be used in the remaining experiments. Experiment 2 addresses a major assumption that was made in developing the allowable strain limit procedure, that is, the healing rate is independent of the applied strain level. In this experiment healing rates will be determined using different strain levels. This experiment will be conducted on mixtures from Experiment 1 that have high and low healing rates. Experiment 3 is a study to verify the applicability of time-temperature superposition to healing in HMA. This was the second major assumption included in the development of the allowable strain limit procedure. Experiment 3 will be conducted on a mixture from Experiment 1 that exhibits a moderate healing rate. Testing and analysis methods for determining allowable strain limits that result in complete healing will be developed in Experiment 4. This experiment will include testing and analysis of selected mixtures from Experiment 1 and mixtures used in the endurance limit testing completed in NCHRP Project 9-38. This experiment will generate the Level 1 test procedure for use with a future modified version of the MEPDG. In the last experiment, Experiment 5, a wide range of mixtures will be tested using the methods developed in Experiment 4 to develop predictive models relating the allowable strain limits to mixture compositional factors. This last experiment will generate the relationships between allowable strain and easily measured mixture compositional properties that will be used in calibrating the procedure and thus verifying the endurance limit for HMA. These relationships will also provide the Level 2 and 3 analyses for a future modified version of the MEPDG.

1.3.4 Task 4. Identify Applicable Projects.

Task 4 consisted of assessing the usefulness of various field projects, both accelerated pavement tests and in-service pavement sections for use in validating an endurance limit for HMA. Results from accelerated pavement tests can be used to tests critical elements of the framework developed in Task 3. These include the effects of temperature, applied strain, and material properties on the allowable strain levels. The accelerated pavement tests recommended for consideration were:

- Fatigue tests conducted during the Superpave validation study at the FHWA Pavement Test Facility (*11*).
- Sections at the NCAT Test Track that have remained in service from the first cycle through the current cycle (*12*).
- Sections from the WesTrack experiment containing mixtures with different composition (*13*).
- Sections from the structural design experiment performed at the NCAT Test Track (*14, 15*).
- Selected sections from the MNRoad project (*16*).

The allowable strain limit design procedure will be calibrated and validated using in-service pavement sections. It is important to recognize that the allowable strain limit design procedure is not intended to be a tool for predicting the extent of bottom initiated cracking with time and traffic like the MEPDG fatigue model. Its purpose is to identify design features that minimize the possibility of bottom initiated fatigue cracking. Thus, field calibration of the allowable strain limit design procedure will be easier and likely more precise than the calibration that was completed for the MEPDG fatigue model.

Sections from the LTPP program (*17*) and pavements that have received perpetual pavement awards from the Asphalt Pavement Alliance (*18*) were considered for use in the calibration and validation. The LTPP sections were selected because these sections have received extensive monitoring over a number of years, and distress, deflection, and material property data are available from the LTPP database (*17*). Since sufficient sections for the analysis are available from the LTPP program, only these sections were included in the research plan. Table 4 presents the test matrix for using LTPP sections to calibrate and validate the allowable strain limit design procedure. Since the procedure is not intended for prediction of the extent of cracking in a pavement section, but rather as a tool to identify design features to minimize the potential for bottom initiated fatigue cracking, an extremely large data set is not required. The recommended matrix includes a total of 32 pavement sections: 16 not exhibiting alligator cracking and 16 exhibiting low to moderate amounts of alligator cracking. An equal number of sections from the four environmental zones are included in the matrix. Only pavements with HMA thicknesses exceeding 8 inches are included. Subgrade deformation becomes an important consideration in thinner HMA pavements. Simultaneous calibration and validation can be performed on this data set using jackknifing as described in Research Results Digest Number 283 (*19*). Jackknifing allows the assessment of model accuracy without separating the 32 sections into calibration and validation subsets. Jackknifing is performed by systematically removing one of the sections, calibrating the model using the remaining sections, then predicting the value of the section that was removed. For the section that was removed, the model error is computed as the difference between the predicted and measured values. The process of withholding, calibrating, and determining the error is repeated until each section has been removed. This process produces *n* values of the error from which the jackknifing goodness of fit statistics can be computed. The advantage of jackknifing is the goodness of fit statistics are based on predictions of measurements that are not included in the calibration. They are, therefore, better estimates of the accuracy of future predictions than goodness of fit statistics based on calibration using the full data set.

Table 4. Matrix for Field Calibration of the Allowable Strain Limit Design Procedure.

Environment	HMA Thickness, in	No Alligator Cracking	Low Alligator Cracking
Wet Freeze	8 to 12	2	2
	>12	2	2
Wet No Freeze	8 to 12	2	2
	>12	2	2
Dry Freeze	8 to 12	2	2
	>12	2	2
Dry No Freeze	8 to 12	2	2
	>12	2	2

1.3.5 Task 5. Prepare Detailed Work Plan.

The HMA Endurance Limit Validation Study Research Plan was prepared in Task 5. The research plan is a comprehensive document describing the research that must be completed to successfully incorporate the concept of an endurance limit for HMA into a fatigue algorithm for bottom initiated fatigue cracking and to validate the resulting procedure using full-scale pavement sections. It includes four major parts. The first is a summary that briefly describes the proposed research and presents overall cost estimates and time requirements. The second part is a description of the required research tasks. This section includes detailed information for each task and subtask, including (1) a description of the work to be performed, (2) preliminary experimental designs when appropriate, (3) a list of milestones related to the task, (4) labor hour estimates, and (5) a listing of pertinent data and reference material that will be needed to accomplish the task. The third part is a detailed schedule for the project. The schedule addresses the sequence of the research tasks and the interactions between tasks. Finally, the fourth part presents the proposed budget for the project. The budget includes detailed estimates of labor and other costs associated with each task and subtask.

1.3.6 Task 6. Prepare Final Report.

The final project task was the preparation of this final report documenting the work performed in NCHRP Project 9-44. The report was prepared in the format required by NCHRP. It includes the workshop summary and research plan as stand-alone appendices.

2. FINDINGS

2.1 HMA Endurance Limit

Recent laboratory and field studies of HMA fatigue behavior indicate that HMA does exhibit endurance limit behavior. Although early HMA fatigue research conducted by Monismith and his colleagues suggested that HMA exhibited an endurance limit at approximately 70 μstrain (*20*), only limited HMA fatigue research was conducted at low strain levels until recently when the Asphalt Pavement Alliance began promoting the concept of perpetual pavement design (*21*). A perpetual pavement is an asphalt pavement that provides a very long life without structural failure and only requires periodic replacement of the surface. A key element of perpetual pavement design is to eliminate fatigue cracking that initiates at the bottom of the HMA base due to repeated flexure under traffic loading and to confine distresses to the surface of the pavement, which can easily be renewed by milling and resurfacing.

In response to increasing interest in perpetual pavements, a substantial amount of laboratory fatigue testing has recently been performed in the United States in an effort to demonstrate that HMA does exhibit an endurance limit. Most of this work has been performed at the University of Illinois (*22*, *23*) and the National Center for Asphalt Technology (NCAT) (*24*). These studies provide clear evidence that the fatigue behavior of HMA is much different in low strain level tests compared to normal strain level tests. Figure 2 shows a consolidated plot of the University of Illinois fatigue data including low and normal strain level test data. Below approximately 100 μstrain, the fatigue life is significantly longer than estimated from extrapolation of normal strain level test data. Healing of microdamage has been proposed as the primary reason for the increased fatigue life at low strain levels (*1, 25, 26*). For cyclic tests at low strain levels, it appears that the damage that is caused by loading is offset by healing that occurs during unloading resulting in essentially infinite fatigue life.

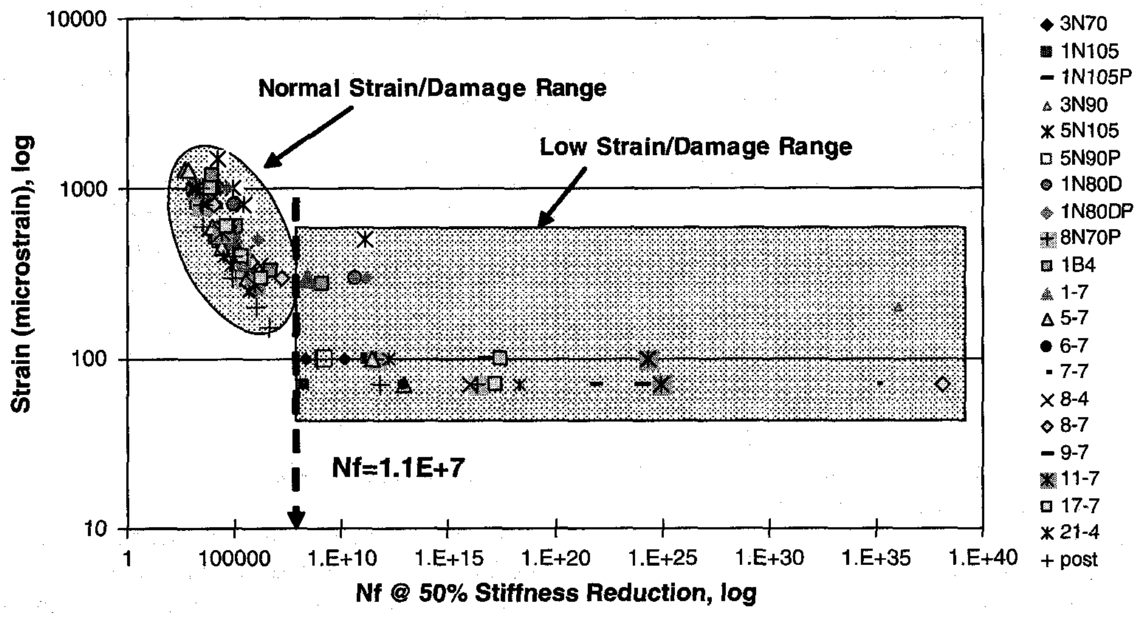


Figure 2. Results of Flexural Fatigue Tests by Carpenter et al., Including Extrapolated Results at Low Strain Levels (*22*).

Detailed investigation of four heavily trafficked pavements in the United Kingdom support the perpetual pavement concept and the likelihood of an endurance limit for HMA. This comprehensive study found no evidence of fatigue damage at the bottom of properly constructed thick flexible pavements with total HMA thickness ranging from 230 to 350 mm (*27*). Cracks in these pavements were found to have initiated at the surface and deflections monitored over a number of years generally showed steady or decreasing deflection with increasing cumulative traffic, indicating that fatigue damage to the bottom of the HMA was not occurring. Similar conclusions concerning the absence of cracking at the bottom of thick HMA pavements have been reported by others (*28, 29, 30*).

In summary, there is mounting evidence that an endurance limit for HMA does exist. It has been observed in laboratory studies of fatigue at low strain levels, and several documented case studies indicate that bottom initiated fatigue cracking is almost non-existent in properly constructed, thick HMA pavements. The HMA endurance limit, however, does not reflect an absence of load induced damage in the HMA. It is the result of a balance of damage caused by loading and healing or damage recovery that occurs during rest periods. The endurance limit for HMA is, therefore, not a single value, but will change depending on the loading and environmental conditions applied to the HMA. To properly consider this form of an endurance limit in flexible pavement design requires consideration of the effects of loading, environment and material properties on both damage accumulation and healing. These findings concerning the endurance limit for HMA served as the research hypothesis upon which the HMA Endurance Limit Validation Study Research Plan was formulated.

2.2 Framework for Incorporating Endurance Limit Behavior in Flexible Pavement Design

The framework for a pavement design procedure that incorporates healing and endurance limit behavior was conceived during NCHRP 9-44. The procedure is based on layered elastic analysis and is compatible with the MEPDG. It uses allowable strains to identify satisfactory conditions for full healing. The allowable strains are a function of the properties of the HMA, the pavement temperature, and the duration of rest periods between traffic loads. The underlying principal of the design procedure is to make sure that the damage induced by loading remains small enough so that healing occurs and there is no accumulation of damage over the life of the pavement. This is a significant departure from current cumulative or incremental damage models, which assume that no healing occurs and that each load cycle uses up a portion of the finite fatigue life of the HMA.

2.2.1 Effect of Rest Periods

Carpenter and Shen (*25*) clearly demonstrated the beneficial effects of rest periods on the fatigue life of HMA. Strain controlled flexural fatigue tests were conducted at 20 °C using a 10 Hz haversine load pulse with a rest period between each pulse to simulate the time between traffic loads. The rest periods ranged from 0 sec (continuous loading) to 9 seconds. Two 19 mm mixtures, one with a neat PG 64-22 binder and one with a polymer modified PG 70-22 binder, were tested. The gradation, binder content and air void content of the two mixtures was the same. The resulting data were analyzed using the ratio of dissipated energy change (RDEC) approach developed at the University of Illinois (*23*). In this approach, the ratio of dissipated energy change reaches a plateau value (PV) where a constant percentage of the input energy is being converted to damage. The University of Illinois research found a unique relationship between the plateau value and the traditional definition of failure in flexural fatigue tests, 50 percent stiffness reduction, that holds for a range of mixtures and loading conditions (*23*).

$$PV = 0.4429 \times \left(N_f\right)^{-1.1102} \tag{1}$$

where:

PV = plateau value

N_f = number of cycles to 50 percent stiffness reduction

Lower plateau values correspond to longer fatigue lives. Based on the ratio of dissipated energy change approach, an HMA mixture will exhibit endurance limit behavior when the plateau value is 6.74×10^{-9} or less, which based on Equation 1 corresponds to a traditional fatigue life of 1.1×10^{7} cycles or greater.

The effect of rest periods on the plateau value is shown in Figure 3 for the two mixtures that were tested. Equations 2 and 3 present the relationship between plateau value and the length of the rest period that were developed for the neat PG 64-22 and the modified PG 70-22 mixtures, respectively for a strain level of 500 μstrain (*25*).

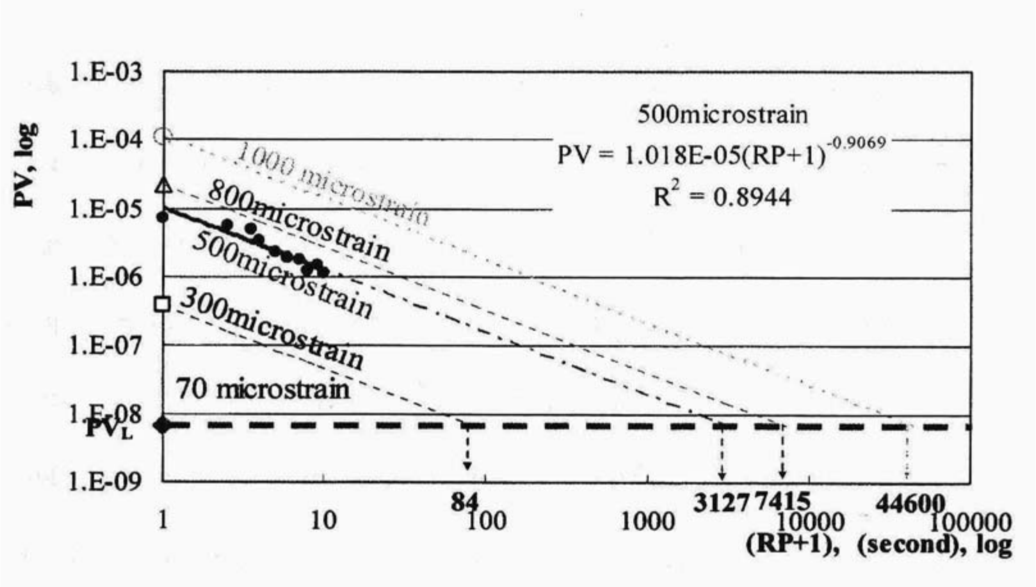
For neat PG 64-22
$$PV = 1.018 \times 10^{-5} \left(RP + 1\right)^{-0.9069} \tag{2}$$

For modified PG 70-22
$$PV = 4.353 \times 10^{-6} \left(RP + 1\right)^{-1.352} \tag{3}$$

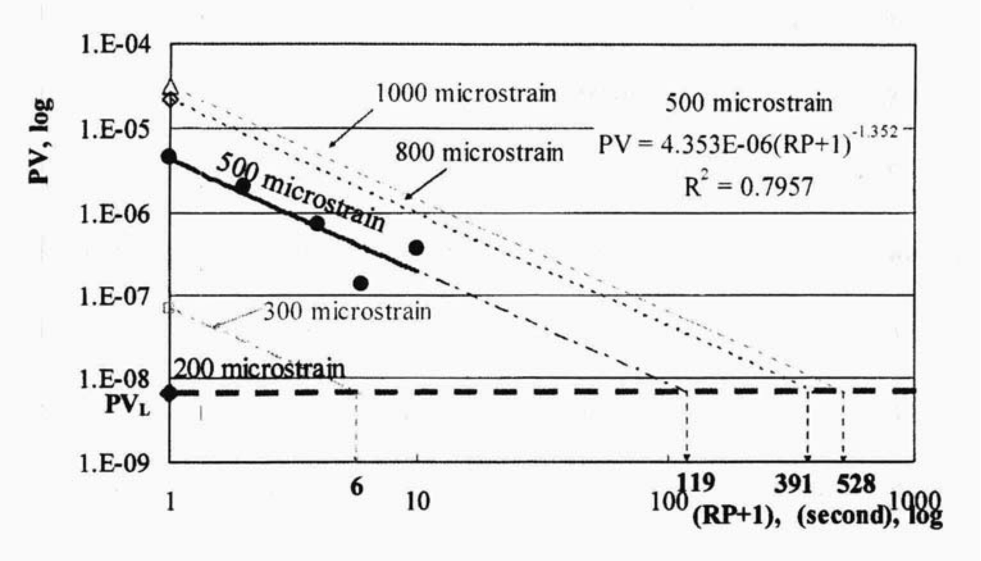
where:

PV = plateau value

RP = duration of intermittent rest period, sec



a. Neat PG 64-22



b. Polymer PG 70-22

Figure 3. Effect of Rest Periods on Plateau Value (*25*).

The decreasing plateau values for tests with rest periods result in increasing fatigue lives. This can be quantified by substituting plateau values from Equations 2 or 3 into Equation 1. The results are summarized in Table 5. Figure 4 shows the beneficial effect of the rest periods on the fatigue lives for the two mixtures. There is a substantial improvement in the fatigue life of both mixtures. The values for the neat PG 64-22 mixture are of similar magnitude to improvements previously reported by Bonnaure, et al. (*31*). The effect of rest periods on the modified PG 70-22 mixture is much more pronounced.

Table 5. Effect of Rest Period on Fatigue Life.

Rest Period, sec	Neat PG 64-22			Modified PG 70-22		
	PV	N_f	Ratio	PV	N_f	Ratio
0	1.02E-05	1.51E+04	1.00	4.35E-06	3.24E+04	1.00
1	5.43E-06	2.65E+04	1.76	1.71E-06	7.53E+04	2.33
2	3.76E-06	3.70E+04	2.45	9.86E-07	1.23E+05	3.81
3	2.90E-06	4.68E+04	3.10	6.68E-07	1.75E+05	5.41
4	2.37E-06	5.61E+04	3.72	4.94E-07	2.30E+05	7.10
5	2.00E-06	6.51E+04	4.32	3.86E-07	2.87E+05	8.86
6	1.74E-06	7.39E+04	4.90	3.13E-07	3.46E+05	10.69
7	1.54E-06	8.24E+04	5.47	2.62E-07	4.08E+05	12.58
8	1.39E-06	9.07E+04	6.02	2.23E-07	4.70E+05	14.52
9	1.26E-06	9.89E+04	6.56	1.94E-07	5.35E+05	16.51
10	1.16E-06	1.07E+05	7.09	1.70E-07	6.01E+05	18.54

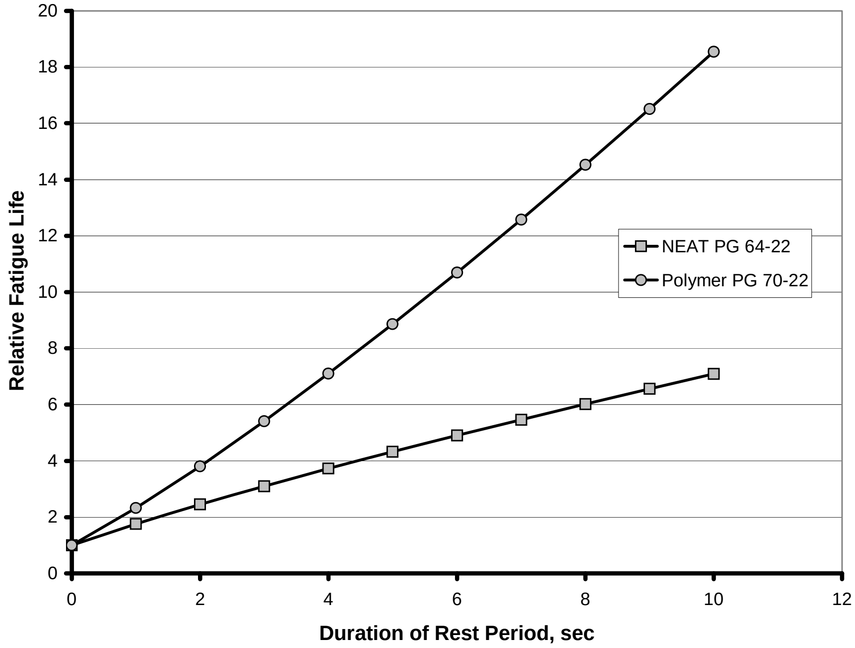


Figure 4. Effect of Rest Period on Fatigue Life.

An estimate of approximate rest periods can be obtained from the 20 year design traffic level typically used in mixture design. Table 6 summarizes rest periods for various design traffic levels. The rest period for a 20 year design traffic level of 100 million ESAL is approximately 6 sec., which results in a factor of 5 improvement in the fatigue life of the mixture with the neat PG 64-22 binder and a factor of 10 improvement for the polymer modified PG 70-22 mixture.

Table 6. Approximate Rest Periods for Various Design Traffic Levels.

20 Year Design ESAL	ESAL/Day	ESAL/sec	Rest Period, sec
1.00E+05	13.7	0.0002	6307.2
3.00E+05	41.1	0.0005	2102.4
1.00E+06	137.0	0.0016	630.7
3.00E+06	411.0	0.0048	210.2
1.00E+07	1369.9	0.0159	63.1
3.00E+07	4109.6	0.0476	21.0
1.00E+08	13698.6	0.1585	6.3
3.00E+08	41095.9	0.4756	2.1

2.2.2 Allowable Strains

Continuous loading tests at different strain levels were also conducted by Carpenter and Shen on the two mixtures and the plateau values are shown in Figure 3 for a rest period of zero (RP+1=1) (*25*). From these data relationships between the plateau value for continuous loading and the applied strain level can be developed as shown in Figure 5. These relationships are given in Equations 4 and 5 for the neat PG 64-22 mixture and the polymer modified PG 70-22 mixture.

For neat PG 64-22 $$PV_0 = 9.142 \times 10^{-16} (\varepsilon)^{3.617} \qquad (4)$$

For modified PG 70-22 $$PV_0 = 5.347 \times 10^{-21} (\varepsilon)^{5.331} \qquad (5)$$

where:

PV_0 = plateau value for continuous loading

ε = tensile strain, μstrain

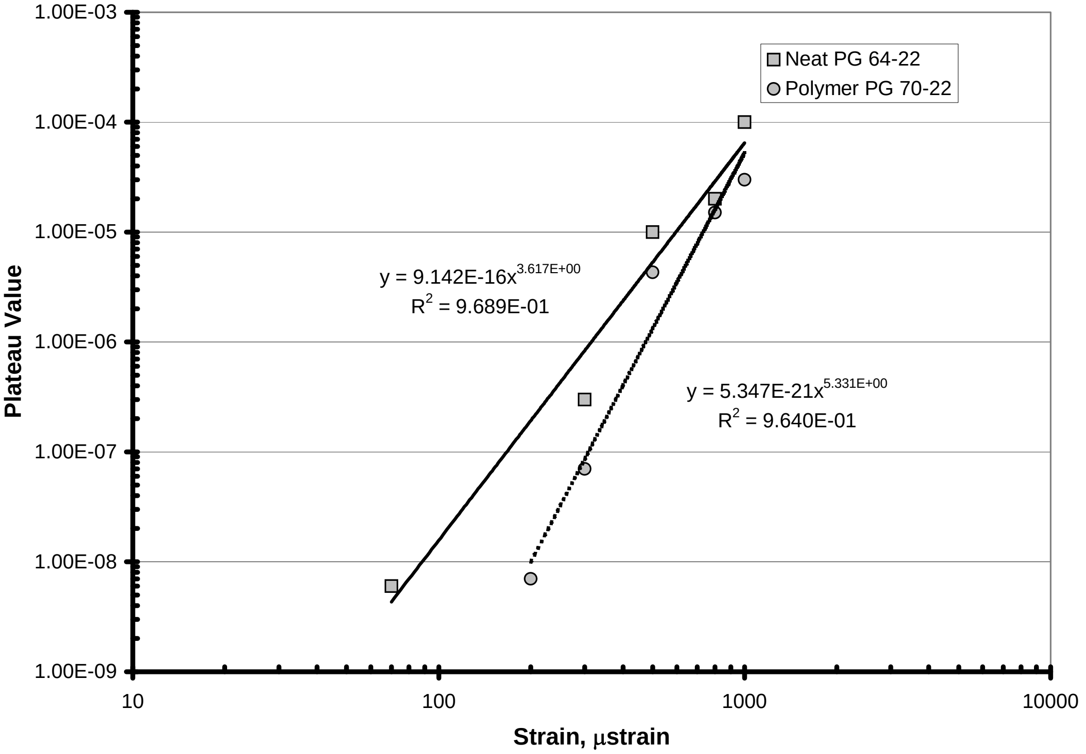


Figure 5. Plateau Value for Continuous Loading as a Function of Applied Strain Level.

Based on previous work by Bonnaure (*31*), it is reasonable to assume that the effect of the rest periods is the same at each strain level. Substituting Equations 4 and 5 for the constants 1.018 x10^{-5} and 4.353 x10^{-6} in Equations 2 and 3 respectively, yield the following relationships between the plateau value, applied strain and rest period for the two mixtures.

For neat PG 64-22 $$PV = 9.142 \times 10^{-16} (\varepsilon)^{3.617} (RP+1)^{-0.9069} \quad (6)$$

For modified PG 70-22 $$PV = 5.347 \times 10^{-21} (\varepsilon)^{5.331} (RP+1)^{-1.352} \quad (7)$$

where:

PV = plateau value

ε = tensile strain, μstrain

RP = duration of intermittent rest period, sec

Equations 6 and 7 can then be substituted into Equation 1 and solved for the allowable strain level to produce a selected mixture fatigue life.

For neat PG 64-22 $$\varepsilon_a = 11483.32\left[\frac{(1+RP)^{0.2507}}{(N_f)^{0.3069}}\right] \tag{8}$$

For modified PG 70 -22 $$\varepsilon_a = 5448.74\left[\frac{(1+RP)^{0.2536}}{(N_f)^{0.2082}}\right] \tag{9}$$

where:

ε_a = allowable tensile strain, μstrain

RP = duration of intermittent rest period, sec

N_f = number of cycles to failure

Recalling that endurance limit behavior occurs when the number of cycles to failure exceeds 1.1 x10^7, then setting the number of cycles to failure in Equations 8 and 9 to a value above 1.1 x 10^7 will ensure that full healing occurs at the selected rest period. Conservatively using 2.0 x 10^7 as the number of cycles to failure yields Equations 10 and 11, which give allowable strain levels as a function of rest period to ensure that full healing occurs.

For neat PG 64-22 $$\varepsilon_{af} = 66.0(1+RP)^{0.2507} \tag{10}$$

For modified PG 70-22 $$\varepsilon_{af} = 164.5(1+RP)^{0.2536} \tag{11}$$

where:

ε_{af} = allowable tensile strain for full healing, μstrain

RP = duration of intermittent rest period, sec

If the strains in a pavement at 20 °C are kept below the values given by Equations 10 and 11, then complete healing will occur during intermittent rest periods, and the pavement will exhibit endurance limit behavior. Table 7 summarizes these strain levels for various 20 year design traffic levels.

Table 7. Allowable Strains for Various Design Traffic Levels.

20 Year Design ESAL	Rest Period, sec	Allowable Strains, µstrain	
		Neat PG 64-22	Modified PG 70-22
1.00E+05	6307.2	592	1513
3.00E+05	2102.4	449	1145
1.00E+06	630.7	332	844
3.00E+06	210.2	253	639
1.00E+07	63.1	187	472
3.00E+07	21.0	143	360
1.00E+08	6.3	109	272
3.00E+08	2.1	88	219

2.2.3 Multiple Temperatures

The allowable strains presented in the previous section were developed from test data obtained at 20 °C. To be useful in a pavement design procedure, the allowable strains for a wide range of temperatures must be available. In this procedure the major concern is the effect of temperature on the healing properties of the mixture. Previous research by Bonnaure, et al. (*31*) concluded that the beneficial effect of rest periods increased with increasing temperature. Since healing can be envisioned as a type of flow phenomenon where the binder flows together to repair microcracks, it has been hypothesized that the effect of healing at multiple temperatures can be accounted for using time-temperature superposition. By applying time-temperature superposition, rest periods at different temperatures can be reduced to an equivalent rest period at 20 °C. The reduced rest period for temperatures above 20 °C will be longer than the actual rest period, while those for temperatures below 20 °C will be shorter than the actual rest period. Research conducted in NCHRP Project 9-19 showed that linear, viscoelastic time-temperature shift factors obtained from dynamic modulus tests could be applied when a high level of nonlinear damage is present (*32*). Equation 12 presents the application of time-temperature superposition to the duration of the rest period.

$$\log(RP_R) = \log(RP) - \log(A_T) \tag{12}$$

where:

RP_R = duration of the rest period at the reference temperature, sec

RP = actual duration of the rest period, sec

A_T = linear viscoelastic time temperature shift factor obtained from dynamic modulus testing.

Figure 6 illustrates the use of time-temperature superposition for rest periods at temperatures of 40, 20, and 4 °C using 20° C as the reference temperature. In developing Figure 6, typical time-temperature shift factors were used (log(A_T) for 4 °C =2.0 and log(A_T) for 40 °C = -2.2).

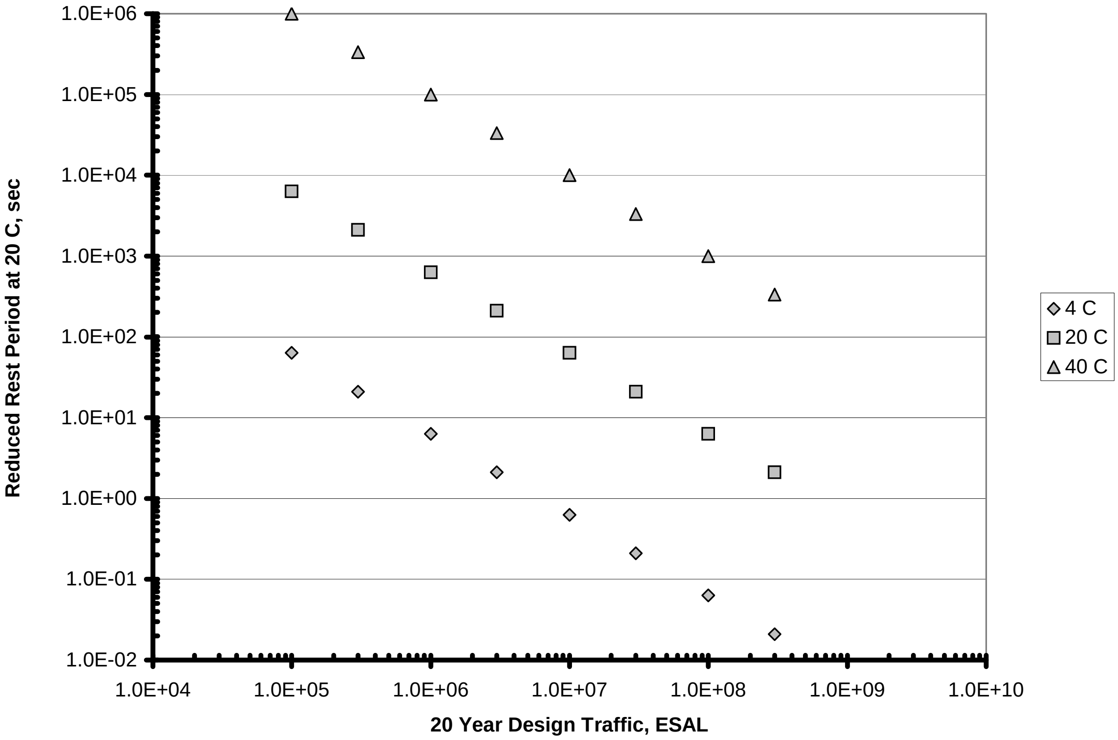


Figure 6. Application of Time-Temperature Superposition to Rest Periods.

2.2.4 Design Example

This section illustrates how the proposed methodology would be used in a mechanistic-empirical design system such as the MEPDG. To limit the number of computations, a monthly analysis is illustrated using typical pavement temperatures estimated from mean monthly air temperature data from Reagan National Airport in Washington, DC. The pavement being analyzed is 9 in of HMA constructed on a 6 in aggregate subbase base layer and a silty clay subgrade. The 20 year design traffic level is 1 x 10^8 ESALs, and the design traffic speed is 45 mph. The purpose of the analysis is to determine if the pavement section is sufficiently thick to resist bottom initiated fatigue cracking assuming the fatigue properties of the neat PG 64-22 mixture discussed in the preceding section.

Material Properties

For this analysis the modulus of the subgrade is assumed to be 4,500 psi and constant throughout the year. The modulus of the aggregate subbase is assumed to be 25,000 psi and is also assumed constant throughout the year. Dynamic modulus testing of a typical 19 mm mixture with PG 64-22 binder using the Simple Performance Test System yielded the master curve and shift factors given in Equations 13 and 14 for a reference temperature of 20 °C. The allowable strains for full healing are given in Equation 15.

$$\log\left|E^*\right| = 0.234 + \left[\frac{3.259}{\left(1 + e^{-1.213 - 0.499\log(f_r)}\right)}\right] \tag{13}$$

$$\log f_r = \log f + 10448.2\left(\frac{1}{T} - \frac{1}{293.2}\right) \tag{14}$$

$$\varepsilon_{af} = 66.0\left(1 + RP_r\right)^{0.2507} \tag{15}$$

where:

$|E^*|$ = dynamic modulus, ksi

f = loading frequency, Hz

f_r = reduced frequency, Hz

T = temperature, °K

ε_{af} = allowable tensile strain of full healing, μstrain

RP_r = reduced rest period at 20 °C, sec

Allowable Strains

Allowable strains at the bottom of the asphalt layer are determined from Equation 15 using reduced rest periods that depend on the traffic volume and the monthly pavement temperature. Mean monthly pavement temperatures can be estimated from the mean monthly air temperature using Equation 16 (*33*).

$$M_p = M_a\left(1+\frac{1}{z+4}\right)-\frac{34}{z+4}+6 \tag{16}$$

where:

M_p = mean monthly pavement temperature at depth z, °F

M_a = mean monthly air temperature, °F

z = depth, in

For a 20 year design traffic of 1 x 10^8 ESAL, the rest period is 6.3 sec. The reduced rest period for each month is determined from Equation 12 using the shift factors from the dynamic modulus master curve and the mean monthly pavement temperature. Table 8 summarizes the computation of the allowable strains. Because the reduced rest period is much shorter during cold months compared to warm months, the allowable strain levels for full healing are significantly lower.

Table 8. Computation of Allowable Strain Strains.

Month	Mean Monthly Pavement Temp, C	Log (A_T)	Rest Period, sec	Reduced Rest Period, sec	Allowable Strain Level, μstrain
Jan	5.5	1.851	6.3	0.09	67
Feb	7.3	1.611	6.3	0.15	68
Mar	12.2	0.971	6.3	0.67	75
Apr	18.0	0.242	6.3	3.61	97
May	23.7	-0.445	6.3	17.56	137
Jun	29.0	-1.065	6.3	73.20	194
Jul	32.0	-1.397	6.3	157.26	235
Aug	30.9	-1.276	6.3	118.95	219
Sep	26.8	-0.803	6.3	40.04	167
Oct	19.7	0.036	6.3	5.79	107
Nov	13.8	0.773	6.3	1.06	79
Dec	8.4	1.469	6.3	0.21	69

Applied Strains

The strains applied by the traffic loading are computed for the design axle load using layered elastic analysis. In this example an 18 kip single axle load was used for computing applied strains. For this example the modulus of the subgrade and subbase are constant at 4.5 and 25 ksi, respectively. The modulus of the asphalt depends on the pavement temperature and the speed of traffic. Recent research by Al-Qadi, et al., using in-situ instrumentation at the Virginia Smart Road (*34*) indicates that loading rates computed by the transformed section analysis in the MEPDG and other approaches such as that recommended by Barksdale (*35*) overestimate the frequency of the load pulse. Based on data presented by Al-Qadi, a loading rate of 16 Hz appears reasonable for a depth of 9 in under 45 mph traffic. Table 10 summarizes the applied strains for each month computed using the KENLAYER software (*33*). The applied strains are compared to the allowable strains in Figure 7. Since the applied strains in Table 9 are less than the allowable strains, the proposed section is acceptable with respect to bottom initiated fatigue cracking. An interesting observation in Figure 7 is that this analysis shows that the critical condition for bottom initiated fatigue cracking occurs at intermediate to low pavement temperatures, which is in contrast with traditional cumulative or incremental damage analyses, which show that the majority of the fatigue damage occurs at high pavement temperatures.

Table 9. Applied Strains for Design Example.

Month	**Mean Monthly Pavement Temp, C**	**Log (A_T)**	**Load Freq, Hz**	**Reduced Freq, Hz**	**AC Modulus, ksi**	**Subbase Modulus, ksi**	**Subgrade Modulus, ksi**	**Applied Strain, μstrain**
Jan	5.6	1.841	16	1108.93	1969.7	25	4.5	51
Feb	7.5	1.584	16	614.01	1858.0	25	4.5	54
Mar	12.8	0.900	16	127.08	1535.8	25	4.5	62
Apr	19.0	0.122	16	21.21	1148.4	25	4.5	77
May	25.1	-0.608	16	3.95	801.7	25	4.5	100
Jun	30.8	-1.265	16	0.87	535.6	25	4.5	133
Jul	33.9	-1.616	16	0.39	418.2	25	4.5	157
Aug	32.8	-1.488	16	0.52	458.9	25	4.5	148
Sep	28.4	-0.987	16	1.65	641.1	25	4.5	117
Oct	20.8	-0.096	16	12.83	1041.1	25	4.5	83
Nov	14.4	0.688	16	78.05	1431.1	25	4.5	65
Dec	8.7	1.432	16	432.33	1789.1	25	4.5	55

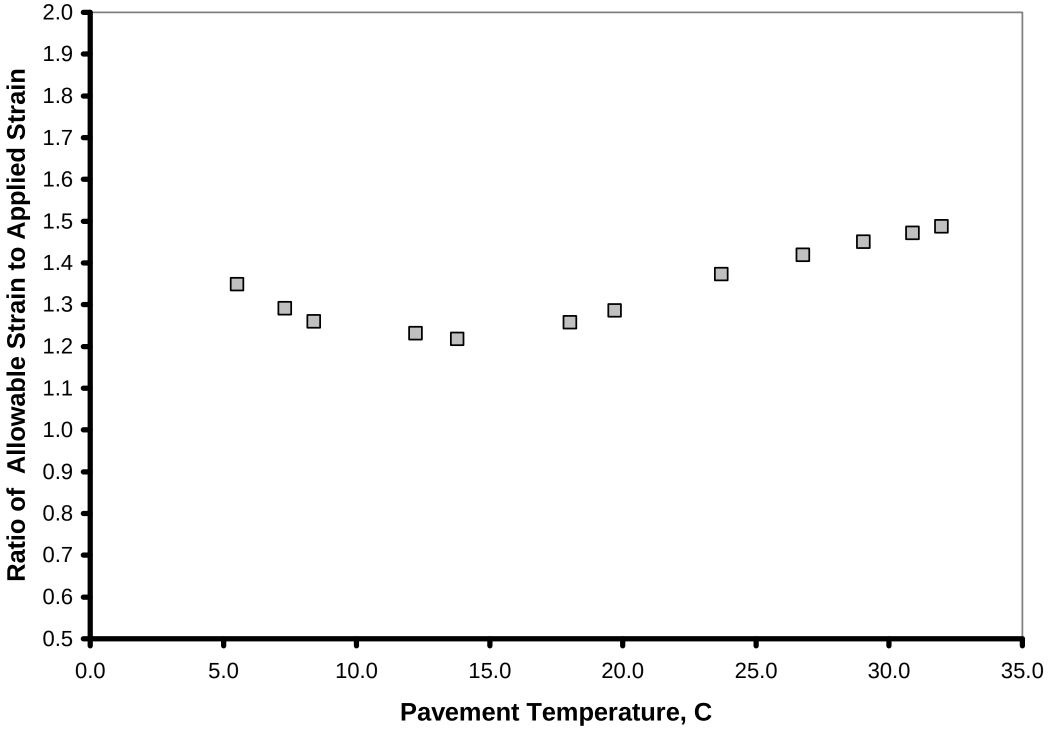


Figure 7. Comparison of Applied and Allowable Strains.

Traffic Level

The analysis presented above can be performed to determine minimum asphalt thicknesses to resist bottom initiated fatigue cracking for the given subgrade and subbase conditions as a function of traffic level. The results are shown in Figure 8 for a 22 kip single axle load. A 22 kip axle load was used to allow comparison with observed data from the analysis of in-service pavements that was conducted in the United Kingdom (*27*). Figure 8 also shows the thickness and accumulated traffic for the four pavements that were analyzed in detail and it was documented that bottom initiated fatigue cracking had not occurred. This comparison shows the engineering reasonableness of the proposed approach. It is reasonable to expect that when the proposed approach is improved to consider the effects of aging and design reliability, the minimum asphalt thicknesses will increase. It is important to note that at the low traffic levels, deformation of the subgrade may govern the analysis rather than bottom initiated fatigue cracking. Research in the United Kingdom indicates that for asphalt thicknesses less than about 7 in subgrade deformation governs the performance of the pavement (*27*). This limit is shown as the dashed line in Figure 8.

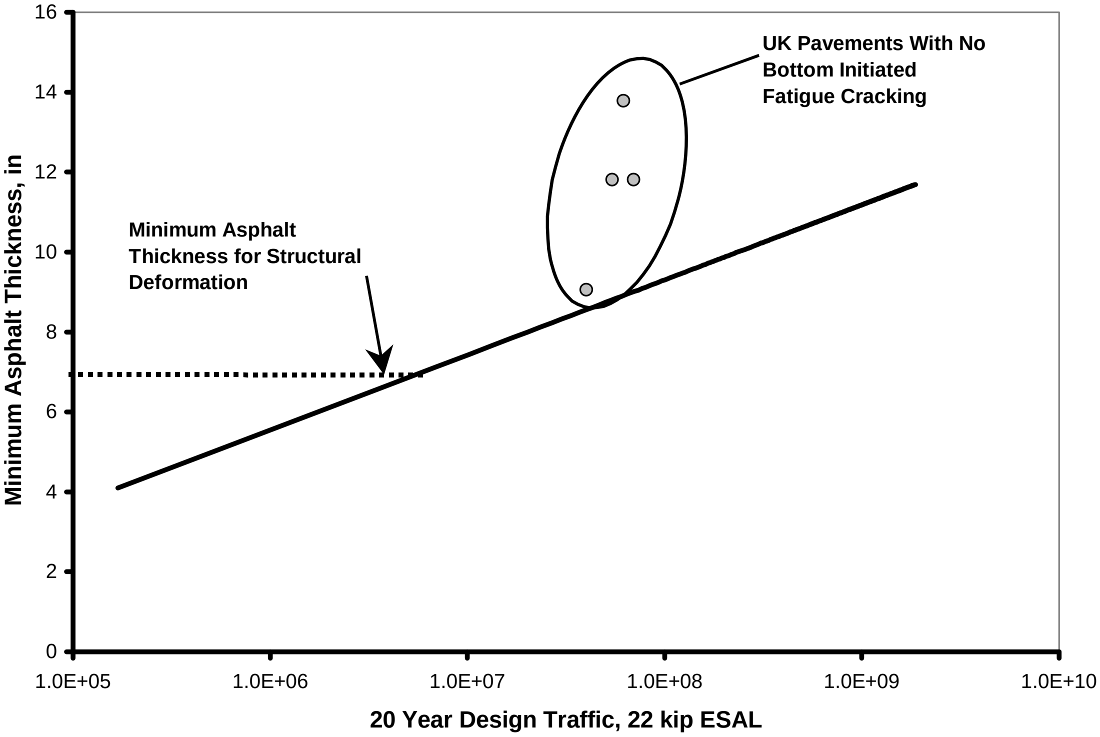


Figure 8. Example of Minimum Asphalt Thicknesses to Resist Bottom Initiated Fatigue Cracking With Observed Performance of Four UK Pavement Sections.

2.2.5 Aging

The example presented above does not consider the important effect of aging on either the applied or allowable strains. As a pavement ages, the modulus of the HMA will increase due to the increased stiffness of the asphalt binder resulting in lower applied strains. Aging will also affect the healing rate for the HMA. Although no data is currently available for the effect of aging on the healing rate, it is reasonable to expect that the healing rate will decrease significantly on aging resulting in lower allowable strains for full healing. Early research on healing by Bonnaure, et al. (*31*) showed that healing rates were much greater in softer binders. The effect of aging can be incorporated in the procedure outlined above, by computing allowable and applied strains as a function of pavement age. The global aging model currently incorporated in the MEPDG provides a method for computing aged modulus values (*36*). Additional research will be required to develop a model of the effect of aging on HMA healing and the allowable strains that result in full healing. For perpetual pavement design, it may only be necessary to perform the analysis for highly aged conditions.

2.2.6 Climate and Mixed Traffic Effects

The MEPDG currently provides excellent capabilities to evaluate the effects of climate and mixed traffic on the applied strains at the bottom of the asphalt layer. This capability can be used with the allowable strains described above to determine the HMA thickness needed to resist bottom initiated fatigue cracking.

2.2.7 Reliability

Because the computations involved in the analysis do not require substantial computer time, reliability can be included in the analysis using Monte-Carlo simulation. This approach has already been implemented in the PerRoad program (*2*). In fact, the allowable strains computed based on rest periods can be input as the threshold criteria for HMA the in the PerRoad program and the analysis for a single season can be performed.

3. INTERPRETATION, APPRAISAL AND APPLICATIONS

The primary product of NCHRP Project 9-44 is the HMA Endurance Limit Validation Study Research Plan. This section presents a summary of the research plan. The complete plan is presented in Appendix B.

The HMA Endurance Limit Validation Study consists of five major tasks: (1) Management and Reporting, (2) Formulate Design Procedure, (3) Database Management, (4) Laboratory Studies, and (5) Analysis of Pavement Sections. Figure 9 presents an overall flow chart for the project with major interactions between tasks identified. Table 10 lists the subtasks for each of the five major tasks and presents estimated labor hours and costs. The HMA Endurance Limit Validation Study is estimated to require approximately 12,923 man-hours of effort at a cost of approximately $1.5 million. Figure 10 presents the overall schedule for the project, which is estimated to require 48 months to complete.

