Comparative Evaluation of Asphalt Concrete Performance Tests

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Abstract

The Minnesota Department of Transportation, similar to most state agencies, relies on volumetrics for their asphalt mix designs. Although volumetric specifications are necessary for a quality asphalt concrete mix, little or no effort is placed on performance-based specifications. These specifications utilize mechanical tests to predict in-service performance of a mix. Research efforts are needed to explore the current availability of performance tests, their suitability, and their usage by state agencies. This thesis focuses on collecting information on both currently practiced and state of the art performance tests, and their suitability for performance prediction in cold-climate regions.

Desirable criteria were developed to analytically discover the most promising test(s) currently available for cracking prediction. A comprehensive literature review found an exhaustive amount of tests available, with varying levels of effectiveness. Although no test is perfect, there *are* tests that have promise. Through comparative evaluation, the Disk-Shaped Compact Tension Test, Semi-Circular Bend Test, and Indirect Tensile Test were found to be the most viable tests available. Other tests researched showed promise on some criteria, but were not well-rounded enough to be considered viable.

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1 Introduction and Background

1.1 Introduction

The Minnesota Department of Transportation, similar to most state agencies, relies on volumetrics for their asphalt mix designs. Although volumetric specifications are necessary for a quality asphalt concrete mix, little or no effort is placed on performance-based specifications. These specifications utilize mechanical tests to predict in-service performance of a mix. Research efforts are needed to explore the current availability of these tests, their suitability, and their usage by state agencies. This thesis focuses on collecting information on both currently practiced and state of the art performance tests, and their suitability for performance prediction in cold-climate regions.

1.2 Research Objectives

The overall goal of this thesis is to begin the process of finding a single performance test to accurately predict asphalt concrete cracking in cold-climate pavements. The process of finding whether this is a current test or a test that needs to be developed begins with the data collected in this thesis.

This thesis performs a comprehensive evaluation of both current and state of the art performance-based asphalt tests. A review of technical literature was performed to investigate both common and upcoming performance tests, and their relation to field performance. In addition, all state specifications were reviewed to see what performance tests are currently specified. The summary of these reviews were prepared and are presented in this thesis.

1.3 Thesis Organization

This thesis is divided into 5 chapters. In this chapter, an introduction to pavement failure types and the Superpave mix design system is presented.

Chapter 2 provides an introduction to performance tests including an overview of the most common and most promising tests.

A comprehensive review of Department of Transportation specifications is discussed in Chapter 3. Data on currently specified test by DOTs can be found in the chapter.

Chapter 4 expands on performance tests by focusing on data available in literature that relates the tests to in-field performance. Information from Chapters 2 and 4 are compiled together for comparative evaluations of the various tests.

Finally, Chapter 5 shows a summary of the previous 4 chapters and presents conclusions of this thesis and recommendations for future research.

1.4 Current State of Knowledge

1.4.1 Pavement Failure Types

Failure of asphalt concrete pavements can be broken down into 4 general categories: moisture damage, rutting, fatigue cracking, and thermal cracking. Depending on the mix design, climate, and other factors, pavements will deteriorate in one or more of these fashions over time.

Dissimilar to other failure types, moisture damage is a material failure. An asphalt mix is considered moisture-susceptible when the presence of water weakens the bond between the aggregate and binder. If this bond is severely weakened, stripping of the binder from the aggregate can occur.

Most typical in warmer climates, rutting occurs as the HMA layer softens and undergoes plastic deformation due to traffic loading. Because asphalt concrete is a thermo-viscoelastic material, as temperatures rise, the material is more prone to plastic deformation. As traffic loads the pavement, ruts occur in the wheel paths creating longitudinal depressions. Rutting can also occur because of excess binder in the mix.

Fatigue cracking occurs in pavements because of repeated traffic loading. Asphalt concrete pavements are engineered with a certain design life. Repeated traffic loading, especially from large trucks, eventually causes significant accumulated damage that leads to pavement failure.

Thermal cracking is the most common failure type in colder climates. As the temperature of asphalt concrete drops, it becomes more brittle. Cold temperatures cause the material to contract. The combination of tensile stresses and increased brittleness leads to cracking. As moisture enters these cracks, it freezes and thaws as the temperature changes. The action of moisture increases the propensity for cracking.

Although the root causes of fatigue cracking and thermal cracking are different, they can be tied together. Increased traffic loading causes both failure mechanisms to occur faster and more severely. Performance tests that measure an engineering property such as modulus or energy are known as *fundamental or engineering* tests. Tests that emulate in-field condition of pavement are known as *simulative* tests. Fundamental tests are often preferred because cracking measured from mechanical and physical properties of a mix can be used for computational or analytical simulation purposes. This leads to a combination of material and structural designs. Typically, simulative tests are limited to material selection process and require significant calibration to correlate measured property with field performance.

