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Project Summary Report 0-4468-S
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Project 0-4468: Evaluate the Fatigue Resistance of Rut Resistant Mixes

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PROJECT SUMMARY REPORT

Initial Development of a Calibrated Mechanistic Approach and Associated Surrogate Test Protocols for HMAC Mixture Fatigue Characterization

Over the past decade, the Texas Department of Transportation (TxDOT) focused research efforts on improving hot mix asphalt concrete (HMAC) mix design to preclude rutting in the early life of pavements. However, these rut-resistant stiff mixtures may be susceptible to long-term fatigue cracking due to oxidative aging.

This project completed initial development of an HMAC mixture fatigue design and analysis system and associated surrogate fatigue tests to ensure adequate mixture fatigue performance in a particular pavement structure under specific environmental and traffic loading conditions. In addition, researchers compared the fatigue resistance of commonly used TxDOT HMAC mixtures and investigated the effects of binder oxidative aging on fatigue performance.

What We Did…

Information Search and Review

Researchers completed an information search and conducted a survey to gather data on: current fatigue design and analysis approaches; related laboratory tests, materials, pavement structures, and designs; corresponding standards or references; and resources or methodologies used to obtain fatigue-resistant HMAC mixtures. This process facilitated selection of four fatigue analysis approaches and the experimental design.

Fatigue Analysis Approaches

Researchers selected the following four fatigue analysis approaches for comparative evaluation:

(1) the mechanistic empirical (ME) approach with flexural bending beam (BB) testing;

(2) the calibrated mechanistic approach (CMSE) with surface energy (SE) measurements, tensile strength (TS), relaxation modulus (RM), and repeated direct-tension (RDT) tests;

(3) the calibrated mechanistic (CM) approach without surface energy measurements; and

(4) the NCHRP 1-37A Mechanistic Empirical Pavement Design Guide (MEPDG) approach with dynamic modulus (DM) testing (as of July 2004).

Experimental Design

The comprehensive laboratory testing program with a full factorial design experiment (16 HMAC mixtures) included the following:

- two typical TxDOT HMAC mixture types: a Basic Type C mixture and a rut-resistant 12.5 mm (0.5-inch) Superpave mixture;
- two aggregate types (limestone and gravel) and three binder types (PG 64-22, PG 76-22 modified with styrene-butadiene-styrene [SBS], and PG 76-22 modified with tire rubber [TR] and SBS);
- two binder content levels: optimum and optimum plus 0.5 percent;
- three laboratory aging exposure conditions for compacted HMAC mixtures (0, 3, and 6 months) at 60 °C (140 °F) that may simulate up to 0, 6, and 12 years, respectively, of Texas field HMAC aging at the critical pavement service temperature depending on air voids (AV) and other factors;
- five hypothetical HMAC pavement structures (PSs) under representative traffic loading conditions;
- two Texas environmental conditions (wet-warm [WW] and dry-cold [DC]) critical to fatigue (alligator) cracking; and
- a typical reliability level of 95 percent for statistical analysis.

Laboratory Testing

Researchers completed an extensive laboratory testing program for both binders and HMAC mixtures at multiple aging exposure conditions for each fatigue analysis approach. These laboratory tests included: the dynamic shear rheometer (DSR), Fourier transform infrared spectroscopy (FT-IR), and size exclusion chromatography (SEC) for the binder; the BB mixture test for the ME approach; the TS, RM, and RDT mixture tests and SE measurements for the binder (Wilhelmy Plate [WP]) and aggregate (universal sorption device [USD]) for the CMSE and CM approaches; and the DM mixture test for the MEPDG approach. Aging of the binder was accomplished through the stirred air flow test (SAFT) and the pressure aging vessel (PAV), while the mixtures were oven-aged for 4 hours at 135 °C (275 °F) in a loose state prior to compaction and for 0, 3, and 6 months at 60 °C (140 °F) in an environmental room after compaction. Note that binder testing included both neat and recovered unaged and aged binders.

These laboratory tests characterized the binder and HMAC mixture properties and enabled prediction of fatigue life (N_f) using the four fatigue analysis approaches. Laboratory tests were either conducted at 20 °C (68 °F) or test data were normalized to 20 °C (68 °F) during the analysis phase using time-temperature superposition.