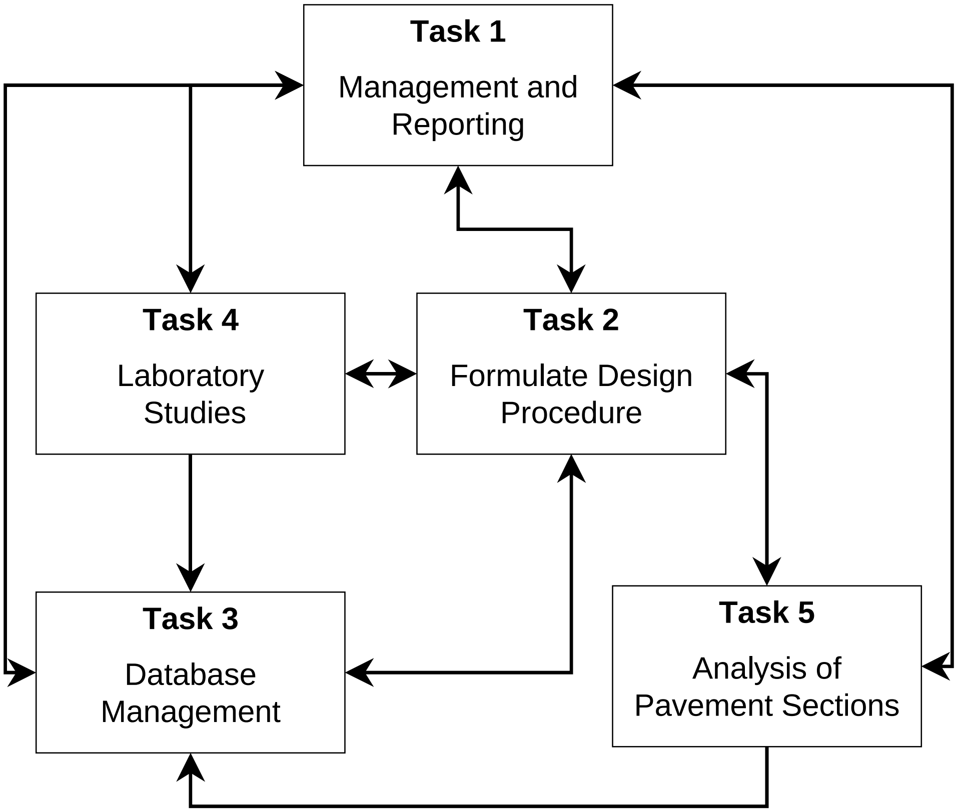


Figure 9. Project Flow Chart.

Table 10. Summary of Man-hour and Cost Estimates.

		Estimated Labor Hours				
Task/ Subtask	**Description**	**Senior Eng./ Stat**	**Eng./ Prog.**	**Tech.**	**Admin.**	**Estimated Cost**
1.0	**Management and Reporting**					
1.1	Project Management	424	0	0	40	$66,000
1.2	Progress Reporting	210	0	0	20	$32,700
1.2	Interim Reports and Presentations	780	0	0	80	$129,780
1.3	Final Report and Presentation	420	0	0	40	$68,400
Task 1 Total		**1834**	**0**	**0**	**180**	**$296,880**
2.0	**Formulate Design Procedure**					
2.1	Review Selected Literature	240	160	0	0	$52,000
2.2	Finalize Preliminary Approach	80	160	0	0	$28,000
2.3	Incorporate Findings from Laboratory Studies	80	160	0	0	$28,000
2.4	Modify Approach Based on Analysis of Accelerated Pavement Tests	80	80	0	0	$20,000
2.5	Prepare Final Design Procedure	120	80	0	0	$26,000
Task 2 Total		**600**	**640**	**0**	**0**	**$154,000**
3.0	**Database Management**					
3.1	Develop Plan to Use NCHRP 9-30 Database	120	0	0	0	$18,000
3.2	Develop Needed Tables	80	240	0	0	$36,000
3.3	Input and Manage Data	40	396	0	0	$45,600
Task 3 Total		**240**	**636**	**0**	**0**	**$99,600**
4.0	**Laboratory Studies**					
4.1	Experiment 1: Mixture Compositional Factors Affecting Healing	42	0	388	0	$39,280
4.2	Experiment 2: Effect of Applied Strain on Healing	32	0	214	0	$22,990
4.3	Experiment 3: Effect of Temperature and Rest Period Duration on Healing	69	0	242	0	$30,920
4.4	Experiment 4: Testing and Analysis Procedures for Allowable Strain Levels	168	0	392	0	$58,520
4.5	Experiment 5: Estimation of Allowable Strain Levels from Mixture Composition	456	0	1890	0	$229,050
Task 4 Total		**767**	**0**	**3126**	**0**	**$380,760**
5.0	**Analysis of Pavement Sections**					
5.1	Review Data Sources and Select Sections for Analysis	52	320	0	0	$39,800
5.2	Obtain Materials and Data for Accelerated Pavement Tests	48	280	0	0	$35,200
5.3	Perform Testing and Analyze Accelerated Pavement Tests	164	512	32	0	$78,520
5.4	Obtain Materials and Data for In-Service Pavement Sections	120	1280	0	0	$195,600
5.5	Perform Testing and Analyze In-Service Pavement Sections	300	512	1280	0	$205,000
Task 5 Total		**684**	**2904**	**1312**	**0**	**$554,120**
	Project Total	***4,125***	***4,180***	***4,438***	***180***	***1,485,360***

Task/Subtask		Months After Notice To Proceed																																														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1.0	**Management and Reporting**																																																
1.1	Project Management	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
1.2	Progress Reporting	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
1.3	Interim Reports and Presentations							▨						▨	P						▨	▨	▨								▨	P										▨	▨						
1.4	Final Report and Presentation																																											▨	▨	▨	P	▨	▨
2.0	**Formulate Design Procedure**																																																
2.1	Review Selected Literature	▨	▨	▨																																													
2.2	Finalize Preliminary Approach				▨	▨	▨																																										
2.3	Incorporate Findings from Laboratory Studies																						▨	▨	▨	▨	▨	▨																					
2.4	Modify Approach Based on Analysis of Accelerated Pavement Tests																												▨	▨					▨	▨													
2.5	Prepare Final Design Procedure																																				▨	▨	▨	▨	▨	▨							
3.0	**Database Management**																																																
3.1	Develop Plan to Use NCHRP 9-30 Database						▨	▨	▨																																								
3.2	Develop Needed Tables								▨	▨	▨			▨	▨	▨						▨	▨	▨													▨	▨	▨	▨	▨	▨							
3.3	Input and Manage Data									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨							
4.0	**Laboratory Studies**																																																
4.1	Experiment 1: Mixture Compositional Factors Affecting Healing					▨	▨	▨																																									
4.2	Experiment 2: Effect of Applied Strain on Healing								▨	▨																																							
4.3	Experiment 3: Effect of Temperature and Rest Period Duration on Healing										▨	▨																																					
4.4	Experiment 4: Testing and Analysis Procedures for Allowable Strain Levels										▨	▨	▨	▨																																			
4.5	Experiment 5: Estimation of Allowable Strain Levels from Mixture Composition														▨	▨	▨	▨	▨	▨	▨	▨																											
5.0	**Analysis of Pavement Sections**																																																
5.1	Review Data Sources and Select Sections for Analysis							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																											
5.2	Obtain Materials and Data for Accelerated Pavement Tests and Test Roads													▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																								
5.3	Perform Lab Testing and Analyze Accelerated Pavement Tests and Test Roads																						▨	▨	▨	▨	▨	▨																					
5.4	Obtain Materials and Data for In-Service Pavement Sections																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																
5.5	Perform Lab Testing and Analyze In-Service Pavement Sections																						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨													

Figure 10. Overall Project Schedule.

Task 1, Management and Reporting, includes all activities normally associated with management and reporting for NCHRP Projects. Major management tasks include scheduling, coordinating, and directing various technical work activities as well as project financial management. Reporting activities include monthly and quarterly progress reports, the preparation of several interim reports and presentations, and the preparation of the final report. Interim reports are required at approximately 6 month intervals and coincide with the completion of five critical milestones:

(1) Formulation of the preliminary design procedure and selection of the laboratory analysis approach,
(2) Selection of pavement sections for analysis,
(3) Completion of the laboratory studies,
(4) Modification of the preliminary design procedure to reflect the findings from the laboratory studies and the analysis of accelerated pavement tests, and
(5) Analysis of the calibration sections and preparation of the final design procedure.

The final report will document the entire study and will be prepared from the interim reports.

Task 2, Formulate Design Procedure, is a critical project task that will be active throughout the project. This task includes finalizing the preliminary approach that was presented in Chapter 2, modifying the preliminary approach based on the results of the laboratory studies and selected accelerated pavement tests, and preparation of the final design procedure after analysis of the calibration pavement sections. It is important to emphasize that the preliminary approach prepared early in this task will shape the laboratory studies and guide the selection of pavement sections, both accelerated pavement tests and in-service pavement sections.

Task 3, Database Management, is a support task that will be active throughout the project. A database will be developed in this task to store and analyze data from the laboratory studies and the analysis of the pavement sections. It is envisioned that the database will be an adaptation of the one developed in NCHRP Project 9-30.

Task 4, Laboratory Studies, includes the planning and execution of five laboratory studies that are needed to complete the design procedure that will be formulated in Task 2. The laboratory studies concentrate on quantifying what affects the healing properties of HMA. The laboratory studies will be sufficient in breadth to develop models relating mixture and binder properties to the key engineering properties required for the analysis.

Task 5, Analysis of Pavement Sections, includes several activities associated with the selection and analysis of full-scale pavements. The preliminary design procedure formulated in Task 2 will be tested using data from completed accelerated pavement tests, such as the fatigue studies from the Federal Highway Administration's (FHWA's) Pavement Testing Facility or the structural sections included in the National Center for Asphalt Technology (NCAT) test track. Calibration of the design procedure will be accomplished through an analysis of in-service pavements where it has been documented that bottom-up fatigue cracking has occurred or has not occurred. These analyses will serve to calibrate the design procedure and validate the HMA endurance limit concept. The predictive models developed in Task 4 will be used in the analysis of the full-scale pavement sections. This will allow consideration of pavement sections where original materials are not available since the required data can be obtained from cores taken from the pavement section.

4. CONCLUSIONS AND RECOMMENDATIONS

Completed laboratory and field investigations clearly show that HMA exhibits endurance limit behavior. This endurance limit, however, does not reflect an absence of load induced damage in the HMA. It is the result of a balance of damage caused by loading and healing or damage recovery that occurs during rest periods. The endurance limit for HMA is, therefore, not a single value, but will change depending on the loading and environmental conditions applied to the HMA. To properly consider this form of an endurance limit in flexible pavement design requires consideration of the effects of loading, environment and material properties on both damage accumulation and healing.

The framework for a pavement design procedure that incorporates healing and endurance limit behavior was conceived during NCHRP 9-44. The procedure is based on layered elastic analysis and is compatible with the MEPDG. It uses allowable strains to identify satisfactory conditions for full healing. The allowable strains are a function of the properties of the HMA, the pavement temperature, and the duration of rest periods between traffic loads. The underlying principal of the design procedure is to make sure that the damage induced by loading remains small enough so that healing occurs and there is no accumulation of damage over the life of the pavement. This is a significant departure from current cumulative or incremental damage models, which assume that no healing occurs and that each load cycle uses up a portion of the finite fatigue life of the HMA.

Additional laboratory and field studies are needed to fully develop and calibrate the design procedure. The HMA Endurance Limit Validation Study Research Plan prepared in NCHRP Project 9-44 presents a comprehensive work plan and cost estimate for the needed research. The research plan includes laboratory experiments to fully develop the new design procedure. Studies using data from completed accelerated pavement tests and test roads are proposed to verify critical aspects of the design procedure. Finally, an experiment to calibrate and validate the new design procedure using selected test sections from the Long Term Pavement Performance Program is presented.

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APPENDIX A. HMA ENDURANCE LIMIT WORKSHOP EXECUTIVE SUMMARY

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Introduction

This report documents the Hot Mix Asphalt (HMA) Endurance Limit Workshop held in Washington, D.C. on August 1 and 2, 2007. The workshop was sponsored by the National Cooperative Highway Research Program (NCHRP) as part of NCHRP Project 9-44, *Developing a Plan for Validating an Endurance Limit for HMA Pavements.* Participants included members of the NCHRP Project 9-44 panel and research team, key researchers and consultants with extensive experience in HMA fatigue analysis, and engineers from highway agencies who are responsible for designing, constructing, and maintaining flexible pavements. The objective of the workshop was to discuss several topics relevant to an endurance limit for HMA pavements, and to provide recommendations for consideration by the research team for the work plan that will be prepared in NCHRP 9-44.

Participants

Participants in the HMA Endurance Limit Workshop included members of the research team, the NCHRP Project 9-44 panel, and invited experts that were recommended by the research team and approved by the project panel. Thirty-four individuals were invited to attend, including four members of the research team, the NCHRP Project 9-44 panel members and Project Manager, and 22 invited experts. There was a high degree of interest in the workshop with 82 percent of the invitees participating. Only three invited experts, two panel members, and one liaison to the panel were not able to participate due to schedule conflicts. Another invited expert was unable to attend due to an airline delay. Table 1 presents summary information about the participants. Detailed information on the invitees and participants is included Sections 2 and 9 of the HMA Endurance Limit Workshop Notebook.

Table 1. HMA Endurance Limit Workshop Invitees and Attendees.

No	Name	Affiliation	Role	Attend
1	Dr. David Anderson	Consultant	Panel Member	Y
2	Dr. Ramon Bonaquist	Advanced Asphalt Technologies, LLC	Research Team	Y
3	Dr. Stephen Brown	University of Nottingham	Invited Expert	N
4	Dr. William Buttlar	University of Illinois	Invited Expert	N
5	Dr. Samuel Carpenter	University of Illinois	Invited Expert	Y
6	Dr. Donald Christensen	Advanced Asphalt Technologies, LLC	Research Team	Y
7	Mr. Danny Dawood	Pennsylvania Department of Transportation	Panel Member	N
8	Dr. Herve Di Benedetto	Ecole Nat. des TPE	Invited Expert	Y
9	Mr. Bruce Dietrich	Florida Department of Transportation	Panel Member	Y
10	Dr. Jon Epps	Granite Construction Company, Inc.	Invited Expert	N
11	Mr. Kenneth Fults	KWF Pavement Consulting	Invited Expert	Y
12	Mr. Roger Green	Ohio Department of Transportation	Panel Member	Y
13	Dr. Kevin Hall	University of Arkansas	Invited Expert	Y
14	Dr. Edward Harrigan	National Cooperative Highway Research Program	Panel Member	Y
15	Mr. Frederick Hejl	Transportation Research Board	TRB Liaison	N
16	Dr. Richard Kim	North Carolina State University	Invited Expert	Y
17	Dr. Dallas Little	Texas A&M University	Invited Expert	Y
18	Dr. Robert Lytton	Texas A&M University	Invited Expert	N
19	Dr. Leslie Ann McCarthy	Federal Highway Administration	Panel Member	Y
20	Mr. Charles Markert	Dynamic Leadership Consulting Group	Research Team	Y
21	Dr. Andre Molenaar	Delft University	Invited Expert	Y
22	Professor Carl Monismith	University of California Berkeley	Invited Expert	Y
23	Dr. David Newcomb	National Asphalt Pavement Association	Invited Expert	Y
24	Dr. Michael Nunn	Lane One Limited	Invited Expert	Y
25	Ms. Linda Pierce	Washington Department of Transportation	Invited Expert	N
26	Dr. Brian Prowell	Advanced Material Services, LLC	Invited Expert	Y
27	Dr. Rey Roque	University of Florida	Invited Expert	Y
28	Ms. Amy Schutzbach	Illinois Department of Transportation	Panel Member	Y
29	Mr. Darin Tedford	Nevada Department of Transportation	Panel Member	N
30	Dr. Jacob Uzan	Technion University	Invited Expert	Y
31	Mr. Harold Von Quintus	Applied Research Associates	Invited Expert	Y
32	Dr. Linbing Wang	Virginia Polytechnic and State University	Panel Member	Y
33	Ms. Rane Wagner	Rane Wagner and Associates	Research Team	Y
34	Dr. Matthew Witczak	Arizona State University	Invited Expert	Y

Workshop Overview

The HMA Endurance Limit Workshop was facilitated by Mr. Charles Markert, a Certified Professional Facilitator. The agenda for the workshop was developed jointly by Mr. Markert and Dr. Ramon Bonaquist, Principal Investigator for NCHRP Project 9-44. A copy of the Facilitator's Agenda is reproduced as Figure 1.

AGENDA Item	Questions to be answered
Sponsor Welcome, Facilitator Opening, Introductions	
Personal Expectations	What are your expectations for this session?
Briefing 1 Fatigue in the MEDPG	How are fatigue and the endurance limit addressed in the MEPDG?
Briefing 2 NCHRP 9-38 Laboratory Evaluation of Endurance Limit	What was found about the endurance limit in NCHRP Project 9-38?
Briefing 3 A Review of UK Pavement Design	What approach is taken in the UK?
Purpose Discussion	What is the purpose of this session?
Discussion: Existence of Fatigue Endurance Limit	Does a Fatigue Endurance- Limit Exist?
Continue Discussion	Does a Fatigue Endurance- Limit Exist?
Issues Related to Fatigue -Endurance- Limit	“What are the other issues?”
Identify Major Issues	Which of these possibilities go on the Short List? Place your dots – one per card.
What is the Meaning of Each Major Issues?	Discussion on the top few.
Discussion: Alternative Methodologies for Characterizing Fatigue	Do we need alternative to Beam Fatigue? Can they address endurance limit? Are they implementable?
Flexible Pavement Damage Analysis	How can we improve flexible pavement damage analysis? What important issues are not currently addressed?
Plus/Delta	
ADJOURN	
DAY TWO	
Review Agenda/Progress/Issues	
Strategies for Incorporating Endurance Limit in Flexible Pavement Damage Analysis	What are the possible strategies for incorporating Endurance Limit?
Identify Barriers to Success?	What are the barriers to success in this effort?
Identify Countermeasures?	What are some countermeasures?
Identify Simplifying Assumptions	Can we identify some simplifying assumptions that will help?
Calibration/Verification	Is calibration necessary? How should it be done? Field sections, accelerated pavement testing, etc?
Suggest Data Evaluation Approaches	What are your suggestions for calibration/verification?
Identify Potential Action for NCHRP 9-44	What should be included in the work plan for future research developed in NCHRP 9-44?
Silver Bullet Actions	Which suggestions from Potential Actions can be addressed in a 3-year project?
Recommendations, Findings & Conclusions	What are your recommendations, findings & conclusions as a group?
Closing	
ADJOURN	

Figure 1. Facilitator’s Agenda.

The HMA Endurance Limit Workshop started with an opening session where the participants expressed their personal expectations concerning the workshop. Excerpts from this session are included in the attachment.

The introductory session was followed by three invited presentations on relevant research to provide background information to the participants. The first presentation, *Use of HMA Fatigue Endurance Limits in the Mechanistic-Empirical Pavement Design Guide*, was made by Dr. Matthew Witczak. Dr. Witczak was responsible for developing the flexible pavement design methodology contained in the Mechanistic-Empirical Pavement Design Guide (MEPDG) developed in NCHRP Project 1-37A. Dr. Witczak's presentation summarized how fatigue cracking is addressed in the MEPDG, and showed the effect of incorporating endurance limits of varying magnitude on fatigue damage predicted with the MEPDG. The second presentation, *Endurance Limit of HMA Mixtures to Prevent Fatigue Cracking in Flexible Pavements: NCHRP 9-38,* was made by Dr. Brian Prowell. Dr. Prowell is Co-Principal Investigator for NCHRP Project 9-38. The objectives of this on-going research project are to: (1) confirm the existence of an HMA endurance limit through laboratory testing, (2) investigate the effect of HMA material properties on the endurance limit, (3) develop a shortcut method to determine the endurance limit, and (4) suggest changes to the MEPDG to include an endurance limit. Dr. Prowell's presentation updated the participants on the progress that has been made in NCHRP Project 9-38. The final presentation, *Mechanistic-Empirical Design and Fatigue in the United Kingdom*, was made by Dr. Michael Nunn. Dr. Nunn played a key role in the work that led to maximum asphalt layer thicknesses being included in the flexible pavement design procedure used in the United Kingdom. His presentation summarized the rationale behind the approach taken in the United Kingdom. Copies of the presentations and supporting materials that were provided by the speakers are included in Sections 5, 6, and 7 of the HMA Endurance Limit Workshop Notebook.

The key element of the HMA Endurance Limit Workshop was a series of discussion sessions focusing on four major topics considered important in the approach for validating an endurance limit for HMA pavements that was proposed by the research team. This approach involves the development of an improved mechanistic-empirical fatigue damage analysis that accounts for the presence of an endurance limit as well as the effects of healing and changes in damage tolerance due to temperature and aging. Elements of this improved damage analysis will be developed through laboratory studies and will require verification using data from accelerated pavement tests before applying the approach to the analysis of in-service pavements. To validate the endurance limit, the improved damage analysis will be applied to several in-service pavements that have documented evidence of no bottom-up fatigue cracking. More detailed information on this approach was included in Section 4 of the HMA Endurance Limit Workshop Notebook. The four major topics relevant to this approach that were discussed during the workshop were:

- Endurance limit and other important fatigue effects,
- Methodologies for HMA fatigue characterization,
- Strategies for incorporating an endurance limit in flexible pavement damage analysis,
- Approaches for calibrating and validating pavement analysis methods that include an endurance limit.

The discussion of these topics concluded with a session to identify action items. In this session, the participants outlined their recommendations for items to be included in the work plan that will be developed in NCHRP Project 9-44.

A variety of techniques were used in these discussion sessions to develop and prioritize ideas, focus the discussion, and develop recommendations for the research team. These included brainstorming ideas on a “sticky wall,” “dot polling” to prioritize ideas, small breakout groups to further develop ideas, and guided discussion. Separate sections discussing each of these sessions are presented later in this report.

An unplanned discussion session was added during the workshop to develop a definition of endurance limit for use in NCHRP Projects 9-38 and 9-44. This session was generated by discussions during the early stages of the workshop. It produced the following definition:

> ***HMA Fatigue Endurance Limit –*** *A level of strain below which there is no cumulative damage over an indefinite number of load cycles.*

The HMA Endurance Limit Workshop concluded with final comments from each of the participants. Excerpts of comments contributed by the participants are included in the attachment.

Endurance Limit and Other Important Fatigue Effects

Objective and Pre-Workshop Position

The objectives of this session were: (1) to discuss whether an endurance limit exists for asphalt concrete and (2) to identify important asphalt concrete fatigue effects that might contribute to long fatigue life. The research team's pre-workshop position was that there is mounting evidence that an endurance limit for asphalt concrete does exist. It has been observed in independent laboratory studies of fatigue at low strain levels, and several documented case studies of in-service pavements indicate that bottom-up fatigue cracking is almost non-existent in properly constructed, thick asphalt concrete pavements. The research team identified three components of fatigue performance: (1) rate of damage accumulation; (2) healing rate; and (3) damage tolerance. Damage accumulation refers to the degradation of material properties during repeated loading and is what is measured in a standard fatigue test. Healing refers to the recovery of damage with time. Finally, damage tolerance pertains to the level of damage that can be sustained before macro-cracking (failure) occurs. Only the first component with a constant damage tolerance is considered in current flexible pavement design methods. The endurance limit is the point where the rate of damage accumulation in a laboratory fatigue test becomes very low and is an important consideration in the design of long-life pavements. The other two components, however, are also important. A pavement subjected to a strain level above the endurance limit may accumulate damage fairly quickly, but may still exhibit no bottom-up fatigue cracking if the healing rate is high, and/or if the damage tolerance is high. All three components must be considered to validate the concept of an endurance limit and to effectively improve the fatigue design of flexible pavements.

Overview of Workshop Activities

Issues related to the existence of an endurance limit for HMA and other important fatigue effects were gathered through an open brainstorming discussion during which the facilitator captured the issues on cards that were later prioritized using a “dot poll” technique. The issues that were identified are summarized in Table 2 along with the number of votes that each issue received. The issues receiving the highest number of votes were then further developed using small breakout groups. Eight breakout groups were formed to address the top 10 issues. Because of their similarities, Issues 7, 8, and 9 were combined. The small breakout groups were asked to further develop an issue by identifying key points and suggestions for the NCHRP Project 9-44 research team. The results from the breakout groups are summarized in Table 3.

Table 2. Issues Identified During Open Brainstorming Discussion.

No.	Issue From Open Brainstorming Discussion	Votes
1	Look at pavements that have and have not cracked.	15
2	Endurance limit may be an algorithm that includes materials, healing, temperature, etc.	15
3	Is what we do in the lab related to field mechanisms?	13
4	Consider developing confidence/risk level into this approach.	12
5	Determine how the endurance limit is to be used in design.	12
6	Relate the endurance limit to material type and climatic conditions.	11
7	How do we use endurance limit design for long-life pavement design?	10
8	How is the endurance limit to be used in design?	12
9	How do we design long-life pavements?	10
10	Reconcile field, lab, theory.	9
11	Prove existence of endurance limit by looking in the field.	5
12	How thin can I build a pavement without bottom up cracking?	4
13	How extensive is the level of bottom up cracking?	3
14	Define what we mean by “long lasting” pavement.	3
15	What is the mechanism?	2
16	Is endurance limit for crack initiation or some level of crack propagation?	2
17	Define fatigue cracking and permanent deformation	1
18	Definition: A strain level at which no cracking will occur.	1
19	Consider aging of pavement (ability to heal).	1
20	Define what endurance limit means.	1
21	What is the strain limit at which pavement has a long fatigue life?	1
22	Is the endurance limit a material property?	1
23	Endurance may be a change in the slope of the fatigue curve at low strain levels	1
24	There are ways to design for zero fatigue damage without using endurance limit.	0
25	Distinguish between perpetual life vs. endurance limit design.	0
26	Should top down cracking be considered (tradeoff)?	0
27	Is there another name for endurance limit?	0
28	Clearly identify the phenomenon in the road.	0

Table 3. Summary of Breakout Group Results.

Issue	**Look at pavements that have cracked and have not cracked.**	**Endurance limit may be an algorithm that includes materials, healing, temperature, etc.**	**Is what we do in the lab related to field mechanisms?**	**Consider developing confidence/risk level into this approach.**

Key Points	• Used to confirm proposed endurance limit values.
	• Must segregate pavements (1) uncracked, (2) no structural cracks, (3) structural cracks, (4) where cracking initiated.
	• Ensure sample covers range within the design procedure that will be used.
	• Most pavements should be in-service roadways as opposed to accelerated pavement sections.
	• Construction defects that may have caused cracking must be identified – segregation, de-bonding between layers, etc.
	• Potential to evaluate strain response magnitude versus mixture composition and local condition for pavements with and without structural cracking.
		• Probably two approaches:
		  • Lab tests.
		  • Field behavior.
		• Concentrate on lab tests:
		  • Visco-elastic material.
		  • Temperature – frequency dependent.
		  • Healing.
		• Lab testing leaves out importance of crack propagation.
			• Stiffness reduction in lab mirrored in field measurements?
			  • Europe – no
			  • LTPP?
			  • NCAT Track- yes 7-5”
			  • Westrack?
			• Aging increases stiffness.
			• Healing?
			• Fatigue properties of aged material are probably different than unaged materials.
				• Complex interaction of variables:
				  • Design.
				  • Thickness.
				  • Properties of each layer.
				  • Load.
				  • Mix Properties
				    • Anisotropy.
				    • Volumetrics.
				    • Binder/Mastic.
				  • External variables
				    • Temperature.
				    • Rest periods.
				    • Traffic speed.
				• Pressing need to weight design and mix properties.
				• Based on above, consider benefit cost ratio approach where the cost is a function of tolerable risk.

Suggestions	• Make deflection measurements to define structural related cracking. Check hysteresis loop between cracked and un-cracked sections.
	• Measure mixture composition between sections.
	• Take cores and trenches to confirm direction of cracking also to ensure construction defects do not exist or identify where construction defects have influenced results.
		• Use crack initiation, number of cycles (N_i) before localization.
		• Number of cycles to failure (N_f) equals 50% stiffness reduction.
		• Use N_i for design of long lasting pavement.
			• Fatigue tests on material from roads of different ages.
			• Measure pavement stiffness as a function of time.
			  • LTPP database for a range of pavement thickness.
			  • Indirect Tensile modulus on field cores.
				• Same as key points.

Table 3. Summary of Breakout Group Results (continued).

Issue	**Determine how the endurance limit is to be used in design.**	**Relate the endurance limit to material type and climatic conditions.**	**How do we use endurance limit design for long-life pavement design? How is the endurance limit to be used in design? How do we design long-life pavements?**	**Reconcile field, lab, theory.**

Key Points	• Design versus analysis:
	  • Design - prevent fatigue from occurring.
	  • Analysis - predict damage e.g. MEPDG.
	• Use endurance limit as an HMA material property.
	• Characterize endurance limit versus using a predetermined value:
	  • Level 1 testing.
	  • Level 2 catalog of values based on mix composition.
	  • Level 3 single default value.
		• Evaluate significance of material type and climate on pavement thicknesses.
		• Develop a catalog of endurance limit values based on binder type, gradation, void content, asphalt content, etc.
		• Evidence both in the lab and field indicate endurance limit is related to temperature.
		• Effect of moisture not clear.
		• Stress state conditions must be considered.
			• Variation of endurance limit with mix and binder properties, temperature, aging, healing (this is not likely to be a routine test).
			• Design approach / philosophy (risk, load definition).
			• Material property relationships (catalog of properties).
			• Seasonal variation in material properties.
			• What is the most appropriate fatigue relationship (or failure)?
				• In-service pavements.
				• Good performance and no bottom up cracks.
				• Traffic history – large commercial volume.
				• Range of environments.
				• Performance vs. time.
				• Only with surface maintenance.
				• Accelerated pavement tests, HVS, NCAT, MnRoad, ALF, WESTRACK
				• Original construction materials, design.

Suggestions	• Recognize need for different levels in material testing.
	• Recognize that use of endurance limit in design is a design policy decision.
	• Healing effects must be identified to account for overloads / seasonal effects.
		• Further lab testing.
		• Use field instrumentation to define lab testing conditions.
		• Review completed lab testing to potentially establish empirical relations.
		• Stress state conditions may be related to the lab to field shift factor. Use computational modeling and field instrumentation to refine lab test conditions.
		• Comprehensive analysis to link endurance limit to shift factor.
			• From a practical point of view:
			  • Pick very long design life – 500 E6 ESALs
			  • Sensitivity analysis to determine thickness beyond which no significant increase in life is observed.
			• Define scope of design approach in terms of:
			  • Design model relations (i.e., approach will depend on model used).
			  • Material properties available – risk
				• Volumetric and binder characteristics in-service.
				• FWD and modulus tests on cores.
				• Analysis**:**
				  • Layered elastic analysis
				  • Fatigue analysis – MEPDG

Project 9-44 Research Team Assessment

There was not consensus among the participants that an endurance limit exists for asphalt concrete. Most participants agreed that data from laboratory studies support a change in the slope of laboratory strain versus number of cycles relationships at low strain levels. However, there was disagreement over the mechanism causing this change in slope. Healing, lack of crack propagation, and non-linearity in flexural fatigue testing were three effects that were postulated as potential causes. Some participants expressed the need for additional laboratory fatigue data to very high numbers of load cycles to confirm that the apparent change in slope at low strain levels is not due to variability in the fatigue testing.

Much of the brainstorming portion of the session was devoted to a discussion of terminology. The terms endurance limit, and long-life or perpetual pavements are often used interchangeably, in spite of the fact that they have different meanings. Endurance limit implies that no damage occurs in the asphalt concrete leading to an infinite fatigue life. However, for asphalt concrete at low strain levels it is possible that damage occurs but it is offset by healing or that only crack initiation without propagation occurs, both resulting in an apparent endurance limit characterized by very long fatigue lives. In the interest of time the discussion of terminology was terminated during this session, but was later addressed in an unplanned session at the end the workshop. This session led to the definition of endurance limit for HMA that was presented earlier.

Another issue raised during the brainstorming session was whether top-down cracking was within the scope of NCHRP Project 9-44. The panel members confirmed that NCHRP Project 9-44 was to develop a work plan to validate an endurance limit for bottom-up fatigue cracking only.

Many of the issues raised during this session, although relevant to the overall objective of the workshop, were not directly related the objectives of this particular session. The participants confirmed the research team’s position that the effects of temperature, aging, healing, and mixture composition must be considered in any laboratory or field experiment included in the work plan. One fatigue effect discussed during this session that was not initially identified by the research team was the concept of crack propagation. At low strain levels cracks that initiate in asphalt concrete may not propagate resulting in a change in the slope of laboratory fatigue relationships. The standard definition of failure in flexural fatigue tests, 50 percent reduction in stiffness, is accompanied by propagation of cracks from the bottom of the specimen. The numbers of cycles to crack initiation, which may be substantially less than the number of cycles to 50 percent stiffness reduction, could potentially be used as a design criterion for long-life pavements. This approach has been used by Dr. Uzan in a methodology for design of perpetual pavements developed for Israel.

Methodologies for HMA Fatigue Characterization

Objective and Pre-Workshop Position

The objectives of this session were to identify and discuss the advantages and disadvantages of using alternatives to the standard flexural fatigue test, AASHTO T321 for laboratory fatigue characterization. The research team's pre-workshop position was that consideration should be given to using an alternative to flexural fatigue testing in the future work that will be required by the NCHRP Project 9-44 work plan. The primary issue with the flexural fatigue test is that the stresses and strains vary over the depth of the specimen. To rationally incorporate the effects of healing, damage tolerance and other fatigue effects that may be stress dependent, a test that has a uniform stress or strain state is needed. A secondary concern is that a standard method for fabricating flexural fatigue specimens is not available. Another pre-workshop position held by the research team is that the NCHRP Project 9-44 work plan should include a study to identify a less cumbersome surrogate method for determining the endurance limit of asphalt concrete so that the endurance limit can be evaluated in practice. The shortcut approach proposed in NCHRP 9-38 involves conducting flexural fatigue tests to a relatively large number of cycles and extrapolating the data to determine the endurance limit. The research team believes that this approach is not appropriate for routine mixture characterization. The two approaches that appeared most promising to the research team based on a review of past work is continuum damage analysis of cyclic direct tension fatigue tests and the dissipated creep strain energy approach using the indirect tensile test.

Overview of Workshop Activities

The participants' views on fatigue testing were gathered through a brainstorming session where Dr. Bonaquist first presented the research team's position, then the facilitator captured the participants' ideas on cards. The ideas generated during the brain storming session are summarized in Table 4. These have been organized into four categories: fatigue test methods, possible surrogate tests, important fatigue test effects, and other considerations.

Table 4. Ideas From the Fatigue Testing Brainstorming Session.

Category	Suggestion
Fatigue Test Methods	NCHRP 9-38 shortcut approach.
	Torsional fatigue test in dynamic shear rheometer. Methodology well defined by work at Texas A&M. Can be used on asphalt/mastic/fine aggregate system. Study healing and effect of fillers.
	Standard flexural fatigue tests. Should be used to generate baseline data. Because it is an AASHTO Standard DOT personnel will have confidence in the results.
	Dissipated creep strain energy from the indirect tension test.
	Continuum damage analysis of cyclic direct tension-compression testing.
	Continuum damage analysis of constant strain rate direct tension tests.
Possible Surrogate Tests	Linear-viscoelastic limit from pseudo strain analysis.
	Linear-viscoelastic limit from strain sweep testing.
	Threshold value from University of Florida HMA Fracture model.
	Crack initiation from two stage Weibull analysis of flexural or tension-compression fatigue test.
Important Fatigue Test Effects	Determine what the impact is of healing.
	Stress control not very good. Constant strain is better.
	Address healing to either account for it or remove it from test
	Consider fracture mechanics & crack propagation.
Other Considerations	Surrogate test is needed.
	Experimental plan should look at all tests with validation at low strain.
	Consider credibility of any other test. (Is it an AASHTO procedure? Will it become a standard?)
	Finite element modeling – with micro damage model.
	Tests to determine magnitude of "correction" factors for surrogate tests.
	Consider multiple tracks with other test facilities in parallel.
	Consider other tests in the work plan.

In addition to the discussion of the various test methods, there was a significant amount of discussion about healing. Some participants questioned whether healing is an important consideration for field pavements. Professor Monismith explained that healing does not seem to be a significant factor in the Heavy Vehicle Simulator (HVS) tests that have been completed in California. When loading is stopped, there appears to be a fairly large recovery of damage, but after reloading the damage quickly returns to close to where it was before the rest period. Others pointed out that healing is most important when the damage is small and that to observe the effect the testing must use short alternating cycles of loading and resting. If long cycles are used, the damage may become too large for healing to occur. It was noted that the torsion fatigue test developed at Texas A&M University for testing asphalt mastics and sand asphalt mixtures provided a very good tool for evaluating the effects of healing.

Another issue that was discussed at length was the credibility of the various fatigue test methods. Only the flexural fatigue test has been standardized. There appeared to be general consensus that if another method was selected, it would be important to demonstrate how the approach related to results from the flexural fatigue for both high and low strain levels.

Project 9-44 Research Team Assessment

Although there was not consensus among the participants concerning the type of fatigue testing that should be considered for future laboratory studies that may be required in the work plan, the recommendations listed below received widespread support.

- If additional long-duration fatigue tests are needed to establish relationships between the endurance limit and mixture properties, the testing should be based on the flexural fatigue test or an alternative that provides equivalent results. This will allow the future researchers to make use of the data developed in the NCHRP 9-38, the University of Illinois extended fatigue studies, and other endurance limit studies. Testing in multiple laboratories may be needed to develop the necessary data in a reasonable time frame.

- Serious consideration should be given to the development of a surrogate test for determining the endurance limit of asphalt concrete for use in routine design and analysis. Several potential tests were identified in Table 4. The strain sweep testing completed at the University of New Hampshire in NCHRP 9-38 appears promising.

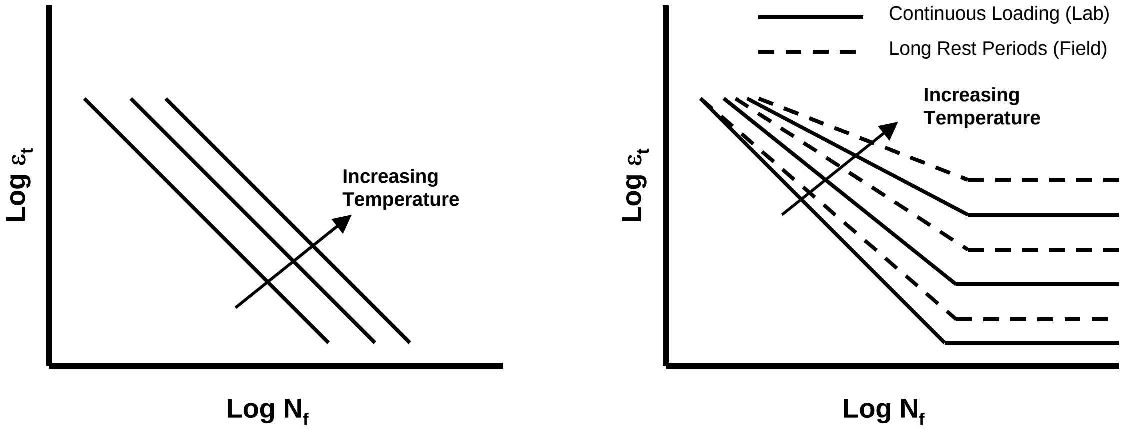
- For studies of healing and other effects that are likely dominated by the binder and filler portion of the mixture the torsional fatigue test in the dynamic shear rheometer should be considered.

- When recommending tests in the work plan, priority should be given to those with standard test methods or where standard test methods are in the process of being accepted.

Flexible Pavement Damage Analysis

Objective and Pre-Workshop Position

The objective of this session was to identify methods for incorporating an endurance limit in flexible pavement damage analysis. The research team's pre-workshop position was that the endurance limit is one of three factors that must be included in an improved flexible pavement damage analysis; the other two being healing and changes in damage tolerance. The research team envisioned that these could be incorporated into an improved mechanistic-empirical analysis by modifying the fatigue relationship. The modification is shown schematically in Figure 2, which compares current fatigue damage models with the modified relationship. Current fatigue models consist of a series of parallel lines that for a given mixture depend on temperature. Note that these models do not include an endurance limit. The research team envisions that a comprehensive fatigue model will include an endurance limit that will change with temperature reflecting the increased damage tolerance of mixtures at higher temperatures. The change in damage tolerance will also result in fatigue lines that are not parallel. The effect of healing is shown as the dashed lines. Longer rest periods result in increased life at a given strain level. This type of fatigue model has the potential to more realistically model the fatigue behavior of HMA mixtures, resulting in smaller calibration factors. Within this model a pavement can still exhibit infinite life and be subjected to strains above the 70 to 100 μstrain level currently considered representative of the endurance limit based on laboratory testing.



a. Current Fatigue Model **b. Proposed Fatigue Model**

Figure 2. Conceptual Representation of Improved Flexible Pavement Fatigue Model.

Overview of Workshop Activities

This session was divided into two parts. First, four breakout groups were formed and asked to develop strategies for incorporating an endurance limit in flexible pavement damage analysis and to identify important issues associated with their strategy. After the breakout groups reported their strategies and issues, a general discussion of barriers to the success of these strategies and possible countermeasures that could be taken to address the barriers was held. The strategies developed by the four breakout groups are briefly described below.

Group A

The strategy suggested by Group A is very similar to the pre-workshop position of the research team and shown in Figure 2b. The endurance limit and fatigue relationship would be a function of temperature and healing. The primary issues identified for this approach were: (1) laboratory data to support the changes in endurance limit and fatigue life with temperature and healing, and (2) field data to calibrate the relationship for use in pavement design models.

Group B

The strategy suggested by Group B is to add a variable or modified endurance limit to current fatigue models. This endurance limit would be a function of the factors that affect the endurance limit: mixture properties, binder properties, temperature, rest periods, etc.

$$EL_{\mathrm{mod}} = EL + C_{gradation} + C_{binder} + C_{temperature} + C_{volumetrics} + C_{rest\ period} + \ldots.. \qquad (1)$$

Where:

EL = average endurance limit for HMA mixtures from laboratory testing

C_i = modification factors to account for factors affecting the endurance limit

This group identified several important issues associated with this approach including:

- Data to support the modification factors.
- Guidance concerning risks associated with using the endurance limit.
- Clear tie between mixture design and pavement design. Select mixtures to obtain expected performance.
- Training for designers to fully understand the ramifications of the endurance limit.

Group C

The strategy suggested by Group C is to base pavement design on a comprehensive analysis of damage and recovery in pavement systems. This analysis would address all forms of pavement distress (rutting, bottom-up cracking, top-down cracking, thermal cracking, etc) not just fatigue cracking. For fatigue cracking, an “endurance limit” would occur when there is a balance between the rate of damage and the rate of healing in the pavement. These rates would be obtained from appropriate fundamental tests. Endurance limit testing would serve as one verification of the overall modeling process.

This group identified several issues associated with this approach. First is research to obtain the damage and healing rates as a function of mixture properties, binder properties, temperature, age hardening, stress state, etc. Second is the development of an appropriate computational tool for the analysis. Third is the selection of critical design conditions.

Group D

This group provided an overview of approaches used in France, Israel, and the Netherlands for fatigue analysis of flexible pavements. This group recommended that to improve flexible pavement fatigue analysis, consideration should be given to using finite element modeling with fracture mechanics because this approach can account for initiation and propagation of cracks in the pavement. They noted, however, that the approach is not practical at this time. They also suggested that it may be important to develop a method to account for construction defects.

The discussion of the barriers and countermeasures focused on two general approaches for incorporating an endurance limit in flexible pavement damage analysis that were suggested by the breakout groups: (1) add an endurance limit that is a function of design factors to current fatigue analysis, which is the approach suggested by Groups A and B, and (2) detailed computation of damage and recovery rates which is the approach suggest by Group C and supported by the issues raised by Group D. Table 5 summarizes the barriers and countermeasures that were identified for these approaches.

Table 5. Barriers and Countermeasures Identified for Incorporating Endurance Limit in Flexible Pavement Damage Analysis.

Add Variable Endurance Limit to Existing Fatigue Analysis		**Detailed Computation of Healing and Damage Rates**	
Barriers	**Countermeasures**	**Barriers**	**Countermeasures**
• Data to support endurance limit as a function of design factors.	• Additional laboratory testing.	• Data to define damage and healing rates.	• Additional laboratory testing.
• Lab to field shift factor.	• Test materials from field pavements. • Calibration.	• Appropriate analysis tool.	• Finite element analysis, fracture mechanics, etc.
• There is an interaction of base/foundation.	• Included in current stress/strain analysis.	• There is an interaction of base/foundation.	• Use mechanistic approach on the entire structure.
• Effect of construction defects.	• Use appropriate material properties.	• Effect of construction defects.	• Use appropriate material properties
• Solving bottom-up cracking will not solve top-down cracking.		• Solving bottom-up cracking will not solve top-down cracking.	• Both forms can be addressed with this approach.
• Cost of implementation.	• Cost of overbuilding.	• Cost of implementation.	• Cost of overbuilding.

Project 9-44 Research Team Assessment

The discussion during this session led to two general approaches for incorporating an endurance limit in flexible pavement analysis. The first is modify current mechanistic-empirical fatigue relationships to include a variable endurance limit that is likely a function of mixture composition, binder properties, temperature, aging, and duration of rest periods. Additional laboratory testing may be required to quantify the effect of some of these variables. This approach is similar to the research team's pre-workshop position. The second approach is to perform a comprehensive analysis of damage and damage recovery in the pavement using an appropriate computational analysis. This approach would require computational analyses that are not practical for use in routine design at this time. Again, the effect of mixture composition, binder properties, temperature, and aging on the rate of damage and damage recovery would be determined through appropriate laboratory study.

There was general agreement among the workshop participants that the work plan to be developed in NCHRP 9-44 should focus on the first approach: modification of current mechanistic-empirical fatigue relationships to include a variable endurance limit.

Verification and Calibration

Objective and Pre-Workshop Position

The objective of this session was to gather recommendations for verification and calibration of an improved mechanistic-empirical fatigue analysis that incorporates an endurance limit. The research team's pre-workshop position was that an improved pavement damage analysis would be assembled from the results of a series of laboratory studies addressing the effect of mixture composition, binder properties, temperature, and rest periods on fatigue damage, damage recovery, and damage tolerance. Elements of this pavement analysis would be verified using accelerated pavement tests before final calibration using data from in-service pavements.

Overview of Workshop Activities

The participants' views on verification and calibration were gathered through a brainstorming session where Dr. Bonaquist first described the objective of the session, then the facilitator captured the participants' ideas on cards. The ideas generated during the brain storming session are summarized in Table 6. These have been organized into three categories: data sources, analysis approaches, and data collection.

Table 6. Ideas From the Verification/Calibration Brainstorming Session.

Category	Suggestion
Data Sources	Published case studies.
	NAPA Perpetual Pavement Award nominees.
	LTPP Sections.
	Accelerated pavement tests.
	Test Roads.
	Rolling Dynamic Deflectometer (RDD).
	Lab testing can be useful if it is used properly.
Analysis Approaches	Find sections with no bottom-up cracking.
	Include some pavements with bottom-up cracks.
	Detailed analysis of a small number of sections.
	LTPP Database provides for analysis of a large number of sections.
	Document assumptions made for each field section (plus forensic data).
	Be careful with accelerated pavement tests; overloading, low number of repetitions, lack of aging, etc.
	Simplifying assumptions will need to be made - know which you are making.
Data Collection	Ground penetrating radar (GPR) to help verify crack existence.
	Spectral Analysis of Surface Waves (SASW) will pick up cracks you can’t see.
	Random trenching to determine bottom-up cracking is merely a “stab in the dark.”
	States will be willing to gather data (including trenching).

Project 9-44 Research Team Assessment

This session generated a number of suggestions concerning data sources, analysis approaches and data collection that will be helpful in developing the work plan. One or more participants supported the use of all of the data sources listed in Table 6. There was extended discussion concerning the advisability of using accelerated pavement tests for calibration because most accelerated pavement tests are conducted with high load levels resulting in strains outside the region of the endurance limit. There seemed to be general agreement that accelerated pavement testing could be used to validate certain effects in the high strain region of the fatigue curve, and that the overall validation and calibration effort should include both accelerated pavement tests and evaluation of in-service pavement sections. Ken Fults noted that the Rolling Dynamic Deflectometer could be used like an accelerated pavement testing machine to rapidly apply a large number of load pulses to selected pavements in a short period of time.

There was also an extended discussion of whether it was important to document whether bottom-up fatigue cracking has occurred. Some participants recommended that it was critical and the validation/calibration must include sections with and without bottom-up fatigue cracks. Others argued that the important issue is whether the cracks have propagated to the surface, noting that is very difficult to propagate bottom initiated cracks to the surface of a thick asphalt concrete pavement. It was suggested that Ground Penetrating Radar (GPR) or Spectral Analysis of Surface Waves (SASW) could be used to identify cracks that have not propagated to the pavement surface.

There was general agreement that for the analysis of in-service pavements it will be very difficult to determine the composition and construction details of the pavements; therefore, many assumptions will have to be made and documented. There were mixed opinions concerning the number of pavements that should be included. Some participants argued for a more in-depth analysis of a small number of pavements, while others recommended an analysis of a large number of pavements.