1.4.2 Superpave Mix Design

The Strategic Highway Research Program (SHRP) was established in 1988 with the goal of improving asphalt material specifications and mix design procedures. At its conclusion in mid-1990s, the goals of SHRP were reached through the development of the Superior Performing Asphalt Pavement System (Superpave). The Superpave system includes the performance graded (PG) asphalt binder specifications as well as the asphalt concrete mix design procedure. The asphalt mix design procedure was developed as a performance based specification (Roberts et al., 2009). The mix design specification is divided into a tiered system with three different design reliability levels (Cominsky et al., 1994). The lowest reliability level, Level I, is typically recommended for pavements with a lifetime design traffic of less than 10 million Equivalent Single Axel Loads (ESALs). Level II and Level III typically correspond to design traffic levels of 10 – 100 million ESALs or higher. The basic premise with different design levels is that Level I relies primarily on the volumetric properties to get good field performance, Level II requires volumetric and performance tests to improve upon the reliability, and Level III includes proof tests in addition to volumetric and performance tests to yield the greatest level of reliability. The requirements of various levels of the Superpave mix design procedure are presented in the following discussion. Additional details can be found in the SHRP project report by Cominsky et al. (1994).

The design approach for Superpave Level I mix design procedure can be summarized as:

- Selection of suitable asphalt binder according to the Superpave PG grading system
- Use of good aggregate structure as dictated by the aggregate source and consensus properties, and gradation control zones
- Selecting optimal asphalt content using various volumetric measures
- Use of Superpave gyratory compactor to simulate field compaction
- Determining moisture damage sensitivity of the mix by use of the AASHTO T-283 test procedure to calculate the tensile strength ratio

Through DOT review, it was found nearly every Department of Transportation follows the Superpave Level I mix design in some capacity. For this reason, state DOT performance specifications focus primarily on moisture damage but not cracking or rutting.

For the Superpave Level II mix design, in addition to the above requirements, a series of performance tests and performance models are utilized to improve upon the reliability of good field performance. The performance tests and models were developed for the three most popular asphalt distresses, rutting or permanent deformation, fatigue cracking, and thermal or low temperature cracking. The required performance tests for Superpave Level II mix design are as follows:

- Permanent Deformation Distress: Series of tests conducted using the Superpave Shear tester (SST). Tests include: repeated shear as constant stress ratio, simple shear at constant height, and frequency sweep test at one temperature.

- Fatigue Cracking Distress: Tests conducted using SST include: simple shear at constant height and frequency sweep test at one temperature. Indirect tensile strength measured using the indirect tensile test (IDT) is also required.
- Low Temperature Cracking Distress: A series of IDT tests include: indirect tensile creep at three temperatures and indirect tensile strength at one temperature. The creep stiffness and slope parameters from the bending beam rheometer (BBR) testing of asphalt binder is also required.

The test results from the above list are used as inputs to three performance models, one for each primary distress. The design process recommends that each set of tests be conducted at three asphalt binder contents, thus giving designer a full picture of the effect of binder content on the predicted performance of pavement.

The Superpave Level III mix design procedure recommends the performance tests of the Level II design with a greater degree of the test parameters (test temperatures, loading frequencies etc.). It also adds a few additional testing requirements. The added requirements for Level III performance tests are the following:

- Permanent Deformation Distress: Using the SST device, uniaxial strain tests at three temperatures, frequency sweep at three temperatures, and simple shear at constant height at three temperatures. Additionally, mix volumetric measurements are required to be taken at three temperatures.
- Fatigue Cracking Distress: Frequency sweep using SST at three temperatures and indirect tensile strength using IDT at three temperatures.

- Low Temperature Cracking Distress: Both indirect tensile creep and indirect tensile strength at three temperatures using IDT.

Once again, the performance test results were used as inputs to the performance prediction models which were used to finalize the mix design. The level III design procedure also recommends a series of proof tests as means to validate the performance of the mix. The recommended proof tests are as follow:

- Permanent Deformation Distress: Wheel Tracking Test
- Fatigue Cracking Distress: Flexural Beam Fatigue Test
- Low Temperature Cracking Distress: Thermal Stress Restrain Specimen Test (TSRST)

2 Bituminous Performance Tests

2.1 Introduction

Both Chapters 2 and 4 focus on state of the art performance tests. This chapter, in contrast to Chapter 4, gives a broad overview of these tests. Test procedures, data parameters, and specimen geometry are the focus. The information presented is designed as a comparative overview of the tests. More detailed information can be found in the cited references. Findings of test effectiveness and comparative evaluation are presented in Chapter 4.

2.2 Review Methodology

A comprehensive literature review was performed to explore state of the art performance tests that have been sufficiently developed. The performance tests focused on in this chapter:

- Are used by other DOTs
- Can predict fatigue or thermal cracking
- Are used for plant-produced hot mix asphalt

Because the list of performance tests is exhaustive, these criteria were used to refine the list to the most suitable performance tests. This thesis focuses primarily on cold-climate regions where rutting is not a primary concern. For this reason, rutting tests are not included in this thesis.

2.3 Review of Asphalt Performance Tests

2.3.1 Asphalt Concrete Cracking Device (ACCD)

The Asphalt Concrete Cracking Device uses a fixed frame apparatus and low temperatures to induce thermal cracking on asphalt concrete samples. ACCD utilizes cylindrical specimens roughly 2.75 inches (70.6 mm) in diameter and 5.9 inches (150 mm) in height. Although this is an unconventional height to diameter ratio, ACCD developers deemed it to be acceptable for this test because of cold HMA's brittleness (Kim et al., 2009). The ACCD is run by cooling the specimen at 10°C/hour with a fixed ring inside. While cooling, the sample contracts, putting stress on the inner ring. The specimen eventually fails and the temperature (fracture temperature) is recorded. The stress and temperature data is put into computational models to predict performance.

