TechBrief

The Asphalt Pavement Technology Program is an integrated, national effort to improve the long-term performance and cost effectiveness of asphalt pavements. Managed by the Federal Highway Administration through partnerships with state highway agencies, industry and academia the program's primary goals are to reduce congestion, improve safety, and foster technology innovation. The program was established to develop and implement guidelines, methods, procedures and other tools for use in asphalt pavement materials selection, mixture design, testing, construction and quality control.

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Testing for Fatigue Cracking in the Asphalt Mixture Performance Tester

This Technical Brief provides an overview of a fatigue characterization test method that can be conducted using an Asphalt Mixture Performance Tester (AMPT) device. This includes a description of the test as well as an introduction to how the test has evolved, what performance information the test provides about an asphalt mixture, and the accompanying stress-strain model.

Introduction

Over the last 20 years, advances have been made towards the development and implementation of a standardized performance tester for asphalt concrete. One such methodology is a provisional test method known as American Association of State Highway and Transportation Officials (AASHTO) Provisional Standard (TP) 107: Determining the Damage Characteristic Curve of Asphalt Mixtures from Direct Tension Cyclic Fatigue Tests (*1*) (or AMPT Cyclic Fatigue Test in this document) which utilizes a stress-strain model centered on the damage characteristic relationship, which is an inherent engineering property rather than an empirical index much like the difference between a soil's resilient modulus and its California Bearing Ratio. This AMPT test procedure enables an enhanced and comprehensive understanding of the complicated fatigue cracking phenomenon because it can explain how a given asphalt mixture behaves in a pavement structure under varying stress or strain conditions. By bridging the gap between pavement structural design and mixture design, the AMPT Cyclic Fatigue Test can offer users and agencies a larger return on investment as it relates to minimizing distress in asphalt pavements.

Fatigue Cracking Concerns

Fatigue cracking of asphalt pavements is considered to be one of the most challenging issues facing pavement engineers today. The cause of these cracks, which are influenced by repeated (i.e., cyclic) loading over time can be tied to weak pavement foundations, insufficiently designed asphalt materials, or changes in strain tolerance of the mixture brought on by long-term field aging (*2*). Fatigue cracks of the asphalt layer propagate through the structure. The end result of cracks are water intrusion, rougher ride quality, worse fuel consumption, and traffic delays from rehabilitation efforts that cost users and agencies time, money, and resources. As transportation budgets continue to tighten, performance tests and specifications for asphalt mixture and structural design, and acceptance of construction are critical to enhancing pavement life, limiting costs, and maximizing available resources.

Asphalt Mixture Performance Tester

In the late-1980s and early-1990s, the Strategic Highway Research Program (SHRP) created the Superpave mixture design methodology that came with a suite of tests for binders as part of the performance grading scheme. However, SHRP delivered mixture tests and models that were challenging to implement. National Cooperative Highway Research Program (NCHRP) Project 9-19: Superpave Support and Performance Models Management provided guidance to the new Superpave process and the search for better asphalt mixture performance tests. This project found value in the dynamic modulus (|E*|), flow number, and flow time as useful parameters to describe rutting and cracking resistance through a performance prediction platform. This prediction approach was later adopted as the asphalt foundation of the Mechanistic-Empirical Pavement Design Guide (MEPDG) of NCHRP Project 1-37A: Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures: Phase II (*3, 4*).

In 2003, building upon the work of NCHRP 9-19, a report was published as part of NCHRP Project 9-29: Simple Performance Tester for Superpave Mix Design which established the AMPT. The device specification was created to account for two objectives: to test the parameters of relevance from NCHRP Project 9-19 (|E*|, flow number, and flow time) and to provide material characterization for input into the MEPDG structural response model. In NCHRP Project 9-29, the AMPT was designed, the equipment manufactured by outside vendors, and evaluated by the NCHRP Project 9-29 research team to assess its applicability to the desired objectives (*5*-*7*).

The AMPT is an instrument capable of providing the asphalt mixture test parameters that have been implemented in the AASHTOWare PavementME Design (formerly the MEPDG) software and National Highway Institute course number FHWA-NHI-131118. The equipment holds the potential to be a standalone device for other types of performance testing and is garnering interest from across the world in part due to its adaptability to a myriad of test procedures. Upgrade kits have been manufactured over the past several years to allow the AMPT to acquire more information on rutting and cracking resistance. The AMPT exists as a servo-hydraulic testing system equipped with a computer controller (see Figure 1). A temperature-controlled chamber is capable of cooling or heating a specimen between 4 and 60°C in order to capture |E*| values suitable for input into the AASHTOWare PavementME Design software. As mentioned in a TechBrief on the AMPT (*8*), a major advantage of the AMPT tests mentioned above is the link between mechanical properties, mixture design, and structural analysis of asphalt pavements.