Recommendations to the Research Team

Four major topics relevant to the approach proposed by the research team were discussed during the workshop: (1) endurance limit and other important fatigue effects, (2) methodologies for HMA fatigue characterization, (3) strategies for incorporating an endurance limit in flexible pavement damage analysis, and (4) approaches for calibrating and validating pavement analysis methods that include an endurance limit. The discussion of these topics concluded with a session designed to identify recommendations for consideration by the NCHRP Project 9-44 research team. In this session, the facilitator asked the workshop participants to record their recommendations on cards, which were then placed on the “sticky wall.” The recommendations were sorted into groups and each group was named by participant consensus. The group names and the related recommendations are summarized in Table 7. The recommendations for each group are discussed below.

Laboratory Materials Characterization

The workshop participants generally agreed that laboratory testing should be included in the work plan. They made several recommendations concerning laboratory materials characterization associated with an endurance limit for asphalt. The individual participant recommendations can be consolidated into the following four general recommendations.

Prove that Endurance Limit Exists

There was not consensus among the workshop participants that an endurance limit exists for asphalt concrete. It was recommended that additional fatigue tests be conducted to clearly show that an endurance limit exists for asphalt concrete. A torsional fatigue test in the dynamic shear rheometer on sand asphalt mixtures was suggested as method to conduct very long cycle fatigue testing to definitely show whether an endurance limit exists for HMA.

Review Completed Endurance Limit Research

There was general consensus that before undertaking additional laboratory testing the results of completed extended cycle fatigue tests should be carefully reviewed. Of particular interest was the identification of relationships between the endurance limit and mixture and binder properties. Any additional testing should build upon the results of the completed testing.

Identify Practical Surrogate Test

Many workshop participants were adamant that a practical surrogate test for estimating the endurance was needed for use in design. The surrogate test should be tied to the results obtained from flexural fatigue testing.

Additional Laboratory Testing

There was general consensus that additional laboratory testing should be conducted to establish relationships between the endurance limit and mixture properties, binder properties, temperature and rest periods. The participants were split over how this additional testing should be done. Some recommended the use of long cycle fatigue tests while others recommended that the surrogate test be used.

Table 7. Summary of Workshop Recommendations for the NCHRP 9-44 Research Team.

Category	Recommendation
Laboratory Material Characterization	Need to go through existing data and literature (material properties).
	Review past work on dissipated energy, rest periods.
	Perform experiments to identify relationships between damage and healing properties from practical short-term tests for endurance limit.
	Identification of surrogate test method for sensitivity analysis.
	Selection of practical short-term tests for endurance limit.
	Lab evaluation of relationships between endurance limit, temperature, rest periods, mix volumetrics, binder properties, etc.
	Additional very long fatigue tests (beam) – evaluate a variety of binders, aggregate types, volumetric factors, temperature, frequency, etc.
	Evaluate surrogate tests (torsion on mastic, push-pull).
	Develop plan to tie surrogate tests to beam fatigue.
	Prove endurance limit by tests with torsion fatigue on mortar including evaluation of factors that influence the endurance limit.
	Identify material properties that resist bottom-up fatigue and influence the level of the endurance limit.
Field Calibration/Validation	European LTPP studies particularly Germany (high quality database).
	Need to consider various accelerated pavement tests (APT) NCAT, Mn/ROAD, WESTRACK, HVS, ALF.
	Need to consider in-service pavements: Perpetual Pavement award, SPS (state forensics), and non-perpetual pavements.
	Select appropriate validation sites and obtain data (in-service and accelerated pavement tests (APT)).
	Determine “shift” or “transfer function” from lab to APT to in-service pavements.
	Field verification/calibration using APT/LTPP/forensic cases studies.
	Must include both cracked and un-cracked sections in work plan. Analyze each with reasonable flexible pavement analysis model.
	Use LTPP sections include (SPS).
	Evaluate how to use APT to measure endurance limit.
	Include APT and in-service pavements (inherent assumptions).
	Test field samples from wheel path and between wheel paths.
Damage Analysis in Design	Identify and evaluate methods to incorporate endurance limit in design.
	Modeling (MEPDG, continuum damage mechanics, Models + FEM, crack propagation).
	Assess cost/conservatism.
Big Picture	Follow-up work should be integrated – suggest single contractor rather then separate contracts – think system.
	Plan should coordinate damage analysis approach with lab/field testing and validation.
	Have all pieces fit together.
Field Evaluation Techniques	Identify nondestructive test methods to detect cracks in HMA layer.
	Identify, evaluate and select methods for identifying macro-cracks.
Technology Transfer	Develop training modules.
Cost (FHWA Life Cycle Cost)	Develop a methodology for benefit/cost ratio calculation.
	Risk analysis.
Definitions	Standardize definition terminology (9-38 – 9-44).
	Develop glossary/definitions of terms related to endurance limit.
	Apparent endurance limit/fatigue endurance limit.

Field Calibration/Validation

The workshop participants agreed that field calibration or validation should be a component of the work plan. Although some participants favored use of in-service pavements over accelerated pavement tests, the participants generally agreed that both should be considered in the work plan. The participants also agreed that both cracked and un-cracked sections should be analyzed. There was a high level of support for using sections from the LTPP program.

Damage Analysis in Design

The workshop participants agreed that validation of an endurance limit for asphalt concrete will require a pavement damage analysis that incorporates the effects of an endurance limit. There was not, however, agreement on the form for the damage analysis. The participants recommended that the research team evaluate an number of approaches and develop the work plan around the most promising approach.

Big Picture

During the workshop, the research team suggested that the future work may require multiple contracts with agencies having experience in laboratory testing of asphalt concrete and evaluation and analysis of field pavements. The workshop participants disagreed with this approach and recommended that the future work be done under a single contract to ensure full coordination of the work.

Field Evaluation Techniques

Some workshop participants supported including a study in the work plan to identify and select nondestructive testing methods that could identify subsurface cracking in pavement sections. It was generally agreed that the ability to identify the presence of subsurface cracking would be beneficial for the selection and analysis of pavements.

Technology Transfer

The workshop participants recommended that the development of initial training materials be included in the work plan. Topics for training materials include: defining terminology associated with the endurance limit, factors affecting the endurance limit in asphalt concrete, methods to incorporate an endurance limit in flexible pavement design, and the effect of an endurance limit of the performance of asphalt concrete pavements.

Cost Analysis

Workshop participants were in general agreement that it is important to use some form of cost analysis to justify the additional effort that may be required to properly consider an endurance limit in the design of flexible pavements. It was generally agreed that a more sophisticated damage analysis with additional material characterization would be required to incorporate an endurance limit in flexible pavement design. Cost savings associated with minimizing the occurrence of overdesigned pavements would more than offset the additional design costs.

Definitions

Most workshop participants agreed that it was important to develop standard definitions for terms associated with the endurance limit. Terms that were mentioned included: endurance limit, apparent endurance limit, long-life pavement, and perpetual pavement. The workshop participants took part in a spirited debate to develop a definition of endurance limit that could be used in NCHRP Project 9-38 and 9-44. This debate produced the following definition:

> ***HMA Fatigue Endurance Limit –*** *A level of strain below which there is no cumulative damage over an indefinite number of load cycles.*

This definition was strongly accepted by only a few participants, but was acceptable to all participants except one. That participant strongly objected to the word “cumulative” in the definition maintaining that endurance limit means there is no damage in the asphalt material.

Summary and Conclusion

This report documents the Hot Mix Asphalt (HMA) Endurance Limit Workshop held in Washington, D.C. on August 1 and 2, 2007. The workshop was sponsored by the National Cooperative Highway Research Program (NCHRP) as part of NCHRP Project 9-44, *Developing a Plan for Validating an Endurance Limit for HMA Pavements.* Participants included members of the NCHRP Project 9-44 panel and research team, key researchers and consultants with extensive experience in HMA fatigue analysis, and engineers from highway agencies who are responsible for designing, constructing, and maintaining flexible pavements. The objective of the workshop was to discuss several topics relevant to an endurance limit for HMA pavements, and to provide recommendations for consideration by the research team for the work plan that will be prepared in NCHRP 9-44.

The HMA Endurance Limit Workshop focused on four topics relevant to this approach being considered by the NCHRP Project 9-44 research team:

- Endurance limit and other important fatigue effects,
- Methodologies for HMA fatigue characterization,
- Strategies for incorporating an endurance limit in flexible pavement damage analysis,
- Approaches for calibrating and validating pavement analysis methods that include an endurance limit.

Numerous recommendations were made by workshop participants that will be considered by the research team in preparing the NCHRP 9-44 work plan.

Attachment. Participant Comments from the Opening and Closing Sessions

Opening Session

Expectations for the workshop from the participants contributed in Round Robin fashion at the beginning of the workshop.

- State of the art perspective on endurance limit and related topics so that I can best serve my role on the panel.
- Take home a few ideas.
- Get an idea of what others are doing in the lab.
- Get a clear definition of what the endurance limit is and what are factors that may affect it.
- See how we can integrate concepts of an endurance limit in design
- How to field verify the endurance limit concept.
- Latest developments in fatigue measurements in the lab, relationships to field performance, and incorporation in the design process.
- Develop a process leading to what states can endorse.
- What others are thinking in terms of material and structural level analysis.
- Looking at mechanism of damage recovery during rest periods affecting the endurance limit.
- Scaling factors from laboratory to field and the testing conditions.
- Practicality.
- What’s now and next generation.
- Getting discussion going on healing and how healing mechanism actually produces an endurance limit.
- Practical methodology that states can handle and use and how it varies by mix.
- Be convinced that endurance limit exists and why it is important.
- Conclude with a clear plan and not repeat work done on previous projects – Don’t reinvent the wheel and move towards the next project.
- Definition and material processes.
- Consensus of what endurance limit is exists and what are the conditions.
- Clarify different concepts: fatigue cracking and deformation.
- Concept of failure defined
- Define endurance limit for asphalt concrete.
- How to integrate the concept into design after calibration.
- Concept taken from steel and does it exist in asphalt.
- Integrate endurance limit into Mechanistic-Empirical Pavement Design Guide (MEPDG) and whether it’s a function of temperature.
- Figure out what needs to go into the work plan.
- Broaden horizons as to what’s going on with endurance limit so that we can better work with the panel members and the contractors.

Closing Session

Final thoughts about the workshop from the participants contributed in Round Robin fashion at the end of the workshop.

- Very helpful exercise – important to get diverse view of different opinions.
- Very productive – Ray has things to work with and all the program was well conducted.
- I appreciate you agreeing on definition.
- We got accomplished what we needed to do. Timing was well set up
- Low strain fatigue testing was good to me. One of the better workshops in terms of getting different viewpoints aired and discussed.
- Feel from panel's perspective that we have a better understanding to give good direction to Ray and Don.
- Constructive ideas, good discussions.
- Productive ideas, valuable.
- Interesting and new experience. Group dynamic was interesting. Concept is complicated and was only touched upon.
- Learned more than I contributed.
- Lot of people with good opinions.
- Useful just hearing different points of view. I took lots of notes.
- Appreciated being part of this and will take back a lot. Wish we had more of this type of meeting.
- Appreciate the selection of people (diverse group), voicing viewpoint, liked overseas visitors.
- Good guidance for Ray and panel.
- Enlightening experience that served purpose of workshop.
- Enjoyable hearing different views
- Thank everyone that participated and learned a lot.
- Thanks for the presentations that helped kick this off – got what I needed to do the work plan.

APPENDIX B. HMA ENDURANCE LIMIT VALIDATION STUDY RESEARCH PLAN

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Acknowledgements

The work reported herein was performed under NCHRP Project 9-44 by Advanced Asphalt Technologies, LLC, and Applied Research Associates, Inc. Ramon Bonaquist, Chief Operating Officer for Advanced Asphalt Technologies, LLC, served as Principal Investigator for the project and was the primary author of this research plan. Mr. Harold Von Quintus, Principal Engineer for Applied Research Associates, Inc. co-authored this research plan.

Special thanks are extended to the participants of the HMA Endurance Limit Workshop listed below. These professionals unselfishly presented ideas to the research team that helped shape the planned research.

Name	Affiliation
Dr. David Anderson	Consultant
Dr. Samuel Carpenter	University of Illinois
Dr. Donald Christensen	Advanced Asphalt Technologies, LLC
Dr. Herve Di Benedetto	Ecole Nat. des TPE
Mr. Bruce Dietrich	Florida Department of Transportation
Mr. Kenneth Fults	KWF Pavement Consulting
Mr. Roger Green	Ohio Department of Transportation
Dr. Kevin Hall	University of Arkansas
Dr. Edward Harrigan	National Cooperative Highway Research Program
Dr. Richard Kim	North Carolina State University
Dr. Dallas Little	Texas A&M University
Dr. Leslie Ann McCarthy	Federal Highway Administration
Dr. Andre Molenaar	Delft University
Professor Carl Monismith	University of California Berkeley
Dr. David Newcomb	National Asphalt Pavement Association
Dr. Michael Nunn	Lane One Limited
Dr. Brian Prowell	Advanced Material Services, LLC
Dr. Rey Roque	University of Florida
Ms. Amy Schutzbach	Illinois Department of Transportation
Dr. Jacob Uzan	Technion University
Dr. Linbing Wang	Virginia Polytechnic and State University
Dr. Matthew Witczak	Arizona State University

Abstract

This document presents a plan for research to rationally incorporate the concept of an endurance limit for hot mix asphalt (HMA) into a mechanistic-empirical algorithm for bottom initiated fatigue cracking in flexible pavements, and to validate the resulting procedure using performance data from full-scale pavement sections.

The planned research is based on the hypothesis that the endurance limit for HMA is the result of a balance of damage caused by loading and healing or damage recovery that occurs during rest periods. Under this hypothesis the primary objective in designing a flexible pavement to resist bottom initiated fatigue cracking will be to make sure that the damage induced by loading remains small enough so that healing occurs and there is no accumulation of damage over the life of the pavement. This is a significant departure from current cumulative or incremental damage models, which assume that no healing occurs and that each load cycle uses up a portion of the finite fatigue life of the HMA.

This research plan includes a preliminary design procedure that is based on layered elastic analysis and compatible with the Mechanistic-Empirical Pavement Design Guide (MEPDG). It uses allowable strains to identify satisfactory conditions for full healing. The allowable strains are a function of the properties of the HMA, the pavement temperature, and the duration of rest periods between traffic loads. Five laboratory experiments that are needed to fully develop the procedure are described. Studies using data from completed accelerated pavement tests and test roads are proposed to verify critical aspects of the design procedure. Finally, an experiment to calibrate the design procedure using selected test sections from the Long Term Pavement Performance Program is presented.

The recommended research study has been titled the HMA Endurance Limit Validation Study. It addresses an important concept in the design of perpetual pavements that is gaining increasing acceptance worldwide. It is envisioned that application of an endurance limit in flexible pavement design will lead to more effective pavement sections with significant benefit and cost savings to the public.

Introduction

Purpose

This document presents a plan for research to rationally incorporate the concept of an endurance limit for hot mix asphalt (HMA) into a mechanistic-empirical algorithm for bottom initiated fatigue cracking in flexible pavements, and to validate the resulting procedure using performance data from full-scale pavement sections. For HMA pavements, the endurance limit has been defined as *a level of strain below which there is no cumulative damage over an indefinite number of load cycles* (*1*).

This research plan is the primary product of National Cooperative Highway Research Program (NCHRP) Project 9-44, *Developing a Plan for Validating an Endurance Limit for HMA Pavements.* The recommended research study has been titled the HMA Endurance Limit Validation Study. It addresses an important concept in the design of perpetual pavements that is gaining increasing acceptance worldwide. It is envisioned that application of an endurance limit in flexible pavement design will lead to more effective pavement sections with significant benefit and cost savings to the public.

Statement of the Problem

In engineering, fatigue refers to the progressive and localized damage that occurs when a material is subjected to repeated loading below its ultimate strength. It is an important consideration in the design of many civil engineering structures including pavements.

The fatigue behavior of materials is evaluated using laboratory fatigue tests, where a sample is loaded repeatedly using a known stress or strain and the number of load applications are counted until the sample fails. By performing tests at different stress or strain levels a Wöhler curve or S-N diagram can be developed. These diagrams are simply plots of the applied stress or strain and the corresponding number of cycles to failure. Figure 1 shows two typical S-N diagrams generated from laboratory test data. In curve (a), the fatigue life increases at a gradually increasing rate with decreasing stress amplitude. In curve (b), on the other hand, the fatigue life gradually increases until a limit is reached (50 MPa in this case) where the fatigue life becomes indefinite. This is called the endurance limit for the material. The endurance limit is a critical concept in the design of structures that must resist large numbers of repeated loads. If stresses or strains are kept below the endurance limit, the structure will be able to withstand an infinite number of load applications.

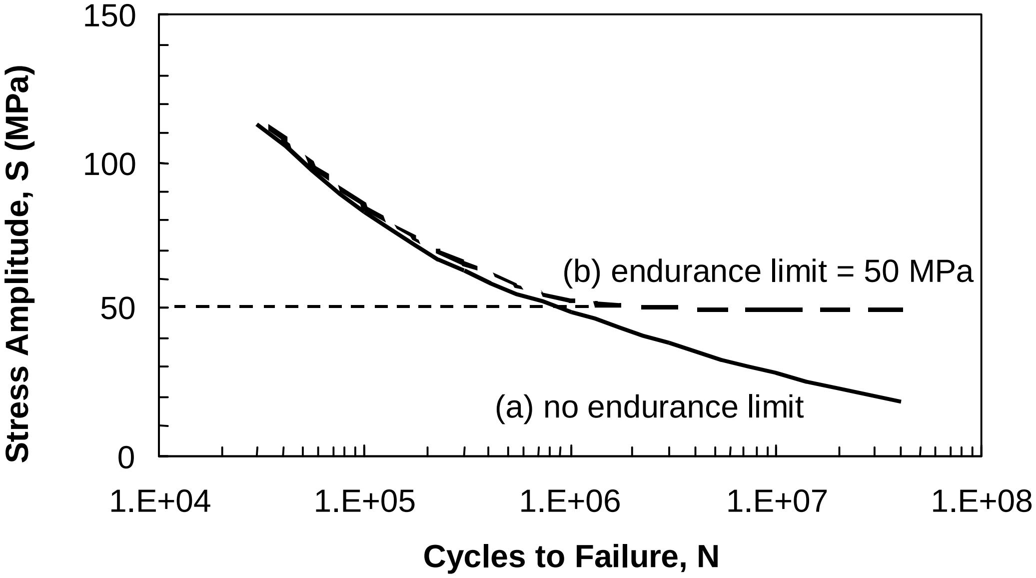

Figure 1. Typical S-N Diagram From Laboratory Fatigue Tests: (a) No Endurance Limit; (b) 50 MPa Endurance Limit.

Many materials do not have the well-defined endurance limit shown schematically in Figure 1. HMA is one of these materials. Although early HMA fatigue research conducted by Monismith and his colleagues suggested that HMA exhibited an endurance limit at approximately 70 μstrain (*2*), only limited HMA fatigue research was conducted at low strain levels until recently when the Asphalt Pavement Alliance began promoting the concept of perpetual pavement design (*3*). A perpetual pavement is an asphalt pavement that provides a very long life without structural failure and only requires periodic replacement of the surface. A key element of perpetual pavement design is to eliminate fatigue cracking that initiates at the bottom of the HMA base due to repeated flexure under traffic loading and to confine distresses to the surface of the pavement, which can easily be renewed by milling and resurfacing.

In response to increasing interest in perpetual pavements, a substantial amount of laboratory fatigue testing has recently been performed in the United States in an effort to demonstrate that HMA does exhibit an endurance limit. Most of this work has been performed at the University of Illinois (*4,5*) and the National Center for Asphalt Technology (NCAT) (*6*). These studies provide clear evidence that the fatigue behavior of HMA is much different in low strain level tests compared to normal strain level tests. Figure 2 shows a consolidated plot of the University of Illinois fatigue data including low and normal strain level test data. Below approximately 100 μstrain, the fatigue life is significantly longer than estimated from extrapolation of normal strain level test data. Healing of microdamage has been proposed as the primary reason for the increased fatigue life at low strain levels (*1, 7, 8*). For cyclic tests at low strain levels, it appears that the damage that is caused by loading is offset by healing that occurs during unloading resulting in essentially infinite fatigue life. Current mechanistic-empirical fatigue criteria for HMA, including the field calibrated criterion in the Mechanistic Empirical Pavement Design Guide (MEPDG), are based on results from normal strain level tests and do not include the low strain level effects shown in Figure 2.

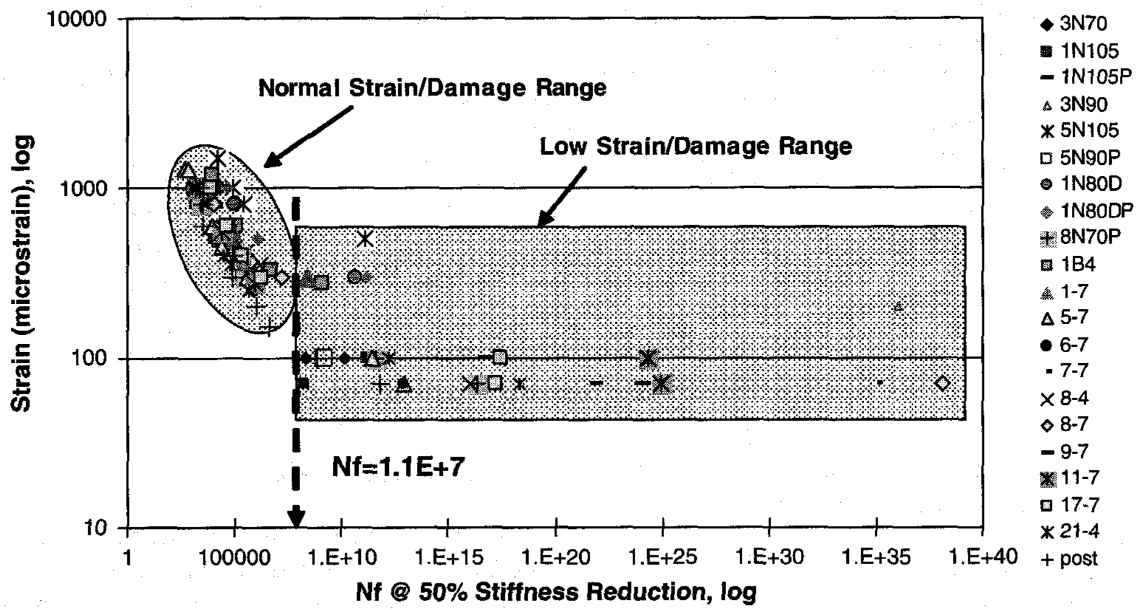

Figure 2. Results of Flexural Fatigue Tests by Carpenter et al., Including Extrapolated Results at Low Strain Levels (*4*).

Detailed investigation of four heavily trafficked pavements in the United Kingdom support the perpetual pavement concept and the likelihood of an endurance limit for HMA. This comprehensive study found no evidence of fatigue damage at the bottom of properly constructed thick flexible pavements with total HMA thickness ranging from 230 to 350 mm (*9*). Cracks in these pavements were found to have initiated at the surface and deflections monitored over a number of years generally showed steady or decreasing deflection with increasing cumulative traffic, indicating that fatigue damage to the bottom of the HMA was not occurring. Similar conclusions concerning the absence of cracking at the bottom of thick HMA pavements have been reported by others (*10, 11, 12*).

In summary, there is mounting evidence that an endurance limit for HMA does exist. It has been observed in laboratory studies of fatigue at low strain levels, and several documented case studies indicate that bottom initiated fatigue cracking is almost non-existent in properly constructed, thick HMA pavements. A concentrated research effort, however, is needed to validate the endurance limit concept, and to devise effective methods for incorporating it in mechanistic-empirical pavement design methods.

Objectives and Hypothesis

The objectives of the HMA Endurance Limit Validation Study are:

1. To incorporate the concept of an endurance limit for HMA into a mechanistic-empirical algorithm for bottom initiated fatigue cracking in flexible pavements.

2. To validate the methodology using performance data from full-scale pavement sections.

These objectives could potentially be satisfied using a number of research approaches. The specific approach presented in this plan is based on the following hypothesis, which was developed from a review of recent literature concerning the fatigue response of HMA, and recommendations made during the HMA Endurance Limit Workshop conducted early in NCHRP Project 9-44 (*1*):

> *HMA does exhibit an endurance limit. This endurance limit, however, does not reflect an absence of load induced damage in the HMA. It is the result of a balance of damage caused by loading and healing or damage recovery that occurs during rest periods. The endurance limit for HMA is, therefore, not a single value, but will change depending on the loading and environmental conditions applied to the HMA. To properly consider this form of an endurance limit in flexible pavement design requires consideration of the effects of loading, environment and material properties on both damage accumulation and healing.*

Under this hypothesis the primary objective in designing a flexible pavement to resist bottom initiated fatigue cracking will be to make sure that the damage induced by loading remains small enough so that healing occurs and there is no accumulation of damage over the life of the pavement. This is a significant departure from current cumulative or incremental damage models which assume that no healing occurs and that each load cycle uses up a portion of the finite fatigue life of the HMA. The hypothesis presented above implies that any flexible pavement structure can be designed to indefinitely resist bottom initiated fatigue cracking. Thicker pavements will be required for heavier loads, shorter rest periods (higher traffic volume), and poorer foundation conditions. To successfully formulate this type of design procedure will require research to quantify the effects of temperature, aging, and materials properties on damage accumulation and damage recovery in HMA. Once formulated, the procedure can be validated using performance data from full-scale pavement sections.

Scope of the Plan

This research plan is a comprehensive document describing the research that must be completed to successfully incorporate the concept of an endurance limit for HMA into a fatigue algorithm for bottom initiated fatigue cracking and to validate the resulting procedure using full-scale pavement sections. It includes four parts in addition to this Introduction. The first is a summary that briefly describes the proposed research and presents overall cost estimates and time requirements. The second is a description of the required research tasks. This section includes detailed information for each task and subtask, including (1) a description of the work to be performed, (2) preliminary experimental designs when appropriate, (3) a list of milestones related to the task, (4) labor hour estimates, and (5) a listing of pertinent data and reference material that will be needed to accomplish the task. The third is a detailed schedule for the project. The schedule addresses the sequence of the research tasks and the interactions between tasks. Finally, the fourth presents the proposed budget for the project. The budget includes detailed estimates of labor and other costs associated with each task and subtask.

Summary of the Research Plan

The HMA Endurance Limit Validation Study consist of five major tasks: (1) Management and Reporting, (2) Formulate Design Procedure, (3) Database Management, (4) Laboratory Studies, and (5) Analysis of Pavement Sections. Figure 3 presents an overall flow chart for the project with major interactions between tasks identified. Table 1 lists the subtasks for each of the five major tasks and presents estimated labor hours and costs. The HMA Endurance Limit Validation Study is estimated to require approximately 12,923 man-hours of effort at a cost of approximately $1.5 million. Figure 4 presents the overall schedule for the project, which is estimated to require 48 months to complete.

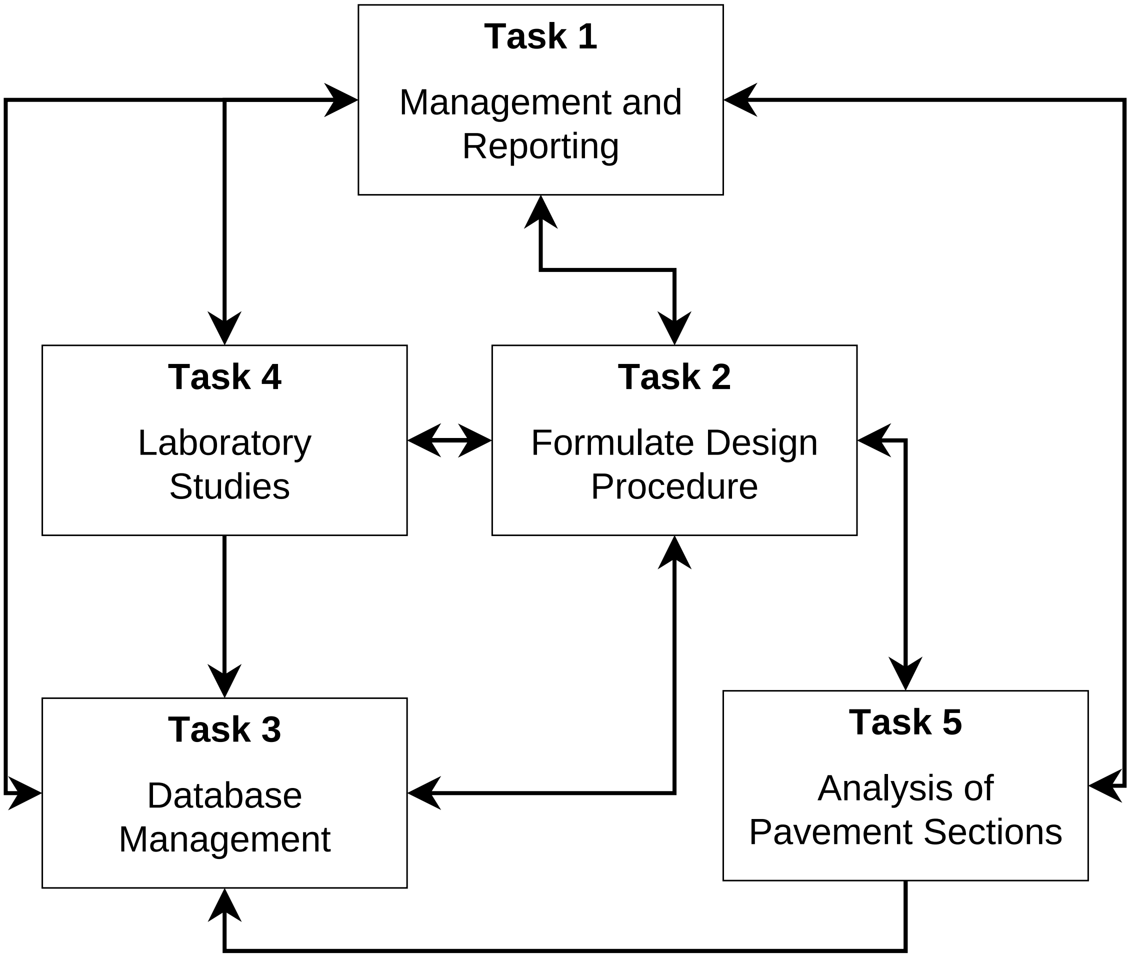

Figure 3. Project Flow Chart.

Table 1. Summary of Man-hour and Cost Estimates.

Task/ Subtask	Description	Estimated Labor Hours				Estimated Cost
		Senior Eng./ Stat	**Eng./ Prog.**	**Tech.**	**Admin.**	
1.0	**Management and Reporting**					
1.1	Project Management	424	0	0	40	$66,000
1.2	Progress Reporting	210	0	0	20	$32,700
1.2	Interim Reports and Presentations	780	0	0	80	$129,780
1.3	Final Report and Presentation	420	0	0	40	$68,400
Task 1 Total		**1834**	**0**	**0**	**180**	**$296,880**
2.0	**Formulate Design Procedure**					
2.1	Review Selected Literature	240	160	0	0	$52,000
2.2	Finalize Preliminary Approach	80	160	0	0	$28,000
2.3	Incorporate Findings from Laboratory Studies	80	160	0	0	$28,000
2.4	Modify Approach Based on Analysis of Accelerated Pavement Tests	80	80	0	0	$20,000
2.5	Prepare Final Design Procedure	120	80	0	0	$26,000
Task 2 Total		**600**	**640**	**0**	**0**	**$154,000**
3.0	**Database Management**					
3.1	Develop Plan to Use NCHRP 9-30 Database	120	0	0	0	$18,000
3.2	Develop Needed Tables	80	240	0	0	$36,000
3.3	Input and Manage Data	40	396	0	0	$45,600
Task 3 Total		**240**	**636**	**0**	**0**	**$99,600**
4.0	**Laboratory Studies**					
4.1	Experiment 1: Mixture Compositional Factors Affecting Healing	42	0	388	0	$39,280
4.2	Experiment 2: Effect of Applied Strain on Healing	32	0	214	0	$22,990
4.3	Experiment 3: Effect of Temperature and Rest Period Duration on Healing	69	0	242	0	$30,920
4.4	Experiment 4: Testing and Analysis Procedures for Allowable Strain Levels	168	0	392	0	$58,520
4.5	Experiment 5: Estimation of Allowable Strain Levels from Mixture Composition	456	0	1890	0	$229,050
Task 4 Total		**767**	**0**	**3126**	**0**	**$380,760**
5.0	**Analysis of Pavement Sections**					
5.1	Review Data Sources and Select Sections for Analysis	52	320	0	0	$39,800
5.2	Obtain Materials and Data for Accelerated Pavement Tests	48	280	0	0	$35,200
5.3	Perform Testing and Analyze Accelerated Pavement Tests	164	512	32	0	$78,520
5.4	Obtain Materials and Data for In-Service Pavement Sections	120	1280	0	0	$195,600
5.5	Perform Testing and Analyze In-Service Pavement Sections	300	512	1280	0	$205,000
Task 5 Total		**684**	**2904**	**1312**	**0**	**$554,120**
	Project Total	***4,125***	***4,180***	***4,438***	***180***	***1,485,360***

Task/Subtask		Months After Notice To Proceed																																															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1.0	**Management and Reporting**																																																
1.1	Project Management	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
1.2	Progress Reporting	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
1.3	Interim Reports and Presentations							▨						▨	P						▨	▨	▨								▨	P										▨	▨						
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3.3	Input and Manage Data									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨							
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4.5	Experiment 5: Estimation of Allowable Strain Levels from Mixture Composition														▨	▨	▨	▨	▨	▨	▨	▨																											
5.0	**Analysis of Pavement Sections**																																																
5.1	Review Data Sources and Select Sections for Analysis							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																											
5.2	Obtain Materials and Data for Accelerated Pavement Tests and Test Roads													▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																								
5.3	Perform Lab Testing and Analyze Accelerated Pavement Tests and Test Roads																						▨	▨	▨	▨	▨	▨																					
5.4	Obtain Materials and Data for In-Service Pavement Sections																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																
5.5	Perform Lab Testing and Analyze In-Service Pavement Sections																						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨													

Figure 4. Overall Project Schedule.

Task 1, Management and Reporting, includes all activities normally associated with management and reporting for NCHRP Projects. Major management tasks include scheduling, coordinating, and directing various technical work activities as well as project financial management. Reporting activities include monthly and quarterly progress reports, the preparation of several interim reports and presentations, and the preparation of the final report. Interim reports are required at approximately 6 month intervals and coincide with the completion of five critical milestones:

(1) Formulation of the preliminary design procedure and selection of the laboratory analysis approach,
(2) Selection of pavement sections for analysis,
(3) Completion of the laboratory studies,
(4) Modification of the preliminary design procedure to reflect the findings from the laboratory studies and the analysis of accelerated pavement tests, and
(5) Analysis of the calibration sections and preparation of the final design procedure.

The final report will document the entire study and will be prepared from the interim reports.

Task 2, Formulate Design Procedure, is a critical project task that will be active throughout the project. This task includes finalizing the preliminary approach that is presented in this research plan, modifying the preliminary approach based on the results of the laboratory studies and selected accelerated pavement tests, and preparation of the final design procedure after analysis of the calibration pavement sections. It is important to emphasize that the preliminary approach prepared early in this task will shape the laboratory studies and guide the selection of pavement sections, both accelerated pavement tests and in-service pavement sections.

Task 3, Database Management, is a support task that will be active throughout the project. A database will be developed in this task to store and analyze data from the laboratory studies and the analysis of the pavement sections. It is envisioned that the database will be an adaptation of the one developed in NCHRP Project 9-30.

Task 4, Laboratory Studies, includes the planning and execution of five laboratory studies that are needed to complete the design procedure that will be formulated in Task 2. The laboratory studies concentrate on quantifying what affects the healing properties of HMA. The laboratory studies will be sufficient in breadth to develop models relating mixture and binder properties to the key engineering properties required for the analysis.

Task 5, Analysis of Pavement Sections, includes several activities associated with the selection and analysis of full-scale pavements. The preliminary design procedure formulated in Task 2 will be tested using data from completed accelerated pavement tests, such as the fatigue studies from the Federal Highway Administration's (FHWA's) Pavement Testing Facility or the structural sections included in the National Center for Asphalt Technology (NCAT) test track. Calibration of the design procedure will be accomplished through an analysis of in-service pavements where it has been documented that bottom-up fatigue cracking has occurred or has not occurred. These analyses will serve to calibrate the design procedure and validate the HMA endurance limit concept. The predictive models developed in Task 4 will be used in the analysis of the full-scale pavement sections. This will allow consideration of pavement sections where original materials are not available since the required data can be obtained from cores taken from the pavement section.

Task by Task Description of the Research Plan

This section of the research plan presents detailed descriptions of each of the tasks and subtasks included in the HMA Endurance Limit Validation Study. Each task description includes a detailed description of the work to be performed including: (1) preliminary experimental designs when appropriate, (2) a list of milestones related to the task, (3) labor hour estimates, and (4) a listing of pertinent data and reference material that will be needed to accomplish the task.

Task 1. Management and Reporting

Task 1 includes all activities normally associated with management and reporting for NCHRP projects. Task 1 has been divided into four subtasks:

1.1 Project Management,
1.2 Progress Reporting,
1.3 Interim Reports and Presentations, and
1.4 Final Report and Presentation.

Each of these subtasks is described in detail below.

Subtask 1.1 Project Management

Effective project management will be critical to the successful completion of the HMA Endurance Limit Study. The study requires that the Principal Investigator have in-depth knowledge of the following technical areas:

- Mechanistic-empirical pavement design and analysis,
- Experimental design,
- Model development,
- Laboratory characterization of HMA,
- Accelerated pavement testing, and
- Pavement evaluation.

Since the design procedure incorporating an endurance limit for bottom initiated fatigue cracking will determine the details of the laboratory and field studies, the Principal Investigator should directly lead Task 2, Formulate Design Procedure. To efficiently manage several tasks that will be conducted concurrently, the team structure shown in Figure 5 is recommended. In this structure, the Principal Investigator is supported by three teams: Laboratory, Pavement, and Data Support, each with a separate team leader. Additionally, it is strongly recommended that a Statistician be included in the project team to assist the Principal Investigator and team leaders with detailed experimental design, model formulation, and model calibration. The Principal Investigator will be responsible for the overall technical content of the project, while the team leaders will be responsible for the details of the work in their area of expertise. In addition to the scenario shown in Figure 5 where the management team consists of the Principal Investigator and three team leaders, other structures are possible depending on the skills and commitment levels of the senior members of the research team. For example, the Principal Investigator may also serve as one of the team leaders and one individual may serve as the leader of the remaining two teams. It is recommended, however, that a single individual not fill more than two leadership roles.

This research plan as modified during the proposal process will serve as the principal project management tool. Shortly after contract award, the research management team should meet and the Principal Investigator should make initial task assignments to the project team. The research management team should then meet semi-monthly to discuss the progress of the work and resolve any problems that may develop. These meetings should be scheduled to provide timely information for the monthly and quarterly progress reports discussed in the next section.

Another important aspect of project management is coordination with other on-going research efforts. Several studies addressing cracking in flexible pavements are on-going including: (1) NCHRP 1-41, *Models for Predicting Reflection Cracking of Hot-Mix Asphalt Overlays*, (2) NCHRP 1-42A, *Models for Predicting Top-Down Cracking of Hot-Mix Asphalt Layers,* and (3) the fatigue studies being conducted in the Asphalt Research Consortium. Although different approaches are being used in each of these studies, it is important that the research team monitor and share information with these studies.

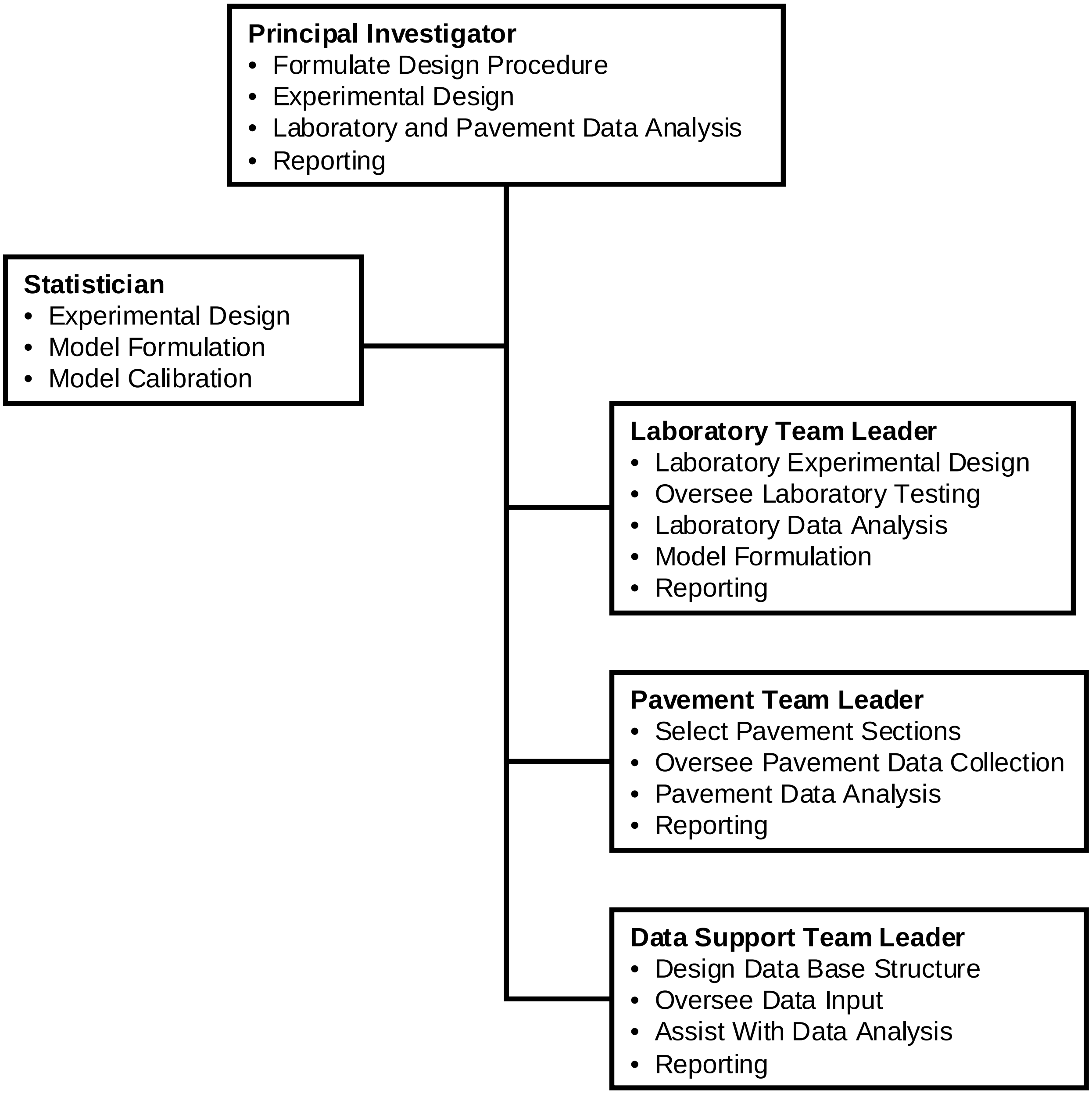


Figure 5. Recommended Research Management Structure.

Subtask 1.2 Progress Reporting

NCHRP has specific requirements for progress reporting (*13*). The required reporting includes brief monthly progress reports and detailed quarterly progress reports. The monthly progress reports briefly summarize the work that has been completed, planned work, problems encountered, and expenditures for the project. The detailed quarterly progress reports describe completed work, planned work, and problems encountered in sufficient detail for review by the project panel during the course of the project. The quarterly progress reports are the means by which the project panel provides direction to the research team. Timely progress reporting and communication with the project panel are essential tools for effective project management.

Subtask 1.3 Interim Reports and Presentations

The HMA Endurance Limit Validation Study includes a series of interim reports that coincide with the completion of five critical milestones:

(1) Formulation of the preliminary design procedure and selection of the laboratory analysis approach,
(2) Selection of pavement sections for analysis,
(3) Completion of the laboratory studies,
(4) Modification of the preliminary design procedure to reflect the findings from the laboratory studies and the analysis of accelerated pavement tests, and
(5) Analysis of the calibration sections and preparation of the final design procedure.

Each interim report should be prepared in accordance with NCHRP requirements (*14*) and specifically address the work completed in the relevant tasks. These interim reports will provide more detailed information than normally contained in the progress reports. The final report will be compiled from the interim reports.

Presentations to the project panel are included after the second and fourth interim reports. The purpose of these presentations is to encourage a dialog between the project panel and the

Principal Investigator on the progress and direction of the work. One full day should be planned for each of these presentations sessions. Each session should include:

(1) A presentation from the Principal Investigator focusing on the completed interim reports, planned work, and any changes to the direction of the research.
(2) A discussion period where the project panel discusses critical aspects of the completed and planned work with the Principal Investigator and other key members of the research team.
(3) Recommendations concerning the direction of the research.

Subtask 1.4 Final Report and Presentation

The final report will document the entire project and will be compiled from the five interim reports. This report will be prepared in accordance with NCHRP requirements (*14*) and revised as required for publication. Upon completion of the review of the draft of the final report, the Principal Investigator will meet with the project panel to discuss the outcome of the project and to jointly develop recommendations concerning implementation and additional research activities.

Task 1 Milestones

Table 2 summarizes the major milestones for Task 1. This milestone schedule assumes that this research plan as modified during the proposal process will serve as the work plan for the project. In addition to the major milestones listed in Table 2, meetings of the research management team will occur semi-monthly throughout the project, and monthly progress reports will be submitted as required by NCHRP.

Task 1 Labor Estimate

Table 3 presents the estimated labor required for Task 1. Table 3 presents estimated labor hours for each of the positions in the research management structure presented in Figure 5. Project management and reporting is estimated to require at total of 2014 man-hours of effort. This is approximately 16 percent of the total effort required for the project.

Table 2. Major Task 1 Milestones.

Milestone	Description	Months After Contract Award
1.1	Initial Work Assignments	0.5
1.2	First Quarterly Progress Report	3
1.3	Second Quarterly Progress Report	6
1.4	First Interim Report (Preliminary Design Procedure and Laboratory Analysis Approach)	7
1.5	Third Quarterly Progress Report	9
1.6	Fourth Quarterly Progress Report	12
1.7	Second Interim Report (Selection of Pavement Sections for Analysis)	13
1.8	First Panel Presentation (Interim Reports 1 and 2)	14
1.9	Fifth Quarterly Progress Report	15
1.10	Sixth Quarterly Progress Report	18
1.11	Seventh Quarterly Progress Report	21
1.12	Third Interim Report (Analysis of Laboratory Studies)	22
1.13	Eighth Quarterly Progress Report	24
1.14	Ninth Quarterly Progress Report	27
1.15	Tenth Quarterly Progress Report	30
1.16	Fourth Interim Report (Design Procedure Incorporating Findings From Laboratory Studies and Analysis of Accelerated Pavement Tests)	30
1.17	Second Panel Presentation (Interim Reports 3 and 4)	31
1.18	Eleventh Quarterly Progress Report	33
1.19	Twelfth Quarterly Progress Report	36
1.20	Thirteenth Quarterly Progress Report	39
1.21	Fifth Interim Report (Analysis of Validation Sections and Final Design Procedure)	42
1.22	Fourteenth Quarterly Progress Report	42
1.23	Submit Draft of Final Report	45
1.24	Fifteenth Quarterly Progress Report	45
1.25	Third Panel Presentation (Draft Final Report and Recommendations for Implementation and Additional Research	46
1.26	Revised Final Report	48

Table 3. Estimated Labor Hours for Task 1.

Subtask	Principal Investigator	Statistician	Laboratory Team Leader	Pavement Team Leader	Data Support Team Leader	Administrative Assistant
1.1 Project Management	112	0	104	104	104	40
1.2 Progress Reporting	120	0	30	30	30	20
1.3 Interim Reports and Presentations	432	0	116	116	116	80
1.4 Final Report and Presentation	216	0	68	68	68	40
Total	**880**	**0**	**318**	**318**	**318**	**180**

Task 1 Sources

Procedural Manual for Agencies Conducting Research in the National Cooperative Highway Research Program, Transportation Research Board, August, 2006.

Preparing Your CRP Final Report, Transportation Research Board, September, 2006

Task 2. Formulate Design Procedure

In Task 2, the procedure for designing pavements to resist bottom initiated fatigue cracking that considers the effects of an endurance limit for HMA will be developed. Task 2 will build on the preliminary procedure described in this research plan in four distinct steps:

1. Finalize preliminary procedure,
2. Incorporate findings from laboratory studies,
3. Modify approach based on analysis of accelerated pavement tests, and
4. Prepare final design procedure.