Figure 1 Asphalt Concrete Cracking Device

Source: Kim et al. 2009

2.3.2 Asphalt Mixture Performance Test (AMPT)

Developed as part of NCHRP 9-29, the Asphalt Mixture Performance Test aims to predict performance through dynamic modulus and flow number. These properties can be used as inputs for Mechanistic-Empirical Pavement Design Guide (MEPDG) software. The AMPT uses different test procedures to find these values as described by AASHTO TP-79: *Determining the Dynamic Modulus and Flow Number for Hot Mix*

Figure 2 Asphalt Mixture Performance Test

Source: University of Nevada, Reno

Asphalt Using the AMPT. To obtain dynamic modulus, a cylindrical specimen of 4 inch diameter by 6 inch height is subjected to sinusoidal compressive stresses at various frequencies. To obtain flow number a similar procedure is used, however, the sinusoidal loading has a constant frequency. Both procedures can be performed as either confined or unconfined, and both tests use the same specimen geometry.

In recent years, great amounts of money have been spent researching AMPT as an effective performance test. AMPT has consistently shown good correlations with rutting performance in this research. Correlations with cracking, however, have not been strong. In addition, very extensive models are needed to relate AMPT data to performance. For these reasons, AMPT was not included in the analysis presented in Chapter 4 of this thesis.

2.3.3 Beam Fatigue Test (4 Point Bending, 4PB)

Because of its complexity and high operating costs, the Beam Fatigue Test is predominantly a laboratory and research testing method. Originally developed in the 1960s at the University of California Berkeley, the test was improved as part of the SHRP A-003A project. The modified test has been standardized as AASHTO T-321: *Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending*.

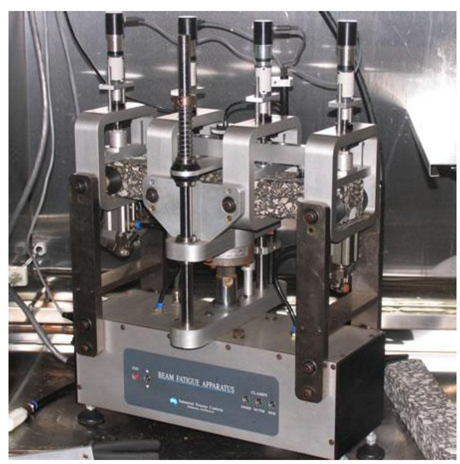

Figure 3 Beam Fatigue Test

Source: pavementinteractive.org

The Beam Fatigue Test uses a four-point bending apparatus that is placed inside an environmental test chamber. A 15x2x2.5 inch specimen is temperature conditioned for two hours prior to the test to a temperature of 68°F. The stress controlled test is run as two inner clamps apply a sinusoidal load to the sample. The outer two clamps remain stationary to provide a reactionary load.

Deflection is measured at the midspan of the beam by LVDTs placed on the sample. The primary performance measure of the 4PB is fatigue life, that is, how many load repetitions are necessary to fail the specimen. Commonly used failure criteria is 50% reduction to the stiffness of material.

Specimen properties can be obtained from the Beam Fatigue Test by using formulas specified in AASHTO T-321. These fundamental properties include maximum tensile stress, maximum tensile strain, flexural stiffness, phase angle, dissipated energy, and stiffness.

2.3.4 Dynamic Mechanical Analyzer (DMA)

The Dynamic Mechanical Analyzer is a torsional loading machine for testing asphalt concrete samples. The DMA was originally intended to be used as a mechanical test system for evaluating viscoelastic properties of materials, including polymers and mastics (Butt et al., 2010). Mechanical data provided by DMA (torque, twist angle, etc.) is used in a continuum damage mechanics model to predict moisture susceptibility.

Figure 4 Dynamic Mechanical Analyzer

Source: King Faisal University

Previous research used rectangular beam samples in the DMA for evaluation. In its current form, developed by Kim et al. (2004) , DMA utilizes cylindrical samples to minimize complex stress calculations. A typical cylinder size has a 0.5 inch (12mm) diameter and 2 inch (50mm) height. A common DMA machine can provide extreme temperature ranges for testing samples. A given machine could have a temperature range from -150°C to 600°C.

2.3.5 Fracture Test- Disk-Shaped Compact Tension Test

The Disk-Shaped Compact Tension Test (DCT) aims to predict thermal and fatigue cracking through fracture energy. The DCT uses a modified cylindrical sample easily obtained from a field core or laboratory gyratory sample. The disk shape is then modified with a flattened edge for gauge placement, and two holes for the loading apparatus.

Figure 5 Disk-Shaped Compact Tension Test

The DCT was developed by Wagoner et al. (2004) to improve upon the SCB. This was done by maximizing the potential failure area of the sample, therefore reducing the variability in the fracture energy results (Wagoner, 2006). A 2 inch specimen depth is commonly used which is beneficial when collecting field cores.

During initial development, localized failure occurred at the loading holes of the DCT samples, leading to poor test results. The specimen geometry, however, has been modified to eliminate these localized failures. The testing procedure and modified specimen geometry are now standardized in ASTM D7317-07a: Standard Test Method for Determining Fracture Energy of Asphalt Aggregate Mixtures Using the Disk Shaped Compact Tension Geometry.