Figure 1. Two commonly used AMPTs (*8*).

Assessing Pavement Performance Using Fatigue-Related Test Methods

Readers can think of the AMPT Cyclic Fatigue Test as an intermediate approach between the classical beam fatigue test and the faster index-based methodologies. As it relates to performance specifications, agencies may elect to use index-based parameters which are compared against a pass/fail threshold. The pass/fail threshold is correlated to pavement performance measured via pavement management system data or through past engineering experiences. There are also methods which use tested material properties to predict pavement performance through structural modeling, such as the AMPT Cyclic Fatigue Test. All of these methods provide insight into material behavior and can be used in performance specification development.

The key aspect to remember with the AMPT Cyclic Fatigue Test in particular is that an engineering property is measured: the damage characteristic relationship (*9*-*11*). Data from this test can be used to determine how the material stiffness and damage change with load repetition. Performance modeling is then based on calculated pavement response, or stresses and strains experienced by the pavement. A fatigue life prediction approach has applications for pavement design and performance-based pay factor determination. It also allows for incorporation of the following critical effects into fatigue resistance recommendations by means of a pavement structural performance prediction:

- Structural – influence of thickness and properties of unbound layers;
- Traffic – influence of intensity and frequency of loading over time; and
- Climatic – influence of seasonal variations and other weather characteristics.

Additional information on performance prediction using the AMPT Cyclic Fatigue Test is provided later on in this document.

AMPT Cyclic Fatigue Testing Procedure

This procedure is being conducted in various projects across the United States, such as part of the now complete NCHRP Project 9-38: Endurance Limit of Hot Mix Asphalt Mixtures to Prevent Fatigue Cracking in Flexible Pavements, NCHRP Project 9-54: Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction, the Transportation Pooled Fund Study TPF-5(230): Evaluation of Plant-Produced High-Percentage Reclaimed Asphalt Pavement (RAP) Mixtures in the Northeast, numerous North Carolina research efforts, as well as at FHWA's Turner-Fairbank Highway Research Center Bituminous Mixtures Laboratory and the FHWA Mobile Asphalt Testing Trailer. Specimen preparation and gauges for the test procedure are identical to AASHTO TP 79: Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT), which follows the AASHTO PP 60: Standard Practice for Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC), except the specimens are cut shorter and tension grip plates are glued to the specimen.

Upgrade kits are available from AMPT manufacturers for the AMPT Cyclic Fatigue Test. To perform the test, users need to purchase or manufacture screws and end plates and/or appropriate spacers to secure the sample into the machine. The test time is usually less than one hour, allowing recommended replication for a mixture to be completed within one to two days. Fabrication and specimen preparation takes about two to three days per mixture (due to coring, cutting, air void determination, and gluing of end plates), but this remains considerably faster than the AASHTO T 321 beam fatigue approach. The test procedure is conducted on 100 mm diameter by 130 mm height cylindrical specimens. Testing can also be conducted on smaller geometries when using field cores. Targets are then epoxied onto the specimen at a typical gauge length of 70 mm for attachment of the sensors. Since AMPT Cyclic Fatigue supplies direct tension loading, the sample must then be attached to end plates via a fully-cured epoxy. This procedure requires the use of a gluing jig, which is commercially available, to ensure the cleaned end plates are parallel with each other to avoid premature failure. It is important to note that while the epoxy cures, the AMPT is free for other testing and the specimen itself can be removed from the gluing jig after a functional cure (typically about four hours). Figure 2 shows the glued specimen alongside a standard (100 mm diameter by 150 mm height) |E*| specimen. Other differences to note in the figure are the heavier and larger end plates with holes for securing into the AMPT device and the gray-colored epoxy for the fatigue specimen.

Figure 2. Typical AMPT Cyclic Fatigue specimen (left) alongside dynamic modulus specimen (right).