Data Analysis

The researchers analyzed the laboratory testing data as follows:

- fatigue life prediction assuming controlled-strain mode of loading,
- evaluation of the effects of binder oxidative aging and mix design parameters,
- correlation of binder and HMAC mixture properties,
- comparison and evaluation of fatigue analysis approaches,
- recommendation of a fatigue analysis approach,
- exploration of methods to quantitatively incorporate aging in fatigue life prediction, and
- investigation of surrogate fatigue test protocols from the recommended fatigue analysis approach.

What We Found…

HMAC Mixture Fatigue Resistance

HMAC mixture fatigue resistance is a complex function of mix design parameters (including binder type/content, air voids), aggregate type/gradation), material properties (binder, aggregate, and HMAC), traffic, pavement structure, and environment. These factors interact in a unique way in each HMAC mixture and should be explicitly taken into account when modeling fatigue resistance.

In general, HMAC mixtures with modified binders (and higher binder contents) exhibited better fatigue resistance than those with unmodified binders; however, higher statistical variability was observed for HMAC mixtures with modified binders.

Fatigue life also exhibited significant dependence on pavement structure and environment.

Impact of Binder Oxidative Aging on HMAC Mixture Fatigue Resistance and Properties

Binder oxidative aging in mixtures has a detrimental effect on both HMAC mixture fracture and healing properties and fatigue resistance under controlled-strain conditions (Figure 1).

Fatigue life decline with binder oxidative aging is mixture dependent (Figure 1), providing a significant opportunity to increase fatigue resistance through mix design.

An HMAC mixture visco-elastic function defined as G′/(η′/G′) and mapped across the three aging exposure conditions provided a useful means of tracking mixture stiffening due to binder oxidative aging without extracting and recovering the binder. This mixture function at 20 °C (68 °F) and 0.002 rad/s correlated linearly with a corresponding binder DSR function at 15 °C (59 °F) and 0.005 rad/s.

The Hirsch model provided a reasonable correlation between binder and mixture G* values after short-term aging, but with long-term aging the increase in mixture stiffness with binder hardening deviates significantly from model predictions.

Binder stiffening with decreasing temperature appeared to mimic stiffening due to oxidative aging and provided the basis for rapid analysis of oxidative aging effects. Similarly, the effect of temperature on N_f may provide a rapid

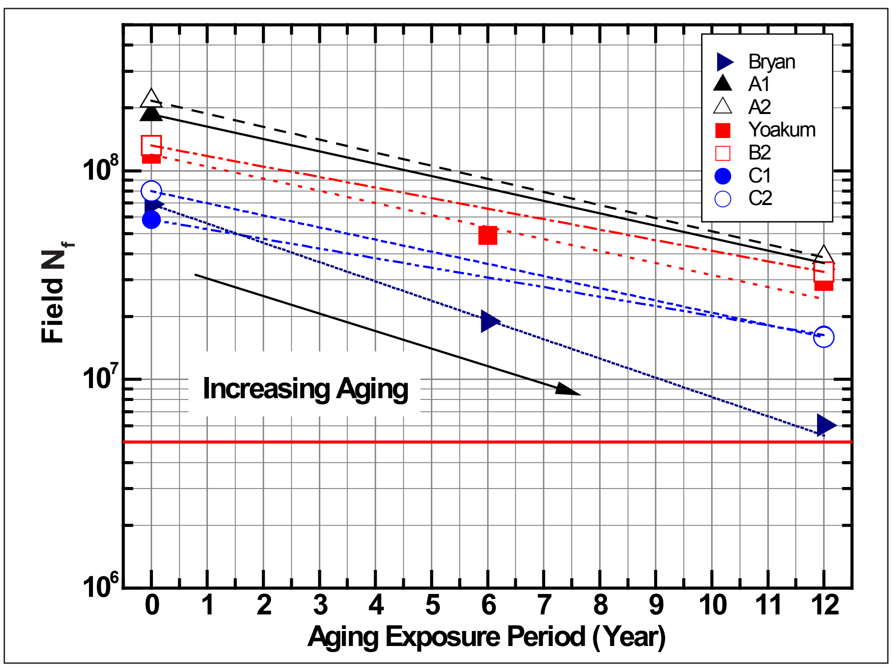

Figure 1. Predicted HMAC Mixture Fatigue Lives (assuming 1 month laboratory aging at 60 °C [140 °F] simulates up to 2 years aging in the field).

means of quantitatively estimating N_f decline with oxidative aging.