In step 1, the research team will become familiar with the preliminary procedure described in this research plan, and develop improvements based on their review of the relevant literature and research in progress. Then in steps 2, 3, and 4 information obtained from Tasks 4 and 5 of the project will be used to further improve the procedure. The final product will be a procedure for designing flexible pavements to resist bottom initiated fatigue cracking that accounts for the effects of an HMA endurance limit. This procedure will be compatible with current mechanistic-empirical flexible pavement design methods such as the MEPDG.

Preliminary Design Procedure

Background

A major part of the work completed during NCHRP 9-44 was the development of a preliminary procedure for designing pavements to resist bottom initiated fatigue cracking that considers the effects of an endurance limit. This preliminary procedure is based on the research hypothesis that the endurance limit for HMA is the result of a balance of damage caused by loading and healing or damage recovery that occurs during rest periods. Under this hypothesis the primary objective in designing a flexible pavement to resist bottom initiated fatigue cracking will be to make sure that the damage induced by loading remains small enough so that healing occurs and there is no accumulation of damage over the life of the pavement. This is a significant departure from current cumulative or incremental damage models, which assume that no healing occurs and that each load cycle uses up a portion of the finite fatigue life of the HMA.

A number of approaches for designing pavements to resist bottom initiated fatigue cracking were reviewed during NCHRP Project 9-44. Table 4 briefly summarizes the approaches that were considered. These range from relatively simple modifications of traditional mechanistic-empirical fatigue algorithms to sophisticated finite element models based on damage mechanics and fracture mechanics. The major deficiency of the more practical approaches is that they do not account for the beneficial effects of healing. In the HMA Endurance Limit Workshop, healing was identified as a significant factor affecting the endurance limit in HMA (*1*). The sophisticated approaches can account for healing, but are not practical at this time for use in routine pavement design.

Effect of Rest Periods

An alternative approach was conceived during NCHRP Project 9-44 based on recent endurance limit research published by Carpenter and Shen (*7*). In this work, Carpenter and Shen clearly demonstrated the beneficial effects of rest periods on the fatigue life of HMA. Strain controlled flexural fatigue tests were conducted at 20 °C using a 10 Hz haversine load pulse with a rest period between each pulse to simulate the time between traffic loads. The rest periods ranged from 0 sec (continuous loading) to 9 seconds. Two 19 mm mixtures, one with a neat PG 64-22 binder and one with a polymer modified PG 70-22 binder, were tested. The gradation, binder content and air void content of the two mixtures was the same.

Table 4. Summary of Existing Pavement Analysis Approaches Considered.

Approach	**Key Elements**	**Selected References**	**Advantages**	**Disadvantages**
Strain Limit	Assume fatigue life is infinite at damage levels below the endurance limit. Use Miner's law for strain levels above the endurance limit.	Timm and Young (15) Witczak (16) Thompson and Carpenter (17)	Easy to implement in existing M-E design. Compatible with layered elastic analysis used in MEPDG.	Does not consider the beneficial effect of rest periods. Relies on Miners law for strains above the endurance limit. Above endurance limit fatigue life of HMA is predefined.
Crack Initiation	Limit strain level to that causing crack initiation in laboratory fatigue tests.	Sidess and Uzan (18)	Easy to implement in existing M-E design. Compatible with layered elastic analysis used in MEPDG. Rational basis for design.	Does not consider the beneficial effect of rest periods. Relies on Miners law. Cycles to crack initiation are predefined.
Strain Limit-Crack Initiation	Assume fatigue life is infinite at damage levels below the endurance limit. Use Miner's law for strain levels above the endurance limit. The endurance limit is estimated from the indirect tensile strength test and is dependent on the modulus of the mixture.	Von Quintus (19, 20)	Relatively easy to implement in existing M-E based methods. Compatible with layered elastic analysis used in the MEPDG. Value is dependent on the temperature (modulus), and volumetric properties of the mixture.	Does not consider the beneficial effect of rest periods. Relies on Miner's law for strains above the endurance limit. Key property used to estimate endurance limit is highly variable.
Recursive Miner's Law	Modify fatigue life of HMA to account for the strength loss of a pavement structure as a function of traffic loading.	Tsai, et al., (21)	Easy to implement in existing M-E design. Compatible with layered elastic analysis used in MEPDG. Accounts for changes in fatigue life of HMA with traffic.	Assumes that HMA fatigue life deteriorates with traffic loading. Does not consider the beneficial effect of rest periods.
Visco-Elastic Continuum Damage	Model the evolution of damage in a viscoelastic continuum.	Mun, et al., (22)	Can be used to predict crack initiation. Directly accounts for damage accumulation and healing.	Computationally intensive. Not compatible with layered elastic analysis used in MEPDG.
Fracture Mechanics	Model responses at the crack tip and the propagation of cracks.	Roque, et al. (23)	Predict crack growth.	Requires crack initiation model. Computationally intensive. Not compatible with layered elastic analysis used in MEPDG.

The resulting data were analyzed using the ratio of dissipated energy change (RDEC) approach developed at the University of Illinois (*5*). In this approach, the ratio of dissipated energy change reaches a plateau value (PV) where a constant percentage of the input energy is being converted to damage. The University of Illinois research found a unique relationship between the plateau value and the traditional definition of failure in flexural fatigue tests, 50 percent stiffness reduction, that holds for a range of mixtures and loading conditions (*5*).

$$PV = 0.4429 \times \left(N_f\right)^{-1.1102} \tag{1}$$

where:

PV = plateau value

N_f = number of cycles to 50 percent stiffness reduction

Lower plateau values correspond to longer fatigue lives. Based on the ratio of dissipated energy change approach, an HMA mixture will exhibit endurance limit behavior when the plateau value is 6.74×10^{-9} or less, which based on Equation 1 corresponds to a traditional fatigue life of 1.1×10^{7} cycles or greater.

The effect of rest periods on the plateau value is shown in Figure 6 for the two mixtures that were tested. Equations 2 and 3 present the relationship between plateau value and the length of the rest period that were developed for the neat PG 64-22 and the modified PG 70-22 mixtures, respectively for a strain level of 500 μstrain (*7*).

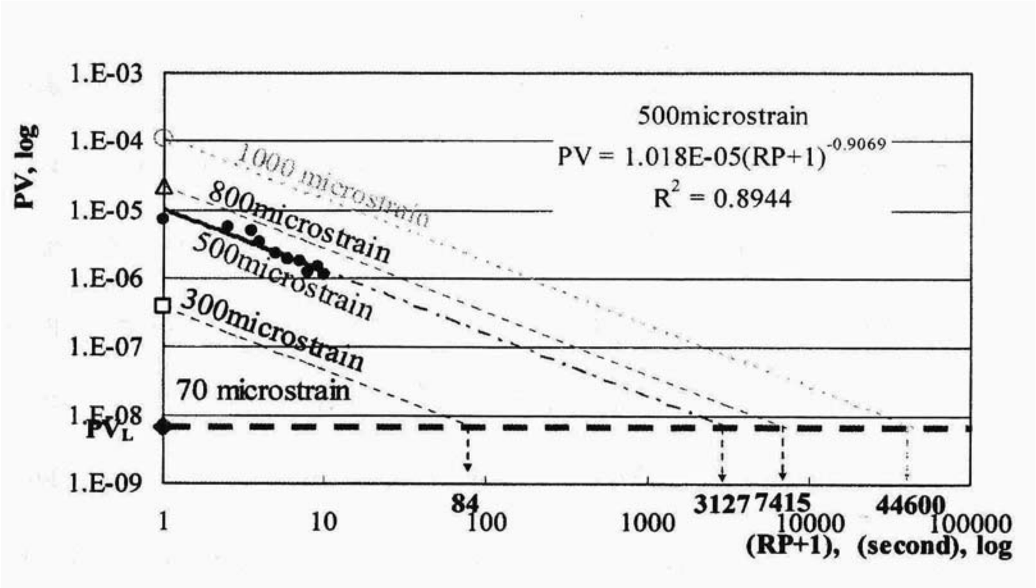
For neat PG 64-22
$$PV = 1.018 \times 10^{-5} \left(RP + 1\right)^{-0.9069} \tag{2}$$

For modified PG 70-22
$$PV = 4.353 \times 10^{-6} \left(RP + 1\right)^{-1.352} \tag{3}$$

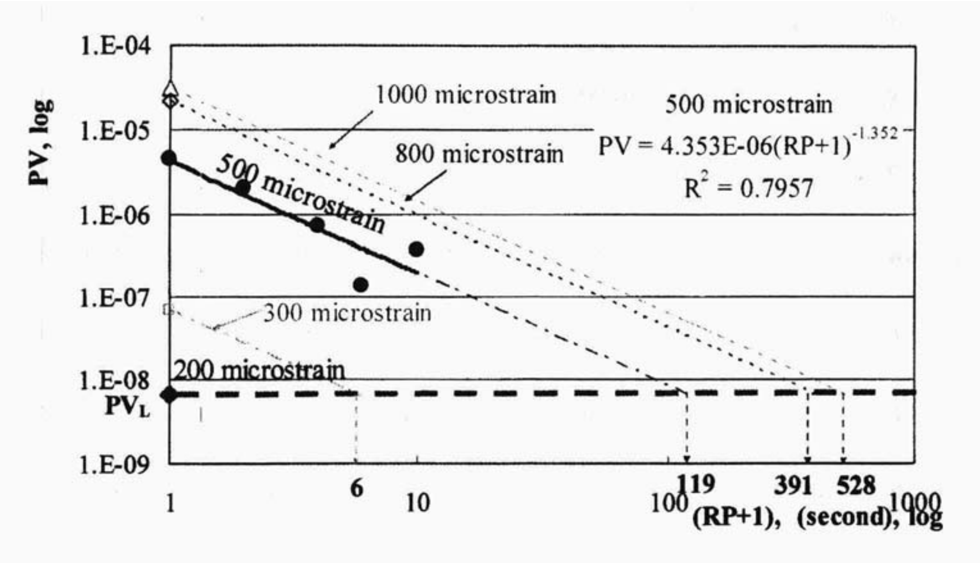
where:

PV = plateau value

RP = duration of intermittent rest period, sec



a. Neat PG 64-22



b. Polymer PG 70-22

Figure 6. Effect of Rest Periods on Plateau Value (*5*).

The decreasing plateau values for tests with rest periods result in increasing fatigue lives. This can be quantified by substituting plateau values from Equations 2 or 3 into Equation 1. The results are summarized in Table 5. Figure 7 shows the beneficial effect of the rest periods on the fatigue lives for the two mixtures. There is a substantial improvement in the fatigue life of both mixtures. The values for the neat PG 64-22 mixture are of similar magnitude to improvements previously reported by Bonnaure, et al. (*24*). The effect of rest periods on the modified PG 70-22 mixture is much more pronounced.

Table 5. Effect of Rest Period on Fatigue Life.

Rest Period, sec	Neat PG 64-22			Modified PG 70-22		
	PV	N_f	Ratio	PV	N_f	Ratio
0	1.02E-05	1.51E+04	1.00	4.35E-06	3.24E+04	1.00
1	5.43E-06	2.65E+04	1.76	1.71E-06	7.53E+04	2.33
2	3.76E-06	3.70E+04	2.45	9.86E-07	1.23E+05	3.81
3	2.90E-06	4.68E+04	3.10	6.68E-07	1.75E+05	5.41
4	2.37E-06	5.61E+04	3.72	4.94E-07	2.30E+05	7.10
5	2.00E-06	6.51E+04	4.32	3.86E-07	2.87E+05	8.86
6	1.74E-06	7.39E+04	4.90	3.13E-07	3.46E+05	10.69
7	1.54E-06	8.24E+04	5.47	2.62E-07	4.08E+05	12.58
8	1.39E-06	9.07E+04	6.02	2.23E-07	4.70E+05	14.52
9	1.26E-06	9.89E+04	6.56	1.94E-07	5.35E+05	16.51
10	1.16E-06	1.07E+05	7.09	1.70E-07	6.01E+05	18.54

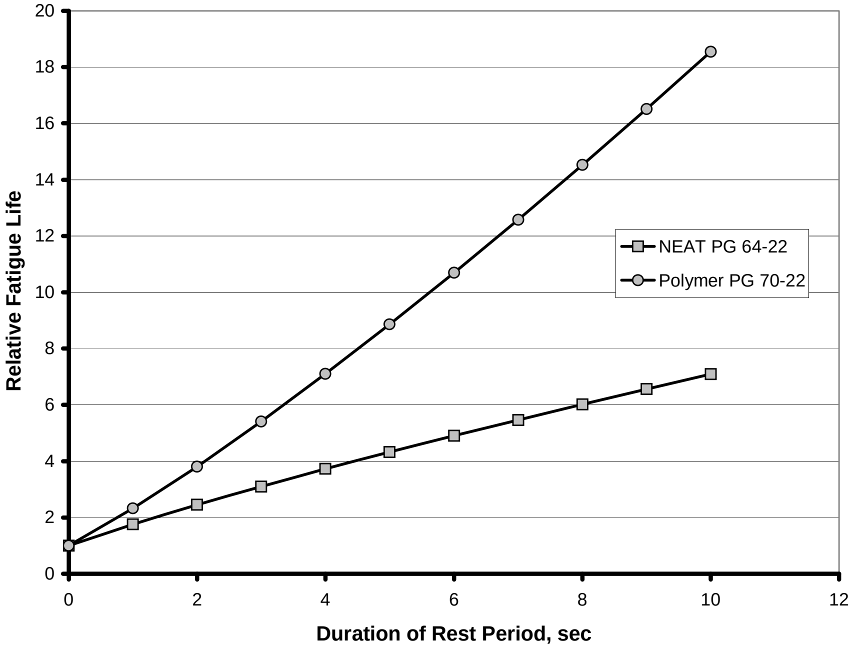


Figure 7. Effect of Rest Period on Fatigue Life.

An estimate of approximate rest periods can be obtained from the 20 year design traffic level typically used in mixture design. Table 6 summarizes rest periods for various design traffic levels. The rest period for a 20 year design traffic level of 100 million ESAL is approximately 6 sec., which results in a factor of 5 improvement in the fatigue life of the mixture with the neat PG 64-22 binder and a factor of 10 improvement for the polymer modified PG 70-22 mixture.

Table 6. Approximate Rest Periods for Various Design Traffic Levels.

20 Year Design ESAL	ESAL/Day	ESAL/sec	Rest Period, sec
1.00E+05	13.7	0.0002	6307.2
3.00E+05	41.1	0.0005	2102.4
1.00E+06	137.0	0.0016	630.7
3.00E+06	411.0	0.0048	210.2
1.00E+07	1369.9	0.0159	63.1
3.00E+07	4109.6	0.0476	21.0
1.00E+08	13698.6	0.1585	6.3
3.00E+08	41095.9	0.4756	2.1

Allowable Strains

Continuous loading tests at different strain levels were also conducted by Carpenter and Shen on the two mixtures and the plateau values are shown in Figure 6 for a rest period of zero (RP+1=1) (*7*). From these data relationships between the plateau value for continuous loading and the applied strain level can be developed as shown in Figure 8. These relationships are given in Equations 4 and 5 for the neat PG 64-22 mixture and the polymer modified PG 70-22 mixture.

For neat PG 64-22 $$PV_0 = 9.142 \times 10^{-16} (\varepsilon)^{3.617} \quad (4)$$

For modified PG 70-22 $$PV_0 = 5.347 \times 10^{-21} (\varepsilon)^{5.331} \quad (5)$$

where:

PV_0 = plateau value for continuous loading

ε = tensile strain, μstrain

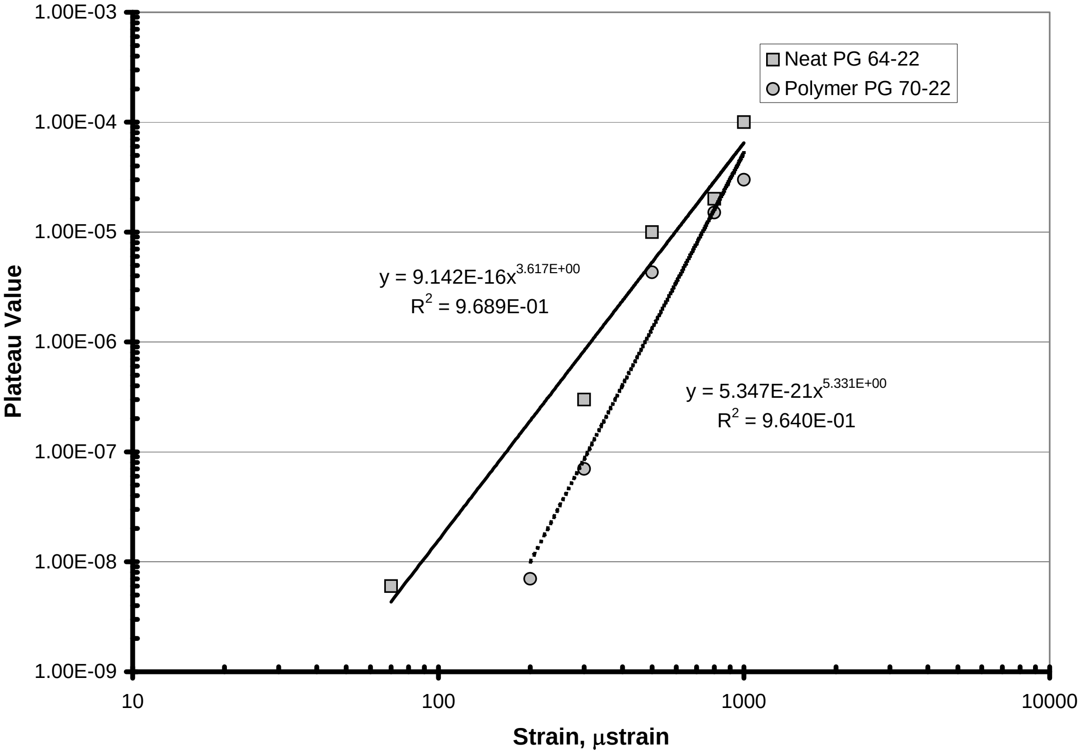


Figure 8. Plateau Value for Continuous Loading as a Function of Applied Strain Level.

Based on previous work by Bonnaure (*24*), it is reasonable to assume that the effect of the rest periods is the same at each strain level. Substituting Equations 4 and 5 for the constants 1.018 x10^{-5} and 4.353 x10^{-6} in Equations 2 and 3 respectively, yield the following relationships between the plateau value, applied strain and rest period for the two mixtures.

For neat PG 64-22 $$PV = 9.142 \times 10^{-16} (\varepsilon)^{3.617} (RP + 1)^{-0.9069} \quad (6)$$

For modified PG 70-22 $$PV = 5.347 \times 10^{-21} (\varepsilon)^{5.331} (RP + 1)^{-1.352} \quad (7)$$

where:

PV = plateau value

ε = tensile strain, μstrain

RP = duration of intermittent rest period, sec

Equations 6 and 7 can then be substituted into Equation 1 and solved for the allowable strain level to produce a selected mixture fatigue life.

For neat PG 64-22 $$\varepsilon_a = 11483.32\left[\frac{(1+RP)^{0.2507}}{(N_f)^{0.3069}}\right] \quad (8)$$

For modified PG 70 -22 $$\varepsilon_a = 5448.74\left[\frac{(1+RP)^{0.2536}}{(N_f)^{0.2082}}\right] \quad (9)$$

where:

ε_a = allowable tensile strain, µstrain

RP = duration of intermittent rest period, sec

N_f = number of cycles to failure

Recalling that endurance limit behavior occurs when the number of cycles to failure exceeds 1.1 x10^7, then setting the number of cycles to failure in Equations 8 and 9 to a value above 1.1 x 10^7 will ensure that full healing occurs at the selected rest period. Conservatively using 2.0 x 10^7 as the number of cycles to failure yields Equations 10 and 11, which give allowable strain levels as a function of rest period to ensure that full healing occurs.

For neat PG 64-22 $$\varepsilon_{af} = 66.0(1+RP)^{0.2507} \quad (10)$$

For modified PG 70-22 $$\varepsilon_{af} = 164.5(1+RP)^{0.2536} \quad (11)$$

where:

ε_{af} = allowable tensile strain for full healing, µstrain

RP = duration of intermittent rest period, sec

If the strains in a pavement at 20 °C are kept below the values given by Equations 10 and 11, then complete healing will occur during intermittent rest periods, and the pavement will exhibit endurance limit behavior. Table 7 summarizes these strain levels for various 20 year design traffic levels.

Table 7. Allowable Strains for Various Design Traffic Levels.

20 Year Design ESAL	Rest Period, sec	Allowable Strains, μstrain	
		Neat PG 64-22	Modified PG 70-22
1.00E+05	6307.2	592	1513
3.00E+05	2102.4	449	1145
1.00E+06	630.7	332	844
3.00E+06	210.2	253	639
1.00E+07	63.1	187	472
3.00E+07	21.0	143	360
1.00E+08	6.3	109	272
3.00E+08	2.1	88	219

Multiple Temperatures

The allowable strains presented in the previous section were developed from test data obtained at 20 °C. To be useful in a pavement design procedure, the allowable strains for a wide range of temperatures must be available. In this procedure the major concern is the effect of temperature on the healing properties of the mixture. Previous research by Bonnaure, et al. (*24*) concluded that the beneficial effect of rest periods increased with increasing temperature. Since healing can be envisioned as a type of flow phenomenon where the binder flows together to repair microcracks, it has been hypothesized that the effect of healing at multiple temperatures can be accounted for using time-temperature superposition. By applying time-temperature superposition, rest periods at different temperatures can be reduced to an equivalent rest period at 20 °C. The reduced rest period for temperatures above 20 °C will be longer than the actual rest period, while those for temperatures below 20 °C will be shorter than the actual rest period. Research conducted in NCHRP Project 9-19 showed that linear, viscoelastic time-temperature shift factors obtained from dynamic modulus tests could be applied when a high level of nonlinear damage is present (*25*). Equation 12 presents the application of time-temperature superposition to the duration of the rest period.

$$\log(RP_R) = \log(RP) - \log(A_T) \tag{12}$$

where:

RP_R = duration of the rest period at the reference temperature, sec

RP = actual duration of the rest period, sec

A_T = linear viscoelastic time temperature shift factor obtained from dynamic modulus testing.

Figure 9 illustrates the use of time-temperature superposition for rest periods at temperatures of 40, 20, and 4 °C using 20° C as the reference temperature. In developing Figure 9, typical time-temperature shift factors were used ($\log(A_T)$ for 4 °C =2.0 and $\log(A_T)$ for 40 °C = -2.2).

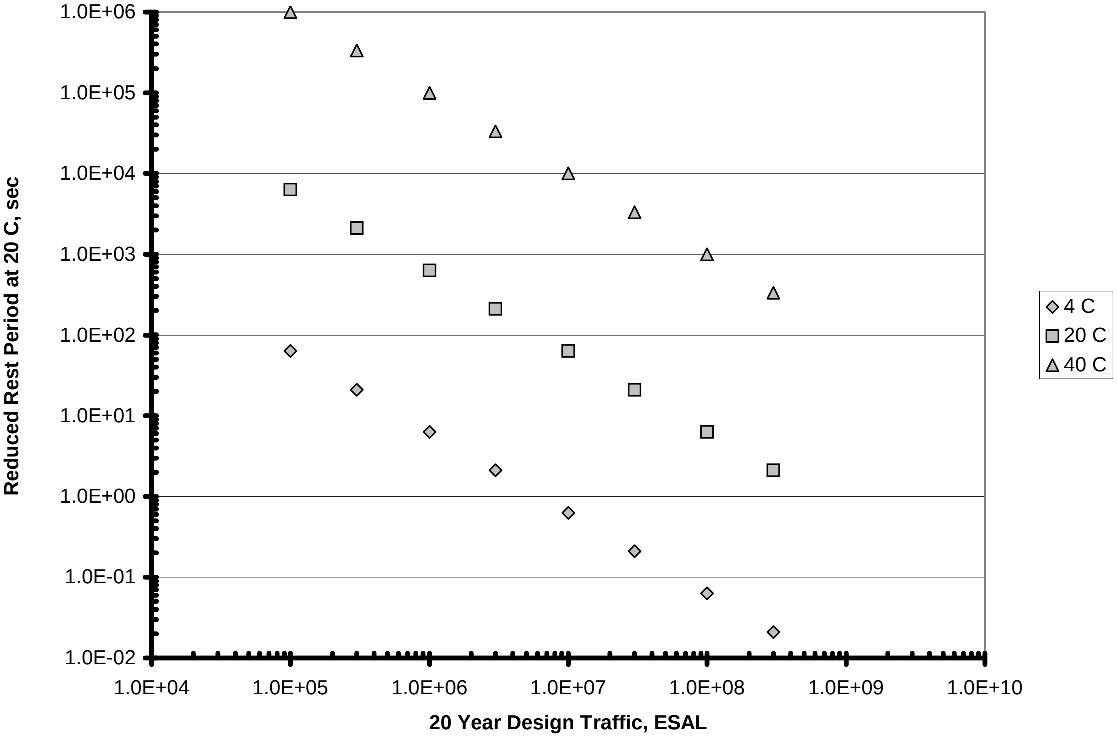


Figure 9. Application of Time-Temperature Superposition to Rest Periods.

Design Example

This section illustrates how the proposed methodology would be used in a mechanistic-empirical design system such as the MEPDG. To limit the number of computations, a monthly analysis is illustrated using typical pavement temperatures estimated from mean monthly air temperature data from Reagan National Airport in Washington, DC. The pavement being analyzed is 9 in of HMA constructed on a 6 in aggregate subbase base layer and a silty clay subgrade. The 20 year design traffic level is 1 x 10^8 ESALs, and the design traffic speed is 45 mph. The purpose of the analysis is to determine if the pavement section is sufficiently thick to resist bottom initiated fatigue cracking assuming the fatigue properties of the neat PG 64-22 mixture discussed in the preceding section.

Material Properties

For this analysis the modulus of the subgrade is assumed to be 4,500 psi and constant throughout the year. The modulus of the aggregate subbase is assumed to be 25,000 psi and is also assumed constant throughout the year. Dynamic modulus testing of a typical 19 mm mixture with PG 64-22 binder using the Simple Performance Test System yielded the master curve and shift factors given in Equations 13 and 14 for a reference temperature of 20 °C. The allowable strains for full healing are given in Equation 15.

$$\log|E^*| = 0.234 + \left[\frac{3.259}{\left(1+e^{-1.213-0.499\log(f_r)}\right)}\right] \tag{13}$$

$$\log f_r = \log f + 10448.2\left(\frac{1}{T} - \frac{1}{293.2}\right) \tag{14}$$

$$\varepsilon_{af} = 66.0\left(1+RP_r\right)^{0.2507} \tag{15}$$

where:

$|E^*|$ = dynamic modulus, ksi

f = loading frequency, Hz

f_r = reduced frequency, Hz

T = temperature, °K

ε_{af} = allowable tensile strain of full healing, μstrain

RP_r = reduced rest period at 20 °C, sec

Allowable Strains

Allowable strains at the bottom of the asphalt layer are determined from Equation 15 using reduced rest periods that depend on the traffic volume and the monthly pavement temperature.

Mean monthly pavement temperatures can be estimated from the mean monthly air temperature using Equation 16 (*26*).

$$M_p = M_a\left(1+\frac{1}{z+4}\right)-\frac{34}{z+4}+6 \qquad (16)$$

where:

M_p = mean monthly pavement temperature at depth z, °F
M_a = mean monthly air temperature, °F
z = depth, in

For a 20 year design traffic of 1 x 10^8 ESAL, the rest period is 6.3 sec. The reduced rest period for each month is determined from Equation 12 using the shift factors from the dynamic modulus master curve and the mean monthly pavement temperature. Table 8 summarizes the computation of the allowable strains. Because the reduced rest period is much shorter during cold months compared to warm months, the allowable strain levels for full healing are significantly lower.

Table 8. Computation of Allowable Strain Strains.

Month	Mean Monthly Pavement Temp, C	Log (A_T)	Rest Period, sec	Reduced Rest Period, sec	Allowable Strain Level, μstrain
Jan	5.5	1.851	6.3	0.09	67
Feb	7.3	1.611	6.3	0.15	68
Mar	12.2	0.971	6.3	0.67	75
Apr	18.0	0.242	6.3	3.61	97
May	23.7	-0.445	6.3	17.56	137
Jun	29.0	-1.065	6.3	73.20	194
Jul	32.0	-1.397	6.3	157.26	235
Aug	30.9	-1.276	6.3	118.95	219
Sep	26.8	-0.803	6.3	40.04	167
Oct	19.7	0.036	6.3	5.79	107
Nov	13.8	0.773	6.3	1.06	79
Dec	8.4	1.469	6.3	0.21	69

Applied Strains

The strains applied by the traffic loading are computed for the design axle load using layered elastic analysis. In this example an 18 kip single axle load was used for computing applied strains. For this example the modulus of the subgrade and subbase are constant at 4.5 and 25 ksi, respectively. The modulus of the asphalt depends on the pavement temperature and the speed of traffic. Recent research by Al-Qadi, et al, using in-situ instrumentation at the Virginia Smart Road (*27*) indicates that loading rates computed by the transformed section analysis in the MEPDG and other approaches such as that recommended by Barksdale (*28*) overestimate the frequency of the load pulse. Based on data presented by Al-Qadi, a loading rate of 16 Hz appears reasonable for a depth of 9 in under 45 mph traffic. Table 10 summarizes the applied strains for each month computed using the KENLAYER software (*26*). The applied strains are compared to the allowable strains in Figure 10. Since the applied strains in Table 9 are less than the allowable strains, the proposed section is acceptable with respect to bottom initiated fatigue cracking. An interesting observation in Figure 10 is that this analysis shows that the critical condition for bottom initiated fatigue cracking occurs at intermediate to low pavement temperatures, which is in contrast with traditional cumulative or incremental damage analyses, which show that the majority of the fatigue damage occurs at high pavement temperatures.

Table 9. Applied Strains for Design Example.

Month	Mean Monthly Pavement Temp, C	Log (A_T)	Load Frequency, Hz	Reduced Frequency, Hz	AC Modulus, ksi	Subbase Modulus, ksi	Subgrade Modulus, ksi	Applied Strain, μstrain
Jan	5.6	1.841	16	1108.93	1969.7	25	4.5	51
Feb	7.5	1.584	16	614.01	1858.0	25	4.5	54
Mar	12.8	0.900	16	127.08	1535.8	25	4.5	62
Apr	19.0	0.122	16	21.21	1148.4	25	4.5	77
May	25.1	-0.608	16	3.95	801.7	25	4.5	100
Jun	30.8	-1.265	16	0.87	535.6	25	4.5	133
Jul	33.9	-1.616	16	0.39	418.2	25	4.5	157
Aug	32.8	-1.488	16	0.52	458.9	25	4.5	148
Sep	28.4	-0.987	16	1.65	641.1	25	4.5	117
Oct	20.8	-0.096	16	12.83	1041.1	25	4.5	83
Nov	14.4	0.688	16	78.05	1431.1	25	4.5	65
Dec	8.7	1.432	16	432.33	1789.1	25	4.5	55

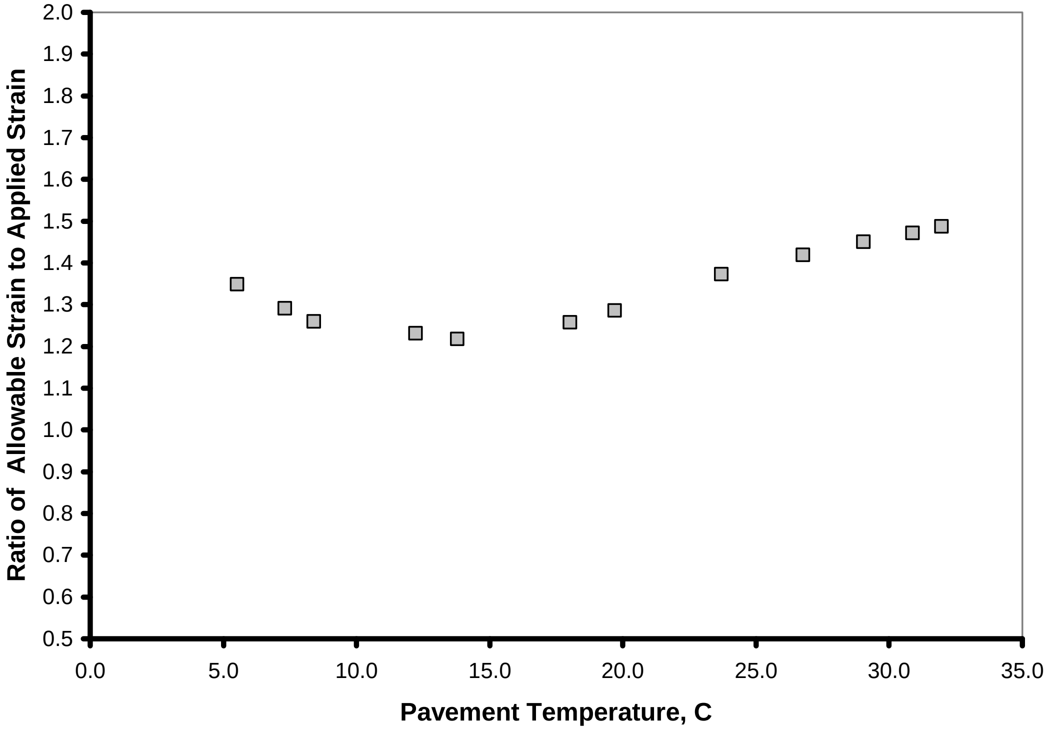


Figure 10. Comparison of Applied and Allowable Strains.

Traffic Level

The analysis presented above can be performed to determine minimum asphalt thicknesses to resist bottom initiated fatigue cracking for the given subgrade and subbase conditions as a function of traffic level. The results are shown in Figure 11 for a 22 kip single axle load. A 22 kip axle load was used to allow comparison with observed data from the analysis of in-service pavements that was conducted in the United Kingdom (*9*). Figure 11 also shows the thickness and accumulated traffic for the four pavements that were analyzed in detail and it was documented that bottom initiated fatigue cracking had not occurred. This comparison shows the engineering reasonableness of the proposed approach. It is reasonable to expect that when the proposed approach is improved to consider the effects of aging and design reliability, the minimum asphalt thicknesses will increase. It is important to note that at the low traffic levels, deformation of the subgrade may govern the analysis rather than bottom initiated fatigue cracking. Research in the United Kingdom indicates that for asphalt thicknesses less than about 7 in subgrade deformation governs the performance of the pavement (*9*). This limit is shown as the dashed line in Figure 11.

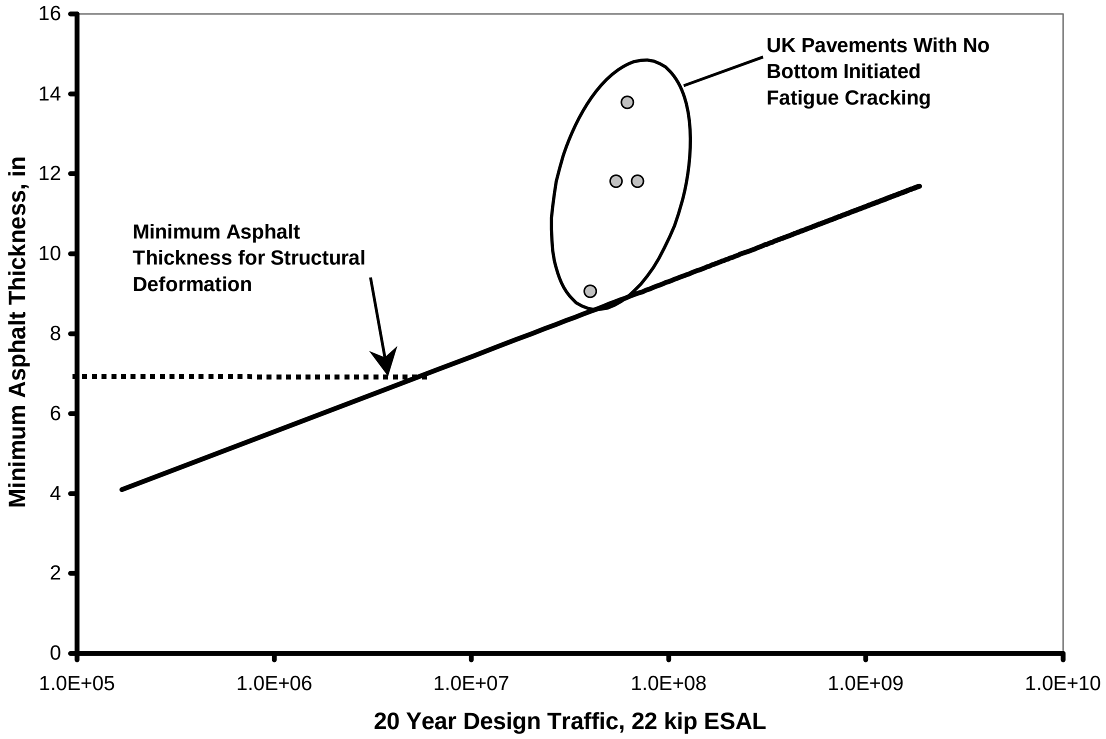


Figure 11. Example of Minimum Asphalt Thicknesses to Resist Bottom Initiated Fatigue Cracking With Observed Performance of Four UK Pavement Sections.

Aging

The example presented above does not consider the important effect of aging on either the applied or allowable strains. As a pavement ages, the modulus of the HMA will increase due to the increased stiffness of the asphalt binder resulting in lower applied strains. Aging will also affect the healing rate for the HMA. Although no data is currently available for the effect of aging on the healing rate, it is reasonable to expect that the healing rate will decrease significantly on aging resulting in lower allowable strains for full healing. Early research on healing by Bonnaure, et al.(*24*) showed that healing rates were much greater in softer binders. The effect of aging can be incorporated in the procedure outlined above, by computing allowable and applied strains as a function of pavement age. The global aging model currently incorporated in the MEPDG provides a method for computing aged modulus values (*29*). Additional research proposed in the laboratory studies discussed in Task 4 will be required to develop a model of the effect of aging on HMA healing and the allowable strains that result in full healing. For perpetual pavement design, it may only be necessary to perform the analysis for highly aged conditions.

Climate and Mixed Traffic Effects

The MEPDG currently provides excellent capabilities to evaluate the effects of climate and mixed traffic on the applied strains at the bottom of the asphalt layer. This capability can be used with the allowable strains described above to determine the HMA thickness needed to resist bottom initiated fatigue cracking.

Reliability

Because the computations involved in the analysis do not require substantial computer time, reliability can be included in the analysis using Monte-Carlo simulation. This approach has already been implemented in the PerRoad program (*15*). In fact, the allowable strains computed based on rest periods can be input as the threshold criteria for HMA the in the PerRoad program and the analysis for a single season can be performed.

Subtask 2.1 Review Selected Literature

The preceding section presented a rational approach for incorporating an endurance limit for bottom initiated fatigue cracking in mechanistic-empirical pavement design methods. The method is based on maintaining tensile strain levels at the bottom of the HMA low enough to ensure that complete healing occurs between traffic loads and that there is no accumulation of damage at the bottom of the asphalt concrete. This is accomplished through the use of allowable strain levels that depend on the damage and healing properties of the HMA, the aging characteristics of the HMA, the duration of rest periods between traffic loads, and the temperature of the pavement. Several improvements to this preliminary procedure should be made based on a detailed review of selected literature. These improvements should be made before the detailed laboratory testing plans are developed in Task 4. Areas where improvements should be considered are summarized below:

Duration of Rest Periods. In the preliminary procedure a very simple approach was used to estimate the duration of rest periods as a function of design traffic level.

Additional effort should be expended to establish representative rest period durations as a function of traffic level and roadway classification. Potential sources of information on the duration of rest periods include: the Highway Capacity Manual (*30*), data from traffic studies performed for the Long Term Pavement Performance Program (*31*), and the approach used in Strategic Highway Research Program (SHRP) Contract 005 (*32*).

MEPDG Modifications. It is envisioned that the design procedure will be implemented in the MEPDG. Because the MEPDG is an AASHTO product, any proposed changes, including research versions of the software, must be approved by AASHTO. AASHTO has approved a research version of the software for use in NCHRP 9-30A. It is envisioned that similar approval will be granted for this project.

A detailed review of the documentation and source code for the MEPDG will be required to determine specific modifications that will be needed to implement the approach. This review should concentrate on how the MEDPG addresses the following:

1. Climatic effects,
2. Mixed traffic (Currently hourly traffic distribution factors are not included in any flexible pavement analysis, they are only considered for the rigid pavement analysis. It may be necessary to tie daily truck traffic distributions to temperature distributions to accurately consider the effect of healing),
3. Vehicle speed effects,
4. Vehicle wander (Currently being considered for revision under NCHRP Project 9-30A),
5. Location of maximum strain at the bottom of the asphalt layer for various axle configurations,
6. Aging, and
7. Reliability.

> The MEPDG source code should also be reviewed to determine how to remove the current bottom initiated fatigue cracking algorithm and implement the allowable strain approach.

Since the major new component of the design procedure is the determination of allowable strain levels that provide for complete healing between traffic loads, completed research on healing in HMA should be reviewed before finalizing the laboratory testing program. Several important publications addressing healing in HMA that should be reviewed are listed at the end of the Task 2 work description.

Subtask 2.2 Finalize Preliminary Approach

In this Subtask, the preliminary design procedure described in this research plan will be improved based on the findings from the literature review conducted in Subtask 2.1. The improved procedure will then be implemented in a research version of the MEPDG software, designated NCHRP9-44A_Version 0.1. The products of this subtask will be detailed documentation of the preliminary procedure and a modified research version of the MEPDG software. The documentation and software will be submitted as part of the first interim report that is scheduled for delivery during the 7th month of the project.

Subtask 2.3 Incorporate Findings from Laboratory Studies

In Subtask 2.3, the preliminary procedure and software developed in Subtask 2.2 will be improved by adding the results from the laboratory studies conducted in Task 4. The laboratory studies are envisioned to result in the following improvements:

1. Verification that time-temperature superposition can be applied to HMA rest periods. This is an assumption that has been included in the preliminary procedure described in this research plan.
2. Verification that healing in HMA is not affected by the strain level provided the strains are low enough that macrocracking does not occur.
3. Testing and data analysis procedures for determining mixture specific allowable strains levels for HMA. Under the current hierarchical structure of the MEPDG, this testing and analysis will be used in Level 1 analyses.

4. A model for estimating allowable strain levels as a function of mixture composition, binder properties, and age. This model will be used for Level 2 and Level 3 analyses, and for the analysis of pavement sections to be completed in Task 5. Von Quintus (*19, 20*) developed a model to estimate the allowable strain levels at which no damage is retained in the HMA mixtures. It is estimated from the indirect tensile strength test, and is dependent on the mixture composition. Healing within this approach is captured through field calibration factors. A similar type of approach is expected for this research plan, but using healing directly.

The products of this subtask will be detailed documentation of the improved procedure and a modified research version of the MEPDG software designated NCHRP9-44A_Version 0.2 that will be used in Subtask 5.3 for the analysis of selected accelerated pavement test and test road sections. This documentation and software will be further improved in Subtask 2.4.

Subtask 2.4 Modify Approach Based on Analysis of Accelerated Pavement Tests

In Subtask 2.4, the improved procedure developed in Subtask 2.3 will be further improved based on the analysis of selected accelerated pavement test and test road sections. The accelerated pavement test and test road sections will be selected in Subtask 5.1 to exercise critical aspects of the design procedure. For example, the fatigue tests conducted at the FHWA Pavement Testing Facility provide data addressing the effect of temperature on HMA fatigue and healing. These field tests provide the ability to investigate time-temperature superposition as applied to rest periods. The structural sections from the NCAT test track provide data addressing the effect of thickness on HMA fatigue, while the WesTrack sections provide data on the effect of HMA material properties on fatigue. In all three cases, the applied strains should exceed the allowable strains for full healing. On the other hand, the original sections from the NCAT test track that are still in-service, should have applied strains that are below the allowable strains for full healing.

The products of this subtask will be detailed documentation of the improved procedure and a modified research version of the MEPDG software designated NCHRP9-44A_Version 0.3 that will be used in Subtask 5.5 for the analysis of selected in-service pavement test sections. The documentation and software will be submitted as part of the fourth interim report that is scheduled for delivery during the 30th month of the project.

Subtask 2.5 Prepare Final Design Procedure

The final subtask in Task 2 is the preparation of the final design procedure. This will be accomplished after analysis of the in-service pavement calibration sections is completed in Subtask 5.5. It is envisioned that design reliability will be the primary effort addressed in this final version of the design procedure.

The products of Subtask 2.5 will be detailed documentation of the final procedure and a modified research version of the MEPDG software designated NCHRP9-44A_Version 1.0. The documentation and software will be submitted as part of the draft final report that is scheduled for delivery during the 45th month of the project.

Task 2 Milestones

Table 10 summarizes the major milestones for Task 2. These are all associated with improvements to the preliminary design procedure described in this research plan, and the development of various modified research versions of the MEPDG software.

Table 10. Major Task 2 Milestones.

Milestone	Description	Months After Contract Award
2.1	Review Selected Literature	3
2.2	Preliminary Approach and NCHRP 944A_Version 0.1 Software	6
2.3	Incorporate Findings from Laboratory Studies into NCHRP 9-44A_Version 0.2 Software	27
2.4	Modify Approach Based on Analysis of Selected Accelerated Pavement Tests and NCHRP 9-44A_Version 0.3 Software	29
2.5	Prepare Final Design Procedure and NCHRP 9-44A_Version 1.0 Software	41

Task 2 Labor Estimate

Table 11 presents the estimated labor required for Task 2. Table 11 presents estimated labor hours for each of the positions in the research management structure presented in Figure 5 and for programming assistance. Task 2 is estimated to require at total of 1240 man-hours of effort. This is approximately 10 percent of the total effort required for the project.

Table 11. Estimated Labor Hours for Task 2.

Subtask	Principal Investigator	Statistician	Laboratory Team Leader	Pavement Team Leader	Data Support Team Leader	Programmer
Review Selected Literature	80	0	80	80	0	160
Finalize Preliminary Approach	40	0	20	20	0	160
Incorporate Findings from Laboratory Studies	40	0	40	0	0	160
Modify Approach Based on Analysis of Accelerated Pavement Tests	40	0	0	40	0	80
Prepare Final Design Procedure	80	0	20	20	0	80
Total	**280**	**0**	**160**	**160**	**0**	**640**

Task 2 Sources

Endurance Limit Studies

Carpenter, S.H., Ghuzlan, K.A., and Shen, S., "Fatigue Endurance Limit for Highway and Airport Pavements," **Transportation Research Record No. 1832**, Transportation Research Board, Washington, D.C., 2003.

Carpenter, S.H., and Shen, S., "Application of the Dissipated Energy Concept in Fatigue Endurance Limit Testing," **Transportation Research Record No. 1929**, Transportation Research Board, Washington, D.C., 2005.

Prowell, B., Brown, E., R., Daniel, J., Bhattacharjee, S., Von Quintus, H., Carpenter, S., Shen, S., Anderson, M., Swamy, A. K., and Maghsoodloo, S., "Endurance Limit of Hot Mix Asphalt Mixtures to Prevent Fatigue Cracking in Flexible Pavements," Updated Draft Final Report, NCHRP 9-38, National Cooperative Highway Research Program, Washington, D.C., May, 2008.

Soltani, A., Solaimanian, M., and Anderson, D.A., "An Investigation of the Endurance Limit of Hot-Mix Asphalt Concrete Using a New Uniaxial Fatigue Protocol," **Report Number FHWA-HIF-07-002**, Federal Highway Administration, Washington, D.C.,

HMA Healing Studies

Bonnaure, F.P, Huibers, A.H.J.J., Boonders, A., “A Laboratory Investigation of the Influence of Rest Periods on the Fatigue Response of Bituminous Mixes,” **Proceedings, Association of Asphalt Paving Technologists**, Vol. 51, 1982.

Carpenter, S.H., and Shen, S., “Application of the Dissipated Energy Concept in Fatigue Endurance Limit Testing,” **Transportation Research Record No. 1929**, Transportation Research Board, Washington, D.C., 2005.

Kim, B. and Roque, R., “Evaluation of Healing Property of Asphalt Mixtures,” **Transportation Research Record No. 1970**, Transportation Research Board, Washington, D.C., 2006.