2.3.6 Fracture Test- Semi-Circular Bend

The Semi-Circular Bend Test aims to predict pavement performance by way of fracture energy or critical strain energy release rate. Typically, the parameter chosen is based upon climate. Fracture energy has shown better correlation with thermal and reflective cracking, while strain energy is more commonly used for rutting.

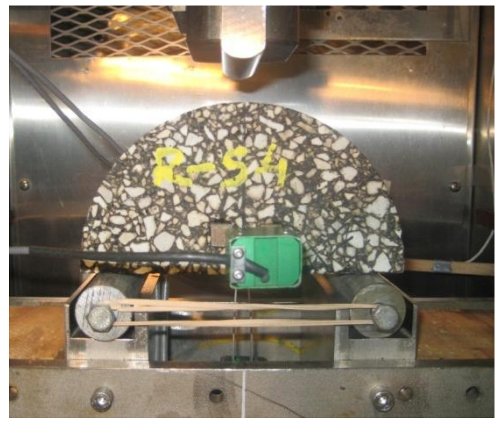

Figure 6 Semi-Circular Bend Test

The SCB uses half-disk shaped samples which are easily available through field cores or using a gyratory compactor in the lab. The half-disk shape allows two samples per field core. Development by Molenaar et al. (2002) allows thin samples (2 inches) to be tested, which is desirable when testing field cores.

Different test parameters are typically collected based on climate. In colder climates, fracture energy is collected as it has shown a good correlation with low-temperature and reflective cracking. In warmer climates, strain energy is collected to predict rutting performance. The two parameters have not shown particularly good correlation outside of their temperature ranges.

The SCB has been criticized because of the size and shape of the specimen. The half-disk shape leads to complex stress analysis. SCB samples are much smaller than typical performance test samples. With the introduction of the notch in the sample, the testing area of the sample becomes quite small. This has raised concern with some researchers (Wagoner, 2005) that the testing area is too small for consistently accurate results.

2.3.7 Indirect Tensile Test- Creep (Static)

The IDT Creep and Strength Test is the most popular test for evaluation of viscoelastic modulus of asphalt concrete at low temperatures. The test procedure and analysis method was refined and standardized by Buttlar and Roque (1992) for its use in the Superpave mix design procedure. IDT Creep methods have been standardized as AASHTO T-322: *Determining the Creep Compliance and Strength of HMA Using the Indirect Tensile Test Device*.

Figure 7 Indirect Tensile Test

The test uses cylindrically shaped samples as an improvement over other tests that use beam shapes. Either Linear Voltage Displacement Transducers (LVDTs) or strain extensometers are used in the testing apparatus and linked to a computer for data collection. IDT collects creep compliance of the specimen. The equipment requirements for this test are comparable to AMPT with a need for close-loop controlled loading frame and four sets of extensometers or LVDTs.

2.3.8 Indirect Tensile Test- Cyclic

Obtaining AMPT specimens from field sites is challenging due to requirement for nearly 8 inch tall cylindrical specimens. The Cyclic Indirect Tension Test improves upon this by using a 2 inch high specimen. In recent years, Kim et al. (2004) have used this test to obtain material parameters similar to AMPT. Thus, this test can serve as good alternative to AMPT and should have similar capabilities in effectiveness of field performance prediction.

Originally developed in Brazil and Japan in the 1940s, the Cyclic IDT is performed by applying a cyclic compressive load to the specimen through two diametrally opposite plates. Through fracture mechanics models, stress, strain, and modulus of the specimen are used to predict performance.

2.3.9 Indirect Tensile Test- Strength

The Indirect Tensile Strength Test for asphalt concrete has been used very extensively, as discussed in previously report. Also developed by Roque and Buttlar (1993), the test is required by several DOTs as part of mix acceptance criteria. There has been large variation amongst the agencies, researchers, and practitioners with testing procedure and data analysis for the IDT Strength Test. These variations include test temperatures, loading rate, displacement measurements, and the selection of load corresponding to the failure, and specimen preparation and conditioning procedures. The test procedure has been standardized as ASTM D6931-12: *Standard Test Method for Indirect Tensile (IDT) Strength of Bituminous Mixtures*.

The IDT Strength Test was developed in conjunction with the Superpave asphalt mix design process. The result from this test is one of the key inputs to the SHRP thermal cracking prediction model or TCMODEL. The testing complexity and equipment needs for the Superpave IDT Strength is relatively high. Typically, a close loop loading system with 100 kN capacity is needed along with four extensometers or LVDTs and data acquisition system. Typically, testing is conducted to obtain results for IDT Creep and Strength simultaneously to compute fracture energy.

On the other end of complexity spectrum is the tensile strength measurement from the AASHTO T-283 procedure. The equipment and measurement requirements are quite low in this case. Only a single peak load measurement is typically needed, and there is minimal need for data post-processing. One of the biggest benefits of this test is that it is already being utilized by most agencies including MnDOT. Presently, most agencies use only one parameter form this test and that is, the ratio of tensile strengths for samples before and after moisture conditioning.

2.3.10 Mix Bending Beam Rheometer (BBR)- Creep

The Bending Beam Rheometer device is used to test asphalt binders. It provides a measure of low temperature stiffness and relaxation properties. The test has been standardized by AASHTO T-313: *Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)*.