Determining the appropriate temperature for the test is based on a simple formula related to the LTPPBind-determined (with 98% reliability) high temperature performance grade (HTPG) and low temperature performance grade (LTPG) for the desired pavement location (see equation in Figure 3 below). Note the maximum testing temperature is set at 21°C. The intermediate testing temperature is based on the calculation below and is selected such that it is not too warm for the binder in the mixture to exhibit viscous and plasticity effects that would otherwise be incorrectly measured as damage due to fatigue. Additionally, the test temperature should not be too cool so that stiff mixtures will be too brittle to obtain the desired specimen failure type.

$$\text{Test Temperature (°C)} = ((\text{HTPG}+\text{LTPG}) / 2) - 3$$

Figure 3. Determining AMPT Cyclic Fatigue Test Temperature.

After the specimens are conditioned to the target temperature, the specimens are screwed tightly into the machine’s top and bottom end plates with a simple torque screwdriver. As the specimen is being secured into the AMPT, it is important to apply a seating load onto the specimen by jogging the actuator until enough contact between specimen end plate and the machine is present to exert 0.09 kN (20 lbf). Users should watch the “Levels” screen on their AMPT to ensure that the seating load does not change during the tightening process. If the seating load changes, the actuator must be jogged to reacquire the specified 0.09 kN. Afterwards, the LVDTs are attached and the chamber shut for temperature stabilization.

Users test a mixture under at least three different prescribed strain levels input to the control software. FHWA is developing a look-up table to guide the technician to select 300, 500, or 800 microstrain as the first test condition depending on the |E*| of the mixture measured in an earlier portion of the test. Once the fatigue life of that first specimen is measured, the next strain level is determined by interpolating the look-up table for different families of curves, which were developed from a testing database at FHWA. This table is being developed for a revised version of AASHTO TP 107 for consideration in 2017.

The software and data acquisition display real-time information for technicians to view when the specimen has failed. As the asphalt mixture becomes damaged, the stress being exerted on the specimen decreases while the on-specimen strain, measured by the LVDTs, increases. The software displays a decreasing modulus curve and an increasing phase angle curve. When the specimen cracks and has failed, the phase angle reaches a peak and begins to decrease with subsequent cycles. A technician can then stop the test and record the experimental cycles to failure. Afterwards, the test is repeated at other strain levels using other specimens of the same asphalt mixture.

Theoretical Foundation

The AMPT Cyclic Fatigue approach is rooted in continuum damage mechanics theory. Basically, continuum damage mechanics represents a body as a homogeneous unit which experiences damage in the form of stiffness or integrity loss. Approximately 25 years ago, a stress-strain model was outlined for asphalt mixtures (*9*) based on models developed over the last 40 years (*12*, *13*) in the aerospace industry for rocket propellant that consisted of asphalt or rubber with hard particles mixed-in. A damage model was needed to ensure the fuel would not crack inside the rockets.

The model is based on three principles that allow for simplification of the testing and analysis approach, but still maintain its power or robustness:

- Filtering of test data such that only fatigue damage is examined and not unwanted effects such as ordinary viscoelasticity or plasticity;
- Define a damage evolution law that universally describes the change in stiffness with load repetition; and
- Takes advantage of how asphalt adheres to time-temperature superposition, which states an asphalt mixture at a warm temperature and a given loading time has the exact same response at a cooler temperature and slower or longer loading time. Use of this principle helps to reduce the testing time from about a month for testing at different strains and temperatures to merely one or two days.

Readers are encouraged to consult other sources for more information (*9-11*; *14-23*).

It is important to consider that while the model relies on viscoelasticity and other complex factors, researchers have developed a software platform, which runs the analysis for users. Engineers who wish to learn more about the software can refer directly to the Appendix of AASHTO TP 107 for the background calculations, the references in this document, or contact FHWA for more information.

AMPT Cyclic Fatigue Test Applications

Since the AMPT Cyclic Fatigue Test provides a mixture-specific stress-strain model that captures a fundamental material property of asphalt mixtures, it can be applied to pavement modeling in several ways. At a material level, the test results and initial analysis can be used to subjectively rank mixtures in terms of fatigue resistance. For more advanced uses, an energy-based failure criterion is available, built on premises of released energy due to damage accumulation. It allows a user to objectively state that at a particular number of cycles to failure (chosen by the user, perhaps influenced by traffic loading at the site), one mixture will experience less damage under repeated loading than another and thus has more fatigue resistance. The procedure carries out damage analyses at multiple temperature and frequency combinations. This opens the interpretation of results to any location and any type of roadway facility. Structural inputs are required to have a comprehensive sense of which pavements will perform better in terms of fatigue. This stands in stark contrast to single index parameter-based test methods.

