TECHBRIEF

Development of Balanced Mixture Design Index Parameters and the Flex Suite of Performance Analysis Tools for Asphalt Pavements

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INTRODUCTION

Over the past few decades, the Federal Highway Administration (FHWA) developed advanced models for asphalt under complex loading conditions, to achieve accurate pavement performance evaluations and predictions. These material models can accurately capture various critical phenomena, such as microcrack-induced damage (critical for fatigue modeling), strain-rate temperature interdependence, permanent deformation behavior (critical for high-temperature modeling), and damage reduction during rest periods between loads. The resultant mechanistic models can evaluate fatigue cracking, permanent deformation (rutting), and healing and are referred to as the simplified viscoelastic continuum damage (S-VECD) model, the shift model, and the healing model, respectively.[1,2,3] A suite of test methods accompanies these mechanistic models. These test methods are designed for use by an asphalt mixture performance tester (AMPT) and have been adopted by the American Association of State Highway and Transportation Officials (AASHTO) as standards.[4]

The research efforts presented in this TechBrief were designed to advance the deployment of FHWA's performance testing and evaluation of asphalt pavements. These efforts can be categorized as follows:

- Development of a thermal cracking model.
- Development of S_{app} (apparent damage capacity) and the Rutting Strain Index (RSI) as the cracking and rutting indexes, respectively.
- Development of FlexMAT™ version 2.1.[5]
- Development of FlexPAVE™ version 2.0.
- Development of performance-volumetrics relationships (PVRs) and index-volumetrics relationships (IVRs).
- Development of AMPT balanced mix design (BMD) methods.
- Reliability analysis of cracking damage and rut depth predictions.

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- Development of PASSFlex™.
- Demonstration of field shadow projects.

This TechBrief provides a brief overview of each of these efforts.

THERMAL CRACKING MODEL

Researchers conducting this study developed a thermal cracking analysis framework, FlexTC, that employs the S-VECD model to characterize asphalt mixture behavior at low temperatures.(6) FlexTC's use of the S-VECD model allows the prediction of both fatigue cracking (top-down and bottom-up cracking) and thermal cracking using a single set of test methods.

One of the important material properties for thermal cracking prediction is the coefficient of thermal contraction (CTC). Three levels determine the CTC of an asphalt mixture. Level 1 assumes direct measurements of the mixture's CTC using ZERODUR®.(7) Level 2 estimates the CTC of the mixture using the voids in mineral aggregate (VMA) of the mixture, aggregate bulk specific gravity, the CTC of the mineral aggregate in the mixture, and the CTC of the binder. Level 3 uses a similar approach to level 2, but instead of using the measured binder CTCs as inputs, level 3 estimates the CTCs using the low-temperature performance grade (PG) of the binder.

The algorithm that FlexTC uses to determine the crack depth in a pavement subjected to thermal fluctuations models the asphalt layer as a layer composed of sublayers of uniaxial rods with fixed ends.(6) The boundary condition for each uniaxial rod is the same as the boundary condition used in the thermal stress restrained specimen test (TSRST). Therefore, research efforts focused on developing a methodology to predict the fracture of asphalt mixture specimens in the TSRST. These efforts resulted in the development of a dissipated pseudostrain energy (DPSE)-based failure criterion. The AMPT dynamic modulus and cyclic fatigue tests characterize the DPSE failure criterion and serve as the characterization tests for fatigue cracking (both bottom-up and top-down cracking).

The research team verified the developed FlexTC framework using the material properties and field performance of eight cells from Minnesota's Cold Weather Pavement Testing Facility (MnROAD).(6,8) The MnROAD cells (and corresponding mixtures) are designed to evaluate various mix design factors for reclaimed asphalt pavement (RAP) and reclaimed asphalt shingle (RAS) mixtures. Therefore, the eight MnROAD cells this study used were paired based on the target mix factor. A comparison of the predicted and observed thermal cracking performance of two paired cells resulted in reasonably good agreement.