Figure 8 Bending Beam Rheometer

Source: pavementinteractive.org

The device requires a rectangular asphalt binder sample. The rectangular beam is 0.25 inches in height by 0.6 inches in width by 5 inches in length. The beam is simply supported with the supports spaced 4 inches apart. The BBR apparatus applies a single point load of 100g at the midspan of the beam. Deflection measurements are recorded by the BBR's software at 8, 15, 30, 60, 120, and 240 seconds. The software records the creep stiffness (beam stiffness) which can be used to create a stiffness master curve. The slope of the master curve at a given time (*m-value*) is often calculated. A strong correlation is found between results from this test and the IDT creep test. Direct predictions to performance, however, are not available.

Although BBR Creep is an asphalt binder test, Zofka et al. (2005) have proposed use of the Bending Beam Rheometer (BBR) device to determine the creep properties of asphalt concrete. Romero et al. (2011) also reported similar findings as the work by Zofka et al. (2005) for test conducted on production mixes from Utah.

2.3.11 Mix Bending Beam Rheometer (BBR)- Strength

The Bending Beam Rheometer device commonly used for testing of asphalt binders has been modified by researchers at the University of Minnesota Twin Cities campus to measure tensile strength by conducting a flexural strength test (Turos, 2010). The preliminary results show a good correlation between the mix BBR strength and IDT results. Thus, the mix BBR Strength Test can be used as a simpler alternative to the Superpave IDT with the expectation that similar efficiency in field cracking performance prediction will be obtained. Similar to BBR Creep, however, direct predictions to performance cannot be made from the test.

2.3.12 Superpave Shear Tester

The Superpave Shear Tester (SST) was developed through SHRP as part of the Superpave design procedure for Level II and Level III mixes. The SST uses repetitive loading in shear to test specimens of 6 inch diameter by 2 inch height. This specimen height can easily be cored from a pavement section,

Figure 9 Superpave Shear Tester

or by using a gyratory compaction machine. The SST equipment can perform 3 different tests: the *Simple Shear Test*, the *Repeated Shear Test*, and the *Shear Frequency Sweep Test*. All three tests are standardized by AASHTO T-320: *Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Tester*.

The SST aims to predict field performance through the fundamental properties of complex shear modulus (G*) and phase angle.

The *Simple Shear Test* procedure can be run at varying test temperatures with a corresponding shear stress. These are values are standardized by the AASHTO specification. The specific load (stress) is applied to the sample for ten seconds, while maintaining the sample height. The load is then released and data is collected from LVDTs placed on the specimen.

When performing the *Repeated Shear Test*, the sample is loaded sinusoidally by a 10 psi shear stress for .1 seconds followed by a .6 second rest period. Typically, the test is run for a minimum of 5000 cycles or until 5% shear strain is reached.

The *Shear Frequency Sweep Test* applies a sinusoidal shear strain of .01% for 100 cycles. The shear frequency sweep process is then started by applying a shear strain of .01% at various frequencies and cycles as prescribed by AASHTO T-320*: Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Tester (SST).*

Although developed for the Superpave mix design procedure, Superpave Shear Tester equipment is very expensive. Thus, it is uncommonly used in the field and is predominantly used as research equipment.

2.3.13 Texas Overlay Tester

The Texas Overlay Tester (OT) was developed at the Texas Transportation Institute (TTI) as a simulative test for reflective cracking in overlays. The testing apparatus requires rectangular specimens of 6x3x1.5 inches obtained from a gyratory sample or 6 inch field core. The tester is a cyclic loading machine that loads the sample in a haversine-shaped loading pattern for 100 cycles. The testing apparatus consists of two plates that move to and from each other in the desired loading pattern. The cyclic loading of the machine is used to initiate failure of the sample.

Research by Zhou and Scullion (2010) at TTI found that the original design of the Overlay Tester often is inadequate for testing pavement sections in Texas. The *regular* OT test uses an opening displacement of .025 inches which is too large for many limestone mixes used in the area, causing a very low number of cycles to specimen failure which are not enough for fracture property determination. Improvements were made to the test to eliminate the *regular* test's issues.

Figure 10 Texas Overlay Tester

Source: Zhou et al., 2010.

The TX Overlay Tester computes fracture properties to relate field performance. These values are used in conjunction with computation models to predict fatigue cracking performance. To obtain the fracture parameters, the test uses crack length and a Stress Intensity Factor found using finite element analysis. The OT can also find values of stress, strain, and dynamic modulus using the mounted external LVDTs.

2.3.14 Thermal Stress Restrain Specimen Test (TSRST)

The Thermal Stress Restrain Specimen Test is a simulative test that was developed through the Strategic Highway Research Program (SHRP) as part of the Superpave Level III mix design process. The test uses thin rectangular specimens (1x1x12 inches) for testing. The testing apparatus includes a temperature controlled chamber which is heated and cooled cyclically. The specimen in the chamber is fixed so the sample is not allowed to contract. The need for rectangular beam samples requires dedicated equipment that cannot be shared with other tests, making TSRST difficult to use on a routine basis.