Kim, Y.R., Little, D.N., and Benson, F.C., “Chemical and Mechanical Evaluation of Healing of Asphalt Concrete, **Journal of the Association of Asphalt Paving Technologists,** Vol. 59, 1990.

Little, D. N., Lytton, R. L., Williams, D., and Chen, C. W., “Microdamage Healing in Asphalt and Asphalt Concrete, Volume I: Microdamage and Microdamage Healing Project Summary Report,” **Report Number FHWA-RD-98-141**, Federal Highway Administration, Washington, D.C., June 2001.

Pronk, A.C., “Partial Healing, “A New Approach for the Damage Process During Fatigue Testing of Asphalt Specimens,” **Asphalt Concrete Simulation, Modeling, and Experimental Characterization,** Geotechnical Special Publication No. 146, American Society of Civil Engineers, Reston, VA, 2005.

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National Cooperative Highway Research Program, http://www.trb.org/mepdg/guide.htm (accessed June 30, 2008).

Rest Periods

Hajek, J. J., Selezneva, O., I., Mladenovic, G., and Jiang, Y., J., “Estimating Cumulative Traffic Loads, Volume II: Traffic Data Assessment and Axle Load Projection for the Sites With Acceptable Axle Weight Data, Final Report for Phase 2,” **Report Number FHWA-RD-03-094**, Federal Highway Administration, Washington, D.C., March, 2005.

Lytton, R L; Uzan, J; Fernando, E G; Roque, R; Hiltunen, D; Stoffels, S M, “Development And Validation Of Performance Prediction Models And Specifications For Asphalt Binders And Paving Mixes,” **Report Number SHRP-A-357**, Strategic Highway Research Program, Washington, D.C., 1993.

Transportation Research Board, **Highway Capacity Manual**, Special Report 209, Third Edition, Transportation Research Board, Washington, DC 1994.

Task 3. Database Management

Task 3 includes the development and management of a database to store and analyze data generated in Task 4, Laboratory Testing, and Task 5, Analysis of Pavement Sections. It is envisioned that the database will be an adaptation of the one developed in NCHRP Project 9-30. Task 3 has been divided into three subtasks:

3.1 Develop a Plan to Use the NCHRP 9-30 Database
3.2 Develop Needed Tables,
3.3 Input and Manage Data

Each of these subtasks are described in detail below.

Subtask 3.1 Develop a Plan to Use the NCHRP 9-30 Database

In NCRHP Project 9-30 a database called M-E Distress Prediction Models (M-E_DPM) was developed to provide an appropriate database structure for storing all HMA pavement data required for the continued improvement of mechanistic-empirical pavement distress prediction models (*33*). It was envisioned that this database would serve future mechanistic-empirical development efforts such as the HMA Endurance Limit Validation Study. Consequently, M-E_DPM was designed to be flexible to accommodate changes in models and test procedures. The database was developed in Microsoft Access to take advantage of the standard and custom features available for entering and storing data, querying data, and generating reports. It consists of three parts that are briefly described below:

- **Descriptive Database.** This part of the database includes text files that document details for the data included in the model inputs portion of the database. This part of the database provides the flexibility to define the new type of data that will be needed in the HMA Endurance Limit Validation Study.

- **Model Inputs.** This part of the database includes the data required to execute the mechanistic-empirical models. The data are contained in tables that define (1) pavement structure, (2) material properties, (3) traffic, and (4) climate. For the HMA Endurance Limit Validation Study new material properties associated with the allowable strain levels for full healing will be required.

- **Performance Data.** This part of the database includes various measures of pavement distress including (1) area of alligator cracking, (2) longitudinal cracking, (3) transverse cracking, (4) rutting, (5) smoothness, and (6) other distresses such as potholes and the extent of patching. Additional detail concerning the performance data will be required by the Endurance Limit Validation Study to differentiate bottom-initiated cracking from surface initiated cracking.

In Subtask 3.1, the current version of M-E_DPM and its documentation will be reviewed and a plan will be developed for modifying this database for use in the analysis of the pavement sections in Task 5. M-E_DPM is currently being improved and additional data is being added in NCHRP Project 9-30A. The key HMA property needed for the analysis approach described earlier in this plan is the allowable strains for full healing, which will be a function of HMA damage and healing properties, age, and climate. The laboratory experiments in Task 4 will establish methods for measuring the HMA damage and healing properties and will develop models for estimating these properties from mixture composition and binder properties that can be easily measured on field cores. The required material property data tables will have to be added to the model inputs portion of M-E_DPM. The extent of bottom-initiated fatigue cracking will be the pavement distress needed for the analysis of the pavement sections. Only the extent of surface cracking is currently contained in M-E_DPM; therefore, additional tables will be needed to store this data. The data will be obtained from the crack coring operations described in Task 5.

A plan for storing the data from the Task 4 laboratory experiments will also be developed in Subtask 3.1. This will likely be a separate database that can be linked to M-E_DPM upon completion of the analysis of the laboratory experiments and the development of the models and procedures for computation of allowable strains for full healing.

Subtask 3.2 Develop Needed Tables

In Subtask 3.2, the various tables required to use M-E_DPM in the HMA Endurance Limit Validation Study will be developed. Work in this task will be coordinated with the data collection and analysis activities in Tasks 4 and 5.

Subtask 3.3 Input and Manage Data

Data from the project will be entered into the database and managed in Subtask 3.3. This subtask includes entering the data, verifying the entered data, and extracting data in support of the analyses that will be performed in Tasks 4 and 5 of the project. Subtask 3.3 will be active during the majority of the project.

Task 3 Milestones

Table 12 summarizes the major milestones for Task 3. These are all associated with the modification of M-E_DPM for use in this project. In addition to the major milestones listed in Table 12, data entry and management will occur as needed from month 8 through the completion of Tasks 3, 4, and 5 in month 41 of the project.

Table 12. Major Task 3 Milestones.

Milestone	Description	Months After Contract Award
3.1	Database Plan	8
3.2	Tables for Laboratory Data	10
3.3	Tables for Analysis of Accelerated Pavement Tests	15
3.4	Tables for Analysis of In-Service Pavement Sections	23
3.5	Final Database	41

Task 3 Labor Estimate

Table 13 presents the estimated labor required for Task 3. Table 13 presents estimated labor hours for each of the positions in the research management structure presented in Figure 5 and for programming/engineering assistance. Task 3 is estimated to require at total of 876 man-hours of effort. This is approximately 6 percent of the total effort required for the project.

Table 13. Estimated Labor Hours for Task 3.

Subtask	Principal Investigator	Statistician	Laboratory Team Leader	Pavement Team Leader	Data Support Team Leader	Programmer/ Engineer
Develop Plan to Use NCHRP 9-30 Database	20	0	10	10	80	0
Develop Needed Tables	0	0	0	0	80	240
Input and Manage Data	0	0	0	0	40	396
Total	**20**	**0**	**10**	**10**	**200**	**636**

Task 3 Sources

Von Quintus, H.L., Schwartz, C., McQuen, R., and Andrei, D., "Experimental Plan for Calibration and Validation of Hot-Mix Asphalt Performance Models for Mix and Structural Design," Final Report for National Cooperative Highway Research Program Project 9-30, National Cooperative Highway Research Program, January, 2004.

Quarterly Reports for NCHRP Project 9-30A.

Task 4. Laboratory Studies

In Task 4 a series of laboratory experiments addressing critical aspects of the allowable strain limit design procedure described earlier in Task 2 will be designed and executed. Table 14 summarizes the laboratory experiments that are needed.

Experiment 1 is a screening study to identify the mixture compositional factors that affect healing and therefore, the allowable strain levels in HMA. The results from this experiment will be used in the remaining experiments. Experiment 2 addresses a major assumption that was made in developing the allowable strain limit procedure that was described in Task 2. In this experiment healing rates will be determined using different strain levels. This experiment will be conducted on mixtures from Experiment 1 that have high and low healing rates. Experiment 3 is a study to verify the applicability of time-temperature superposition to healing in HMA. This was the second major assumption included in the development of the allowable strain limit procedure described in Task 2. Experiment 3 will be conducted on a mixture from Experiment 1 that exhibits a moderate healing rate. Testing and analysis methods for determining allowable strain limits that result in complete healing will be developed in Experiment 4. This experiment will include testing and analysis of selected mixtures from Experiment 1 and mixtures used in the endurance limit testing completed in NCHRP 9-38. This experiment will generate the Level 1 test procedure for use with the modified version of the MEPDG. In the last experiment, Experiment 5, a wide range of mixtures will be tested using the methods developed in Experiment 4 to develop predictive models relating the allowable strain limits to mixture compositional factors. This last experiment will generate the relationships between allowable strain and easily measured mixture compositional properties that will be used in the analysis of the pavement sections in Task 5. These relationships will provide the Level 2 and 3 analysis for the modified version of the MEPDG.

Table 14. Summary of Proposed Laboratory Experiments.

Experiment	Topic	Factors
1	Mixture Compositional Factors Affecting Healing in HMA	• Binder Type • Binder Age • Effective Binder Content • Air Voids • Design Compaction • Gradation • Filler Content
2	Effect of Applied Strain on Healing	• Strain Level • Healing Rate From Experiment 1
3	Effect of Temperature and Rest Period Duration on Healing	• Temperature • Rest Period Duration
4	Development of Testing and Analysis Procedures to Determine Allowable Strain Levels	• Healing Rate From Experiment 1 • Mixtures From NCHRP 9-38
5	Estimation of Allowable Strain Levels from Mixture Composition	• Mix Compositional Factors Affecting Damage Accumulation • Significant Factors From Experiment 1 • Temperature • Rest Period Duration

For each experiment, detailed laboratory work plans will be prepared based on the experiment descriptions and preliminary designs in this research plan and the results from completed experiments. The experiments will then be executed and the resulting data analyzed. Pertinent interim findings from the laboratory studies will be included in the quarterly progress reports. The laboratory testing and analysis will be fully documented in the third interim report that will be submitted at the end of the 22nd month of the project. The five experiments are described in greater detail below.

Subtask 4.1 Experiment 1: Mixture Compositional Factors Affecting Healing in HMA

Experimental Design

Past studies of healing in HMA have assumed that only the properties of the binder affect the healing characteristics of the mixture (*7*, *24*, *34*). Experiment 1 is a screening study that will use an appropriate statistical design to verify or refute this assumption and to identify mixture compositional factors affecting healing in HMA that should be included in Experiment 5.

Experiment 1 is based on a Plackett-Burman experimental design. This is a specific type of partial factorial experiment that can simultaneously assess the effect of multiple factors with a limited amount of testing. It is routinely used in ruggedness testing to quickly assess the effect of a number of controllable test factors. ASTM E 1169 presents detailed information on the design and analysis of Plackett-Burman experiments. Inherent to this type of statistical design is the assumption that the effect of each of the factors on the result is independent. Therefore, the observed effect resulting from simultaneous variation of several factors is simply the sum of the individual effects. Since screening experiments are concerned with identifying significant effects and not necessarily the form of the effect, each factor is evaluated at only two levels. Replication is included in the experiment to estimate the variance of a single measurement.

A Plackett-Burman design with replication to simultaneously evaluate 7 factors requires only 16 tests, two for each of the specific combinations shown in Table 15. The seven factors are designated by letters ***A*** through ***G***. A "+" indicates high levels for the factors while a "-" indicates low levels. Thus, determination 1 will be made with factors ***A***, ***B***, ***C*** and ***E*** at high levels, and factors ***D***, ***F***, and ***G*** at low levels. The order of the tests should be randomized within each replication of the experiment. ASTM E1169 describes designs for other numbers of factors.

Table 15. Design for a Two Level, Seven Factor Plackett-Burman Experiment.

	Factor						
Determination	***A***	***B***	***C***	***D***	***E***	***F***	***G***
1	+	+	+	-	+	-	-
2	-	+	+	+	-	+	-
3	-	-	+	+	+	-	+
4	+	-	-	+	+	+	-
5	-	+	-	-	+	+	+
6	+	-	+	-	-	+	+
7	+	+	-	+	-	-	+
8	-	-	-	-	-	-	-

Selection of Factors

The selection of factors for Experiment 1 was based on a review of literature concerning fatigue damage and healing in HMA. The factors are discussed individually below.

Binder Type. Several studies of fatigue and healing in HMA have shown that binder properties affect the fatigue response of the mixture (*35*). The Shell fatigue equation is, perhaps, the earliest example (*36*). It included the penetration index, which was an early measure of the rheology of the binder. Research into healing that has been conducted at the Texas Transportation Institute has shown that the properties of the binder affect healing (*34*).

Less information is available on the effect of polymer modification on the fatigue and healing characteristics HMA. Using continuum damage analysis, Lee, et al.demonstrated better fatigue resistance for mixtures incorporating SBS modified binders (*37*). Recent research on healing conducted at the University of Illinois using one neat and one polymer modified binder showed the mixture with the polymer modified binder had improved healing characteristics compared to the mixture with the neat binder (*7*). In both of these studies, the neat and polymer modified binders were different grades.

Clearly, Experiment 5 will have to include a wide variety of binders, both neat and modified, from different sources. In an attempt to better quantify the effect of polymer modification on healing, Experiment 1 will use two binders from the same source having the same performance grade, one neat and one modified with styrene butadiene styrene (SBS). The recommended binders are neat PG 70-22 and a modified PG 70-22 produced by adding SBS polymer to neat PG 58-28 binder obtained from the same refinery as the neat PG 70-22.

Binder Aging. It is generally assumed by pavement and materials engineers that binder aging has a detrimental effect on the fatigue life of asphalt mixtures. With this in mind, it is interesting that only one study was identified where the effect of binder aging on laboratory fatigue results was directly evaluated (*38*). In most laboratory fatigue studies, unaged or short-term aged binders of different consistencies were used, and the results generalized to describe the effect of mixture stiffness on fatigue life. The general conclusions drawn from these studies that used relatively unaged binders are (*35*):

1. For continuous, controlled stress flexural testing, which is typically associated with thick asphalt pavements, laboratory fatigue life increases with increasing mixture stiffness.
2. For continuous, controlled strain flexural testing, which is typically associated with thin asphalt pavements, laboratory fatigue life decreases with increasing mixture stiffness.
3. When the results from either controlled stress or controlled strain flexural tests are used in a mechanistic-empirical analysis of pavements with 6 or more inches of asphalt, the predicted fatigue life increases with increasing mixture stiffness.

These conclusions imply that binder aging improves the fatigue life of pavements with relatively thick asphalt layers. Because unaged and short-term aged binders were used in these studies, the important effect of binder embittlement was not included in the analysis. As asphalt binders age, they become, not only stiffer, but also more brittle due to oxidation.

Recently, researchers at the Texas Transportation Institute performed controlled strain flexural fatigue testing on compacted specimens from two mixtures that were aged for 0, 3, and 6 months at 60 °C (*38*). Three months of aging at 60 °C simulates 3 to 6 years of field service for Texas conditions while 6 months of aging simulates 6 to 12 years of field service (*38*). The loose mix for all specimens was short-term oven aged for 4 hours at 135 °C prior to compaction. Fatigue lives were 25 percent shorter for specimens aged for three months, and 50 percent shorter for specimens aged for six months (*38*). The study also included direct tension strength tests. In these tests strength increased while the strain at failure decreased with increased aging, confirming that the mixtures become stiffer and more brittle on aging (*38*). Aged, brittle mixtures would be expected to have significantly poorer healing characteristics compared to unaged, ductile mixtures. Short-term and long-term aged mixtures will be included in Experiment 1. The short-term aging will be done for 4 hours at 135 °C as specified in AASHTO R30 for mixture performance testing. The long-term aged specimens will be oven aged for 120 hours at 85 °C in accordance with AASHTO R30. Since the effects of aging are binder specific, preliminary dynamic modulus and tensile strength tests should be conducted to ensure that the selected binders exhibit significant stiffening and embrittlement as a result of the laboratory, long-term aging process.

Effective Binder Content. Models for predicting the fatigue life of asphalt concrete based on the results of continuous laboratory fatigue tests all indicate that fatigue life increases as the mixture becomes increasingly rich in asphalt binder (*39*). These models use either the effective volumetric binder content of the mixture, *VBE*, or voids filled with asphalt, *VFA*, to indicate the richness of the mixture. Binder content effects have not been included in past studies of healing in asphalt concrete.

It is reasonable to expect that richer mixtures may have improved healing characteristics, resulting in improved fatigue lives, and higher allowable strains for complete healing. Binder content will, therefore, be one of the factors included in Experiment 1. Volumetric design procedures for asphalt mixtures set minimum limits for the effective binder content of the mixture. These limits depend on the nominal maximum aggregate size; increasing with decreasing nominal maximum aggregate size. Since this project is concerned with fatigue cracking that initiates at the bottom of the asphalt layer, a typical 25 mm base course mixture will be used. The minimum effective binder content for 25 mm mixtures in AASHTO M323 is 8.0 percent by volume. The recommended production tolerance for asphalt content in ASTM D 3535 is ± 0.5 percent by weight, which is approximately ± 1 percent for the effective binder content by volume. These are reasonable ranges for use in Experiment 1.

Air Voids. Nearly all laboratory fatigue studies have found the air void content of the mixture to be a significant factor affecting mixture fatigue life (*35, 39*). Fatigue life decreases with increasing air voids. It is reasonable to expect that air voids will also have a significant effect on healing in asphalt concrete mixtures. Based on typical compaction specifications, specimen air void contents of 4 and 8 percent will be included in Experiment 1.

Design Compaction. An interesting finding in NCHRP Report 567, *Volumetric Requirements for Superpave Mix Design*, is that the fatigue life of asphalt concrete mixtures is significantly affected by the design compaction level; increasing as the design gyration level increases (*39*).

Design compaction level was included in Experiment 1 to determine if healing properties of asphalt mixtures are affected by the design compaction level. Considering the current design compaction levels in AASHTO R35, the recommendations in NCHRP Report 573, *Superpave Mix Design: Verifying the Gyration Levels in the* N_{design} *Table* (*40*) and approximate equivalencies between Marshall and gyratory compaction (*39*), design gyration levels of 65 and 100 will be used in Experiment 1.

Gradation. The WesTrack project demonstrated that there is a difference in the fatigue life of coarse-graded mixtures compared to fine-graded mixtures. Significantly more cracking was observed in the coarse-graded mixture sections (*41*). Mixture gradation has not been found to be a significant factor in fatigue models based on analysis of laboratory test data.

As a result of the WesTrack experience, gradation was included in Experiment 1 to determine if healing is different in coarse-graded compared to fine-graded mixtures. The primary control sieve designation in AASHTO M323 will be used to distinguish between coarse-graded and fine-graded mixtures. For 25 mm mixtures, the 4.75 mm sieve is the primary control sieve and mixtures with less than 40 percent passing the 4.75 mm sieve are considered coarse-graded.

Filler Content. Like aging, the effect of filler on the fatigue life of asphalt concrete has not been systematically investigated. Currently, the influence of mineral filler on HMA properties is being studied in NCHRP Project 9-45. The dust to binder ratio, defined as the percent by weight passing the 0.075 mm sieve divided by the effective binder content by weight of total mixture, is used in AASHTO M323 to control the filler content of mixtures. A reasonable median value for the dust to binder ratio for design is 1.0. The recommended production tolerance for the percent passing the 0.075 mm sieve in ASTM D 3535 is ± 3.0 percent. This range is considered reasonable for Experiment 1.

Table 16 summarizes the factors and factor levels to be included in Experiment 1. Experiment 1 requires the selection of a neat and polymer modified binder from the same source and having the same performance grade, and the design of four 25 mm mixtures.

- 100 gyration coarse-graded
- 100 gyration fine-graded
- 65 gyration coarse-graded
- 65 gyration fine-graded

Table 16. Summary of Proposed Experiment 1.

Determination	**Factor**						
	Binder	***Aging***	***Binder Content***	***Air Voids***	N_{design}	***% Passing 4.75 mm***	***Filler***
1	Polymer	LTOA	+ 0.5	4.0	100	Coarse	Low
2	Neat	LTOA	+ 0.5	8.0	65	Fine	Low
3	Neat	STOA	+ 0.5	8.0	100	Coarse	High
4	Polymer	STOA	- 0.5	8.0	100	Fine	Low
5	Neat	LTOA	- 0.5	4.0	100	Fine	High
6	Polymer	STOA	+ 0.5	4.0	65	Fine	High
7	Polymer	LTOA	- 0.5	8.0	65	Coarse	High
8	Neat	STOA	- 0.5	4.0	65	Coarse	Low

In designing these mixtures, the target effective binder content for all mixtures should be kept constant at approximately 8.5 percent by volume, which will result in design voids in the mineral aggregate (VMA) of 12.5 percent. The design dust to binder ratio should also be kept constant for the four mixtures at approximately 1.0. These binder selection and mixture design requirements will eliminate major interactions between the factors. During binder selection, preliminary dynamic modulus and tensile strength tests should be conducted on specimens after short- and long-term aging to ensure that the selected binders exhibit significant stiffening and embrittlement as a result of the long-term aging.

The factor levels for binder content and filler will be obtained by making the appropriate adjustment to the design mixture during batching. The factor levels for aging will be obtained by appropriately aging the loose mixture and, for long-term aging, the test specimen. Finally, the factor levels for air voids will be obtained by compacting specimens to the height needed to achieve the target air voids.

Replicate tests for each determination in Table 16 will be made. This results in a total of 16 healing tests for Experiment 1.

Test Procedure

The objective of Experiment 1 is to identify the mixture compositional factors that affect healing in asphalt concrete. To evaluate healing, a pulsed, strain controlled fatigue test must be used. Either direct tension or flexural beam fatigue tests may be used, but the loading must be such that a rest period is included after each load pulse. Figure 12 presents a schematic of the required loading. The amount of healing that occurs will be evaluated by conducting fatigue tests at 20 °C using two rest periods: 0 sec (continuous loading), and 3 sec. The modulus of the specimen will be recorded for each load pulse. For each test, the accumulated damage in the specimen will be determined from the ratio of the current modulus to the initial modulus. Figure 13 presents a schematic of the expected results when significant healing occurs.

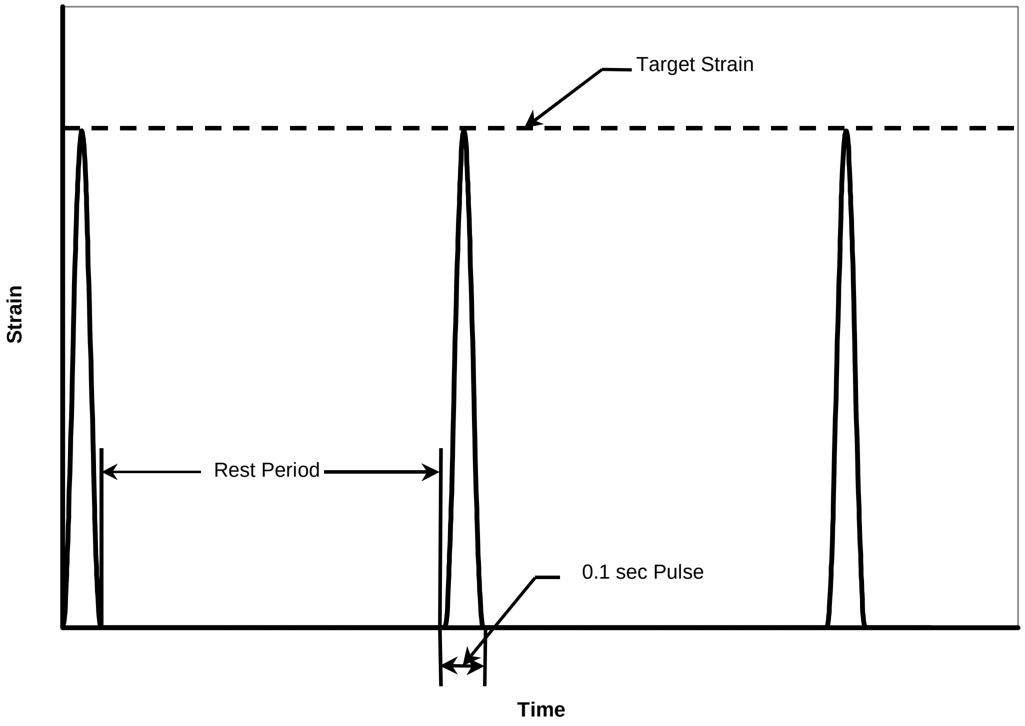


Figure 12. Schematic of Pulsed, Strain Controlled Fatigue Loading.

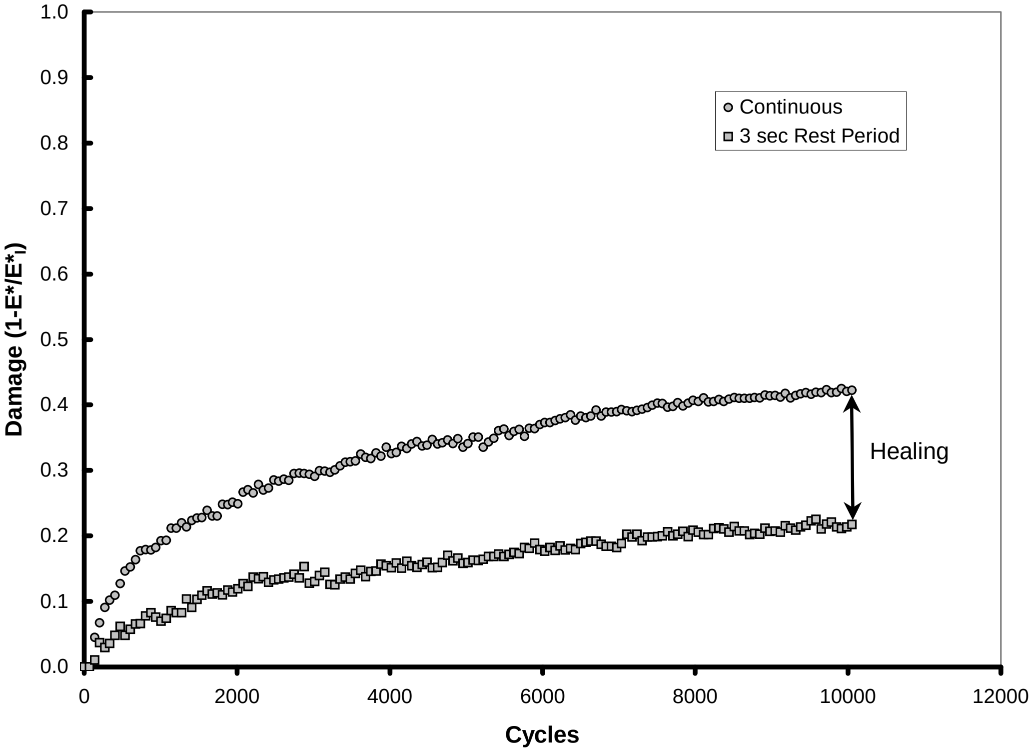


Figure 13. Expected Results When Healing is Significant.

The same strain level must be used for all specimens tested in Experiment 1. The strain level should be selected to produce a high degree of damage, approximately 30 to 40 percent, in the specimens after 10,000 cycles when tested with continuous loading. Fifty percent damage is typically used as the failure criterion for controlled strain tests. A maximum of 10,000 cycles was selected because tests using the 3 sec rest period will require approximately 8.6 hours to complete. Selection of an appropriate strain level will require some initial trial and error testing with selected combinations. For example, the combination of factors used in Determination 6 in Table 16 (polymer modified binder, short-term aging, high binder content, low air voids) would be expected to give low amounts of damage during the testing. On the other had, the combination of factors used in Determination 7 (polymer modified binder, long-term aging, low binder content, high air voids) would be expected to give high amounts of damage during the testing. Initial testing with these combinations at various strain levels will be needed to select an appropriate strain level for the testing.

Data Analysis

For Experiment 1, healing is defined as the difference in damage between continuous loading and loading with 3 sec rest period at 30,000 cycles. Linear regression is an efficient method for analyzing the resulting healing data. The healing can be fit to a linear model of the form:

$$Y = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + B_4 X_4 + B_5 X_5 + B_6 X_6 + B_7 X_7 + Error \qquad (17)$$

where:

Y = healing
X_i = seven factors included in the experiment
B_i = model coefficients
Error = model error

From this analysis, the statistical significance of the model coefficients can be used to determine which factors affect healing in HMA. For statistically significant factors, the model coefficients can be used to select appropriate factor levels to be used in other experiments. Combinations yielding low, moderate, and high levels of healing in Experiment 1 will be used in Experiments 2, 3, and 4. Significant factors identified in Experiment 1 will be included in Experiment 5.

Subtask 4.2 Experiment 2: Effect of Applied Strain on Healing

Experimental Design

One of the major assumptions that was made in developing the allowable strain limit design approach described in Task 2 is that healing in HMA is independent of the applied strain level. Early healing research provided some data supporting this assumption, but the testing was not specifically designed to evaluate the effect of strain level (*24*).

In Experiment 2, the healing tests described for Experiment 1 will be conducted using three different strain levels. Two different mixtures from Experiment 1 will be used: one exhibiting a high amount of healing and one exhibiting a low amount of healing. All tests will be conducted at 20 °C. The strain level used in Experiment 1 will be the medium strain level for Experiment 2. Tests at higher and lower strain levels will be added to complete the factorial. In selecting the high strain level, it is important that the strain be such that macro-cracking does not occur during the tests. Three replicates will be tested for each mixture. The experimental design is summarized in Table 17.

Table 17. Strain Level Experiment.

Mixture	Strain Level	**Replicates**
Low Healing	Low	3
	Medium	3
	High	3
High Healing	Low	3
	Medium	3
	High	3

Data Analysis

Analysis of variance will be used to analyze the data from Experiment 2. For each mixture a one-way analysis of variance will be conducted. It is anticipated that this analysis will confirm that healing in HMA is not significantly affected by the applied strain level, provided the strains are low enough that macro-cracking does not occur.

Subtask 4.3 Experiment 3: Effect of Temperature and Rest Period Duration on Healing

Experimental Design

The second major assumption that was made in developing the allowable strain limit design approach described in Task 2 is that time-temperature superposition can be applied to the rest periods to account for the effect of varying temperatures. The objective of Experiment 3 is to confirm that this assumption is valid. Previous research on healing clearly showed that healing effects were greater at higher temperatures (*24*). It is reasonable to expect that time-temperature superposition will apply to rest period effects as it does for many other aspects of asphalt material response. It is well known that time-temperature superposition is valid for measures of binder and mixture stiffness. Time-temperature superposition is also an integral part of the continuum damage approach to fatigue analysis that has become popular with a number of researchers (*42, 43, 44*).

In Experiment 3, the healing tests described for Experiment 1 will be conducted using a factorial of temperatures and rest period duration. A single mixture from Experiment 1, one exhibiting a moderate amount of healing, will be used. Two replicates will be tested for each mixture. The experimental design is summarized in Table 18. In addition to the healing tests outlined in Table 18, dynamic modulus tests will be performed on replicate specimens at the temperatures and frequencies listed in Table 19 to determine time-temperature shift factors for the mixture. The dynamic modulus testing will be performed in accordance with NCHRP 9-29: PT1, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Simple Performance Test System* (*45*).

Table 18. Experimental Design for Experiment 3.

Mixture	Temperature, C	Rest Period, sec	Replicates
Moderate Healing	4	0	2
	4	0.1	2
	4	1	2
	4	10	2
	10	0	2
	10	0.1	2
	10	1	2
	10	10	2
	20	0	2
	20	0.1	2
	20	1	2
	20	10	2
	30	0	2
	30	0.1	2
	30	1	2
	30	10	2
	40	0	2
	40	0.1	2
	40	1	2
	40	10	2

Table 19. Temperature and Frequency Combinations for Dynamic Modulus Tests.

Temperature, C	Frequency, Hz
4	10
4	1
4	0.1
4	0.01
10	10
10	1
10	0.1
10	0.01
20	10
20	1
20	0.1
20	0.01
30	10
30	1
30	0.1
30	0.01
40	10
40	1
40	0.1
40	0.01

Data Analysis

The data analysis for Experiment 3 is somewhat more complicated than that for Experiments 1 and 2. First, time-temperature shift factors must be determined from the dynamic modulus measurements. Then the time-temperature shift factors will be applied to the rest periods to shift the measured healing data. If time-temperature superposition applies to the rest periods, then the healing results will form a continuous function after shifting.

Dynamic Modulus Master Curve and Shift Factors

Equation 18 presents a modified version of the dynamic modulus master curve equation included in the MEPDG that is appropriate for this analysis (*46*).

$$\log\left|E^*\right| = \delta + \frac{\left(\log\left|E^*\right|_{\max} - \delta\right)}{1 + e^{\beta + \gamma \log f_r}} \tag{18}$$

where:

$|E^*|$ = dynamic modulus
f_r = reduced frequency, Hz
$|E^*|_{max}$ = limiting maximum modulus
δ, β, and γ = fitting parameters

A second order polynomial can be used to describe the time-temperature shift factors:

$$\log[A(T)] = a_1(T_R - T) + a_2(T_R - T)^2 \tag{19}$$

where:

$A(T)$ = time-temperature factor
T = test temperature
T_R = reference temperature (normally 20 °C)
a_1, a_2 = fitting coefficients

The reduced frequency in Equation 18 is given by:

$$\log f_r = \log f + a_1(T_R - T) + a_2(T_R - T)^2 \tag{20}$$

where:

f_r = reduced frequency at the reference temperature
f = loading frequency at the test temperature

Substituting Equation 20 into Equation 18 yields the final form of the dynamic modulus master curve equation.

$$\log|E^*| = \delta + \frac{\left(\log|E^*|_{\max} - \delta\right)}{1 + e^{\beta + \gamma\left[\log f + a_1(T_R - T) + a_2(T_R - T)^2\right]}} \tag{21}$$

The limiting maximum modulus, $|E^*|_{max}$, in Equation 21 is estimated from mixture volumetric properties using the Hirsch model (*47*) and a limiting binder modulus of 1 GPa (145,000 psi), using Equations 22 and 23. Chirstensen and Anderson recommended 1 GPa as a reasonable estimate of the glassy modulus for all asphalt binders (*48*).

$$|E^*|_{\max} = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+435{,}000\left(\frac{VFA\ x VMA}{10{,}000}\right)\right]+\frac{1-P_c}{\left[\dfrac{\left(1-\dfrac{VMA}{100}\right)}{4{,}200{,}000}+\dfrac{VMA}{435{,}000(VFA)}\right]} \quad (22)$$

where

$$P_c = \frac{\left(20+\dfrac{435{,}000(VFA)}{VMA}\right)^{0.58}}{650+\left(\dfrac{435{,}000(VFA)}{VMA}\right)^{0.58}} \quad (23)$$

$|E^*|_{max}$ = limiting maximum mixture dynamic modulus, psi
VMA = Voids in mineral aggregates, %
VFA = Voids filled with asphalt, %

Using the limiting maximum modulus estimated from the volumetric properties of the test specimens, the fitting coefficients (δ, β, γ, a_1, and a_2) are determined by numerical optimization of Equation 21 using the measured modulus data. The optimization can be performed using the Solver function in Microsoft EXCEL®. This is done by setting up a spreadsheet to compute the sum of the squared errors between the logarithm of the average measured dynamic moduli at each temperature/frequency combination and the values predicted by Equation 21.

$$\sum error^2 = \sum_1^n \left(\log\left|\hat{E}^*\right|_i - \log\left|E^*\right|_i\right)^2 \quad (24)$$

where:

$\sum error^2$ = sum of squared errors

n = number of temperature/frequency combinations used in the testing

$\log\left|\hat{E}^*\right|_i$ = value predicted by Equation 20 for each temperature/frequency combination

$\log\left|E^*\right|_i$ = logarithm of the average measured dynamic modulus for each temperature/frequency combination.

The time-temperature shift factors are then determined from Equation 18 using the fitting coefficients, a_1 and a_2, obtained from the numerical optimization.

Reduced Rest Period

Knowing the time-temperature shift factors from the dynamic modulus testing, the results of the healing tests will be shifted according to Equation 25. If time-temperature superposition applies to the rest periods, then the healing results will form a continuous function after shifting. This is shown schematically in Figure 14.

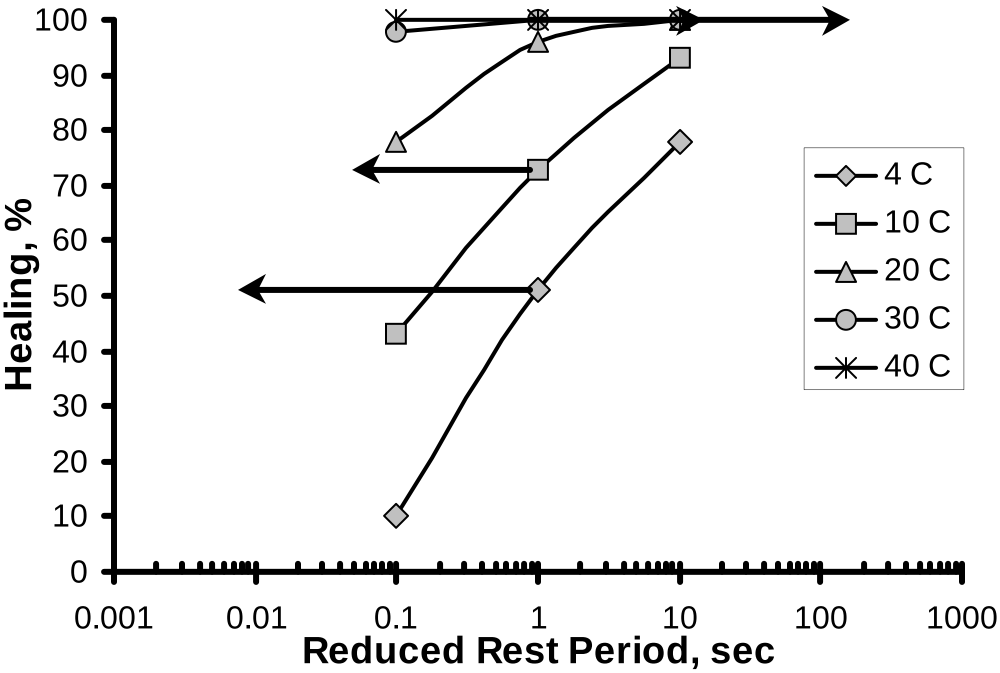
$$\log(RP_R) = \log(RP) - \log(A_T) \qquad (25)$$

where:

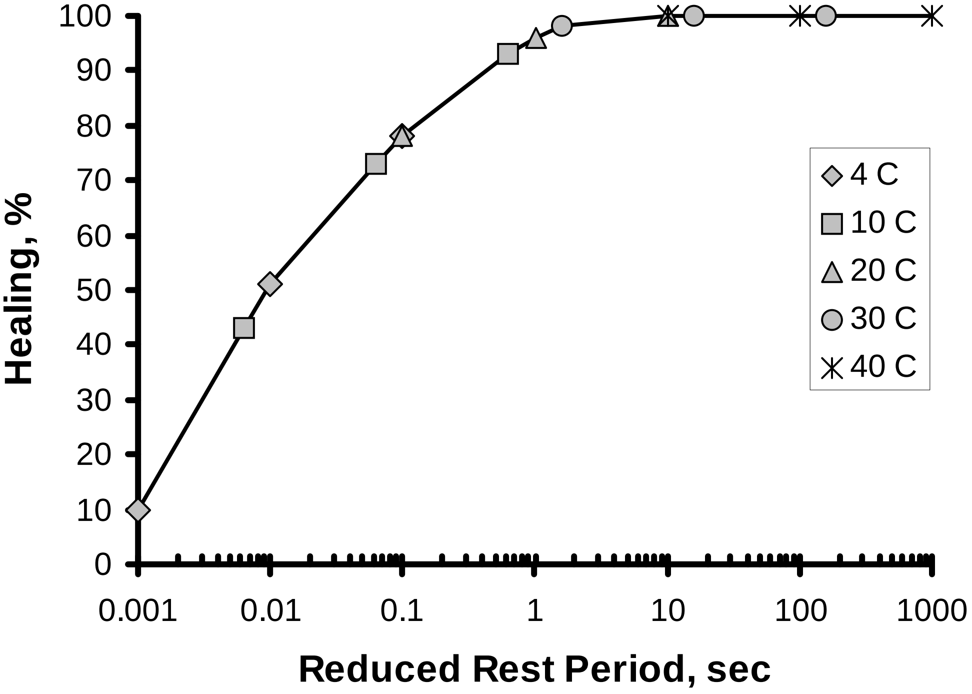
RP_R = duration of the rest period at the reference temperature, sec

RP = actual duration of the rest period, sec

A_T = linear viscoelastic time temperature shift factor obtained from dynamic modulus testing.



a. Original Data



a. Shifted Data

Figure 14. Schematic of Time-Temperature Superposition Applied to Rest Periods.

Subtask 4.4 Experiment 4: Development of Testing and Analysis Procedures to Determine Allowable Strain Levels

Possible Approaches

In Experiment 4, testing and analysis procedures for determining the allowable strain levels will be developed. One approach, using flexural fatigue testing and the ratio of dissipated energy change (RDEC) method was illustrated in the description of Task 2. A second approach based on cyclic direct tension testing and continuum damage analysis is also possible. Brief descriptions of these two approaches are presented below.

Ratio of Dissipated Energy Change

Recently a substantial amount of HMA fatigue research has been performed at the University of Illinois (*4, 5, 7*). This research has concentrated on using the ratio of dissipated energy change to describe the fatigue response of HMA. The basic premise of this research is that the change in dissipated energy per cycle of loading is related to the growth of damage that occurs in HMA. The dissipated energy for each cycle of loading is the area within the stress-strain hysteresis loop generated for that cycle of loading. The ratio of dissipated energy change is defined as the average change in dissipated energy between two cycles divided by the dissipated energy from the first of the two cycles:

$$RDEC_a = \frac{\left(DE_a - DE_b\right)}{(b-a)\times DE_a} \tag{26}$$

where:

$RDEC_a$ = ratio of dissipated energy change for cycle a

DE_a = dissipated energy for cycle a

DE_b = dissipated energy for cycle b

For a given mixture a plot of the ratio of dissipated energy change as a function of loading cycles forms a broad “U” shape as shown in Figure 15. The ratio of dissipated energy change initially decreases, then reaches a broad plateau, where a constant percentage of the input energy is being converted to damage, then finally increases as the sample begins to fail. Because of the high variability of the cyclic dissipated energy measurements due to the small amount of energy dissipated in each cycle, statistical methods were developed to determine the plateau value (*5*). Lower plateau values imply lower damage per cycle. The plateau value for a given mixture depends on the mixture properties, the applied strain level, and the duration of rest periods. Plateau values decrease with decreasing applied strain and increasing rest period duration (*7*). The effect of mixture properties on the plateau value is not clear from the research that has been completed to date. From tests on a number of mixtures, the University of Illinois researchers also found a unique relationship between the plateau value and number of cycles to 50 percent reduction in stiffness, the traditional definition of failure in constant strain fatigue tests (*7*).

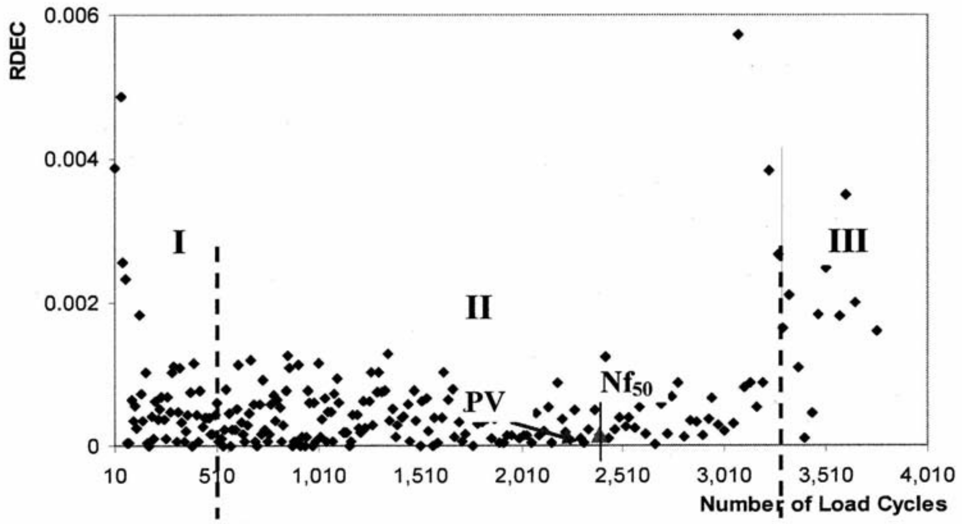


Figure 15. Typical Plot of Ratio of Dissipated Energy Change Versus Loading Cycles (*6*).

$$PV = 0.4429 \times \left(N_f\right)^{-1.1102} \tag{27}$$

where:

PV = plateau value

N_f = number of cycles to 50 percent stiffness reduction

The University of Illinois research further found that an HMA mixture will exhibit endurance limit behavior when the plateau value is 6.74×10^{-9} or less, which based on Equation 27 corresponds to a traditional fatigue life of 1.1×10^{7} cycles or greater.

The testing and analysis required to use the ratio of dissipated energy change to establish allowable strain limits for complete healing is summarized below:

1. Conduct dynamic modulus tests on the mixture and develop a dynamic modulus master curve and associated time-temperature shift factors.

2. Conduct continuous loading, controlled strain flexural fatigue tests at 20 °C using different strain levels to develop a relationship between the plateau value and the applied strain (Equations 4 and 5 in Task 2).

3. Conduct pulsed, controlled strain flexural fatigue tests at a moderate strain level using various temperatures and rest periods to determine a relationship between the plateau value and reduced rest period (Equations 2 and 3 in Task 2).

4. Combine the relationships from Steps 2 and 3 to form a relationship for the plateau value as a function of applied strain level and reduced rest period (Equations 6 and 7 in Task 2).

5. Substitute the relationship from Step 4 into the unique plateau value – number of cycles to 50 percent stiffness reduction relationship (Equation 27) established by the University of Illinois research (Equations 8 and 9 in Task 2).

6. Solve the equation developed in Step 5 for the allowable strain level for full healing by substituting a value greater than 1.1×10^{7} for the number of cycles to 50 percent stiffness reduction (Equations 10 and 11 in Task 2).

Continuum Damage Analysis

Continuum damage analysis has recently been introduced as a rapid method for characterizing fatigue properties of HMA (*44*). Pioneering work in the application of continuum damage analysis to HMA was performed at the North Carolina State University (*42*). Since its introduction, continuum damage analysis has been used by several researchers in the United States and abroad. The analysis is usually applied to the results of direct tension cyclic fatigue tests or monotonic direct tension tests, although an approximate solution has been developed for use with flexural fatigue tests (*44*).