The research team has implemented the three different levels for CTC determination and the verified FlexTC algorithm in FlexMAT version 2.1 and FlexPAVE version 2.0, respectively.(5,6)

S_{app} AND THE RUTTING STRAIN INDEX

As the paving industry moves toward BMD, index parameters are receiving more attention from researchers and practitioners. With this phenomenon in mind, the research team developed S_{app} and RSI parameters for cracking and rutting by simplifying the S-VECD model and permanent strain shift model, respectively.(6,9,10)

S_{app} accounts for the effects of a mixture's modulus and toughness on the mixture's fatigue resistance and is a measure of the amount of fatigue damage the mixture can tolerate under loading. Higher S_{app} values indicate better fatigue resistance. The S_{app} value is determined at the average temperature of the high and low PGs, as given in LTPPBind Online at the location for the project of interest, −3 °C.(11) Sapp threshold values were determined for different traffic levels using 105 mixtures that include hot mix asphalt (HMA) mixtures with varying percentages of RAP, warm mix asphalt (WMA) mixtures with different technologies, and polymer-modified asphalt (PMA) mixtures. These threshold values apply to surface, intermediate, and base course mixtures. The S_{app} value was found to be sensitive to mixture factors (e.g., aggregate gradation, binder content, RAP content, binder grade, and type of binder modifier), compaction, and aging and meets general expectations with respect to the effects of these parameters on fatigue cracking performance.

The RSI is the average permanent strain (in percent) and is defined as the ratio of the permanent deformation in an asphalt layer to the thickness of that layer at the end of a 20-yr period, over which 30 million 18-kip equivalent single-axle load repetitions are applied to a standard pavement structure. A mixture with lower RSI values has more rutting resistance than a mixture with higher RSI values.

Because permanent deformation in asphalt pavements is a function of temperature, stress level, and loading time, which all change with pavement depth, the research team used FlexPAVE to run an array of conditions to develop the stress and loading time profiles of standard pavement structures. To calculate RSI values under realistic temperature profiles, the user selects a city (in a U.S. territory or State) closest to the project location in FlexMAT.(5) Then FlexMAT extracts the temperature profile across the entire depth of the pavement structure from a database created using Enhanced Integrated Climatic Model (EICM) simulations that include 20 yr (1996–2015) of air temperature data from the National

Aeronautics and Space Administration Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) dataset.[12,13] FlexMAT uses the shift model to calculate the permanent strain in each sublayer of asphalt (using the temperature and the precalculated stress and loading time for that sublayer) and produces the RSI value within a few seconds. RSI threshold values were determined using 79 mixtures that include the HMA mixtures with varying RAP contents and volumetric properties, WMA mixtures with different technologies, and PMA mixtures. The RSI value was found to decrease with a coarser gradation, lower asphalt binder content, higher RAP content, and higher compaction density (lower air void content).

FlexMAT calculates S_{app} and RSI values using AMPT test results.[5] The test results generated to determine the S_{app} and RSI values for a given mixture can be used in FlexPAVE for long-term pavement performance predictions. This link is the main difference between the S_{app} and RSI parameters and other BMD indexes.

FLexMAT VERSION 2.1

FlexMAT is designed to take output files from the AMPT and perform all the complex calculations required for the mechanistic material models.[5] During this project, the research team made various improvements to FlexMAT Cracking and FlexMAT Rutting version 1.1.[14,15] The version number for the resulting FlexMAT is version 2.1. The following list summarizes the improvements made and capabilities added to FlexMAT for Cracking:

- Fitting the dynamic modulus data to the two springs, two parabolic elements, one dashpot (2S2P1D) model using generalized reduced gradient nonlinear fitting with a multistart configuration.
- Defining the failure of the cyclic fatigue test data as the maximum value of stress times the number of loading cycles.
- Including the three levels needed to determine the CTC.
- Including the three levels needed to determine the rheological aging index values for the National Cooperative Highway Research Project (NCHRP) 09-54 aging models.[16]
- Calculating the DPSE as a function of the reduced strain rate for the thermal cracking analysis.
- Including a bridge routine to import data from previous versions of FlexMAT.[5]
- Selecting a city for S_{app} determination.
- Including data quality indicators.
- Including U.S. units of measurement.
- Adding a dynamic modulus table that is compatible with Pavement ME.[17]
- Ensuring Section 508 of the Rehabilitation Act of 1973 (Section 508) compliance.[18]