Figure 11 Thermal Stress Restrain Specimen Test

Source: University of Nevada, Reno

TSRST aims to predict thermal cracking through fracture temperature. The fracture temperature is the temperature at which the thermal stress equals the tensile strength in the specimen. Formerly standardized as AASHTO TP-10 (TP designates a provisional specification), the test has since been eliminated from the AASHTO specification catalog.

2.3.15 Uniaxial Cyclic Fatigue (Push-Pull) Test

The Push-Pull Test was developed by Soltani et al. (2006) to be an upgraded performance test from the 4 Point Bending Test. The Push-Pull Test uses cylindrical samples 3.9 inches (100 mm) in diameter which can easily be made in the lab or collected from the field. The specimens, however, are typically 4.7 inches (120 mm) in height. These typically will not be found in the field due to typical pavement depths.

Figure 12 Push-Pull Test

The Push-Pull Test loads the sample sinusoidally starting with an initial compressive load, hence the name Push-Pull. The Push-Pull Test uses tensile strain to find an endurance limit of the sample. This endurance limit can be put into computational models to predict field performance.

3 Bituminous Performance Tests

3.1 Introduction

This chapter focuses on the state of the practice of performance-based specifications in the United States. For this thesis, *state of the practice* is a test required by a state Department of Transportation for conventional asphalt mixes. An overview of specification methodologies is also presented.

3.2 Asphalt Concrete Material Specification Methodologies

Over the years, the specifications for asphalt concrete by state highway agencies have varied significantly. A review of asphalt specification development can be found elsewhere (Anderson and Russell, 2001, and Gallivan, 2011). The evolution of asphalt material specifications is visualized in Figure 1. The most common categories which describe various agency specifications are as follows:

- Method Specifications: These are usually highly prescriptive in nature and describe the asphalt mix design and manufacture and paving processes. The major shortcoming of this approach is that a majority of the performance risk is placed on the mix design and construction procedure. Presently, the most commonly adopted mix design procedure is the Level I Superpave volumetric mix design, defined in Section 1.4.2. This methodology does not require any major mechanical test to evaluate in-field performance of the mix.
- Quality Control and Quality Assurance (QC/QA) Specifications: These types of specifications improve upon the method specifications by ensuring the quality of final product. Typically these involve quality tests for as-constructed asphalt

concrete lifts. Typical quality parameters include, mix laydown temperature, mix volumetrics (air void, asphalt content etc.), and as-built thicknesses of asphalt lifts. In the case of QC/QA specifications, the risk of inadequate field performance is still undertaken by the agency, as assumptions are made that the quality indication parameters will assure good field performance. Once again, the most commonly used quality indicators are linked to mix volumetrics and not a mechanical test procedure.

- End Result Specifications (ERS) and Performance-Related Specifications (PRS): The use of ERS builds upon the QC/QA methodology by the inclusion of risk assessment (Buttlar and Manik, 2007). While the assessment of risk inherently links the pavement performance end result to commonly measured QC/QA quantities, usually a mechanical test for performance evaluation is not included in this type of specification (unlike performance-*based* specifications). In some cases, such as the California DOT PRS system (Deacon et al., 1997), the material volumetric and structural properties are jointly used as means of pavement specifications. Typically, these types of specifications rely on well-established links between mix volumetrics and layers thicknesses and commonly anticipated pavement distresses.
- Performance-Based Specifications (PBS): These types of specification procedures commonly utilize results from a mechanical test or series of mechanical tests commonly referred to as performance tests. Such performance test results allow for agencies to predict the field performance of the pavement. By specifying a

limit on the performance test result agencies can ensure good pavement life. The key hindrance in wide-spread usage of this type of specification method is lack of a widely accepted and proven asphalt performance test. Several research studies have been conducted to develop performance based specifications for asphalt concrete; for example, a study by Williams et al. (2004) developed trial specifications for the Michigan DOT. It is worthwhile to notice that the review of various DOT material specifications from United States showed that PBS are not currently in routine practice. Furthermore, from a research perspective, much focus has been placed on rutting distresses, but very limited research has been conducted on use of PBS for thermal cracking distresses.

- Warranty Based Projects: These types of projects are commonly specified to minimize the performance related risks to the agency. Typically in case of warranty projects, the final field performance goal is established by the agencies and contractors are given greater freedom over the choice of pavement structure and materials to meet those performance goals. Due to greater risk on the part of contractor, these types of projects are usually associated with higher costs.

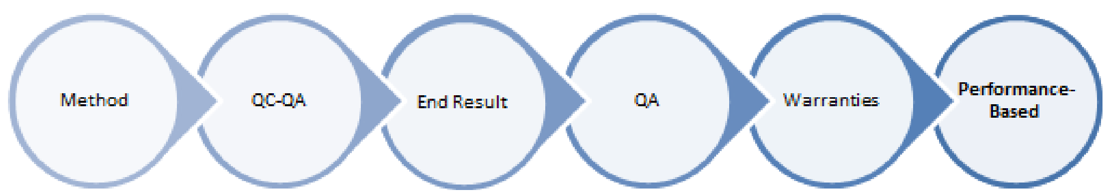

Figure 13 Evolution of Asphalt Material Specifications

From the perspective of the material specification process, the tasks of this study fall most closely to the PBS. This is mainly due to a requirement of a robust, validated, and simple mechanical test in the PBS system to link laboratory measured properties with anticipated field performance. There are some implications to ERS, PRS and warranty projects, as all of these also require some link between the asphalt material and field performance.