As part of NCHRP Project 9-38, the AMPT Cyclic Fatigue model was also used to predict the fatigue endurance limit for a particular mixture, which is a strain value at which perpetual pavements could exist if the exhibited strain remains below this threshold. This concept relates primarily to the development of bottom-up fatigue cracking and has been the topic of many studies aspiring to design pavements which could last 50 or more years with only minor surface repairs required.

For a more traditional fatigue analysis, shown in terms of a stress (or strain)-cycles to failure, the model can be fit to classical fatigue laws, such as the Asphalt Institute method (*24*). This allows the test results to be related to the flexural beam fatigue-based prediction approach that is being used in the AASHTOWare Pavement ME Design software. Since the AMPT Cyclic Fatigue testing and analysis time is less than that of the beam fatigue approach, there is a benefit to users who wish to use the classical fatigue laws. This is one of the ways the AMPT Cyclic Fatigue approach can be built into a structural model.

While a user can fit the empirical fatigue laws for use in AASHTOWare Pavement ME Design software, the AMPT Cyclic Fatigue approach has been made compatible with a new structural analysis platform with the potential to also become a performance specification tool. Current research being funded by FHWA is using the AMPT Cyclic Fatigue model with existing pavements to determine stresses and strains on a particular pavement structure. These results, coupled with climatic and traffic inputs, can be used to simulate damage on the structure in both bottom-up and top-down fatigue cracking modes. Several field validation projects (see Figure 4) have been analyzed to determine the software's effectiveness at modeling real-world pavements and to develop transfer functions so that the software can provide users with a calibrated predicted distress value. For example, researchers in Brazil are also using the AMPT Cyclic Fatigue Test with 44 pavement sections in a nationally-funded project to move towards a mechanistic-empirical pavement design framework.

Figure 5 shows a promising sample of calibration results from the National Center for Asphalt Technology (NCAT) test track, with control (C), open-graded friction (O), high reclaimed asphalt pavement (R), foamed warm mix asphalt (FW), warm mix asphalt (WMA) with reclaimed asphalt pavement (RW), and WMA with chemical additive (AW) sections. The plots show field, pre-calibration, and post-calibration results in terms of cracked area on the pavement surface. The pavement information and test data was programmed into the AMPT Cyclic Fatigue structural response model to develop pre-calibration predictions and is able to capture most of the field ranks and the magnitude of the FW and RW sections, which both include warm mix asphalt. By using a transfer function similar in form to that of the MEPDG to improve the pre-calibration results, the AMPT Cyclic Fatigue model can predict the distress with a similar magnitude and rank as the field. This data gives a glance into AMPT Cyclic Fatigue's robustness as a testing and analysis approach and how it transitions quite well to a performance prediction tool for fatigue cracking.

Figure 4. Map of field validation sites for the AMPT Cyclic Fatigue performance prediction platform.