The following list summarizes the improvements made and capabilities added to FlexMAT for Rutting:[15]

- Expanding the temperature database to 20 yr using 2,798 stations from MERRA-2.[13]
- Including U.S. units of measurement.
- Including a bridge routine to import data from previous versions of FlexMAT.[5]
- Ensuring Section 508 compliance.[18]

In addition to these improvements and added capabilities, the research team developed and implemented a universal input data structure in both FlexMAT programs, so FlexMAT can be used with any loading machine if the machine can generate test results according to the universal data structure.[5] Also, FlexMAT version 2.1 generates output files that can be used in FlexPAVE versions 1.1 and 2.0, thus allowing the use of the previous FlexPAVE version.[19]

The S_{app} and RSI values are calculated using FlexMAT, thus making FlexMAT an important element in index-based BMD and index-based performance-related specifications (PRS) protocols.[5]

PRELIMINARY TRANSFER FUNCTIONS FOR FLexPAVE VERSION 1.1

The research team developed preliminary transfer functions for fatigue cracking and rut depth predictions using 39 pavement sections from 4 field projects: 5 sections from the National Center for Asphalt Technology (NCAT) test track in Alabama, United States (data are from NCAT's 2009 research cycle); 14 sections from the 2016 MnROAD project in Minnesota, United States; 4 sections from the Manitoba Transportation and Infrastructure test road in Manitoba, Canada; and 16 sections from the Korean Expressway Corporation Test Road in Yeoju, South Korea.[8,20–22] The research team used the suite of AMPT performance tests on all the original asphalt mixtures used in the construction of these pavement sections. The test results were analyzed by FlexMAT, and the performance of these pavement sections was analyzed using FlexPAVE version 1.1.[5,19] In general, the research team found agreement between the observed and predicted performance. This comparison resulted in preliminary transfer functions for fatigue cracking and rutting. This project refers to these transfer functions as *preliminary* because the amount of data used in the development of these functions was limited.

FLexPAVE VERSION 2.0

The following list summarizes the significant improvements made to FlexPAVE version 1.1, which resulted in FlexPAVE version 2.0:[19]

- Implementing full finite element analysis instead of the layered analysis in FlexPAVE version 1.1.[19]
- Including the NCHRP 09-54 aging models.[16]
- Including the DPSE-based thermal cracking model.
- Including the seasonal effects of unbound materials.
- Including EICM with the MERRA-2 database.[12,13]
- Including a graphical user interface based on Microsoft® Excel®.[23]
- Ensuring Section 508 compliance.

In summary, FlexPAVE version 2.0 allows the user to predict fatigue cracking, thermal cracking, and rutting with the effects of aging. FlexPAVE version 2.0 uses the same test methods to predict both fatigue cracking and thermal cracking. FlexPAVE's major strength is in using not only realistic loading and climatic conditions, but also material characterization methods that are much simpler than other mechanistic-empirical asphalt pavement analysis methodologies.

PERFORMANCE-VOLUMETRICS RELATIONSHIP AND INDEX-VOLUMETRICS RELATIONSHIP

The paving community's move toward mechanistic-empirical pavement design, BMD, and PRS raises the importance of performance testing asphalt mixtures more than ever. Mechanistic models typically require detailed material property information that can be time-consuming to measure. This time becomes even more critical considering how often the properties need to be measured for PRS, where construction variability must be evaluated on a lot-by-lot basis. To complete the full testing and analysis of each lot, the agency may spend several workdays on laboratory tests to determine the material properties. Owing to these challenges, state-of-the-practice technologies primarily utilize volumetric methods for asphalt mixture design and quality control and assurance specifications. These volumetric methods have a great advantage over those based on mechanistic properties, because the volumetric properties can be measured quickly, and the results can be used to make production adjustments if necessary. However, volumetric methods' disadvantage is that although volumetric-based methods are related to performance, the specific relationship to performance for a given mixture is unknown.