3.3 State of the Practice

3.3.1 Methodology

One goal of this project was to understand if and what Departments of Transportation are using as performance-based specifications. In order to conduct this evaluation, a comprehensive review of Standard Bridge and Road Construction Specification manuals was conducted for 51 agencies. The review included DOTs from all 50 United States as well as the District of Columbia. With many of the manuals being very large in size, the following conditions were focused on as a screening process:

- The most current version of the standard specifications was reviewed. Older versions were referred in some instances, such as, citation in a reviewed literature.
- Unless otherwise indicated in this report, the focus was on the standard specifications and not the provisional specifications. Again, if other literature indicated that provisional specifications are requiring performance test, then those were reviewed.
- Testing requirements were focused for plant produced asphalt concrete. Other asphaltic materials such as surface treatments or emulsified tack-coats were not focused upon in this project.

3.3.2 Presentation of Review Results

The findings from the literature review were converted into numerical data in the form of charts and graphs. The raw data of these figures can be found in Appendix A.

The first observation from this review is that most standard specifications describe method and QC/QA specifications and very few used the terminology "performance related specifications". No standard specification was found to explicitly use the term "performance based specifications". Another observation was that all 51 specifications broadly follow Superpave Level I volumetric mix design requirements (volumetrics and TSR only). The Level II or Level III type requirements are not present in any instances.

It was found that 47 DOTs have at least one mechanical test requirement. Only Delaware, Maine, Massachusetts, and New Mexico DOTs do not. The majority of the requirements are to evaluate the moisture damage susceptibility of the asphalt mixture. The requirements span across a variety of tests including tensile strength ratio (TSR), tensile strength, Hamburg wheel tracking test, asphalt pavement analyzer (APA), Marshall flow and stability tests, and others. Figure 14 shows the break-down of various testing requirements with respect to tests (not DOTs). As evident from this figure, the majority of tests required are moisture damage susceptibility (total of 61%), with the majority of these tests being TSR. While the testing procedures for TSR vary slightly between various agencies, in broader sense they follow the AASHTO T-283 specifications. Other than moisture damage tests, the APA testing for rutting performance is the next most common test, with a 11% share of all tests.

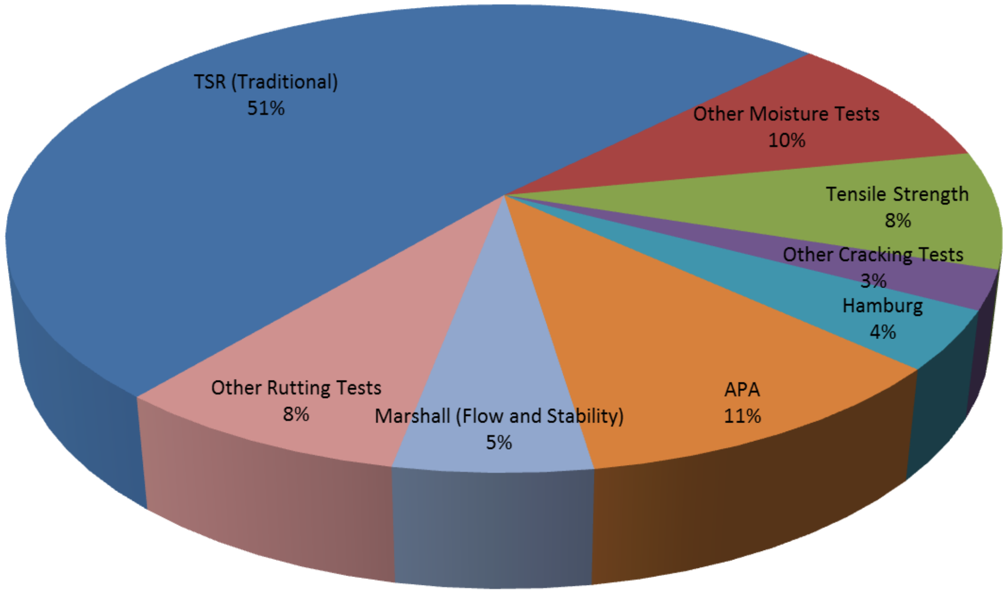

Figure 14 Mechanical Testing Requirements by DOTs (w.r.t. test)

As shown in Figure 15, twenty-one DOTs require mechanical tests other than moisture susceptibility. Of these 21 DOTs:

- 6 require a tensile strength test
- 3 require the Hamburg Wheel Test
- 8 require APA
- 4 require the Marshall Stability and Flow Test
- 6 require another or additional non-moisture mechanical test