Continuum damage analysis models the decay of the modulus of the mixture with increasing load cycles. Figure 16 shows typical cyclic direct tension data. In traditional continuum damage analysis, the curves for different strain levels and temperatures are collapsed into a unique relationship by introducing an internal state variable, *S*, to represent the current damage in the material. The internal state variable is difficult for many practicing engineers to understand and can only be computed using approximate, numerical integration. Additionally, traditional continuum damage analysis assumes that even very small levels of strain induce damage in the material, implying that asphalt concrete does not exhibit endurance limit behavior. Recently Christensen and Bonaquist, simplified continuum damage analysis and included the direct consideration of the endurance limit (*49*). This improved analysis uses the concept of reduced cycles defined by Equation 28 to collapse the data shown in Figure 16 into a unique relationship. The endurance limit of asphalt concrete is accounted for using the concept of effective strain. Effective strain is defined as applied strain minus the endurance limit. This innovation in continuum damage analysis allows for the calculation of endurance limits from relatively limited fatigue data.

$$N_R = N_{R-ini} + N\left(\frac{f_0}{f}\right)\left(\frac{|E^*|_{LVE}}{|E^*|_{LVE/0}}\right)^{2\alpha}\left(\frac{\varepsilon^E}{\varepsilon_0^E}\right)^{2\alpha}\left[\frac{1}{a(T/T_0)}\right] \tag{28}$$

Where

N_R = reduced cycles

$N_{R\text{-}ini}$ = initial value of reduced cycles, prior to the selected loading period

N = actual loading cycles

F_0 = reference frequency (10 Hz suggested)

f = actual test frequency

$|E^*|_{LVE}$ = undamaged (linear viscoealstic or LVE) dynamic modulus under given conditions, lb/in^2

$|E^*|_{LVE/0}$ = reference initial (LVE) dynamic modulus, lb/in^2 (the LVE modulus at 20°C is suggested)

α = continuum damage material constant with a typical value of about 2.0

ε^E = effective applied strain level = applied strain minus the endurance limit strain

ε_0^E = reference effective strain level (0.0002 suggested)

$a(T/T_0)$ = shift factor at test temperature T relative to reference temperature T_0

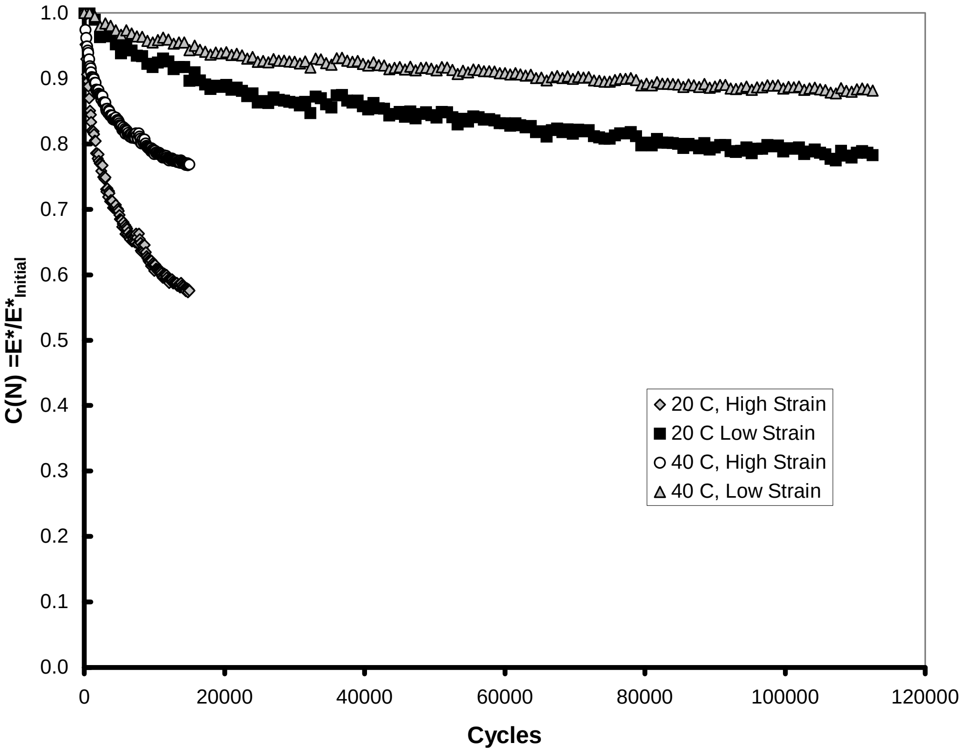


Figure 16. Typical Damage Ratio Curves From a Cyclic Direct Tension Fatigue Test.

Analysis of uniaxial fatigue data using the reduced cycles approach is done using the following procedure.

1. Select the reference conditions. The suggested reference strain is 0.000200, peak-to-peak. The recommended reference temperature is 68 °F (20°C). The reference modulus should be the undamaged dynamic modulus or linear viscoelastic LVE modulus at 68 °F (20°C). The reference frequency should be 10 Hz—the same as the most commonly used test frequency for modulus and fatigue testing of asphalt concrete mixtures.

2. Perform dynamic modulus master curve testing on two samples to determine time-temperature shift factors for the mixture.

3. Test a total of four to eight specimens, two to four at both 39.2 °F (4°C) and 68 °F (20°C). Other temperatures may be used if desired, but temperatures much higher or lower than these might prove difficult to test using the procedures given here. At each test temperature, the specimens should be tested at different strain levels for each test.

4. Set up a spreadsheet to compute the damage ratio, *C*, and the reduced cycles for each test. The damage ratio is given by Equation 29:

$$C = \frac{|E^*|_n}{|E^*|_{LVE}} \tag{29}$$

where:

C = damage ratio

$|E^*|_n$ = damaged modulus at cycle n

$|E^*|_{LVE}$ = undamaged (linear viscoealstic or LVE) dynamic modulus

Reduced cycles are calculated using Equation 28 and value of 2.00 for the continuum damage constant α and an endurance limit strain of zero. Variation in the applied strain during the test can be accounted for by splitting the data up into a number of segments, calculating reduced cycles for each segment, and adding this value to the initial value calculated at the end of the previous segment.

The LVE modulus can be estimated by visual examination of a plot of $|E^*|$ as a function of loading cycles at the lowest strain level tested. The LVE modulus should be within a few percent of the maximum observed value.

In some tests, macro damage (“localization”) might occur, which means that data beyond this point is not valid for analysis using continuum damage methods. Macro damage is indicated when there is a sudden drop in the modulus, or if modulus values suddenly become erratic, rather than decreasing smoothly. Data after macro damage has occurred should be eliminated from the analysis.

5. Fit Equation 30 to the C versus N_R data.

$$C = \frac{1}{1 + \left(N_R / K_1 \right)^{K_2}} \tag{30}$$

where

K_1 = cycles to 50 % damage = the fatigue half-life
K_2 = fitting parameter

Linear regression can be used for the fitting by performing a logarithmic transformation of Equation 30 to produce:

$$\ln\left(\frac{1}{C} - 1 \right) = A + B \ln N_R \tag{31}$$

where:

$A = -K_2(\ln K_1)$
$B = K_2$

A problem in practical application of this approach is that because of noise in the experimental data at low strains, the measured modulus can approach the LVE, resulting in very noisy data when it is transformed using Equation 31. For this reason, a weighted least squares approach to linear regression should be used, with a weight of $N_R^{0.5}$. This approach gives very little weight to data points representing little or no damage, while giving relatively more weight to data points associated with more heavily damaged states. This prevents noisy data collected at low temperatures and/or low strains from skewing the function relating C and N_R, and also results in a more ideal distribution of the residuals.

6. Keeping the value of α at 2.00, adjust the endurance limit strain for the data at 68 °F (20°C) until the R^2 value for the regression is maximized. Then adjust the endurance limit strain value for the data at 39.2 °F (4°C), again, until the R^2 value for the regression is maximized.

Although it is possible to vary the value of α, it has been found that excellent convergence of the data is generally possible while keeping α at 2.00 for all asphalt concrete mixtures tested to date using this procedure. However, if the steps above do not result in complete convergence, it might be necessary to vary the assumed value of α.

Figure 17 presents a typical fatigue damage curve developed using the procedure described above.

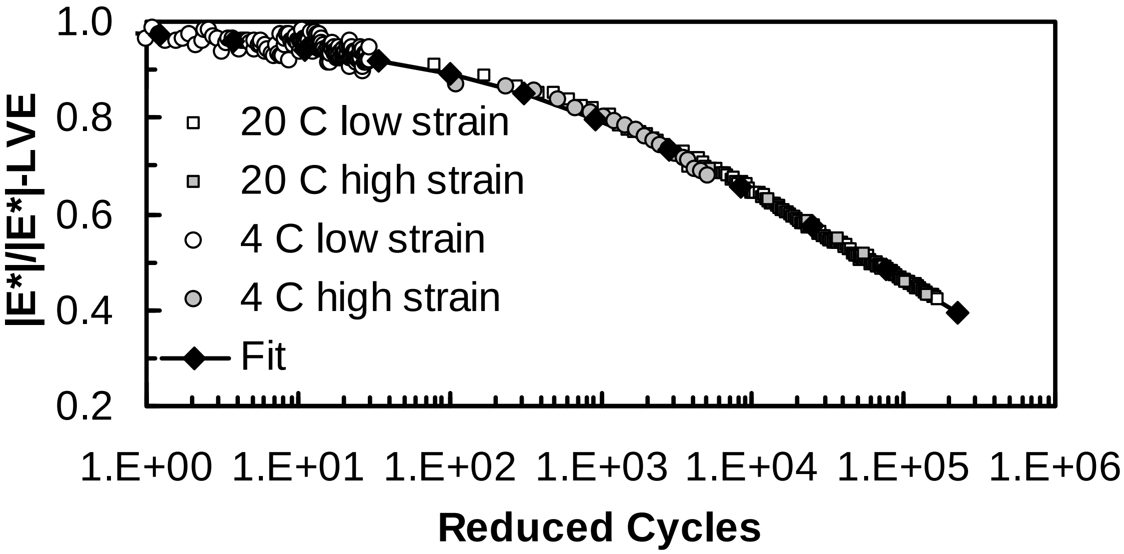


Figure 17. Typical Damage Relationship From Continuum Damage Analysis.

Continuum damage analysis has not been applied to pulsed fatigue tests where intermittent healing is permitted to occur. It is expected that the endurance limit will increase as the duration of rest period increases. The testing and analysis required to use continuum damage analysis to establish allowable strain limits for complete healing is summarized below:

1. Conduct dynamic modulus tests on the mixture and develop a dynamic modulus master curve and associated time-temperature shift factors.
2. Conduct cyclic direct tension controlled strain fatigue tests using various temperatures, strain levels, and rest periods.
3. Perform continuum damage analysis and determine the endurance limit for each of the test conditions.
4. Develop a relationship of the endurance limit as a function of temperature and rest period using time-temperature superposition if appropriate.
5. The endurance limit relationship developed in Step 4 is the allowable strain for full healing.

It should be noted that the allowable strains from the continuum damage analysis will likely be lower than the allowable strains developed using flexural fatigue testing and the RDEC method. The reason is the endurance limit in the continuum damage analysis is defined as the strain below which no measurable damage occurs in the mixture. The endurance limit in the RDEC approach is defined as the strain that results in less than a 50 percent reduction in the modulus of the material after an infinite number of loading cycles.

Experimental Design and Data Analysis

The two approaches are very similar. In both cases the rate of damage accumulation should depend on the HMA properties, the applied strain level, the temperature, and the duration of rest periods. The allowable strain limit for design is the strain level for specific temperatures and rest periods where no damage accumulates in the HMA. The primary issue for both approaches is determining the testing conditions that provide for an efficient and robust analysis. This includes:

- Strain levels,
- Test temperatures,
- Duration of rest periods,
- Number of replicates.

The results of Experiments 1, 2, and 3 will provide initial estimates for the testing conditions. Data will then be collected on two mixtures from Experiment 1, one exhibiting a low healing rate and one exhibiting a high healing rate using a wider than estimated range and more intervals for each of the testing conditions. The analysis will then be repeated using a reduced data set to determine the optimum testing conditions. Tests using the optimum testing conditions will then be conducted on selected mixtures from NCHRP 9-38 and the results will be compared to the endurance limit strain levels determined in NCHRP 9-38.

Subtask 4.5 Experiment 5: Estimation of Allowable Strain Levels from Mixture Composition

The final experiment that will be conducted is one to establish a predictive model to estimate allowable strain levels from mixture composition. This is an extremely important experiment for two reasons. First, it is unlikely that original materials or appropriate size field specimens will be available from the calibration pavement sections; therefore, estimates of allowable strain levels will be needed for the Task 5 analyses. Using the models developed in Experiment 5, estimates of allowable strain levels can be made using test data from standard tests on a small number of cores removed from the pavement sections. Second, a method of estimating allowable strain levels will also be needed for use in Level 2 and 3 design with the modified version of the MEPDG. The testing and analysis procedure developed in Experiment 4 will provide methods for Level 1 analysis. The predictive model developed in Experiment 5 will provide relationships for Level 2 and Level 3 analyses.

Experiment Design

Regression analysis will be used to develop a predictive model to estimate allowable strain levels from mixture composition. In Experiment 5 a database of allowable strains and mixture properties will be assembled by performing the analysis developed in Experiment 4 on a representative sample of HMA base course mixtures. Since it is envisioned that the model will be used for both analysis of existing pavements and the design of future pavements, the mixtures tested should include past, current, and likely future features that affect HMA fatigue response and healing. For example the base course of many existing pavements was designed using Marshall compaction resulting in somewhat richer mixtures than designed today using gyratory compaction. If healing is found to be much greater in modified binders, then it may be likely that modified binders will be considered for base courses in the future, an uncommon practice today.

Guidance on the factors and their ranges to be included in Experiment 5 will be obtained from Experiment 1. As discussed previously, the following factors have been identified as potentially affecting the allowable strain levels:

- Binder grade
- Binder modification
- Aging
- Effective Binder Content
- Air Voids
- Design Compaction
- Gradation
- Filler Content

The purpose of Experiment 1 is to narrow this list to the factors that significantly affect the fatigue damage and healing characteristics of HMA. The results of Experiment 1 and a review of past and current mixture design and mixture production specifications will be used to determine the specific factors and the ranges that must be included in Experiment 5. It is envisioned that approximately 30 mixtures will be tested in Experiment 5. It is not necessary that Experiment 5 be a full or partial factorial design. The major experimental design requirements are that (1) the mixtures that are selected to be representative of base courses (2) they span the desired range of each important factor, and (3) at least three levels are included for each factor so that non-linear analyses can be made.

Data Analysis

The database of allowable strains and associated mixture compositional properties will be analyzed using graphical and regression techniques. First scatter plots will be prepared for each of the factors included in the experiment to determine appropriate mathematical functions for the model. At this point consideration will be given to using a more general factor that combines some of the individual factors. For example, the effects of binder grade and aging could both be addressed using the rheological index obtained from a binder master curve. Or the effects of air voids and effective binder content could both be addressed using the voids in the mineral aggregate or voids filled with asphalt. Additionally, consideration will be given to using easily measured or estimated mechanical properties such as indirect tensile strength or modulus.

Once appropriate model forms have been identified using graphical analysis, a regression analysis will be performed to determine the model coefficients. Most likely the relationships will be non-linear resulting in the need to use numerical optimization. Several statistical packages are available for performing non-linear regression analyses.

The final step in the process, which is often overlooked, is to evaluate the appropriateness of the model. There are several analyses that must be performed to evaluate the model including:

1. **Goodness of Fit.** Two measures of the goodness of fit of the model should be evaluated. The first is the square of the correlation coefficient, R^2, which is the percentage of the variance of the criterion variable explained by the predictor variables. The second measure of the goodness of fit of the model is the standard error of estimate, S_e, which is the standard deviation of the errors. The standard error of estimate has the same units as the criterion, and its magnitude is a direct indicator of the model errors. If the model

provides a good prediction, the standard error of estimate should be much lower than the standard deviation of the data used to fit the model.

2. **Statistical Significance of the Predictor Variables.** Only statistically significant predictor variables should be included in the model. If predictor variables that are not statistically significant are included, then irrational effects may be predicted for important predictor variables. The standard error of the parameter estimates should be used in a t-test to determine if each of the model parameters is significantly different from zero.

3. **Residual Analysis.** An analysis of the residuals or errors should always be performed to ensure that the underlying assumptions of regression analysis are not violated by the model. The model errors should (1) be independent, (2) have zero mean, (3) have a constant variance across all predictor variables, and (4) be normally distributed. Plots of the residuals as a function of the predictor variables should be used to identify bias in the model and to identify potential violations of the underlying regression assumptions.

4. **Reliability of the Model.** Confidence intervals should be constructed to assess the reliability of the model. Since the model will be used to predict properties for design and analysis, the width of prediction intervals for the model are of primary concern. The prediction interval is the confidence interval associated with the prediction of a future value.

Task 4 Milestones

Table 20 summarizes the major milestones for Task 4. These are all associated with the design, execution, and analysis of the five laboratory experiments.

Table 20. Major Task 4 Milestones.

Milestone	Description	Months After Contract Award
4.1	Select Analysis Approach and Prepare Detailed Work Plan for Experiment 1	5
4.2	Complete Experiment 1	8
4.3	Detailed Work Plan for Experiments 2	8
4.4	Complete Experiment 2	10
4.5	Detailed Work Plan for Experiment 3 and Experiment 4	10
4.6	Complete Experiment 3	11
4.7	Complete Experiment 4	13
4.8	Detailed Work Plan for Experiment 5	13
4.9	Complete Experiment 5	21

Task 4 Labor Estimate

Table 21 presents the estimated labor required for Task 4. Table 21 presents estimated labor hours for each of the positions in the research management structure presented in Table 5 and for laboratory technicians. Task 4 is estimated to require a total of 3,893 man-hours of effort. This is approximately 30 percent of the total effort required for the project.

Table 21. Estimated Labor Hours for Task 4.

Subtask	Principal Investigator	Statistician	Laboratory Team Leader	Pavement Team Leader	Data Support Team Leader	Technicians
Experiment 1: Mixture Compositional Factors Affecting Healing	4	4	34	0	0	388
Experiment 2: Effect of Applied Strain on Healing	4	4	24	0	0	214
Experiment 3: Effect of Temperature and Rest Period Duration on Healing	8	4	57	0	0	242
Experiment 4: Testing and Analysis Procedures for Allowable Strain Levels	54	16	98	0	0	392
Experiment 5: Estimation of Allowable Strain Levels from Mixture Composition	146	40	270	0	0	1890
Total	216	68	483	0	0	3126

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Task 5. Analysis of Pavement Sections

The final task in the HMA Endurance Limit Validation Study is an analysis of full-scale pavement sections using the allowable strain limit design procedure formulated in Task 2 and improved through the laboratory experiments in Task 4. Two types of full-scale pavement sections will be analyzed. First data from selected accelerated pavement tests and test roads will be used to test critical elements of the procedure. These include the effects of temperature, applied strain, and material properties on the allowable strain levels. Results from these analyses will be used to further improve the allowable strain limit design procedure for use in analysis of the second type of full-scale pavement: in-service pavement sections. For the in-service pavements, both cracked and uncracked pavements will be analyzed. These analyses will be used to calibrate the procedure and serve as validation of the concept of an endurance limit for flexible pavement design. It is important to recognize that the allowable strain limit design procedure is not intended to be a tool for predicting the extent of bottom initiated cracking with time and traffic like the MEPDG fatigue model. Its purpose is to identify design features that minimize the possibility of bottom initiated fatigue cracking. Thus field calibration of the allowable strain limit design procedure will be easier and likely more precise than the calibration that was completed for the MEPDG fatigue model. Task 5 has been divided into five subtasks:

5.1 Review Data Sources and Select Sections for Analysis
5.2 Obtain Materials and Data for Accelerated Pavement Tests and Test Roads
5.3 Perform Testing and Analyze Accelerated Pavement Tests and Test Roads
5.4 Obtain Materials and Data for In-Service Pavement Sections
5.5 Perform Testing and Analyze In-Service Pavement Sections

Each of these subtasks are described in detail below.

Subtask 5.1 Review Data Sources and Select Sections for Analysis

In this subtask the sources identified in this research plan will be reviewed considering the final preliminary approach developed in Subtask 2.2 and specific pavement sections will be selected for subsequent analysis. Subtask 5.1 will begin immediately after the preliminary approach is finalized in Subtask 2.2. Initial selection of sections for analysis will be documented in the second interim report that will be submitted at the end of the 13th month of the project. This initial selection will be reviewed as results from the laboratory experiments become available and adjusted as needed. Two types of full-scale pavements: accelerated pavement tests and test roads, and in-service pavements will be selected for analysis. The sections that follow describe specific pavement sections that are recommended for consideration in Task 5.

Accelerated Pavement Tests and Test Roads

Selected, well documented accelerated pavements tests and test roads will serve the important role of verifying critical aspects of the allowable strain limit design procedure. Specific elements of the procedure that can be verified include:

1. The overall engineering reasonableness of the approach,
2. Applicability of time-temperature superposition to healing and allowable strains,
3. Independence of healing on applied strain, and
4. Effect of material properties on allowable strains.

Although there are now a number of accelerated pavement testing devices and test road facilities in the United States, few of the testing programs have addressed fatigue of HMA in a structured manner. For flexible pavements, accelerated pavement testing has mostly been used to investigate rutting in HMA surfaces, or to evaluate specific materials or design features. Only four projects were identified where structured, full-scale testing was conducted that is useful in verifying the above aspects of the allowable strain limit design procedure. The following projects are recommended for analysis:

- Fatigue tests conducted during the Superpave validation study at the FHWA Pavement Test Facility (*50*).
- Sections at the NCAT Test Track that have remained in service from the first cycle through the current cycle (*51*).
- Sections from the WesTrack experiment containing mixtures with different composition (*41*).
- Sections from the structural design experiment performed at the NCAT Test Track (*52, 53*).
- Selected sections from the MNRoad project (*54*).

Although the MNRoad sections are actually in-service pavements loaded with normal traffic, they are included in the verification studies because there are a number of sections that can be analyzed and all of the sections are exposed to the same environmental conditions. If MNRoad sections are included in the calibration, then only a limited number of sections can be used, otherwise the analysis will be biased toward the environmental and construction conditions at MNRoad. The sections that follow describe analyses that should be conducted considering the preliminary design approach described in Task 2.

Overall Engineering Reasonableness

All of the accelerated pavement tests will be used to judge the engineering reasonableness of the allowable strain limit design procedure. An analysis of each section using the procedure should provide the correct conclusion concerning cracking in the pavement. For sections that have cracked, the analysis should show that the allowable strain levels were exceeded. For sections that have not yet cracked, such as the first cycle sections at the NCAT Test Track that remain in-service, the analysis should show that the allowable strain levels were not exceeded.

It should be noted that the allowable strain limit design procedure developed in Task 2 does not require the pavement to exhibit endurance limit behavior. Equations 8 and 9 in Task 2 can be solved for the allowable strains for any number of loading cycles. Endurance limit behavior occurs when the number of cycles to failure exceeds $1.1\text{x}10^7$. This will be very useful for analysis of the structural sections at the NCAT test track. Table 22 presents the HMA thicknesses in the NCAT structural sections (*51*). For the materials used in the base course of these sections, analysis can be done assuming endurance limit behavior, then the analysis can be repeated using the observed load cycles to failure and the allowable and actual strains can be compared.

Table 22. HMA Thicknesses in NCAT Structural Sections

	2003 Construction		2006 Construction	
Section	HMA Thickness, in	HMA Base Binder	HMA Thickness, in	HMA Base Binder
N1	5	Polymer 76-22	7	Neat PG 67-22
N2	5	Neat 67-22	7	Polymer 76-22
N3	9	Neat 67-22	NA	NA
N4	9	Polymer 76-22	NA	NA
N5	7	Polymer 76-22	7	Neat PG 67-22
N6	7	Neat 67-22	NA	NA
N7	7	Neat 67-22	NA	NA
N8	7 (rich bottom)	Neat 67-22	10	Polymer 76-28
N9	NA	NA	14	Polymer PG 76-28
N10	NA	NA	8	Polymer PG 70-22

The MNRoad sections also provide the opportunity to perform a systematic analysis of the overall reasonableness of the approach for pavements of different thickness and composition exposed to the same traffic and environment. At MNRoad, sections were constructed using different thicknesses, design compaction levels, and binders. Table 23 summarizes the main line HMA cells at MNRoad that could be used in the verification analyses (*54*). Although bottom initiated fatigue cracking was not reported as a distress for any of the HMA sections in the last condition report (*55*), the pavements have received seven years of additional traffic and selected sections will remain in service after reconstruction is completed in 2008 and 2009 (*54*).

Table 23. Summary of MNRoad Mainline HMA Pavement Sections.

Section	HMA Thickness, in	Design Compaction	Binder
1	6.0	75 Blow Marshall	PG 58-28
2	6.1	35 Blow Marshall	PG 58-28
3	6.3	50 Blow Marshall	PG 58-28
4	9.1	Gyratory	PG 58-28
14	10.9	75 Blow Marshall	PG 58-28
15	11.1	75 Blow Marshall	PG 64-22
16	8.0	Gyratory	PG 64-22
17	7.9	75 Blow Marshall	PG 64-22
18	7.9	50 Blow Marshall	PG 64-22
19	7.8	35 Blow Marshall	PG 64-22
20	7.8	35 Blow Marshall	PG 58-28
21	7.9	50 Blow Marshall	PG 58-28
22	7.9	75 Blow Marshall	PG 58-28
23	8.2	50 Blow Marshall	PG 58-28

Applicability of Time-Temperature Superposition to Rest Periods

The fatigue experiment that was conducted during the Superpave validation study at the FHWA Pavement Testing Facility provides an excellent opportunity to validate that application of time-temperature superposition to rest periods. In this study, accelerated pavement tests were conducted with the FHWA Accelerated Loading Facility on two pavements at three different pavement temperatures. The tests were performed when ambient air temperatures were low. An infrared heating system was used to maintain the pavement temperatures (*50)*. Table 24 summarizes the tests that were performed. Analysis of these tests at different temperatures using the allowable strain limit design procedure will provide validation of the use of time-temperature superposition to model HMA healing effects.

Table 24. FHWA Pavement Testing Facility Superpave Fatigue Experiment.

HMA Thickness, mm	Binder	Load, kN	10 °C	19 °C	28 °C
100	AC-5	53	X	X	X
	AC-20	53	X	X	X
200	AC-5	53	X	X	X
	AC-20	53	X	X	X

The instrumented structural sections at the NCAT Test Track can be used to evaluate the effect of damage and healing during different temperature conditions. Measured strains and deflections in these sections can be used to determine the effects of rest periods on healing at different temperatures. Within the current loading experiment, four of the structural test sections are instrumented.

Independence of Healing on Strain Level

The FHWA Superpave validation study fatigue experiments also provide the opportunity to verify that healing is independent of strain level. Since the same mixtures were tested at the same temperature and load in two different pavement structures, the effect of strain level on healing can be evaluated. The thicker pavement has significantly lower tensile strains at the bottom of the HMA compared to the thinner pavement. The structural sections at the NCAT Test Track and sections at MNRoad where the same base course material was used in pavements of different thicknesses can also be used to verify that healing is independent of strain level.

Effect of Material Properties on Allowable Strains

All four recommended projects can be used to assess how well the allowable strain limit design procedure addresses the effect of changes in mixture composition. The WesTrack experiment included variations in gradation, filler content, binder content, and in-place density (*41*). A single asphalt binder and aggregate source were used in the original sections. In the replacement sections a different aggregate was used (*41*). As shown in Table 22, the structural sections at the NCAT Test Track includes pavements of the same thickness made with a polymer modified PG 76-22 binder and a neat PG 67-22 binder. The FHWA experiment included two neat binders, AC-5 and AC-20. Finally as shown in Table 23, the MNRoad project includes sections of the same thickness designed with different compaction and two different binders.

The predictive model developed in Experiment 5 of Task 4 addresses the effect of material properties on allowable strains. The effects predicted by this model can be compared to the observed effects within each of the experiments.

In-Service Pavement Sections

Calibration of the allowable strain limit design procedure will be performed using in-service pavements. Analyses will be conducted for a number of sections, both cracked and uncracked, using the procedure. Sections from the LTPP program (*56*) and pavements that have received perpetual pavement awards from the Asphalt Pavement Alliance (*57*) were considered for use in the calibration. The LTPP sections were selected because these sections have received extensive monitoring over a number of years, and distress, deflection, and material property data are available from the LTPP database (*56*). Since sufficient sections for the analysis are available from the LTPP program, only these sections are included in this research plan.

LTPP Sections

In NCHRP Project 9-38, analyses were conducted using data from the LTPP database to determine if an endurance limit for HMA could be identified from field data (*6*). The following assumptions were made in these analyses:

1. Alligator cracking reported in the LTPP database initiated at the bottom of the section.
2. Wheel path longitudinal cracking reported in the LTPP database initiated at the surface.
3. The endurance limit can be defined by a single value of strain that is independent of temperature, mixture modulus, and type of mixture.

From these analyses, an endurance limit could not be definitively identified. The NCHRP 9-38 research team hypothesized that one of the reasons why an endurance limit could not be defined is that the endurance limit is mixture composition dependent and it varies with temperature.

Figures 18 and 19 compare the amount of fatigue cracking (percent of wheel path area) from the most recent LTPP distress survey with HMA thickness and maximum tensile strain at the bottom of the HMA, respectively. As shown and expected, the test sections with thinner HMA layers and higher tensile strains generally exhibit more fatigue cracking.

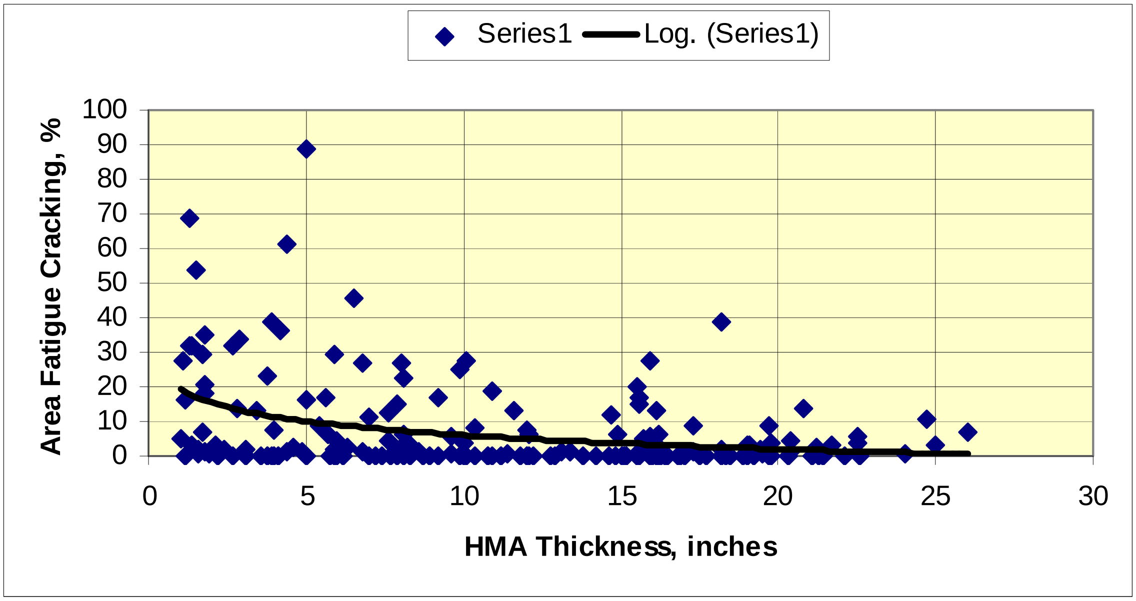

Figure 18. Comparison of Area Fatigue Cracking (Area Alligator Cracking Based on a Percent of Wheel Path Area) and HMA Layer Thickness (*6*).

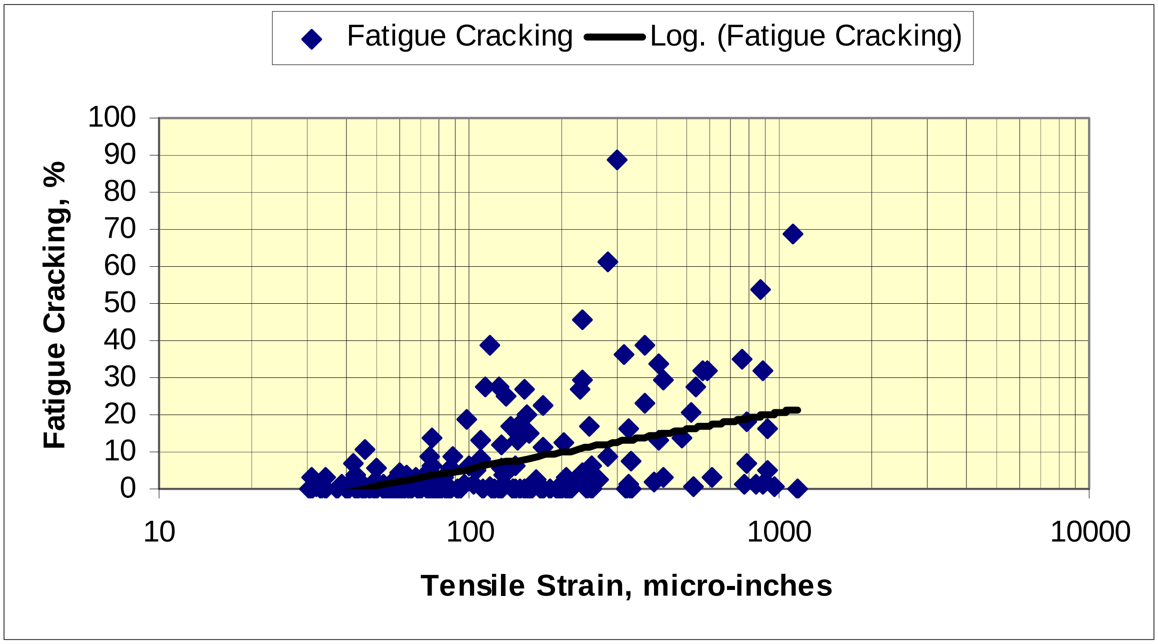

Figure 19. Comparison of the Area Fatigue Cracking for and Maximum Tensile Strain Computed at the Bottom of the HMA Layer (*6*).

A number of test sections with thick HMA layers and low tensile strains, however, have levels of fatigue cracking exceeding 5 percent. Reasons given for the cracking in these sections included (*6*):

- Misclassification of longitudinal cracking as alligator cracking.
- The presence of construction defects, such as high air voids, debonding of layers, etc.
- Moisture damage in the section,
- The endurance limit is dependent on the quality of the HMA base; therefore, sections with poor HMA base quality require lower strains to exhibit endurance limit behavior.

Forensic evaluation of the thick HMA sections with reported alligator cracking was recommended for future endurance limit validation studies.

An observation of the data in Figures 18 and 19 that was not made by the NCHRP Project 9-38 research team is the pavements in the LTPP database are generally properly designed to resist fatigue cracking for the level of traffic that they have received. This is indicated by the large number of sections having zero alligator cracking. This is particularly true for pavements having maximum tensile strains at the bottom of the asphalt layer below about 100 microstrain when calculated using the equivalent annual layer moduli for each pavement layer. Figure 20 presents a plot of tensile strain at the bottom of the asphalt layer versus HMA layer thickness that was used to develop Figure 19. From Figure 20 tensile strains of 100 microstrain correspond to approximately 10 inches of HMA, which is similar to the thicknesses reported for the heavily trafficked pavements in the United Kingdom having no evidence of bottom initiated fatigue cracking (*9*). This observation suggests that the thick sections with high levels of alligator cracking likely contain construction defects and should not be included in the calibration of the allowable strain limit design procedure. Forensic evaluation of these sections should definitely be conducted, but not as part of the HMA Endurance Limit Validation Study.

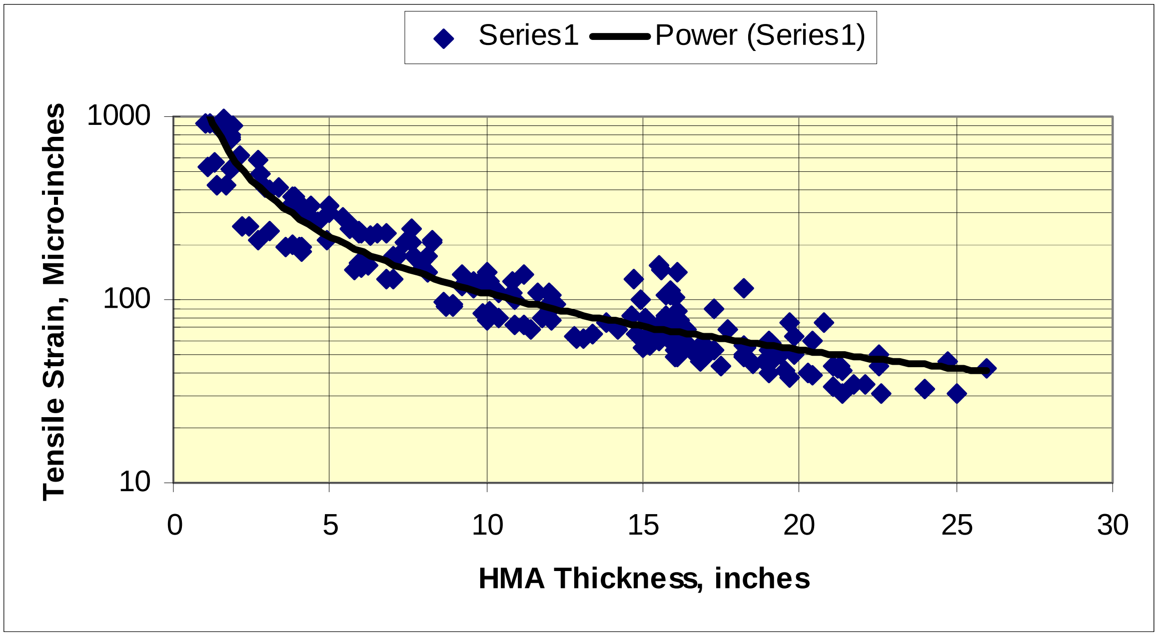

Figure 20. Comparison of the Maximum Tensile Strain at the Bottom of the HMA Layer and HMA Thickness (*6*).

Table 25 presents the preliminary test matrix for using LTPP sections to calibrate the allowable strain limit design procedure. Since the procedure is not intended for prediction of the extent of cracking in a pavement section, but rather as a tool to identify design features to minimize the potential for bottom initiated fatigue cracking, an extremely large data set is not required. The recommended matrix includes a total of 32 pavement sections: 16 not exhibiting alligator cracking and 16 exhibiting low to moderate amounts of alligator cracking. An equal number of sections from the four environmental zones are included in the matrix. Only pavements with HMA thicknesses exceeding 8 inches are included. Subgrade deformation becomes an important consideration in thinner HMA pavements.

Table 25. Preliminary Matrix for Field Calibration of the Allowable Strain Limit Design Procedure.

Environment	HMA Thickness, in	No Alligator Cracking	Low Alligator Cracking
Wet Freeze	8 to 12	2	2
	>12	2	2
Wet No Freeze	8 to 12	2	2
	>12	2	2
Dry Freeze	8 to 12	2	2
	>12	2	2
Dry No Freeze	8 to 12	2	2
	>12	2	2

Table 26 presents a summary of applicable LTPP sections for each of the cells in the experimental matrix. Information from the LTPP database on these sections and others that may be considered is presented in the attachment. Specific sections to be included in the calibration effort will be selected in Subtask 5.1. Items that should be considered in the final selection include:

- Current status of the section (active or out of service).
- Willingness of the state agency to assist with providing traffic control for distress verification and seismic testing, and to provide limited coring to investigate cracking and obtain samples for laboratory testing.
- Consistency of time series distress data for the section in the LTPP database.
- Consistency of time series deflection data for uncracked sections.
- Availability of traffic information or an estimate of traffic for the section.

Table 26. LTPP Sections Recommended for Consideration.

Climate	HMA Total Thickness, in.	Fatigue or Alligator Cracking	
		None	Appreciable
Wet-No Freeze	8 to 12	12-0101; 12-0103; 22-0114; 40-0160	01-0101; 05-0114; 12-0107; 40-0114
	>12	05-3071; 12-0106; 12-0104; 13-4113; 22-0116; 40-0115	01-0111; 05-0115; 05-0116
Dry-No Freeze	8 to 12	35-0111; 35-0103; 35-0107	04-0162; 48-1070
	>12	04-1065; 35-0106; 48-0116	04-1062; 04-0116
Dry-Freeze	8 to 12	32-0101; 32-0105	16-9034; 30-0114; 32-0103
	>12	31-0115; 31-0116; 32-0106; 32-0104	30-0116; 30-0115; 30-0124
Wet-Freeze	8 to 12	19-0101; 19-0105; 55-01114; 55-C901	19-0103; 55-C960
	>12	19-0112; 26-0115; 39-0902; 55-0116	39-0106; 39-0112; 39-0903

Subtask 5.2 Obtain Materials and Data for Accelerated Pavement Tests and Test Roads

The primary activity required in Subtask 5.2 is extracting the data required for analysis of the accelerated pavement tests and test road sections from various research reports. This includes information on the pavement structure, loading, environmental conditions, material properties, and distress for each section that will be analyzed. The data will be entered into the database and managed in Subtask 3.2.

The inputs needed to apply the allowable strain limit design procedure to accelerated pavement tests and test roads are similar to those required for current mechanistic-empirical design, such as the MEPDG. Table 27 summarizes the required inputs. The elements in bold in Table 27 are ones required by the allowable strain limit design procedure that are not included in current mechanistic-empirical analysis. Since mechanistic-empirical pavement analyses were included in the recommended projects, most of the information needed for the analyses are in published reports for the projects or available from the project websites (*41*, *50*, *51*, *52*, *53*, *54*, *58*).

Table 27. Summary of Required Inputs for Allowable Strain Limit Design.

Category	Required Input
Pavement Structure	Layer thicknesses Layer moduli Layer Poisson's ratios **Mixture composition and binder properties for HMA base**
Traffic	Axle configuration Tire configuration Tire loads Tire pressure Speed Wander **Rest Period**
Environmental	Pavement temperature history Base modulus history Subgrade modulus history

It is envisioned that the model for predicting allowable strains in HMA developed in Experiment 5 of Task 4 will relate allowable strains to mixture composition and binder properties. The required mixture composition data are available in the published research reports; however, it is expected that binder properties in addition to the performance grade of the binder will be required. Extensive testing of the binders used in the FHWA Superpave validation study, WesTrack, and MNRoad was completed during NCHRP Project 9-19 (*59, 60, 61*). Therefore, the only material sampling and testing that will be needed for analysis of the accelerated pavement tests and test roads will be characterization of the binders used in the structural sections at the NCAT Test Track. One quart samples of these binders will be requested from NCAT or the test section sponsors.

The required performance data for the recommended projects are included in published reports. Updated information on performance of the MNRoad test sections is available by request through the MNRoad website (*54*). Traffic loading for the 2006 sections included in the structural sections at the NCAT Test Track is scheduled for completion in the Fall of 2008 (*51*).

Subtask 5.3 Perform Lab Testing and Analyze Accelerated Pavement Tests and Test Roads

The only laboratory testing envisioned in Subtask 5.3 is further characterization of the binders used in the structural test sections from the NCAT test track. It is unlikely that master curves characterizing the flow characteristics of the binders over a wide temperature range and for various aging conditions are available; therefore, they will have to be developed. Master curves are developed by testing the binder at multiple temperatures and frequencies using the dynamic shear rheometer, AASHTO T315, and conducting bending beam rheometer tests, AASHTO T313, at multiple temperatures.

For each accelerated pavement test and test road section, an analysis will be performed with the research version of the MEPDG software, NCHRP9-44A_Version 0.2, using section specific material properties, loading, and environment. Two analyses will be performed. For all sections an analysis will be conducted to determine the allowable strains that will produce endurance limit behavior (full healing). Then, for those sections that have exhibited cracking an analysis will be performed using the observed cycles to first cracking. Comparisons will be made within projects and between projects to verify the following aspects of the allowable strain limit design procedure:

- The overall engineering reasonableness of the approach,
- Applicability of time-temperature superposition to healing and allowable strains,
- Independence of healing on applied strain, and
- Effect of material properties on allowable strains.

Pertinent interim results from these analyses will be discussed in the quarterly progress reports. The analyses will be thoroughly documented in the fourth interim report submitted at the end of the 30th month of the project.

Subtask 5.4 Obtain Materials and Data for In-Service Pavement Sections

In this Subtask, data and materials needed to analyze each of the LTPP sections included in the final matrix of in-service pavements will be obtained. First, the most recent data for the test section will be retrieved from the LTPP database (*56*). This data will be entered into the project database and managed under Subtask 3.2. The relevant data for the analyses include:

- Traffic.
- Time-series deflection data.
- Time-series fatigue cracking.
- Time-series longitudinal cracking.
- Layer material properties.

A site visit to each of the selected pavement sections is required. The site visit will include:

1. A visual condition survey to confirm the distresses obtained from the LTPP database,
2. Non-destructive testing at various locations in the section using the Portable Seismic Pavement Analyzer (PSPA) (*62, 63*) to identify damage in the base layers that is not apparent from surface distress measurements.
3. Coring to obtain 3 to 5 full depth samples for laboratory testing, and
4. Additional coring to confirm the distress survey and seismic testing. If cracks are present, cores will be taken through selected cracks to confirm where the cracks initiated and confirm the cause of cracking.

Each site visit will require two full days. It is envisioned that the necessary traffic control and coring will be provided by the state highway agencies. Their willingness to participate in the field testing is an important consideration in the final selection of pavements for analysis.

Subtask 5.5 Perform Lab Testing and Analyze In-Service Pavement Sections

Laboratory Testing

The pavement section cores will be used to determine modulus values for analysis of the seismic test data and to obtain the properties of the HMA base for use in the predictive model developed in Experiment 5 of Task 4. This model will relate allowable strains for full healing to easily measured volumetric properties of the mixture and flow characteristics of the binder. Mixture properties will be obtained from normal volumetric analysis of the cores. The binder will be recovered to determine the required binder properties. A preliminary testing plan is presented in Table 28 assuming that an indirect tensile strength will be used in the model and a binder master curve will be required to characterize the flow properties of the binder in the predictive model developed in Experiment 5 of Task 4.

Table 28. Preliminary Testing Plan for Cores From the LTPP Sections.

Test	Method	Number	Reason
Bulk specific gravity	AASHTO T169	3	Volumetric properties
Indirect Tensile Modulus	Modified AASHTO T322	3	Analysis of seismic data
Indirect Tensile Strength	AASHTO T322	3	Mixture strength
Asphalt content	AASHTO T164	3	Volumetric properties
Sieve analysis	AASHTO T30	3	Gradation
Aggregate bulk specific gravity	AASHTO T84 AASHTO T85	1 1	Volumetric properties
Binder Recovery	AASHTO T170	3	Obtain binder for rheological testing
Dynamic Shear Rheometer	AASHTO T315	Frequency sweep at 6 temperatures	Binder master curve
Bending Beam Rheometer	AASHTO T313	3 temperatures	Binder master curve

Analysis

Analysis of the LTPP sections will be performed using the research version of the MEPDG software, NCHRP9-44A_Version 0.3, developed in Subtask 2.4. The analysis will involve performing simulations for each of the 32 pavement sections to determine the frequency at which the allowable strains for full healing (endurance limit behavior) are exceeded. For all of the simulations, the best available information on the traffic and unbound layers will be used.

Since the field data consists of cracked and uncracked sections, the analysis will produce binary data (either cracked or uncracked) as shown schematically in Figure 21. From this data a model for the probability that bottom initiated cracking will occur can be developed using the logistic function given in Equation 32.

$$p = \frac{e^{\left[b_0 + b_1(PE)\right]}}{1 + e^{\left[b_0 + b_1(PE)\right]}} \tag{32}$$

where:

p = probability of bottom initiated fatigue cracking

PE = percent of axle loads with strains exceeding the endurance limit

b_0 and b_1 = fitting parameters

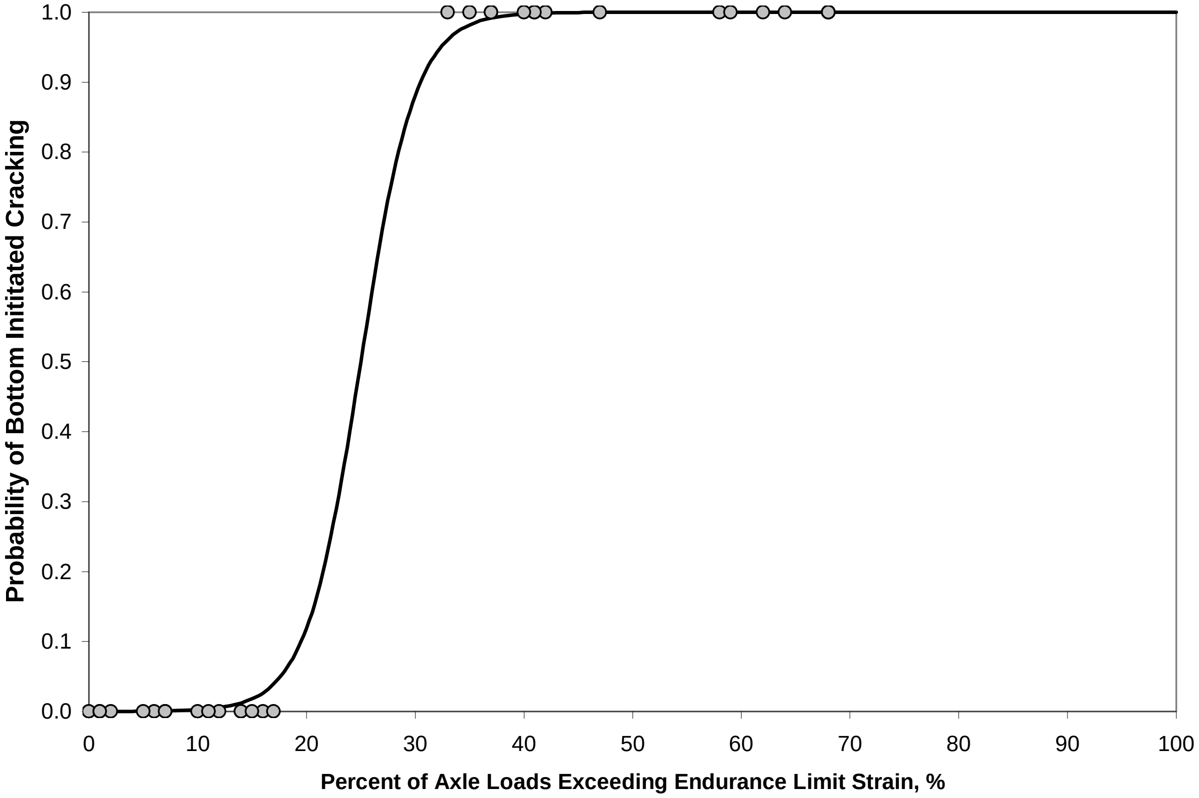

Figure 21. Schematic of Field Section Data Analysis.