To address this issue for PRS, the research team developed the PVR and IVR. This development effort began with the finding that the volumetric properties measured at the design number of gyrations during quality assurance (QA) procedures and in-place density can be combined into two in-place volumetric properties, i.e., in-place VMA (VMA_{IP}) and in-place voids filled with asphalt (VFA) (VFA_{IP}). The research team also found a linear relationship between performance (cracking and rutting) and these two in-place volumetric properties. This relationship can be best established using the four corners approach. The four corners are the volumetric conditions located furthest apart from each other in the VMA_{IP} versus VFA_{IP} space, but within the limit for mixture acceptance. The four corners approach is based on the finding that the performance of an asphalt mixture at any volumetric condition can be predicted if the performance of the mixture at the four corners is measured. This study used several mixtures, both laboratory-mixed and plant-produced mixtures, to characterize and verify the PVRs and IVRs.

The major benefits of PVR and IVR are as follows:

- PVR and IVR allow engineers to continue to use current test methods and equipment for QA purposes.
- PVR and IVR allow material characterization to be completed in a short period during the mixture design and QA processes.
- PVR and IVR bridge the gap between the volumetric properties and performance of asphalt mixtures and allow engineering judgment in mixture design and QA processes to be based on performance.

ASPHALT MIXTURE PERFORMANCE TESTER BALANCED MIX DESIGN

The successful development and verification of PVR and IVR allowed the research team to use those relationships in BMD. In addition, the ability of PVR and IVR to predict the performance of a mixture at various gradations, binder contents, and air void contents enabled the resultant BMD to optimize the mixture for both aggregate gradation and binder content for a given set of aggregate stockpiles and binder. In this project, the research team developed three tiers of BMD based on the AMPT suite of performance tests. Tiers 1 and 2 use the S_{app} and RSI parameters, whereas tier 3 uses the pavement life that FlexPAVE predicted. In tier 1, the S_{app} and RSI values of the design mix are measured and compared against the threshold values for the given traffic to determine pass or fail. Tier 2 BMD is similar to the tier 3 predictive BMD.

The main difference is that tier 2 uses the IVR concept, and all the tests and analyses are performed at a fixed design air void content (e.g., 4 percent), thus requiring the AMPT performance tests to be performed at two points rather than at four corners.

For purposes of tier 2 BMD, the IVR function is considered as the volumetric relationship for different gradations at the fixed design air void content (4 percent) at the design compaction level. For the general IVR function based on the four corners concept, three coefficients are considered as the fitting coefficients needed to calibrate the IVR. However, at the fixed design air void content, due to the intercorrelation of the VMA, VFA, and fixed design air void content, the IVR function can be calibrated using only two fitting coefficients.

The mixture characterization in tier 3 is the most demanding of the three tiers. Tier 3 uses PVRs characterized using the pavement life predicted from FlexPAVE at the four corners volumetric conditions. That is, fatigue cracking and rutting PVRs are used to determine the optimal combination of aggregate gradation and asphalt content for a given set of aggregate stockpiles and binder. Although the required mixture characterization efforts in tier 3 BMD are much greater than those in tier 2, the data generated in tier 3 provide information about the changes in mixture performance that occur as the air void content changes. Therefore, the data generated for tier 3 BMD can be readily used for developing payment provisions in PRS.

In contrast to the design methodology employed for other BMD methods, tiers 2 and 3 of the AMPT-based BMD methods allow users to determine the optimal combination of aggregate gradation and asphalt content for a given set of aggregate and binder.

RELIABILITY ANALYSIS

Although mechanistic-based methods strive to systematically account for the physical properties and active mechanisms in a pavement, these methods are not perfect representations of the real system. As such, the mechanistic prediction of pavement performance is an inherently uncertain approach. The research team evaluated the known uncertainties as those uncertainties pertain to model characterization, and the propagation of these uncertainties into long-term pavement performance simulations. Specifically, the research team used the Bayesian inference-based Markov Chain Monte Carlo (MCMC) method to investigate the ways that the uncertainties from the S-VECD and rutting shift model input parameters propagate to pavement performance simulation errors.[6,24] The goal was to estimate the reliability of the %Cracking and rut depth predictions in pavement simulations. For this purpose, the research team used mixtures of varying composition and behaviors (in both the mean and the uncertainty of these behaviors) and performed thousands of FlexPAVE simulations using different levels of material property variability, climate, loading, and structural conditions.