Evaluation of Fatigue Analysis Approaches

Based on a value engineering assessment, the CMSE fatigue analysis approach is recommended for characterizing HMAC mixture fatigue resistance. Compared to the other approaches, the CMSE approach:

- utilizes fundamental material and mixture properties to estimate HMAC mixture fatigue resistance;
- exhibits greater potential and flexibility to account for HMAC nonlinearity, visco-elasticity, anisotropy, healing, and aging effects;
- provides a more realistic fatigue failure criterion in terms of simulation of the fatigue damage process in an in-situ HMAC pavement structure;
- exhibits potential for multiple distress analyses; and
- exhibits lower statistical variability in terms of N_f prediction.

The ME approach exhibited the highest statistical variability, and its failure criterion does not provide a realistic simulation of actual fatigue damage accumulation in the field. While the MEPDG offers the best traffic and environmental analysis models, this approach incorrectly represents aging effects and does not directly account for binder healing or anisotropic effects. Concerning binder oxidative aging, the MEPDG only considers aging in the top 12.5 mm (0.5 inches) of the pavement, underestimates the extent to which oxidative aging stiffens binders in the pavement, and predicts that binder oxidative aging improves N_f.

The CM approach produced results comparable to those obtained with the CMSE approach and is recommended as an alternative to the CMSE approach. The simplified CM approach does not require SE measurements and RM tests in compression, and thus both laboratory and analysis time are reduced.

Exploration of Methods to Quantitatively Incorporate Aging in N_f Prediction

One method (denoted as SF_{ag}) utilized the N_f predicted for a short-term oven-aged mixture and the properties of short-term and long-term aged neat binders measured with the DSR to predict N_f including the effects of aging. The SF_{ag} method uses a single shift without considering the simultaneous and continuous processes of trafficking and aging throughout the HMAC design life. This simple method considers important binder properties related to mixture cracking potential, and preliminary validation began in this project using N_f values predicted for long-term aged mixtures.

A second method (denoted as SF_{aging}) utilized the N_f predicted for both short-term oven-aged and long-term aged mixtures, the DSR properties of both short-term and long-term aged neat binders, and a cumulative damage hypothesis. The SF_{aging} method quantitatively estimates the decline in N_f caused by both trafficking and binder aging and the resulting pavement service life. Cumulative damage results showed a rapidly accelerating decline in pavement life as binder oxidative aging progressed. These results also suggested that the impact of aging on N_f is significant with the potential to offset substantial initial N_f values. While this method is not practical for routine mix design because it requires extensive time to age and then test the mixtures, it does provide a more fundamental and reliable understanding of the effects of changes in binder properties and the influence of other mix design parameters and traffic loading on mixture fatigue resistance.

Both methods (SF_{ag} and SF_{aging}) produced promising results, but additional research is needed to combine these methods and take advantage of the strengths of each.

Investigation of Surrogate Fatigue Tests

The TS test is selected and proposed as a surrogate fatigue test protocol for mix design and HMAC mixture screening based on its practicality and correlation with CMSE N_f results. The following fatigue limiting threshold value was established: $\varepsilon_f \geq 3180\ \mu\varepsilon$. Any HMAC mixture not meeting this requirement is considered inadequate in terms of fatigue resistance, and improvements are needed prior to use. The TS test takes only 5 minutes at ambient temperature.

The Researchers Recommend…

Researchers' recommendations include:

- a laboratory testing program that includes additional HMAC mixtures and aging conditions to further quantify the binder-HMAC mixture and N_f-aging relationships;
- investigation of the effects of AV and temperature variations on aging and N_f;
- selection of a method to quantitatively incorporate aging in N_f prediction while simultaneously considering mix design parameters, temperature variations, and traffic loading;
- field validation of the CMSE approach through pilot implementation projects or accelerated pavement testing;
- sensitivity analysis and software development for the CMSE approach;
- exploration of the possibility of incorporating multiple distress analyses (moisture sensitivity and rutting) in the CMSE approach; and
- additional HMAC mixture testing to further evaluate and validate the CMSE surrogate fatigue test protocols and fatigue limiting threshold values.

For More Details...

The research is documented in Report 0-4468-1, *Preliminary Fatigue Analysis of a Common TxDOT Hot Mix Asphalt Concrete Mixture;* Report 0-4468-2, *Comparison of Fatigue Analysis Approaches for Two Hot Mix Asphalt Concrete (HMAC) Mixtures;* and Report 0-4468-3, *Application of Calibrated Mechanistic Fatigue Analysis with Aging Effects.*

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