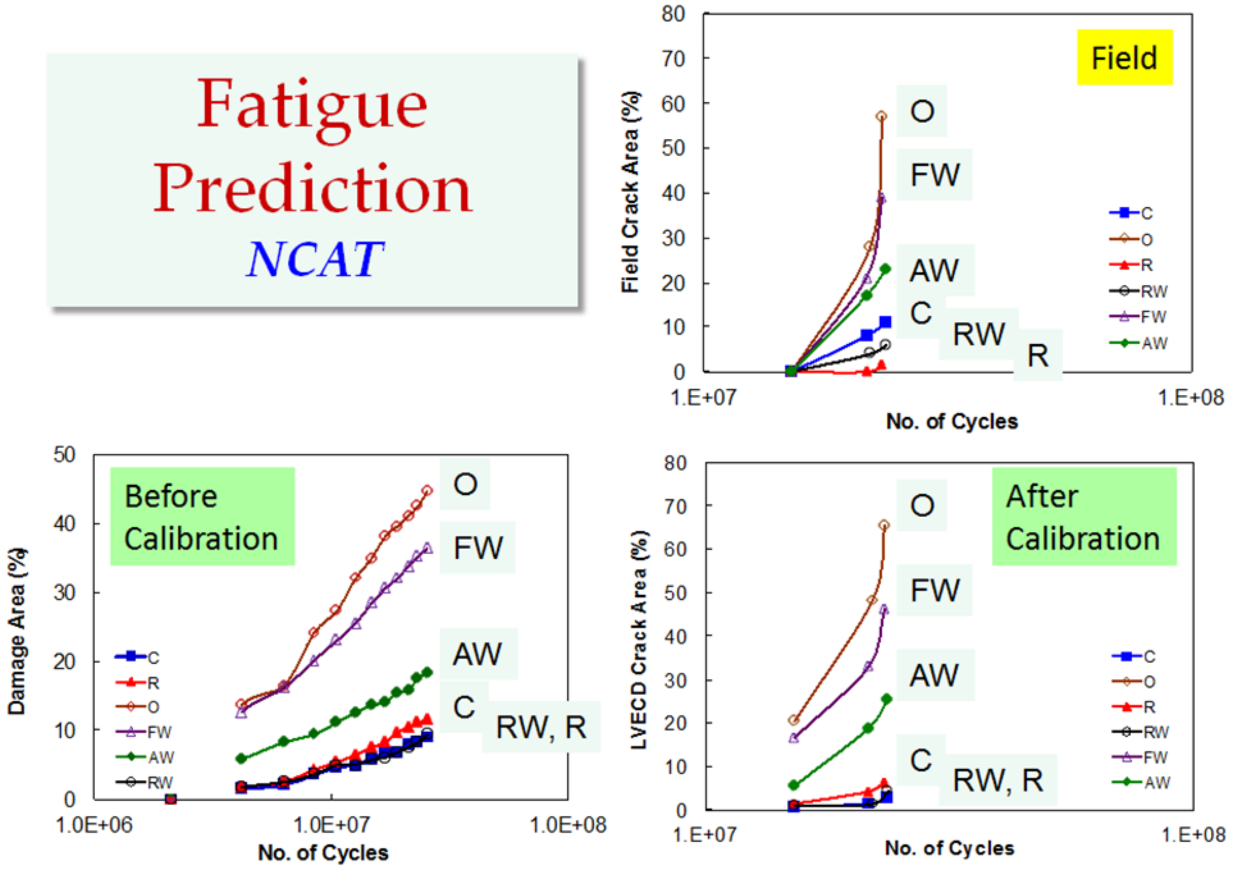

Figure 5. AMPT Cyclic Fatigue performance prediction calibration results for NCAT test sections (*25*). O indicates open-graded friction course, FW indicates a foamed WMA, AW indicates a WMA with chemical additive, C indicates a control mixture, RW indicates a WMA with RAP, and R indicates a high-RAP mixture.

Implementation Potential

Perhaps the most enticing element to the AMPT Cyclic Fatigue methodology is its potential as a link between pavement design and mixture design. The software being developed through FHWA not only has the potential to be the next-generation mechanistic-empirical structural design tool, but also a performance specification tool. In this scenario, a user would design a mixture guided by AMPT testing and conforming to certain performance requirements from the companion structural model. Next, the as-built material would be evaluated through relationships between performance prediction and volumetric quality assurance parameters after a calibrated prediction model between volumetrics and performance is established by researchers and state agencies in advance for a catalog of materials. A pay factor could then be determined based on a quality difference between the as-designed and as-built material properties, which are based on a sound structural model. It is believed that a performance specification holds the potential for increased innovation as it relates to asphalt mixture technologies including resource-conscious material inclusion.

Summary

The AMPT is a testing machine which is gaining interest in the asphalt industry as a tool capable of characterizing asphalt mixtures and closing the gap between pavement design and mixture design. Over the past several years, fixtures have been manufactured for the AMPT to conduct a wide range of test procedures. One of these tests, the AMPT Cyclic Fatigue Test, provides a material property that describes fatigue damage resistance and can be used in a structural response model capable of describing how the pavement behaves under varying repeated stress or strain conditions. This is particularly important when considering fatigue cracking in asphalt pavements, a major challenge for pavement engineers throughout the country. The AMPT Cyclic Fatigue Test uses direct tension loading to determine the damage characteristic relationship, which is considered a fundamental material property for a particular asphalt mixture of interest regardless of temperature and stress/strain levels. The AMPT Cyclic Fatigue methodology holds the potential to provide material and pavement system predictions which will lead to a sound mechanistic-empirical pavement design and performance specification framework. Agencies could apply this approach at critical locations to minimize fatigue cracking and provide substantial return on investment to the infrastructure network moving forward.

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