Jackknifing as described in Research Results Digest Number 283 (*64*) can be used to assess the accuracy of the of the model coefficients without having to separate the 32 sections into calibration and validation subsets. Jackknifing is performed by systematically removing one of the sections, calibrating the model using the remaining sections, then predicting the value of the section that was removed. For the section that was removed, the model error, e_i, is computed as the difference between the predicted and measured values. The process of withholding, calibrating, and determining the error is repeated until each section has been removed. This process produces *n* values of the error from which the following jackknifing goodness of fit statistics can be computed.

$$S_e = \left[\frac{1}{\nu}\sum_{i=1}^{n} e_i^{\,2}\right]^{0.5} = \left[\frac{1}{\nu}\sum_{i=1}^{n}(\hat{Y}_i - Y_i)^2\right]^{0.5} \tag{33}$$

where

S_e = standard error

e_i = errors computed from jackknifing

n = number of measurements taken

ν = degrees of freedom = n minus number of unknowns

$\hat{Y}_i$ = predicted value for the ith jackknifing set

Y_i = measured value for the ith jackknifing set

$$R^2 = 1 - \left[\left(\frac{S_e^{\,2}}{S_y^{\,2}}\right)\left(\frac{n-p}{n-1}\right)\right] \tag{34}$$

where

R^2 = explained variance

S_e = standard error

S_y = standard deviation of the measured data

n = number of measurements taken

p = number of unknowns

$$bias = \sum_{i=1}^{n} e_i \tag{35}$$

where

e_i = errors computed from jackknifing

n = number of measurements taken

The advantage of jackknifing is the goodness of fit statistics are based on predictions of measurements that are not included in the calibration. They are, therefore, better estimates of the accuracy of future predictions than goodness of fit statistics based on calibration using the full data set. The stability of the model can also be assessed by performing the jackknifing again by withholding two sets of measurements and calibrating using the remaining n-2 measurements. For n-2 jackknifing, two errors are computed for each set of two measurements that are withheld. The change in the jackknifing goodness of fit statistics between n-1 and n-2 jackknifing is an indicator of the stability of the statistics. Stable goodness of fit statistics indicate a model with reliable prediction accuracy.

Pertinent interim results from these analyses will be discussed in the quarterly progress reports. The analyses will be thoroughly documented in the fifth interim report submitted at the end of the 42nd month of the project.

Task 5 Milestones

Table 29 summarizes the major milestones for Task 5. Initially the emphasis of the project will be on the formulation of the design procedure and the laboratory testing and analysis. This provides substantial time for compiling the accelerated pavement test and test road data and for final selection of the LTPP sections. After the laboratory testing and analysis are complete, the emphasis of the project shifts to collection and analysis of the data from the LTPP sections.

Table 29. Major Task 5 Milestones.

Milestone	Description	Months After Contract Award
5.1	Initial Selection of Sections for Analysis	12
5.2	Final Selection of LTPP Sections for Analysis	20
5.3	Compile Data From Accelerated Pavement Tests and Test Roads	24
5.4	Complete Analysis of Accelerated Pavement Tests and Test Roads	27
5.5	Complete Data Collection for LTPP Sections	32
5.6	Complete Testing and Analysis of LTPP Sections	35

Task 5 Labor Estimate

Table 30 presents the estimated labor required for Task 5. Table 30 presents estimated labor hours for each of the positions in the research management structure presented in Figure 5, engineering support for collection and analysis of the pavement sections, and technician support for laboratory testing. Task 5 is estimated to require a total of 4,900 man-hours of effort. This is approximately 38 percent of the total effort required for the project.

Table 30. Estimated Labor Hours for Task 5.

Subtask	Principal Investigator	Statistician	Laboratory Team Leader	Pavement Team Leader	Data Support Team Leader	Engineers	Technicians
5.1 Review Data Sources and Select Sections for Analysis	16	8	0	28	0	320	0
5.2 Obtain Materials and Data for Accelerated Pavement Tests and Test Roads	20	0	0	28	0	280	0
5.3 Perform Lab Testing and Analyze Accelerated Pavement Tests and Test Roads	36	16	4	108	0	512	32
5.4 Obtain Materials and Data for In-Service Pavement Sections	20	0	0	100	0	1280	0
5.5 Perform Lab Testing and Analyze In-Service Pavement Sections	90	30	90	90	0	512	1280
Total	**182**	**54**	**94**	**354**	**0**	**2904**	**1312**

Task 5 Sources

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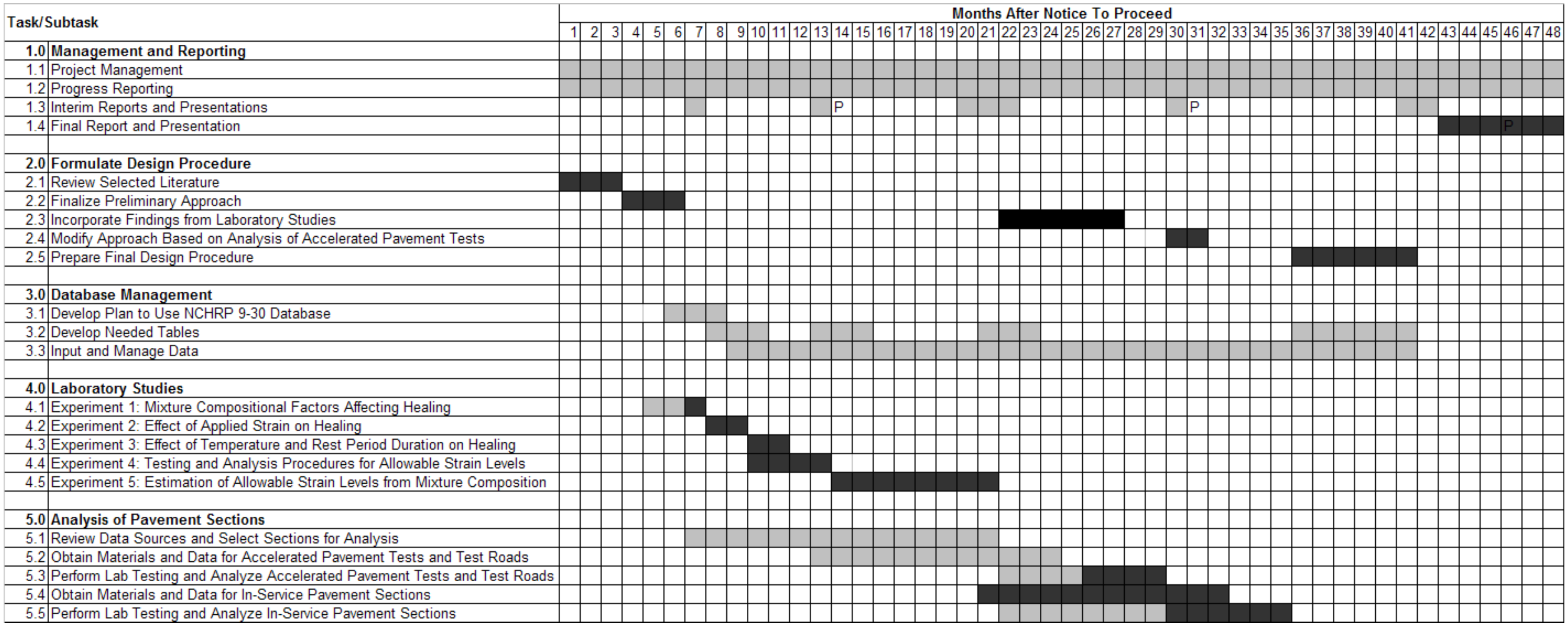
Schedule of Tasks

The HMA Endurance Limit Validation Study will require 48 months to complete. Figure 22 presents a Gantt Chart for the project with the critical path identified. Table 31 presents a complete listing of milestones for the project.

Perhaps the most critical task in the project is Task 2.2, Finalize Preliminary Approach, because the procedure assembled in this task will shape the final design of the laboratory experiments and the final selection of in-service pavements for analysis. Once the preliminary design procedure is finalized, then the critical path shifts to the laboratory studies in Task 4. When the laboratory studies are completed, the critical path splits. The development of NCHRP944A_Version 0.2 of the research MEPDG software in Task 2.3 becomes critical. This version of the software will be used to analyze the accelerated pavement and test road data in Task 5.3. Then based on the finding from these analyses, NCHRP944A_Version 0.3 will be developed for the calibration studies using data from the LTPP sections. The collection of data from the LTPP sections in Task 5.4 also becomes critical. The site visits required in this task can not begin until the form of the model for predicting allowable strains from mixture composition is determined. The final field coring and laboratory testing plans will depend on the form of the model developed in Task 4.5. The schedule provides 12 months to perform the 32 site visits. This is a compressed schedule for the site visits and likely will require at least two field engineers to complete the work as scheduled.

Analysis of the LTPP sections can begin as soon as the NCHRP944A_Version 0.3 is completed in Task 2.4. Laboratory testing of the field cores will lag the site visits by approximately 1 month; therefore, the data required to analyze most of the LTPP sections will be available when NCHRP944A_Version 0.3 is completed.

The final tasks of the project begin after the calibration analyses are completed in Task 5.5. This includes development of the final design procedure, NCHRP9-44A_Version 1.0 of the software, and the preparation of the final report for the project.



Task/Subtask		Months After Notice To Proceed																																													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1.0	**Management and Reporting**																																																
1.1	Project Management	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
1.2	Progress Reporting	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
1.3	Interim Reports and Presentations							▨						▨	P						▨	▨	▨								▨	P									▨	▨							
1.4	Final Report and Presentation																																											■	■	■	■P	■	■
2.0	**Formulate Design Procedure**																																																
2.1	Review Selected Literature	■	■	■																																													
2.2	Finalize Preliminary Approach				■	■	■																																										
2.3	Incorporate Findings from Laboratory Studies																						■	■	■	■	■	■																					
2.4	Modify Approach Based on Analysis of Accelerated Pavement Tests																														■	■																	
2.5	Prepare Final Design Procedure																																				■	■	■	■	■	■							
3.0	**Database Management**																																																
3.1	Develop Plan to Use NCHRP 9-30 Database						▨	▨	▨																																								
3.2	Develop Needed Tables								▨	▨	▨			▨	▨	▨						▨	▨	▨													▨	▨	▨	▨	▨	▨							
3.3	Input and Manage Data									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨							
4.0	**Laboratory Studies**																																																
4.1	Experiment 1: Mixture Compositional Factors Affecting Healing					▨	▨	■																																									
4.2	Experiment 2: Effect of Applied Strain on Healing								■	■																																							
4.3	Experiment 3: Effect of Temperature and Rest Period Duration on Healing										■	■																																					
4.4	Experiment 4: Testing and Analysis Procedures for Allowable Strain Levels										■	■	■	■																																			
4.5	Experiment 5: Estimation of Allowable Strain Levels from Mixture Composition														■	■	■	■	■	■	■	■																											
5.0	**Analysis of Pavement Sections**																																																
5.1	Review Data Sources and Select Sections for Analysis							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																											
5.2	Obtain Materials and Data for Accelerated Pavement Tests and Test Roads													▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																								
5.3	Perform Lab Testing and Analyze Accelerated Pavement Tests and Test Roads																						▨	▨	▨	▨	■	■	■	■																			
5.4	Obtain Materials and Data for In-Service Pavement Sections																					■	■	■	■	■	■	■	■	■	■	■	■																
5.5	Perform Lab Testing and Analyze In-Service Pavement Sections																						▨	▨	▨	▨	▨	▨	▨	▨	■	■	■	■	■	■													

Figure 22. Project Schedule With Critical Path Shown in Black.

Table 31. Project Milestone Summary.

Month	Milestone	Description
1	1.1	Initial Work Assignments
2		
3	1.2	First Quarterly Progress Report
	2.1	Review Selected Literature
4		
5	4.1	Select Analysis Approach and Prepare Detailed Work Plan for Experiment 1
6	1.3	Second Quarterly Progress Report
	2.2	Preliminary Approach and NCHRP 944A_Version 0.1 Software
7	1.4	First Interim Report (Preliminary Design Procedure and Laboratory Analysis Approach)
8	3.1	Database Plan
	4.2	Complete Experiment 1
	4.3	Detailed Work Plan for Experiments 2
9	1.5	Third Quarterly Progress Report
10	3.2	Tables for Laboratory Data
	4.4	Complete Experiment 2
	4.5	Detailed Work Plan for Experiment 3 and Experiment 4
11	4.6	Complete Experiment 3
12	1.6	Fourth Quarterly Progress Report
	5.1	Initial Selection of Sections for Analysis
13	1.7	Second Interim Report (Selection of Pavement Sections for Analysis)
	4.7	Complete Experiment 4
	4.8	Detailed Work Plan for Experiment 5
14	1.8	First Panel Presentation (Interim Reports 1 and 2)
15	1.9	Fifth Quarterly Progress Report
	3.3	Tables for Analysis of Accelerated Pavement Tests
16		
17		
18	1.10	Sixth Quarterly Progress Report
19		
20	5.2	Final Selection of LTPP Sections for Analysis
21	1.11	Seventh Quarterly Progress Report
	4.90	Complete Experiment 5
22	1.12	Third Interim Report (Analysis of Laboratory Studies)
23	3.4	Tables for Analysis of In-Service Pavement Sections
24	1.13	Eighth Quarterly Progress Report
	5.3	Compile Data From Accelerated Pavement Tests and Test Roads
25		
26		
27	1.14	Ninth Quarterly Progress Report
	2.3	Incorporate Findings from Laboratory Studies into NCHRP 9-44A_Version 0.2 Software
	5.4	Complete Analysis of Accelerated Pavement Tests and Test Roads
28		
29	2.4	Modify Approach Based on Analysis of Selected Accelerated Pavement Tests and NCHRP 9-44A_Version 0.3 Software
30	1.15	Tenth Quarterly Progress Report
	1.16	Fourth Interim Report (Design Procedure Incorporating Findings From Laboratory Studies and Analysis of Accelerated Pavement Tests)
31	1.17	Second Panel Presentation (Interim Reports 3 and 4)
32	5.5	Complete Data Collection for LTPP Sections
33	1.18	Eleventh Quarterly Progress Report
34		
35	5.6	Complete Testing and Analysis of LTPP Sections
36	1.19	Twelfth Quarterly Progress Report
37		
38		
39	1.20	Thirteenth Quarterly Progress Report
40		
41	2.5	Prepare Final Design Procedure and NCHRP 9-44A_Version 1.0 Software
	3.5	Final Database
42	1.21	Fifth Interim Report (Analysis of Validation Sections and Final Design Procedure)
	1.22	Fourteenth Quarterly Progress Report
43		
44		
45	1.23	Submit Draft of Final Report
	1.24	Fifteenth Quarterly Progress Report
46	1.25	Third Panel Presentation (Draft Final Report and Recommendations for Implementation and Additional Research
47		
48	1.26	Revised Final Report

Budget

The budget for the project is based on the labor hour estimates provided in the Task by Task Description of the Research Plan and the loaded hourly rates presented in Table 32 for various categories of labor. Travel costs were included for the panel meetings in Task 1.3 and for the LTPP site visits in Task 5.4. Printing costs were also included in Task 1.3 for each of the Interim Reports and the Final Report. The overall budget is presented in Figure 23. Details of the travel and printing estimates are provided in Tables 33 and 34, respectively.

Table 32. Labor Costs Used in Budget Preparation.

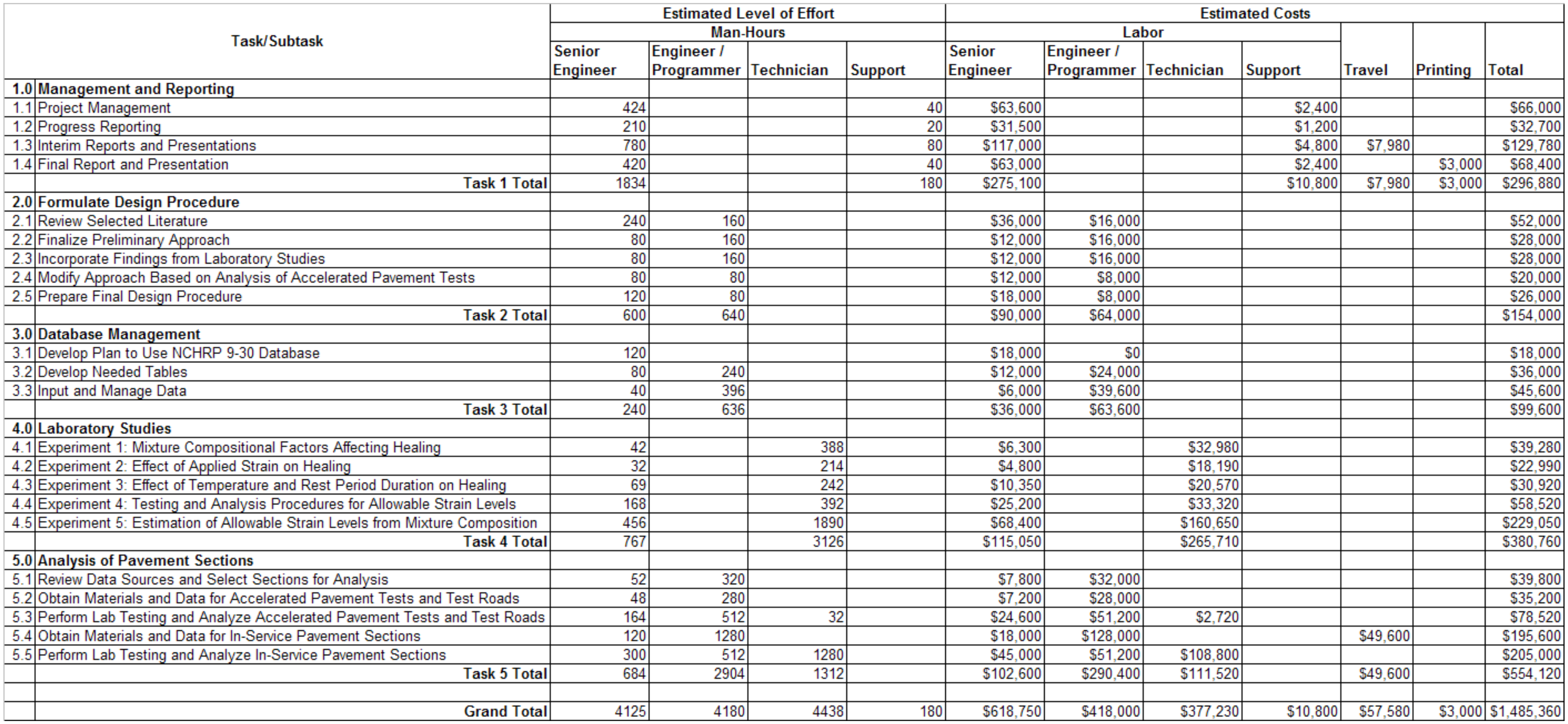
Labor Category	Loaded Hourly Rate
Senior Engineers and Statistician	$150.00
Engineers and Programmers	$100.00
Technicians	$85.00
Administrative Support	$60.00

Table 33. Travel Cost Estimate.

Task	Item	Detail	Estimate
1.3	Transportation	3 presentations × 2 people × $800 per trip	$4,800
1.3	Lodging & Per Diem	3 presentations × 2 people × 2 days × $265/day	$3,180
		Task 1.3 Total	**$7,980**
5.4	Airfare	2 person × 16 projects × $800 per site	$25,600
5.4	Rental Car	1 car × 4 days × 16 sites × $75.00/day	$4,800
5.4	Lodging & Per Diem	2 × 5 days × 16 sites × $120.00/ day	$19,200
		Task 5.4 Total	**$49,600**

Table 34. Estimate of Report Printing Costs.

Report	Pages	Copies	Cost /Page	Cost
Interim 1	300	20	$0.05	$300
Interim 2	300	20	$0.05	$300
Interim 3	300	20	$0.05	$300
Interim 4	300	20	$0.05	$300
Interim 5	300	20	$0.05	$300
Revised Final	300	100	$0.05	$1,500
Total				**$3,000**



Task/Subtask		Estimated Level of Effort				Estimated Costs						
		Man-Hours				Labor						
		Senior Engineer	Engineer / Programmer	Technician	Support	Senior Engineer	Engineer / Programmer	Technician	Support	Travel	Printing	Total
1.0	**Management and Reporting**											
1.1	Project Management	424			40	$63,600			$2,400			$66,000
1.2	Progress Reporting	210			20	$31,500			$1,200			$32,700
1.3	Interim Reports and Presentations	780			80	$117,000			$4,800	$7,980		$129,780
1.4	Final Report and Presentation	420			40	$63,000			$2,400		$3,000	$68,400
	Task 1 Total	1834			180	$275,100			$10,800	$7,980	$3,000	$296,880
2.0	**Formulate Design Procedure**											
2.1	Review Selected Literature	240	160			$36,000	$16,000					$52,000
2.2	Finalize Preliminary Approach	80	160			$12,000	$16,000					$28,000
2.3	Incorporate Findings from Laboratory Studies	80	160			$12,000	$16,000					$28,000
2.4	Modify Approach Based on Analysis of Accelerated Pavement Tests	80	80			$12,000	$8,000					$20,000
2.5	Prepare Final Design Procedure	120	80			$18,000	$8,000					$26,000
	Task 2 Total	600	640			$90,000	$64,000					$154,000
3.0	**Database Management**											
3.1	Develop Plan to Use NCHRP 9-30 Database	120				$18,000	$0					$18,000
3.2	Develop Needed Tables	80	240			$12,000	$24,000					$36,000
3.3	Input and Manage Data	40	396			$6,000	$39,600					$45,600
	Task 3 Total	240	636			$36,000	$63,600					$99,600
4.0	**Laboratory Studies**											
4.1	Experiment 1: Mixture Compositional Factors Affecting Healing	42		388		$6,300		$32,980				$39,280
4.2	Experiment 2: Effect of Applied Strain on Healing	32		214		$4,800		$18,190				$22,990
4.3	Experiment 3: Effect of Temperature and Rest Period Duration on Healing	69		242		$10,350		$20,570				$30,920
4.4	Experiment 4: Testing and Analysis Procedures for Allowable Strain Levels	168		392		$25,200		$33,320				$58,520
4.5	Experiment 5: Estimation of Allowable Strain Levels from Mixture Composition	456		1890		$68,400		$160,650				$229,050
	Task 4 Total	767		3126		$115,050		$265,710				$380,760
5.0	**Analysis of Pavement Sections**											
5.1	Review Data Sources and Select Sections for Analysis	52	320			$7,800	$32,000					$39,800
5.2	Obtain Materials and Data for Accelerated Pavement Tests and Test Roads	48	280			$7,200	$28,000					$35,200
5.3	Perform Lab Testing and Analyze Accelerated Pavement Tests and Test Roads	164	512	32		$24,600	$51,200	$2,720				$78,520
5.4	Obtain Materials and Data for In-Service Pavement Sections	120	1280			$18,000	$128,000			$49,600		$195,600
5.5	Perform Lab Testing and Analyze In-Service Pavement Sections	300	512	1280		$45,000	$51,200	$108,800				$205,000
	Task 5 Total	684	2904	1312		$102,600	$290,400	$111,520		$49,600		$554,120
	Grand Total	4125	4180	4438	180	$618,750	$418,000	$377,230	$10,800	$57,580	$3,000	$1,485,360

Figure 23. Project Budget.

The total cost of the the project is $1,485,360. Figure 24 provides a estimate of monthly expenditures for the project. Monthly expenditures reach approximately $52,000 per month when the laboratory experiments are being conducted.

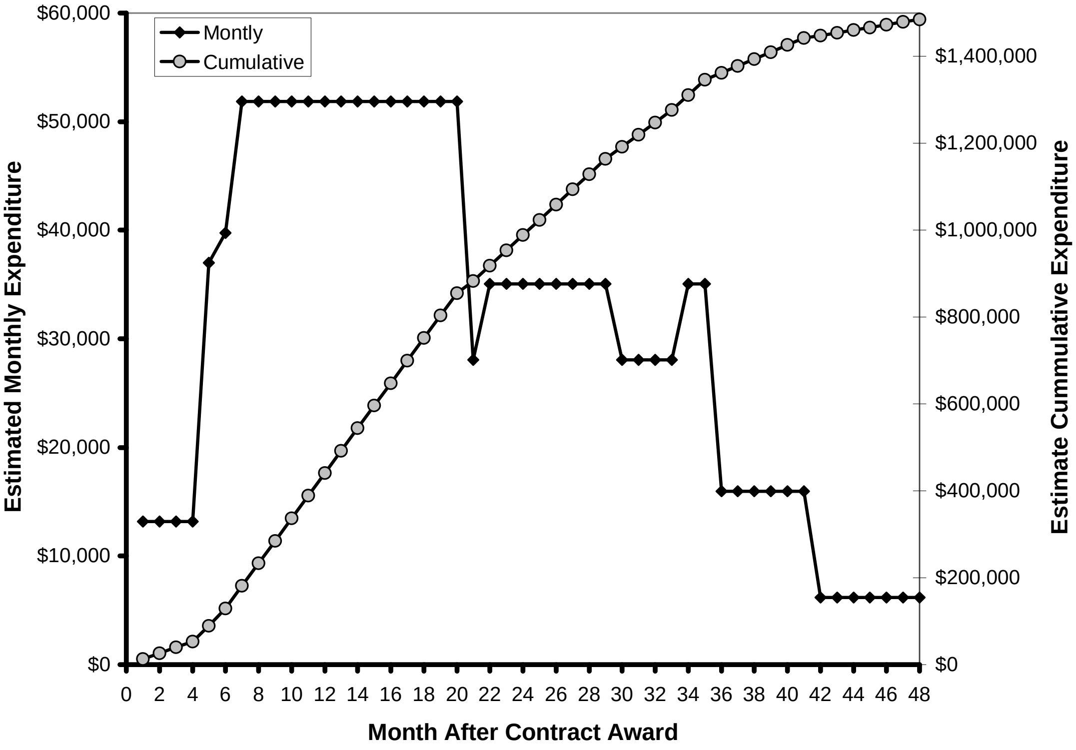


Figure 24. Estimated Monthly and Cumulative Expenditures.

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Attachment: Recommended LTPP Test Sections

The following provides location and summary information for the LTPP test sections that are applicable for use in confirming the endurance limit and values. The distress information listed for each test sections are the values included within the LTPP database. Specifically, the longitudinal cracking and transverse cracking values are in meters, while the block and alligator cracking values are in square meters.

LTPP Site Identification Number: 0103 State: Alabama (01)
Roadway or Route No.: US-280
Date of Construction: April 1991 Status: In Service

Location:
Longitude: 85.25 Latitude: 32.62 Elevation: 151

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid HMA, Dense Graded (1)	1.5
3	HMA	Hot Mixed, Hot Laid HMA, Dense Graded (1)	3.1
2	ATB	Asphalt Treated Base (319)	7.4
1	Subgrade Soil	Sandy Lean Clay (114)	---

Traffic Data:
Number of Years with Data: ______________
AADTT (One-way): ______________ Year: _______
KESALS per year: ______________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Sandy Lean Clay	6

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 200
Type of Asphalt: PG64-22

	HMA	HMA	ATB	
Asphalt Content, %	5.1	4.0	4.3	
Air Voids, %	3.3	5.1	11.6	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	83	61	24	6.7
HMA	90	66	48	21	7.2
ATB	90	65	42	18	5.6

Tensile Strain at Bottom of HMA Layer: ______________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1994	0	0	0	0	2001	22.9	0	9.7	0
1995	0	0	0	0	2002	28.7	0	0	1.5
1996	0	0	0	0	2003	34.4	0	0	7.9
2000	34.9	0	30.6	0	2004	40.1	0	0	8.7
					2005	41.4	0	0	8.0

LTPP Site Identification Number: 0101 State: Alabama (01)
Roadway or Route No.: US-280
Date of Construction: April 1991 Status: In Service

Location:
Longitude: 85.25 Latitude: 32.62 Elevation: 151

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid HMA, Dense Graded (1)	1.3
3	HMA	Hot Mixed, Hot Laid HMA, Dense Graded (1)	6.2
2	GB	Crushed Stone, Granular Base (303)	7.9
1	Subgrade Soil	Sandy Silt (145)	---

Traffic Data:
Number of Years with Data: ______________
AADTT (One-way): ______________ Year: _______
KESALS per year: ______________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Sandy Lean Clay	6

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 200
Type of Asphalt: PG64-22

	HMA	HMA		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					

Tensile Strain at Bottom of HMA Layer:______________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1995	0	0	0	0	2001	25.3	0	13.7	0.8
1996	1.2	0	4.5	0	2002	31.1	0	0	3.5
1997	0	0	37.5	0	2003	64.9	0	0	14.6
1998	3.0	0	0.2	0.3	2004	68.0	0	0	15.7
2000	38.6	0	16.2	0.6	2005	70.4	0	0	14.6

LTPP Site Identification Number: 0111 State: Alabama (01)
Roadway or Route No.: US 280
Date of Construction: April 1991 Status: In Service

Location:
Longitude: 85.25 Latitude: 32.61 Elevation: 151

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4,5	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	4.0
3	ATB	Hot Mixed, Hot Laid AC Dense Graded Mix (319)	7.9
2	PATB	Open-Graded Hot Laid Mix (325)	3.7
1	Subgrade Soil	Silt with Sand (143)	---

Traffic Data:
Number of Years with Data: _______
AADTT (One-way): _______ Year: _______
KESALS per year: _______

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Silt with Sand	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 200
Type of Asphalt: PG62-22

	HMA	HMA	ATB	PATB
Asphalt Content, %	5.2	4.0	4.3	2.2
Air Voids, %	3.3	5.1	11.6	---

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	83	61	24	6.7
HMA	90	66	48	21	7.2
ATB	90	65	42	18	5.6
PATB	71	19	10	7.0	4.3

Tensile Strain at Bottom of HMA Layer: 144.29

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1994	0	0	0	0	2001	92.7	0	0.5	0
1995	0	0	0	0	2001	67.8	0	0	1.2
1996	0	0	5.5	0	2003	86.4	0	0	2.4
2000	60.2	0	23.2	0	2004	86.9	0	0	3.3
					2005	89.0	0	0	3.5

LTPP Site Identification Number: 0116 State: Arizona (04)
Roadway or Route No.: US 93
Date of Construction: Jan. 1993 Status: In Service

Location:
Longitude: 114.2 Latitude: 35.39 Elevation: 3580

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	AC	Surface Seal (72), 2003	4.0
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	
2	ATB	Hot Mix, Hot Laid, AC, Dense Graded (1)	12.1
1	Subgrade Soil	Silty Sand with Gravel (215)	132

Traffic Data:
Number of Years with Data: 3
AADTT (One-way): 1190 Year: 1995
KESALS per year: 300

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus. ksi
1	Silty Sand with Gravel	4
	Last	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 200
Type of Asphalt:

	HMA	ATB		
Asphalt Content, %	4.7	4.5		
Air Voids, %	10.3	6.1		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	99	82	64	18	3.9
ATB	88	72	56	16	4.0

Tensile Strain at Bottom of HMA Layer: 142.48

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1995	0	0	0	0	2002	69.9	0	16.2	1.5
1998	0	0	0	0	2003	5.8	0	19.2	1.1
1999	1.4	0	2.1	0	2004	11.2	0	17.3	2.8
2000	4	0	3.3	0	2005	11.6	0	28.5	5.3
2001	9.9	0	22	0					

LTPP Site Identification Number: 04-0162 State: Arizona (04)
Roadway or Route No.: US 93
Date of Construction: Jan. 1993 Status: In Service

Location:
Longitude: 114.2 Latitude: 35.39 Elevation: 3580

Pavement Cross Section:

Layer		Material Type	Thickness, inches
3	AC	Seal Coat (72), 2003	9.0
2	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	
1	Subgrade Soil	Well Graded Gravel with Sand & Silt (261)	---

Traffic Data:
Number of Years with Data: 3
AADTT (One-way): 1190 Year: 1995
KESALS per year: 300

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus. ksi
1	Silty Sand with Gravel	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 200
Type of Asphalt: ______

	HMA			
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					

Tensile Strain at Bottom of HMA Layer: ______

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1995	0	0	0	0	2002	1.7	0	3.8	2.0
1998	0	0	0	0	2005	2.8	0	4.5	10.4
1999	0	0	0	0	2006	4.4	0	1.4	20.4
2000	0	0	0	0					
2001	0	0	1.0	0					

LTPP Site Identification Number: 1062 State: Arizona (04)
Roadway or Route No.: I 40
Date of Construction: 10-1-1977 Status: Milled/Overlay; Friction Course

Location:
Longitude: 113.34 Latitude: 35.19 Elevation: 5060

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	AC	Open-Graded Friction Course (82); 9-1999	0.3
5	AC	Open Graded, Sand Seal (2)	4.6 – after milling (5.8 – Original)
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	
3	ATB	Asphalt Treated Mixture (321)	11.2
2	TS	Lime Treated Mixture (338)	6
1	Subgrade Soil	Clayey Gravel with Sand (267)	54

Traffic Data:
Number of Years with Data: 8
AADTT (One-way): 1900 Year: 1998
KESALS per year: 1200

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lime Treated Mixture	28
1	Clayey Gravel with Sand	15

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ________

	HMA			
Asphalt Content, %	5.3			
Air Voids, %	5.5			

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	80.5	57	48.5	14.5	7.4

Tensile Strain at Bottom of HMA Layer: 49.15

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	6.4	2005	7.0	0	1.4	0.6
1998	0	0	0	8.7					
2000	0	0	0	0					
2003	0	0	0	0					

LTPP Site Identification Number: 1065 State: Arizona (04)
Roadway or Route No.: I 40
Date of Construction: 10-1-1977 Status: Milled/Overlay; Friction Course

Location:
Longitude: 113.26 Latitude: 35.2 Elevation: 5301

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	AC	Open-Graded Friction Course (82); 9-1999	0.3
4	AC	Hot Mixed, Hot Laid AC, Dense Graded (1)	5.3
3	TB	Asphalt Treated Mixture (319)	13.7
2	TS	Lime Treated Soil (338)	5
1	Subgrade Soil	Clayey Gravel with Sand (A-2-6)	---

Traffic Data:
Number of Years with Data: 8
AADTT (One-way): 1900 Year: 1998
KESALS per year: 1200

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lime Treated Soil	28
1	Clayey Gravel with Sand	15

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt:

	HMA			
Asphalt Content, %	5.6			
Air Voids, %	4.2			

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	77	54.5	47.5	14.5	7.2

Tensile Strain at Bottom of HMA Layer: 39.96

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1992	0	0	0	0	2005	0	0	2.7	0.7
1998	0	0	0	12.2					
2000	0	0	0	0					
2003	0	0	0	0.3					

LTPP Site Identification Number: 0115 State: Arkansas (05)
Roadway or Route No.: US 63
Date of Construction: Jan. 1993 Status: In Service

Location:
Longitude: 90.58 Latitude: 35.72 Elevation: 222

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.8
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	5.1
2	ATB	Hot Mixed, Hot Laid, Dense Graded (319)	7.4
1	Subgrade Soil	Silty Sand (214)	---

Traffic Data:
Number of Years with Data: 3
AADTT (One-way): 800 Year: 1998
KESALS per year: 776

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Silty Sand	---

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ---
Type of Asphalt:

	HMA	HMA	ATB	
Asphalt Content, %	4.5	3.7	2.95	
Air Voids, %	9.9	9.9	6.7	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	98	78	53	12	5.0
HMA	91	61	43	20	6.0
ATB	77	47	35	16	4.5

Tensile Strain at Bottom of HMA Layer: 0.00

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2003	21	0	0.7	7.7
2000	6.7	0	1.7	0.5	2004	22	0	0.8	8.9
2001	10.2	0	0	1.7	2005	25.4	0	0	12.6
2002	17.3	0	0	4.3					

LTPP Site Identification Number: 0114 State: Arkansas (05)
Roadway or Route No.: US 63
Date of Construction: Jan. 1993 Status: In Service

Location:
Longitude: 90.58 Latitude: 35.72 Elevation: 222

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.5
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	5.5
2	GB	Crushed Stone, Granular Base (303)	11.3
1	Subgrade Soil	Silty Sand (214)	---

Traffic Data:
Number of Years with Data: 3
AADTT (One-way): 800 Year: 1998
KESALS per year: 776

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Silty Sand	---

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ---
Type of Asphalt:

	HMA	HMA		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					

Tensile Strain at Bottom of HMA Layer:

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2003	39.8	0	0	18.6
2000	6.2	0	2.3	0.4	2004	59.1	0	1.2	37.3
2001	10.7	0	1.0	2.4	2005	81.6	0	0	79.3
2002	31.2	0	0	9.7					

LTPP Site Identification Number: 0116 State: Arkansas (05)
Roadway or Route No.: US 63
Date of Construction: Jan. 1993 Status: In Service

Location:
Longitude: 90.58 Latitude: 35.72 Elevation: 222

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.6
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	2.5
2	ATB	Hot Mixed, Hot Laid, Dense Graded (319)	12.0
1	Subgrade Soil	Poorly Graded Sand with Silt (204)	---

Traffic Data:
Number of Years with Data: 3
AADTT (One-way): 800 Year: 1998
KESALS per year: 776

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Silty Sand	---

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ---
Type of Asphalt:

	HMA	HMA	ATB	
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer:

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2003	15.5	0	0	11.7
2000	2.7	0	0.7	1.4	2004	15.5	0	0	16.9
2001	5.4	0	0	0.8	2005	19.9	0	0	21.1
2002	10.8	0	0	6.3					

LTPP Site Identification Number: 3071 State: Arkansas (05)
Roadway or Route No.: US 71
Date of Construction: 7-1-1987 Status: In Service

Location:
Longitude: 94.15 Latitude: 36.26 Elevation: 1311

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	AC	Seal Coat (72); Placed after construction	0.4
5	AC	Seal Coat (71)	0.5
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.5
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	3.9
2	ATB	Hot Mix, Hot Laid, Dense Graded (319)	10.5
1	Subgrade Soil	Lean Clay (214)	---

Traffic Data:
Number of Years with Data: 6
AADTT (One-way): 2925 Year: 1998
KESALS per year: 3102

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Subgrade Soil/Lean Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ______

	HMA	HMA		
Asphalt Content, %	4.9	4.45		
Air Voids, %	3.7	6.0		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	80	64	30	8.5
HMA	84	58	45	21	7.4

Tensile Strain at Bottom of HMA Layer: 69.28

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1991	0	0	0	0	1999	0	0	0	0
1994	0	0	1	0	2000	0	0	0	2.2
1995	0	0	0	0	2003	0.7	0	0	60.7
1997	0	0	0	0	2004	0.6	0	0	95.9

LTPP Site Identification Number: 0106 State: Florida (12)
Roadway or Route No.: US 27
Date of Construction: Jan. 1993 Status: In Service

Location:
Longitude: 80.69 Latitude: 26.54 Elevation: 14

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	2.1
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	5.0
3	ATB	Hot Mixed, Hot Laid AC, Dense Graded (319)	8.4
2	GB	Crushed Stone (303)	4
1	Subgrade Soil	Silty Sand with Gravel (215)	87.6

Traffic Data:
Number of Years with Data: ______
AADTT (One-way): ______ Year: ______
KESALS per year: ______

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Crushed Stone	25
1	Silty Sand with Gravel	12

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ______

	HMA	HMA	ATB	
Asphalt Content, %	6.2	5.2	2.5	
Air Voids, %	8.1	5.5	4.6	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	90	68	28	3.1
HMA	99	77	60	25	3.2
ATB					

Tensile Strain at Bottom of HMA Layer: 60.33

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	0	2003	0	0	0	0
2000	0	0	0	0	2004	0	0	1.7	1.1
2001	0	0	0	0	2005	0	0	2.3	1.3
2002	0	0	0	0					

LTPP Site Identification Number: 0104 State: Florida (12)
Roadway or Route No.: US 27
Date of Construction: Jan. 1993 Status: In Service

Location:
Longitude: 80.69 Latitude: 26.54 Elevation: 14

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.9
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	4.9
2	ATB	Hot Mixed, Hot Laid, Dense Graded (319)	12.1
1	Subgrade Soil	Poorly Graded Sand with Silt and Gravel (205)	87.6

Traffic Data:
Number of Years with Data: ______
AADTT (One-way): ______ Year: ______
KESALS per year: ______

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Poorly Graded Sand with Silt and Gravel	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ______

	HMA	HMA	ATB	
Asphalt Content, %	6.2	5.2	2.5	
Air Voids, %	4.2	3.9	5.9	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	90	68	28	3.1
HMA	99	77	60	25	3.2
ATB					

Tensile Strain at Bottom of HMA Layer: 45.71

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	0	2003	0	0	0	0
2000	0	0	0	0	2004	0.2	0	0	0
2001	0	0	0	0	2005	0.5	0	1.2	0
2002	0	0	0	0					

LTPP Site Identification Number: 0101 State: Florida (12)
Roadway or Route No.: US 27
Date of Construction: Jan. 1993 Status: In Service

Location:
Longitude: 80.69 Latitude: 26.54 Elevation: 14

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	2.0
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	4.8
2	GB	Crushed Stone (303)	8.1
1	Subgrade Soil	Silty Sand with Gravel (215)	68.4

Traffic Data:
Number of Years with Data: ______________
AADTT (One-way): ______________ Year: _______
KESALS per year: ______________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Crushed Stone	25
1	Silty Sand with Gravel	12

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ______________
Type of Asphalt: ______________

	HMA	HMA		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					

Tensile Strain at Bottom of HMA Layer:______________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	0	2003	0	0	0	0
2000	0	0	0	0	2004	0.1	0	0	0.3
2001	0	0	0	0	2005	0.2	0	0	0.8
2002	0	0	0	0					

LTPP Site Identification Number: 0103 State: Florida (12)
Roadway or Route No.: US 27
Date of Construction: Jan. 1993 Status: In Service

Location:
Longitude: 80.69 Latitude: 26.54 Elevation: 14

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	2.0
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	2.1
2	ATB	Hot Mixed, Hot Laid AC, Dense Graded (319)	8.0
1	Subgrade Soil	Poorly Graded Sand with Gravel & Silt (205)	87.6

Traffic Data:
Number of Years with Data: ________
AADTT (One-way): ________ Year: ______
KESALS per year: ________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Silty Sand with Gravel	12

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ________

	HMA	HMA	ATB	
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer: ________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	0	2003	0.6	0	0	0
2000	0	0	0	0	2004	2.6	0	0.6	0
2001	0	0	0	0	2005	3.4	0	7.8	0
2002	0	0	0.4	0					

LTPP Site Identification Number: 0107 State: Florida (12)
Roadway or Route No.: US 27
Date of Construction: Jan. 1993 Status: In Service

Location:
Longitude: 80.69 Latitude: 26.54 Elevation: 14

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	3.8
3	ATB	Hot Mixed, Hot Laid AC, Dense Graded (325)	4.1
2	GB	Crushed Stone (303)	4.1
1	Subgrade Soil	Poorly Graded Sand with Gravel & Silt (205)	105.6

Traffic Data:
Number of Years with Data: ______________
AADTT (One-way): ______________ Year: _______
KESALS per year: ______________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Crushed Stone	25
1	Silty Sand with Gravel	12

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ______________
Type of Asphalt: ______________

	HMA	HMA	ATB	
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer: ______________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	0	2003	1.6	0	5.9	0
2000	0	0	0	0	2004	11.6	0	54.3	0.3
2001	0	0	0	0	2005	12.1	0	52.8	0.6
2002	0	0	0	0					

LTPP Site Identification Number: 0111 State: Florida (12)
Roadway or Route No.: US 27
Date of Construction: Jan. 1993 Status: In Service

Location:
Longitude: 80.69 Latitude: 26.54 Elevation: 14

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.8
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	2.1
3	ATB	HMAC, Hot Laid, Dense Graded (319)	8.2
2	PATB	Open Graded Hot Mix, Hot Laid (325)	4.0
1	Subgrade Soil	Silty Sand with Gravel (215)	75.6

Traffic Data:
Number of Years with Data: ______
AADTT (One-way): ______ Year: ______
KESALS per year: ______

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Silty Sand with Gravel	12

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ______

	HMA	HMA	ATB	
Asphalt Content, %	6.1	5.2		
Air Voids, %	7.9	6.8	5.3	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	98	78	59	29	2.5
HMA	99	77	60	25	3.2
ATB					

Tensile Strain at Bottom of HMA Layer: 60.35

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	0	2003	0	0	0	0
2000	0	0	0	0	2004	0.3	0	8.0	1.2
2001	0	0	0	0	2005	0.5	0	13.1	1.6
2002	0	0	0	0					

LTPP Site Identification Number: 4113 State: Georgia (13)
Roadway or Route No.: IH 95
Date of Construction: 6-1-1977 Status: In Service

Location:
Longitude: 81.61 Latitude: 31.08 Elevation: 13

Pavement Cross Section:

Layer		Material Type	Thickness, inches
	AC	Seal Coat (71)	0.1
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	3.7
2	ATB	Asphalt Treated Mixture (321)	11.5
1	Subgrade Soil	Poorly Graded Sand with Silt (204)	---

Traffic Data:
Number of Years with Data: 6
AADTT (One-way): 3703 Year: 1997
KESALS per year: 1933

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Poorly Graded Sand with Silt	12

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt:

	HMA	ATB		
Asphalt Content, %	5.31	4.14		
Air Voids, %	2.1	4.5		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	99	63	46	27	3.7
ATB	74	47	40	22	3.9

Tensile Strain at Bottom of HMA Layer: 65.52

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1991	0	0	0	0	1999	0	0	0	0
1994	0	0	0	1	2000	0	0	0	0
1997	4.4	0	9.5	2					
1998	4.1	0	11.3	2.1					

LTPP Site Identification Number: 4119 State: Georgia (13)
Roadway or Route No.: IH 75
Date of Construction: 6-1-1978 Status: In Service

Location:
Longitude: 84.21 Latitude: 34.09 Elevation: 815

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	AC	Friction Course (2)	0.8
4	HMAA	Hot Mixed, Hot Laid AC, Dense Graded (1)	2.0
3	ATB	Hot Mixed, Hot Laid, Dense Graded (319)	13.8
2	GS	Soil Agg. Mix (308)	16.4
1	Subgrade Soil	Sandy Silt (145)	---

Traffic Data:
Number of Years with Data: 3
AADTT (One-way): 5568 Year: 1996
KESALS per year: 2906

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus ksi
1	Soil Agg. Mix	14
2	Sandy Silt	9

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: __________

	HMA	ATB		
Asphalt Content, %	5.6	4.75		
Air Voids, %	3.0	5.9		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	96	75	61	17	9.5
ATB	72	63	52	15	8.5

Tensile Strain at Bottom of HMA Layer: 58.55

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1992	0	0	0	0					
1994	0	0	0	0					
1995	0	0	0	1.7					

LTPP Site Identification Number: 4112 State: Georgia (13)
Roadway or Route No.: IH 95
Date of Construction: 6-1-1977 Status: In Service

Location:
Longitude: 81.6 Latitude: 31.02 Elevation: 13

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	AC	Seal Coat (72)	0.1
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	3.2
2	ATB	Hot Mixed, Hot Laid, Dense Graded (319)	12.7
1	Subgrade Soil	Poorly Graded Sand (202)	---

Traffic Data:
Number of Years with Data: 6
AADTT (One-way): 3703 Year: 1997
KESALS per year: 1933

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Poorly Graded Sand	12

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt:

	HMA	ATB		
Asphalt Content, %	5.69	4.63		
Air Voids, %	2.1	5.9		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	99	59	44	31	3.5
ATB	84	51	44	25	3.5

Tensile Strain at Bottom of HMA Layer: 60.74

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1991	0	0	0	0	1998	0	0	0	0
1994	0	0	0	0	1999	0	0	0	0
1997	0	0	0	0	2000	0	0	0	0

LTPP Site Identification Number: 9034 State: Idaho (16)
Roadway or Route No.: 95
Date of Construction: 9-30-1988 Status: In Service