For %Cracking, the research team analyzed material variations and found that their analysis yielded a simplified and predictable relationship with the uncertainty in long-term performance predictions. Thus, the research team characterized and verified simplified expressions involving parameters readily calculable from laboratory experiments (linear viscoelastic, damage, and failure criteria). The predictive models can predict the propagation of the testing variability to %Cracking variations at any desired level of reliability with more than 98 percent accuracy.

For rutting, the research team developed an even more simplified approach using the same algorithm used to determine RSI. Here the error in material variation was found to propagate at a rate of approximately 1.5 to 3.5 times that of the variation in viscoplastic strain observed in the AASHTO TP 134 experiments.[25] The research team also concluded that to improve the accuracy of the test results, a ruggedness study should be undertaken to identify the effects of the SSR test factors on the shift model's coefficients. Once the ruggedness study on AASHTO TP 134 is done, the effect of sample-to-sample variability on the model coefficients could be studied and the limits for the Bayesian inference-based MCMC method could be selected based on the more robust analysis.

PASSFlex

PASSFlex is an analysis tool based on Microsoft Excel that combines FlexMAT and FlexPAVE into a framework to support the user (e.g., agencies, contractors, and researchers) in the different steps of a performance project.[5,23] PASSFlex was designed to offer the user five main features:

- Ability to develop a local database of mixtures based on AMPT testing.
- Ability to develop specifications using a choice of protocol.
- Mix approval based on an index or on performance.
- QA evaluation by means of measured acceptance quality characteristics and calibrated volumetric relationships.
- A toolbox that contains FlexMAT and FlexPAVE in a single environment.[5]

This report takes one of the three protocols developed under the auspices of the TFRS-01 project, Quality Assurance (QA) Aspects of Performance Related Specifications (PRS), and uses that protocol to describe the various elements of PASSFlex and how those elements work together to develop tables for payment provisions, which constitute the most critical element in successful PRS.[26]

SHADOW PROJECTS

The research team undertook three shadow projects in concert with the Western Federal Lands Highway Division, Maine Department of Transportation, and Missouri Department of Transportation to introduce the AMPT suite of performance tests and performance models to State departments of transportation. The research team used samples from ongoing construction projects to develop PVRs and to evaluate the PVRs' accuracy as a function of mixture volumetrics and in-place density values. The data from the shadow projects have no bearing on currently specified payments to contractors; however, agencies and the research team can use the results of the shadow projects to evaluate the methods in realistic environments and prepare agencies for the deployment of PRS in the future.

The general steps involved in a shadow project include the following activities:

- Hands-on, 2-day AMPT workshop.
- AMPT training at the agency's laboratory.
- Proficiency testing.
- Shadow project selection.
- Acquisition of construction samples and QA data.
- Selection of the four corners volumetric conditions.
- AMPT testing and data analysis using FlexMAT and FlexPAVE.[5]
- PVR and IVR development.
- Evaluation of the effects of construction variability on pavement performance.

The analysis results for the shadow project data clearly demonstrate the importance of in-place density on a pavement's cracking and rutting performance. The analysis found less variation for binder content and aggregate gradation. The PVRs and IVRs that the research team generated using the construction samples from the shadow projects were verified using the AMPT performance test results from an independent set of construction samples. However, future research should include laboratory-mixed and laboratory-compacted mixtures to evaluate the effects of binder content and aggregate gradation.

NEXT STEPS

The following activities would enhance the products the research team already has developed:

- Performance of a ruggedness and interlaboratory study of AASHTO TP 134.[25]
- Incorporation of the NCHRP 1-53 permanent deformation model of unbound materials into FlexPAVE version 2.0 (once FlexPAVE version 2.0 has been fully vetted by AASHTO).[6,27]
- Development of a reflective cracking model based on the S-VECD model and incorporation of the developed model into FlexPAVE version 2.0.[6]
- Development of transfer functions for FlexPAVE version 2.0 using a wide range of pavement sections with available original paving materials and reliable performance data.
- Verification of PVRs and IVRs that were developed using laboratory-mixed and laboratory-compacted mixtures.
- Incorporation of different protocols into PASSFlex.

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