Location:
Longitude: 116.5 Latitude: 48.42 Elevation: 2119

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	AC	Seal Coat (71)	0.6
5	AC	Seal Coat (71)	
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	2.9
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	6.0
2	GB	Crushed Stone Base (303)	18.8
1	Subgrade Soil	Silty Gravel with Sand (265)	---

Traffic Data:
Number of Years with Data: ______
AADTT (One-way): ______ Year: ______
KESALS per year: ______

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Poorly Graded Sand	

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ______
Type of Asphalt: ______

	HMA	HMA		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					

Tensile Strain at Bottom of HMA Layer: ______

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1994	0	0	44.5	0.7	2004	17.3	0	0	4.8
1997	2.3	0	66.2	5.3					
1998	2.3	0	68.8	3.5					
2001	0	0	0	0					

LTPP Site Identification Number: 2009 State: Indiana (18)
Roadway or Route No.: ST 37
Date of Construction: Jan. 1981 Status: Out of Service; 4-1999

Location:
Longitude: 86 Latitude: 40.03 Elevation: 785

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	AC	Seal Coat, Slurry Seal (72)	0.5
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	5.7
4	ATB	Dense Graded, Cold Laid, Plant Mix (326)	6.5
3	PATB	Open Graded, Hot Mix, Hot Laid (323)	3.3
2	GB	Gravel, Uncrushed (302)	9.5
1	Subgrade Soil	Sandy Lean Clay (114)	---

Traffic Data:
Number of Years with Data: 2
AADTT (One-way): 481 Year: 1991
KESALS per year: 408

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Gravel (uncrushed)	100
1	Sandy Lean Clay	7

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt:

	HMA	ATB		
Asphalt Content, %	3.4			
Air Voids, %	6.6			

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	78	45	32	8.0	3.7
ATB					

Tensile Strain at Bottom of HMA Layer: 103.87

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1993	3.7	0	0	44.7					
1995	5.9	0	12	51.7					

LTPP Site Identification Number: 0112 State: Iowa (19)
Roadway or Route No.: US 61
Date of Construction: May 1992 Status: In Service

Location:
Longitude: 91.25 Latitude: 40.70 Elevation: 530

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.5
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.1
4	ATB	HMAC, Hot Laid, Dense Graded	12.4
3	PATB	Open-Graded Hot-Mix, Hot Laid;	4.1
2	GS	Lean Clay with Sand	24
1	Subgrade Soil	Clay	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 425 Year: 1992
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lean Clay with Sand	6
1	Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: PG70-22

	HMA	ATB		
Asphalt Content, %	4.8	4.5		
Air Voids, %	10.0	8.5		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	92	57	39		5.3
ATB	96	68	47		6.2

Tensile Strain at Bottom of HMA Layer: 43.50

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1995	0	0	0	0	2005	0.3	0	16.4	12.3
1999	0	0	1.2	10.4					
2001	0	0	5	17.3					
2002	0	0	0	6.3					

LTPP Site Identification Number: 0101 State: Iowa (19)
Roadway or Route No.: US 61
Date of Construction: May 1992 Status: In Service

Location:
Longitude: 91.25 Latitude: 40.70 Elevation: 530

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.0
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	6.0
3	GB	Crushed Stone Base (303)	8.0
2	GS	Embankment Soil; Clay with Gravel (104)	24
1	Subgrade Soil	Clay with Gravel (104)	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 425 Year: 1992
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lean Clay with Sand	6
1	Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA:
Type of Asphalt: PG70-22

	HMA	HMA		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					

Tensile Strain at Bottom of HMA Layer:

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1995	15.0	0	0	0	2005	0.8	0	0	14.8
1999	7.5	0	7.3	15.3					
2001	12.1	0	15.3	32.0					
2002	1.3	0	0	9.9					

LTPP Site Identification Number: 0103 State: Iowa (19)
Roadway or Route No.: US 61
Date of Construction: May 1992 Status: In Service

Location:
Longitude: 91.25 Latitude: 40.70 Elevation: 530

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	2.1
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.7
3	ATB	Dense Graded Asphalt Treated Base (319)	8.4
2	GS	Embankment Soil; Clay with Gravel (104)	24
1	Subgrade Soil	Clay with Sand (107)	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 425 Year: 1992
KESALS per year: ______________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lean Clay with Sand	6
1	Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ______________
Type of Asphalt: PG70-22

	HMA	HMA	ATB	
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer:______________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1995	0	0	0	0	2005	9.8	0	0	12.5
1999	5.3	0	17.1	16.4					
2001	5.4	0	21.4	34.6					
2002	2.2	0	6.8	12.8					

LTPP Site Identification Number: 0105 State: Iowa (19)
Roadway or Route No.: US 61
Date of Construction: May 1992 Status: In Service

Location:
Longitude: 91.25 Latitude: 40.70 Elevation: 530

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.8
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.7
3	ATB	Dense Graded Asphalt Treated Base (319)	4.7
3	GB	Crushed Stone Base (303)	4.0
2	GS	Embankment Soil; Clay with Gravel (104)	24
1	Subgrade Soil	Clay with Gravel (104)	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 425 Year: 1992
KESALS per year: ______

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lean Clay with Sand	6
1	Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ______
Type of Asphalt: PG70-22

	HMA	HMA	ATB	
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer: ______

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1995	0	0	18.5	1.0	2005	1.1	0	0	23.0
1999	0	0	105.0	25.7					
2001	2.1	0	103.4	26.7					
2002	0.7	0	0	8.9					

LTPP Site Identification Number: 0115 State: Louisiana (22)
Roadway or Route No.: US 171
Date of Construction: Nov. 1992 Status: In Service

Location:
Longitude: 93.20 Latitude: 30.33 Elevation: 27

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.7
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	5.3
3	ATB	Hot Mixed, Hot Laid AC, Dense Graded (319)	9.0
2	GS	Crushed Stone (131)	12.0
1	Subgrade Soil	Lean Inorganic Clay (102)	---

Traffic Data:
Number of Years with Data: ______
AADTT (One-way): ______ Year: ______
KESALS per year: ______

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Crushed Stone	8
1	Lean Inorganic Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ______

	HMA	HMA	ATB	
Asphalt Content, %	4.0	4.1	4.1	
Air Voids, %	5.4	2.0	4.8	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	82	58	24	6.0
HMA	100	83	57	25	5.3
ATB					

Tensile Strain at Bottom of HMA Layer: 69.98

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0					
1999	0	0	0	0					
2004	0	0	0	0					

LTPP Site Identification Number: 0116 State: Louisiana (22)
Roadway or Route No.: US 171
Date of Construction: Nov. 1992 Status: In Service

Location:
Longitude: 93.20 Latitude: 30.33 Elevation: 27

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.9
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	2.8
3	ATB	Hot Mixed, Hot Laid AC, Dense Graded (319)	11.3
2	GS	Crushed Stone (131)	18.0
1	Subgrade Soil	Lean Inorganic Clay (102)	---

Traffic Data:
Number of Years with Data: ________
AADTT (One-way): ________ Year: ____
KESALS per year: ________

Unbound Layers Resilient Modulus:

Layer No.	Material/Soil Type	Equivalent Resilient Modulus
2	Crushed Stone	8
1	Lean Inorganic Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ________

	HMA	HMA	ATB	
Asphalt Content, %	4.0	4.1	4.1	
Air Voids, %	2.1	3.3	6.1	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	82	58	24	6.0
HMA	100	83	57	25	5.3
ATB					

Tensile Strain at Bottom of HMA Layer: 69.28

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0					
1999	0	0	0	0					
2004	0	0	0	0					

LTPP Site Identification Number: 0114 State: Louisiana (22)
Roadway or Route No.: US 171
Date of Construction: Nov. 1992 Status: In Service

Location:
Longitude: 93.20 Latitude: 30.33 Elevation: 27

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.4
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	8.1
3	GB	Crushed Stone (303)	11.4
2	GS	Embankment, Silty Clay with Sand (133)	12.0
1	Subgrade Soil	Lean Inorganic Clay (102)	---

Traffic Data:
Number of Years with Data: ______
AADTT (One-way): ______ Year: ______
KESALS per year: ______

Unbound Layers Resilient Modulus:

Layer No.	Material/Soil Type	Equivalent Resilient Modulus
3	Crushed Stone	8
1	Lean Inorganic Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ______
Type of Asphalt: ______

	HMA	HMA		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					

Tensile Strain at Bottom of HMA Layer: ______

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0					
1999	0	0	0	0					
2004	0	0	0	0					

LTPP Site Identification Number: 0124 State: Louisiana (22)
Roadway or Route No.: US 171
Date of Construction: Nov. 1992 Status: In Service

Location:
Longitude: 93.20 Latitude: 30.33 Elevation: 27

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	1.3
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	5.9
4	ATB	Hot Mixed, Hot Laid, Plant Mix (319)	10.6
3	PATB	Open Graded, Hot Mix, Hot Laid (325)	3.6
2	GS	Embankment; Silt (141)	30
1	Subgrade Soil	Lean Inorganic Clay (102)	---

Traffic Data:
Number of Years with Data: ______
AADTT (One-way): ______ Year: ______
KESALS per year: ______

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Silt	8
1	Lean Inorganic Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ______

	HMA	HMA	ATB	
Asphalt Content, %	4.0	4.1	4.1	
Air Voids, %	5.3	2.9	6.8	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	82	58	24	6.0
HMA	100	83	57	25	5.3
ATB					

Tensile Strain at Bottom of HMA Layer: 41.06

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0					
1999	0	0	0	0					
2004	0	0	0	0					

LTPP Site Identification Number: 0116 State: Michigan (26)
Roadway or Route No.: US 27
Date of Construction: Aug. 1995 Status: Out of Service; 10-2002

Location:
Longitude: 84.52 Latitude: 42.99 Elevation: 810

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.8
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.1
2	ATB	HMAC	12.0
1	Subgrade Soil	Sandy Clay	---

Traffic Data:
Number of Years with Data: ________
AADTT (One-way): ________ Year: ____
KESALS per year: ________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Sandy Clay	4

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 300
Type of Asphalt: ________

	HMA	HMA	ATB	
Asphalt Content, %	5.1	5.0		
Air Voids, %	5.0	2.7	4.8	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	78	47		
HMA	86	58	42		5.5
ATB					4.8

Tensile Strain at Bottom of HMA Layer: 106.03

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1995	0	0	0	0	2000	0	0	0	0
1996	0	0	0	0	2001	0	0	0	0
1998	0	0	0	0	2002	30.5	0	0	0
1999	0	0	0	0	2003	0	0	0	0

LTPP Site Identification Number: 0115 State: Michigan (26)
Roadway or Route No.: US 27
Date of Construction: Aug. 1995 Status: Out of Service; 10-2002

Location:
Longitude: 84.52 Latitude: 42.99 Elevation: 810

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.7
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.6
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.6
2	ATB	HMAC	9.6
1	Subgrade Soil	Sandy Clay	---

Traffic Data:
Number of Years with Data: ______________
AADTT (One-way): ______________ Year: _______
KESALS per year: ______________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Sandy Clay	4

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 300
Type of Asphalt: ______________

	HMA	HMA	ATB	
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer: ______________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1995	0	0	0	0	2000	0	0	0	0
1996	0	0	0	0	2001	0	0	0	0
1998	0	0	0	0	2002	105.7	0	0	0
1999	0	0	0	0	2003	0	0	0	0

LTPP Site Identification Number: 0116 State: Montana (30)
Roadway or Route No.: Interstate 15
Date of Construction: Oct. 1997 Status: In Service

Location:
Longitude: 111.53 Latitude: 47.41 Elevation: 3343

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	4.7
3	ATB	Hot Mixed, Hot Laid AC, Dense Graded	12.6
2	SS	Embankment Soil; A2-4, (SP-SM)	24
1	Subgrade Soil	Poorly Graded Sand with Silt; A-2-6	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 800 Year: 1998
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Subgrade Soil	12

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: AC-10

	HMA	HMA	ATB	
Asphalt Content, %	5.0	5.0	4.7	
Air Voids, %	7.5	6.0	5.5	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	85	45		6.0
HMA	88	57	39		4.2
ATB	84	48	32		4.5

Tensile Strain at Bottom of HMA Layer: 52.58

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0	2002	3	0	0	0
1999	0	0	0	0	2003	8.1	0	0	0
2000	0	0	0	0	2004	55.4	0	0	0
2001	0.4	0	0	0	2005	0	0	0	0

LTPP Site Identification Number: 0114 State: Montana (30)
Roadway or Route No.: Interstate 15
Date of Construction: Oct. 1997 Status: In Service

Location:
Longitude: 111.53 Latitude: 47.41 Elevation: 3343

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5			
4	AC	Seal Coat	0.2
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded	7.2
2	GB	Granular Base, Crushed Stone (303)	12.4
1	Subgrade Soil	Poorly Graded Sand with Silt; A-2-6	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 800 Year: 1998
KESALS per year: ______________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Subgrade Soil	12

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ______________
Type of Asphalt: AC-10

	HMA			
Asphalt Content, %	5.0			
Air Voids, %	7.5			

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					

Tensile Strain at Bottom of HMA Layer: ______________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0	2002	20.0	0	1.5	0
1999	0	0	0	0	2003	46.6	0	0	0
2000	5.9	0	0	0	2004	47.8	0	2.7	3.8
2001	9.0	0	5.1	0	2005	1.4	0	0	7.0

LTPP Site Identification Number: 0115 State: Montana (30)
Roadway or Route No.: Interstate 15
Date of Construction: Oct. 1997 Status: In Service

Location:
Longitude: 111.53 Latitude: 47.41 Elevation: 3343

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5			
4	AC	Seal Coat	0.2
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded	7.4
2	ATB	Hot Mixed, Hot Laid AC, Dense Graded	9.2
1	Subgrade Soil	Poorly Graded Sand with Silt; A-2-6	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 800 Year: 1998
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Subgrade Soil	12

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA:
Type of Asphalt: AC-10

	HMA	ATB		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer:

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0	2002	26.5	0	0	0
1999	0	0	0	0	2003	64.5	0	11.2	8.6
2000	0	0	0	0	2004	48.5	0	10.0	7.0
2001	23.1	0	0	0	2005	1.2	0	0	0

LTPP Site Identification Number: 0124 State: Montana (30)
Roadway or Route No.: Interstate 15
Date of Construction: Oct. 1997 Status: In Service

Location:
Longitude: 111.53 Latitude: 47.41 Elevation: 3343

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded (1)	7.1
3	ATB	HMAC, Hot Laid, Central Plant Mix (319)	13.7
2	PATB	Open Graded, Hot Mixed, Hot Laid (323)	4.2
1	Subgrade Soil	Poorly Graded Sand with Silt	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 800 Year: 1998
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Poorly Graded Sand with Silt	8

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 400
Type of Asphalt: AC-10

	HMA	HMA	ATB	
Asphalt Content, %	5.0	5.0	4.7	
Air Voids, %	7.5	6.0	5.5	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	85	45		6.0
HMA	88	57	39		4.2
ATB	84	48	32		4.5

Tensile Strain at Bottom of HMA Layer: 31.16

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0	2002	8	0	1.4	0
1999	0	0	0	0	2003	14.8	0	0	0
2000	0.6	0	3.3	0	2004	29.0	0	0	2.3
2001	4.3	0	5.4	0	2005	0.2	0	0	3.7

LTPP Site Identification Number: 0124 State: Nebraska (31)
Roadway or Route No.: US 281
Date of Construction: July 1995 Status: Out of Service; 9-2002

Location:
Longitude: 97.62 Latitude: 40.07 Elevation: 1611

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	7.4
4	ATB	HMAC, Hot Laid, Central Plant Mix	10.5
3	PATB	Open Graded, Hot Mixed, Hot Laid	3.4
2	GS	Lean Inorganic Clay	24
1	Subgrade Soil	Lean Inorganic Clay	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 450 Year: 1997
KESALS per year:

Unbound Layers Resilient Modulus:

Layer No.	Material/Soil Type	Equivalent Resilient Modulus
2	Lean Inorganic Clay	5
1	Lean Inorganic Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: PG64-22

	HMA	ATB		
Asphalt Content, %	4.5	4.5		
Air Voids, %	6.8	3.0		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	87	74		6.9
ATB	97	72	53		3.9

Tensile Strain at Bottom of HMA Layer: 43.40

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1995	0	0	0	0					
1999	0	0	0	0					
2002	0	0	0	0					

LTPP Site Identification Number: 0115 State: Nebraska (31)
Roadway or Route No.: US 81
Date of Construction: July 1995 Status: In Service

Location:
Longitude: 97.62 Latitude: 40.07 Elevation: 1611

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	6.5
3	ATB	HMAC	8.6
2	GS	Lean Inorganic Clay; A-6	24
1	Subgrade Soil	Lean Inorganic Clay; A-7-5	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 450 Year: 1997
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lean Inorganic Clay	5
1	Lean Inorganic Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt:

	HMA	ATB		
Asphalt Content, %	4.8	4.1		
Air Voids, %	5.0	9.0		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	87	74		6.9
ATB	97	72	53		3.9

Tensile Strain at Bottom of HMA Layer: 79.91

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1995	0	0	0	0					
1999	0	0	0	0					
2002	0	0	0	0					

LTPP Site Identification Number: 0116 State: Nebraska (31)
Roadway or Route No.: US 81
Date of Construction: July 1995 Status: In Service

Location:
Longitude: 97.62 Latitude: 40.07 Elevation: 1611

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded; (1)	4.1
3	ATB	Hot Mixed, Hot Laid AC, Dense Graded (1)	12.2
2	GS	Lean Inorganic Clay; A-6	24.0
1	Subgrade Soil	Lean Inorganic Clay; A-7-6	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 450 Year: 1997
KESALS per year:

Unbound Layers Resilient Modulus:

Layer No.	Material/Soil Type	Equivalent Resilient Modulus
2	Lean Inorganic Clay	5
1	Lean Inorganic Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: PG64-22

	HMA	ATB		
Asphalt Content, %	4.7	4.1		
Air Voids, %	4.5	7.0		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	87	74		6.9
ATB	95	68	50		2.2

Tensile Strain at Bottom of HMA Layer: 70.02

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1995	0	0	0	0					
1999	0	0	0	0					
2002	0	0	0	0					

LTPP Site Identification Number: 0104 State: Nevada (32)
Roadway or Route No.: Interstate 80
Date of Construction: Aug. 1995 Status: In Service

Location:
Longitude: 117.01 Latitude: 40.69 Elevation: 4550

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	7.3
4	ATB	Hot Mixed, Hot Laid, Plant Mix	12.4
3	GS	Soil Agg. Mix.	18.4
2	TS	Lime Treated Soil	12.0
1	Subgrade Soil	Silty Sand	---

Traffic Data:
Number of Years with Data: 1
AADTT (One-way): 926 Year: 1996
KESALS per year: 492

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
3	Lime Treated Soil	14
2	Soil Agg. Mix.	28
1	Silty Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: PG64-22

	HMA	ATB		
Asphalt Content, %	4.7	4.6		
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	96	73	62	21	5.6
ATB					

Tensile Strain at Bottom of HMA Layer: 37.37

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	0	2002	0	0	0	0
1998	0	0	18.8	0	2003	0	0	0	0.9
1999	5	0	0	0	2004	0	0	0	1.2
2000	0	0	0	0	2005	0	0	0	3.1
2001	0	0	0	0	2006	0	0	0	5.6

LTPP Site Identification Number: 0101 State: Nevada (32)
Roadway or Route No.: Interstate 80
Date of Construction: Aug. 1995 Status: In Service

Location:
Longitude: 117.01 Latitude: 40.69 Elevation: 4550

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	7.2
4	GB	Crushed Gravel (304)	8.5
3	GS	Soil Agg. Mix, predominately coarse grained (308)	22.8
2	TS	Lime Treated Soil (338)	12.0
1	Subgrade Soil	Silty Sand (214)	---

Traffic Data:
Number of Years with Data: 1
AADTT (One-way): 926 Year: 1996
KESALS per year: 492

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lime Treated Soil	14
3	Soil Agg. Mix.	28
1	Silty Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ____________________
Type of Asphalt: PG64-22

	HMA			
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					

Tensile Strain at Bottom of HMA Layer:______________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2002	1.2	0	10.6	0
1998	0	0	7.3	0	2003	0	0	12.0	0
1999	0	0	0	0	2004	0.9	0	0	1.3
2000	0.5	0	0.3	0	2005	1.6	0	0	2.5
2001	1.4	0	0	0	2006	2.0	0	0	6.5

LTPP Site Identification Number: 0103 State: Nevada (32)
Roadway or Route No.: Interstate 80
Date of Construction: Aug. 1995 Status: In Service

Location:
Longitude: 117.01 Latitude: 40.69 Elevation: 4550

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	4.1
4	ATB	Hot Mixed, Hot Laid AC, Dense Graded	8.1
3	GS	Soil Agg. Mix.; coarse grained (308)	24.5
2	TS	Lime Treated Soil (338)	12.0
1	Subgrade Soil	Clayey Sand (216)	---

Traffic Data:
Number of Years with Data: 1
AADTT (One-way): 926 Year: 1996
KESALS per year: 492

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lime Treated Soil	14
3	Soil Agg. Mix.	28
1	Clayey Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: __________
Type of Asphalt: PG64-22

	HMA			
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					

Tensile Strain at Bottom of HMA Layer: __________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2002	28.8	0	0	0
1998	0	0	0	0	2003	32.9	0	0	0
1999	0	0	0	0	2004	34.1	0	0	0
2000	33.8	0	0	0					
2001	16.5	0	0	0					

LTPP Site Identification Number: 0105 State: Nevada (32)
Roadway or Route No.: Interstate 80
Date of Construction: Aug. 1995 Status: In Service

Location:
Longitude: 117.01 Latitude: 40.69 Elevation: 4550

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	HMA	Hot Mixed, Hot Laid AC, Dense Graded	4.2
5	ATB	Hot Mixed, Hot Laid AC, Dense Graded	4.8
4	GB	Crushed Gravel (304)	3.6
3	GS	Soil Agg. Mix.; coarse grained (308)	23.7
2	TS	Lime Treated Soil (338)	12.0
1	Subgrade Soil	Silty Sand (214)	---

Traffic Data:
Number of Years with Data: 1
AADTT (One-way): 926 Year: 1996
KESALS per year: 492

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lime Treated Soil	14
3	Soil Agg. Mix.	28
1	Silty Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ____________________
Type of Asphalt: PG64-22

	HMA	ATB		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer:______________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2002	0	0	1.5	0
1998	0	0	0	0	2003	1.3	0	0	0
1999	0.4	0	0	0	2004	1.5	0	0	0
2000	16.4	0	0	0					
2001	10.4	0	0	0					

LTPP Site Identification Number: 0106 State: Nevada (32)
Roadway or Route No.: Interstate 80
Date of Construction: Aug. 1995 Status: In Service

Location:
Longitude: 117.01 Latitude: 40.69 Elevation: 4550

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	HMA	Hot Mixed, Hot Laid AC, Dense Graded	7.2
5	ATB	Hot Mixed, Hot Laid AC, Dense Graded	8.8
4	GB	Crushed Gravel (304)	3.7
3	GS	Soil Agg. Mix.; coarse grained (308)	18.3
2	TS	Lime Treated Soil (338)	12.0
1	Subgrade Soil	Clayey Sand (216)	---

Traffic Data:
Number of Years with Data: 1
AADTT (One-way): 926 Year: 1996
KESALS per year: 492

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lime Treated Soil	14
3	Soil Agg. Mix.	28
1	Clayey Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ____________________
Type of Asphalt: PG64-22

	HMA	ATB		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer:______________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2002	0	0	1.3	1.0
1998	0	0	0	0	2003	0.2	0	0	1.3
1999	0	0	0	0	2004	0.2	0	0	1.7
2000	0	0	0	0	2005	0.3	0	0	2.3
2001	0	0	0	1.2	2006	0.5	0	0	3.9

LTPP Site Identification Number: 0112 State: Nevada (32)
Roadway or Route No.: Interstate 80
Date of Construction: Aug. 1995 Status: In Service

Location:
Longitude: 117.01 Latitude: 40.69 Elevation: 4550

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	HMA	Hot Mixed, Hot Laid AC, Dense Graded	4.5
5	ATB	HMAC, Hot Laid, Central Plant Mix	12.4
4	PATB	Open Graded, Hot Mixed, Hot Laid	4.2
3	GS	Soil Agg. Mix.	15.1
2	TS	Lime Treated Soil	12.0
1	Subgrade Soil	Clayey Sand	---

Traffic Data:
Number of Years with Data: 1
AADTT (One-way): 926 Year: 1996
KESALS per year: 492

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
3	Lime Treated Soil	14
2	Soil Agg. Mix.	28
1	Clayey Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: PG64-22

	HMA	ATB		
Asphalt Content, %	4.7	4.6		
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	95	70	54	16	5.0
ATB					

Tensile Strain at Bottom of HMA Layer: 33.35

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	0	2002	0	0	0	1.1
1998	0	0	0	0	2003	0	0	0	1.1
1999	0	0	0	0	2004	0	0	0	1.1
2000	0	0	0	0	2005	0.3	0	0	4.8
2001	0	0	0	1.1	2006	0.3	0	0	4.6

LTPP Site Identification Number: 0106 State: New Mexico (35)
Roadway or Route No.: IH 25
Date of Construction: Nov. 1995 Status: In Service

Location:
Longitude: 107.07 Latitude: 32.68 Elevation: 4117

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	AC	Friction Course	0.6
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	7.0
3	ATB	Hot Mixed, Hot Laid AC, Dense Graded	8
2	GB	Crushed Stone	2.9
1	Subgrade Soil	Sandy Fat Clay	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 594 Year: 1997
KESALS per year: 152

Unbound Layers Resilient Modulus:

Layer No.	Material/Soil Type	Equivalent Resilient Modulus
2	Crushed Stone	25
1	Sandy Fat Clay	5.5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt:

	HMA	ATB		
Asphalt Content, %	4.8	4.5		
Air Voids, %	7.0	7.3		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	95	71	53	17	5.2
ATB	97	78	57	19	4.5

Tensile Strain at Bottom of HMA Layer: 70.15

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2003	0	0	3.5	0
1999	0	0	0	0	2004	0	0	3.6	0
2000	0	0	0	0	2005	0	0	3.6	0
2001	0	0	0	0	2006	0.6	0	5.1	0
2002	0	0	3.5	0					

LTPP Site Identification Number: 0103 State: New Mexico (35)
Roadway or Route No.: IH 25
Date of Construction: Nov. 1995 Status: In Service

Location:
Longitude: 107.07 Latitude: 32.68 Elevation: 4117

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5			
4	AC	Friction Course (2)	0.6
3	HMA	Hot Mixed, Hot Laid AC, Dense Graded	4.7
2	ATB	Hot Mixed, Hot Laid AC, Dense Graded (319)	7.2
1	Subgrade Soil	Fat Inorganic Clay (103)	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 594 Year: 1997
KESALS per year: 152

Unbound Layers Resilient Modulus:

Layer No.	Material/Soil Type	Equivalent Resilient Modulus
1	Fat Inorganic Clay	5.5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ______________

	HMA	ATB		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer: ______________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2003	0.1	0	12.5	0
1999	0	0	0	0	2004	0.2	0	20.4	0
2000	0	0	0	0	2005	0.3	0	26.7	0
2001	0	0	0	0	2006	0.3	0	36.2	0.4
2002	0.1	0	11.0	0					

LTPP Site Identification Number: 0107 State: New Mexico (35)
Roadway or Route No.: IH 25
Date of Construction: Nov. 1995 Status: In Service

Location:
Longitude: 107.07 Latitude: 32.68 Elevation: 4117

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	AC	Friction Course (2)	0.6
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	5.3
3	ATB	Open Graded, Hot Mixed, Hot Laid AC (325)	3.7
2	GB	Crushed Stone Base (303)	4.0
1	Subgrade Soil	Sandy Fat Clay with Sand (109)	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 594 Year: 1997
KESALS per year: 152

Unbound Layers Resilient Modulus:

Layer No.	Material/Soil Type	Equivalent Resilient Modulus
1	Fat Clay with Sand	5.5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: __________

	HMA	ATB		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer: __________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2003	0.5	0	33.0	0
1999	0	0	0	0	2004	1.0	0	46.6	1.7
2000	0	0	0	0	2005	1.0	0	48.1	1.8
2001	0	0	0	0	2006	1.2	0	56.4	6.0
2002	0	0	22.6	0					

LTPP Site Identification Number: 0111 State: New Mexico (35)
Roadway or Route No.: IH 25
Date of Construction: Nov. 1995 Status: In Service

Location:
Longitude: 107.07 Latitude: 32.68 Elevation: 4117

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	AC	Friction Course	0.6
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	4.3
3	ATB	HMAC, Hot Laid, Central Plant Mix	7.6
2	PATB	Open Graded Mix	3.7
1	Subgrade Soil	Clayey Sand	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 594 Year: 1997
KESALS per year: 152

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Clayey Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt:

	HMA	ATB		
Asphalt Content, %	4.3	4.2		
Air Voids, %	8.2	7.3		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	95	73	51	16	4.0
ATB	97	78	57	19	4.5

Tensile Strain at Bottom of HMA Layer: 61.73

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2003	0	0	0	0
1999	0	0	0	0	2004	0	0	0	0
2000	0	0	0	0	2005	0	0	0	0
2001	0	0	0	0	2006	0	0	0	0
2002	0	0	0	0					

LTPP Site Identification Number: 0106 State: Ohio (39)
Roadway or Route No.: US 23
Date of Construction: Jan. 1994 Status: In Service

Location:
Longitude: 83.07 Latitude: 40.43 Elevation: 950

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	6.8
3	ATB	Hot Mixed, Hot Laid AC, Plant Mix	7.9
2	GB	Crushed Stone	3.9
1	Subgrade Soil	Silty Clay	---

Traffic Data:
Number of Years with Data:
AADTT (One-way): Year:
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Crushed Stone	10
1	Silty Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 250
Type of Asphalt:

	HMA	HMA	ATB	
Asphalt Content, %	6.5	6.5	5.2	
Air Voids, %	10.4	6.8	14.6	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	88	52	13	5.9
HMA	89	61	44	10	5.0
ATB	67	54	37	12	7.0

Tensile Strain at Bottom of HMA Layer: 128.23

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	0	2002	62.8	0	223.4	0
1997	0	0	0	0	2004	204.1	0	0	0
1999	0	0	9.5	0	2005	274.1	290	0	0
2001	17.7	0	201.6	0					

LTPP Site Identification Number: 0112 State: Ohio (39)
Roadway or Route No.: US 23
Date of Construction: Jan. 1994 Status: In Service

Location:
Longitude: 83.07 Latitude: 40.43 Elevation: 950

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.7
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.3
3	ATB	Hot Mixed, Hot Laid AC, Plant Mix	11.8
2	PATB	Open Graded, Plant Mix	4.0
1	Subgrade Soil	Silty Clay	---

Traffic Data:
Number of Years with Data: ______________
AADTT (One-way): ______________ Year: _______
KESALS per year: ______________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
1	Silty Clay	5

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 250
Type of Asphalt: ______________

	HMA	HMA	ATB	
Asphalt Content, %	6.5	6.5	5.2	
Air Voids, %	11.3	7.6	5.0	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	89	53	12	5.7
HMA	94	74	54	12	6.1
ATB	62	49	33	12	7.3

Tensile Strain at Bottom of HMA Layer: 128.23

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	0	2004	138.3	0	0	0
1999	0	0	3.5	0	2005	244.0	320	0	0
2001	0	0	107.5	0					
2002	20.5	0	37.8	0					

LTPP Site Identification Number: 0902 State: Ohio (39)
Roadway or Route No.: US 23
Date of Construction: Jan. 1994 Status: In Service

Location:
Longitude: 83.07 Latitude: 40.43 Elevation: 950

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.8
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.3
4	ATB	Asphalt Treated Mixture, Plant Mix	12.0
3	PATB	Open Graded, Hot Laid, Central Plant Mix	3.7
2	GS	Crushed Stone	6
1	Subgrade Soil	Silty Clay	---

Traffic Data:
Number of Years with Data:
AADTT (One-way): Year:
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
3	Open Graded, Hot Laid, Central Plant Mix	25
2	Crushed Stone	80
1	Silty Clay	8

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt:

	HMA	ATB		
Asphalt Content, %	6.4	5.4		
Air Voids, %	7.1	9.1		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	88	61		4.6
ATB	100	78	58		4.8

Tensile Strain at Bottom of HMA Layer: 49.22

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	0	2004	1.3	0	0	0
1999	0	0	0	0					
2001	0	0	4.9	0					

LTPP Site Identification Number: 0903 State: Ohio (39)
Roadway or Route No.: US 23
Date of Construction: Jan. 1994 Status: In Service

Location:
Longitude: 83.07 Latitude: 40.43 Elevation: 950

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.8
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.2
4	ATB	Asphalt Treated Mixture, Plant Mix	12.0
3	PATB	Open Graded, Hot Laid, Plant Mix	3.7
2	GS	Crushed Stone	6.0
1	Subgrade Soil	Silty Clay	---

Traffic Data:
Number of Years with Data: ______
AADTT (One-way): ______ Year: ______
KESALS per year: ______

Unbound Layers Resilient Modulus:

Layer No.	Material/Soil Type	Equivalent Resilient Modulus
3	Open Graded, Hot Laid, Central Plant Mix	25
2	Crushed Stone	80
1	Silty Clay	8

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ______

	HMA	ATB		
Asphalt Content, %	5.4	5.4		
Air Voids, %	12.8	11.4		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	86	51		4.7
ATB	100	67	49		7.0

Tensile Strain at Bottom of HMA Layer: 49.07

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1996	0	0	0	0	2004	154.1	0	0	0
1999	0	0	0	0					
2001	0	0	123.8	0					

LTPP Site Identification Number: 0115 State: Oklahoma (40)
Roadway or Route No.: US 62
Date of Construction: July 1997 Status: In Service

Location:
Longitude: 98.66 Latitude: 34.64 Elevation: ____

Pavement Cross Section:

Layer		Material Type	Thickness, inches
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	7.5
3	ATB	Asphalt Treated Base, Plant Mix	9.0
2	TS	Lime Treated Soil	8.0
1	Subgrade Soil	Clayey Sand	144

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 775 Year: 1997
KESALS per year: ____

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lime Treated Soil	28
1	Clayey Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: PG-6422

	HMA	HMA	ATB	
Asphalt Content, %	4.8	4.7	4.6	
Air Voids, %	4.5	3.0	4.5	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	86	63	46		5.3
HMA	82	55	41		7.6
ATB	79	52	38		8.9

Tensile Strain at Bottom of HMA Layer: 53.19

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2001	0	0	0	3.8
1997	0	0	0	0	2002	0	0	0	3.8
1999	0	0	0	0	2003	0	0	0	3.8
2000	0	0	0	2.2					

LTPP Site Identification Number: 0114 State: Oklahoma (40)
Roadway or Route No.: US 62
Date of Construction: July 1997 Status: In Service

Location:
Longitude: 98.66 Latitude: 34.64 Elevation: ________

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6			
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.0
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	6.1
3	GB	Granular, Crushed Stone (303)	11.3
2	TS	Lime Treated Soil (338)	8.0
1	Subgrade Soil	Clayey Sand (216)	6

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 775 Year: 1997
KESALS per year: ________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
3	Crushed Gravel	25
2	Lime Treated Soil	28
1	Clayey Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: PG64-22

	HMA	HMA		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					

Tensile Strain at Bottom of HMA Layer: ________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2002	3.9	0	0	0
1999	0	0	0	0	2003	12.6	0	0	0
2000	0	0	0	0	2004	22.5	0	0	0.6
2001	0	0	0	0	2006	32.3	0	0	5.0

LTPP Site Identification Number: 0117 State: Oklahoma (40)
Roadway or Route No.: US 62
Date of Construction: July 1997 Status: In Service

Location:
Longitude: 98.66 Latitude: 34.64 Elevation: ____________

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.9
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.7
4	ATB	Asphalt Treated Base, Plant Mix	8.3
3	GB	Granular, Crushed Gravel	3.6
2	TS	Lime Treated Soil	8.0
1	Subgrade Soil	Clayey Sand	72

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 775 Year: 1997
KESALS per year: ______________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
3	Crushed Gravel	25
2	Lime Treated Soil	28
1	Clayey Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: PG64-22

	HMA	HMA	ATB	
Asphalt Content, %	4.4	4.2	4.5	
Air Voids, %	8.0	5.0	3.0	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	82	63		4.1
HMA	85	50	47		4.8
ATB	82	55	41		8.3

Tensile Strain at Bottom of HMA Layer: 53.19

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2002	0	0	0	0
1999	0	0	0	0	2003	0.5	0	0	0
2000	0	0	0	0					
2001	0	0	0	0					

LTPP Site Identification Number: 0160 State: Oklahoma (40)
Roadway or Route No.: US 62
Date of Construction: July 1997 Status: In Service

Location:
Longitude: 98.66 Latitude: 34.64 Elevation:

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.5
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	6.5
4	ATB	Asphalt Treated Base, Plant Mix (319)	4.0
3	GB	Granular, Crushed Stone (303)	5.4
2	TS	Lime Treated Soil (338)	8.0
1	Subgrade Soil	Clayey Sand (216)	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 775 Year: 1997
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
3	Crushed Gravel	25
2	Lime Treated Soil	28
1	Clayey Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: PG64-22

	HMA	HMA	ATB	
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer:

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2002	0	0	0	0
1999	0	0	0	0	2003	0	0	0	0
2000	0	0	0	0	2004	0	0	0	0
2001	0	0	0	0	2006	0	0	0	0

LTPP Site Identification Number: 0116 State: Texas (48)
Roadway or Route No.: US 281
Date of Construction: April 1997 Status: Out of Service; 4-2002

Location:
Longitude: 98.11 Latitude: 26.74 Elevation: 84

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.4
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	3.5
3	ATB	Asphalt Treated Base, Plant Mix	10.9
2	TS	Lime Treated Soil	24.0
1	Subgrade Soil	Poorly Graded Sand With Silt	---

Traffic Data:
Number of Years with Data: ______
AADTT (One-way): ______ Year: ______
KESALS per year: ______

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lime Treated Soil	28
1	Poorly Graded Sand With Silt	12

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ______

	HMA	ATB		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer: 46.00

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2002	0	0	0	0
1998	0	0	0	0	2002	0	0	0	0
1999	0	0	0	0	2003	0	0	0	0
2000	0	0	0	0	2004	0	0	0	0
2001	0	0	0	0	2005	0.4	0	0	0

LTPP Site Identification Number: 0124 State: Texas (48)
Roadway or Route No.: US 281
Date of Construction: April 1997 Status: Out of Service; 4-2002

Location:
Longitude: 98.11 Latitude: 26.74 Elevation: 84

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.2
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	4.2
4	ATB	HMAC, Hot Laid, Central Plant Mix	10.8
3	PATB	Open Graded, Plant Mix	4.2
2	TS	Lime Treated Soil	24.0
1	Subgrade Soil	Poorly Graded Sand with Silt	---

Traffic Data:
Number of Years with Data: ______
AADTT (One-way): ______ Year: ______
KESALS per year: ______

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lime Treated Soil	28
1	Poorly Graded Sand with Silt	12

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ______

	HMA	ATB		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer: 30.69

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1997	0	0	0	0	2002	0	0	0	0
1998	0	0	0	0	2003	0	0	0	0
1999	0	0	0	0	2004	0	0	0	0
2000	0	0	0	0	2005	0	0	0	0
2001	0	0	0	0					

LTPP Site Identification Number: 1070 State: Texas (48)
Roadway or Route No.: SH 175
Date of Construction: 7-1-1977 Status: Out of Service; 7-2003

Location:
Longitude: 96.38 Latitude: 32.59 Elevation: 429

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.2
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	9.3
3	ATB	Other; Treated Layer	13.5
2	TS	Lime Treated Soil	10.0
1	Subgrade Soil	Fat Inorganic Clay	---

Traffic Data:
Number of Years with Data: 8
AADTT (One-way): 532 Year: 1997
KESALS per year: 153

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Lime Treated Soil	28
1	Fat Inorganic Clay	6

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: ______

	HMA	ATB		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer: 32.30

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1991	0	0	46	82	2000	1.8	216.7	25.6	215.2
1993	0	0	53.2	85.7	2002	1.5	220.8	23.6	215.0
1995	0	0	77.9	147.6	2003	1.7	211.6	16.1	245.9
1998	3.2	320.3	3	30.9					

LTPP Site Identification Number: 1048 State: Texas (48)
Roadway or Route No.: US 385
Date of Construction: 11-1-1974 Status: Out of Service; 8-1996

Location:
Longitude: 102.38 Latitude: 31.88 Elevation: 2942

Pavement Cross Section:

Layer		Material Type	Thickness, inches
3	HMA	Hot Mixed, Hot Laid, Dense Graded Mix (1)	1.2
2	ATB	Open Graded, Plant Mix (319)	9.8
1	Subgrade Soil	Coarse Grained Soil (215)	---

Traffic Data:
Number of Years with Data: 6
AADTT (One-way): 103 Year: 1996
KESALS per year: 20

Unbound Layers Resilient Modulus:

Layer No.	Material/Soil Type	Equivalent Resilient Modulus
1	215	---

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: ---
Type of Asphalt:

	HMA	ATB		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
ATB					

Tensile Strain at Bottom of HMA Layer:

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1991	0	0	0	56.4					
1993	0	0	35.1	61.1					
1995	0.7	0	46.2	63.5					
1996	7	7.5	7	51.9					

LTPP Site Identification Number: 0124 State: Wisconsin (55)
Roadway or Route No.: US 29
Date of Construction: Nov. 1997 Status: Out of Service in 2008

Location:
Longitude: 89.29 Latitude: 44.87 Elevation: 1239

Pavement Cross Section:

Layer		Material Type	Thickness, inches
6	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.9
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	5.2
4	ATB	HMAC, Hot Laid, Central Plant Mix	11.7
3	PATB	Open Graded, Plant Mix	3.3
2	GS	Soil Agg. Mix.; A-1-b	8.0
1	Subgrade Soil	Silty Sand; A-1-b	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 260 Year: 1997
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Soil Agg. Mix.	14
1	Silty Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: AC-20

	HMA	HMA	ATB	
Asphalt Content, %	4.9	5.0	3.3	
Air Voids, %	7.5	6.2	5.9	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	99	86	66		3.5
HMA	99	86	66		3.5
ATB	92	53	37		3.0

Tensile Strain at Bottom of HMA Layer: 34.73

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0	2005	0	0	0	0
2000	0	0	0	0					
2002	0	0	0	0					
2004	0	0	0	0					

LTPP Site Identification Number: 0116 State: Wisconsin (55)
Roadway or Route No.: US 29
Date of Construction: Nov. 1997 Status: Out of Service in 2008

Location:
Longitude: 89.29 Latitude: 44.87 Elevation: 1239

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.1
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.0
3	ATB	HMAC, Hot Laid, Central Plant Mix	12.0
2	GB	Granular Base; A-1-a	10.8
1	Subgrade Soil	Silty Sand; A-1-b	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 260 Year: 1997
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Granular Base, Soil Agg. Mix.	14
1	Silty Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: AC-20

	HMA	HMA	ATB	
Asphalt Content, %	5.2	4.9	3.8	
Air Voids, %	5.1	7.3	6.6	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	88	69		6.5
HMA	99	80	57		3.9
ATB	92	53	37		3.0

Tensile Strain at Bottom of HMA Layer: 34.73

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0	2005	0	0	0	0
2000	0	0	0	0					
2002	0	0	0	0					
2004	1.61	0	0	0					

LTPP Site Identification Number: 0118 State: Wisconsin (55)
Roadway or Route No.: US 29
Date of Construction: Nov. 1997 Status: Out of Service in 2008

Location:
Longitude: 89.29 Latitude: 44.87 Elevation: 1239

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.9
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.1
3	ATB	HMAC, Hot Laid, Central Plant Mix	8.9
2	GB	Granular Base; A-1-b	14.2
1	Subgrade Soil	Silty Sand; A-1-a	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 260 Year: 1997
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Granular Base, Soil Agg. Mix.	14
1	Silty Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: AC-20

	HMA	HMA	ATB	
Asphalt Content, %	5.0	4.9	3.8	
Air Voids, %	6.6	7.2	6.1	

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	99	86	66		3.5
HMA	99	86	66		3.5
ATB	88	68	58		4.1

Tensile Strain at Bottom of HMA Layer: 34.73

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0	2005	0	0	0	0
2000	0	0	0	0					
2002	0	0	0	0					
2004	0	0	0	0					

LTPP Site Identification Number: 0114 State: Wisconsin (55)
Roadway or Route No.: US 29
Date of Construction: Nov. 1997 Status: Out of Service in 2008

Location:
Longitude: 89.29 Latitude: 44.87 Elevation: 1239

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.7
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	6.4
3	GB	Crushed Stone Base (303)	11.0
2	GS	Soil Agg. Mix.; A-1-b (308)	10.0
1	Subgrade Soil	Poorly Graded Sand with Gravel & Silt (205)	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 260 Year: 1997
KESALS per year: __________

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Soil Agg. Mix.	14
1	Poorly Graded Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: AC-20

	HMA	HMA		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					

Tensile Strain at Bottom of HMA Layer: __________

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0	2005	0	0	0	0
2000	0	0	0	0					
2002	0	0	0	0					
2005									

LTPP Site Identification Number: C903 State: Wisconsin (55)
Roadway or Route No.: US 29
Date of Construction: Nov. 1996 Status: In Service

Location:
Longitude: 89.29 Latitude: 44.87 Elevation: 1239

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.0
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	7.2
3	GB	Crushed Stone Base; A-1-a	13.0
2	GS	Embankment; Coarse-Fine soil; A-3	5.0
1	Subgrade Soil	Silty Sand; A-1-b	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 260 Year: 1997
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Granular Base, Soil Agg. Mix.	14
1	Silty Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: PG58-340

	HMA	HMA		
Asphalt Content, %	5.0	5.0		
Air Voids, %	8.0	8.0		

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA	100	73	42		3.7
HMA	99	69	51		3.4

Tensile Strain at Bottom of HMA Layer: 34.73

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0	2005	5.2	0	0	1.0
2000	0	0	0	0					
2002	0	0	0	0					
2004	2.9	0	0	0					

LTPP Site Identification Number: C901 State: Wisconsin (55)
Roadway or Route No.: US 29
Date of Construction: Nov. 1996 Status: In Service

Location:
Longitude: 89.29 Latitude: 44.87 Elevation: 1239

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	2.0
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	7.8
3	GB	Crushed Stone Base; A-1-a (303)	13.0
2	GS	Embankment; Coarse-Fine soil; A-3 (210)	24.0
1	Subgrade Soil	Well Graded Sand with Silt & Gravel (211)	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 260 Year: 1997
KESALS per year: ______

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Granular Base, Soil Agg. Mix.	14
1	Well Graded Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: PG58-340

	HMA	HMA		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					

Tensile Strain at Bottom of HMA Layer: ______

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0					
2000	0	0	0	0					
2002	0	0	0	0					
2004	0	0	0	0					

LTPP Site Identification Number: C960 State: Wisconsin (55)
Roadway or Route No.: US 29
Date of Construction: Nov. 1996 Status: In Service

Location:
Longitude: 89.29 Latitude: 44.87 Elevation: 1239

Pavement Cross Section:

Layer		Material Type	Thickness, inches
5	HMA	Hot Mixed, Hot Laid AC, Dense Graded	1.9
4	HMA	Hot Mixed, Hot Laid AC, Dense Graded	6.4
3	GB	Crushed Stone Base; A-1-a (303)	13.0
2	GS	Embankment; Coarse-Fine soil; A-3 (210)	5.0
1	Subgrade Soil	Silty Sand; A-1-b (214)	---

Traffic Data:
Number of Years with Data: 4
AADTT (One-way): 260 Year: 1997
KESALS per year:

Unbound Layers Resilient Modulus:

Layer	Material/Soil Type	Equivalent Resilient Modulus, ksi
2	Granular Base, Soil Agg. Mix.	14
1	Silty Sand	10

Hot Mix Asphalt Mixtures:
Equivalent Annual Modulus of HMA: 450
Type of Asphalt: PG58-340

	HMA	HMA		
Asphalt Content, %				
Air Voids, %				

Gradation; percent passing:

	#3/4	#3/8	#4	#40	#200
HMA					
HMA					

Tensile Strain at Bottom of HMA Layer:

Total Amount of Fatigue Cracking:

Year	Alligator	Block	Long.	Transverse	Year	Alligator	Block	Long.	Transverse
1998	0	0	0	0					
2000	52.4	0	0	0					
2004	262.6	0	0	0					