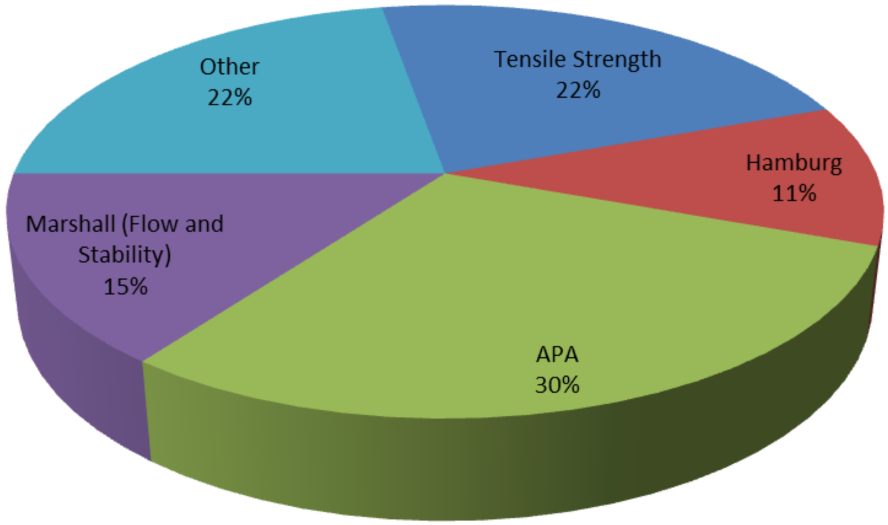

Figure 15 Breakdown of Performance Testing Requirements (w.r.t. DOT)

The performance test requirements can be further divided by the type of pavement distress that they are applicable to, that being rutting related tests and cracking related tests. The breakdown of the eighteen rutting test requirements is presented in Figure 16 and the seven cracking related tests in Figure 17. The majority of the cracking performance requirements are in the form of tensile strength. It should be noted that this tensile strength is usually available from the TSR test and does not require additional testing and specimen procurement and preparation. The other two cracking tests described in the DOTs specifications are the flexural beam fatigue test and the Texas Overlay Test. While the Texas Overlay Test is required for asphalt mixtures placed on existing deteriorated pavements in Texas, the flexural beam fatigue test from the Georgia DOT specifications is a recommended test which may be conducted as a part of the mix design process.

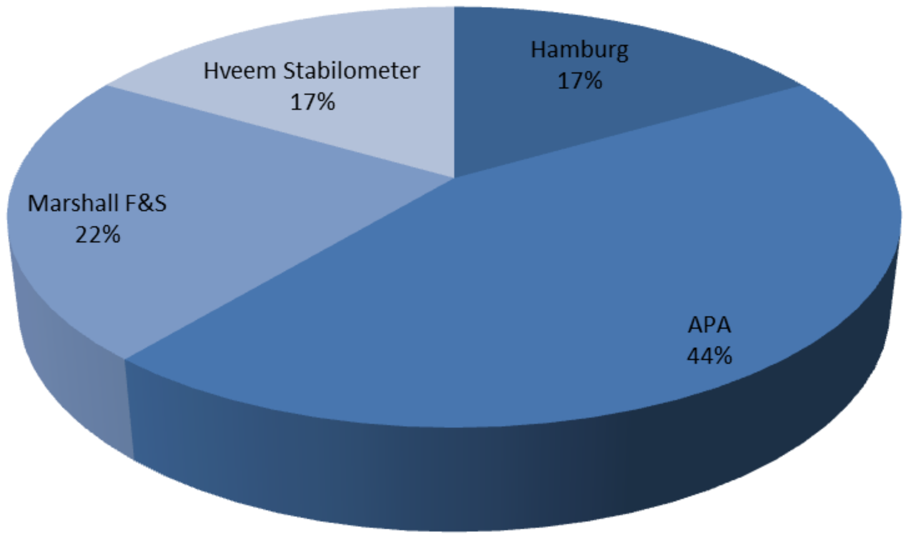

Figure 16 Rutting Performance Tests (w.r.t. test)

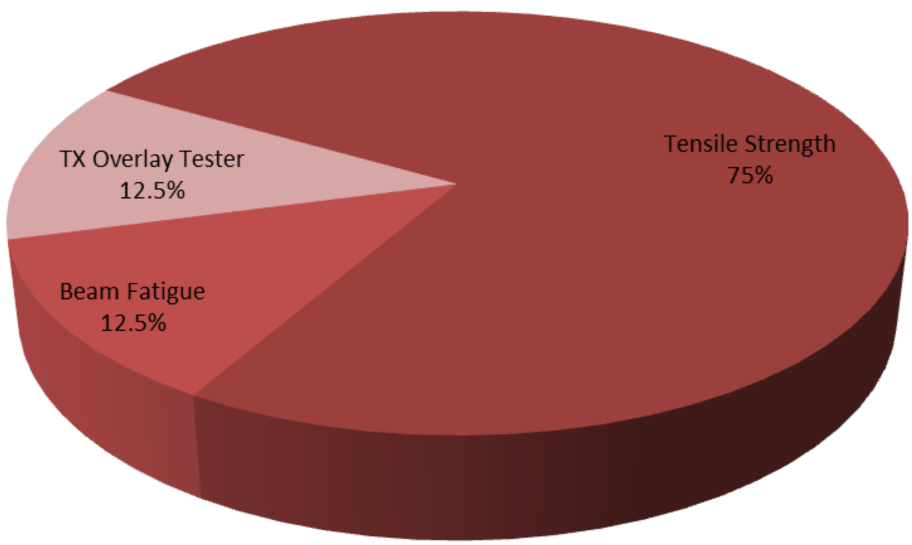

Figure 17 Cracking Performance Tests (w.r.t. test)

3.3.3 Summary of Findings

Based on the results from the review of State DOT standard specifications, the following key points can be summarized:

- Method and QC/QA specification procedures are most widely utilized
- Asphalt concrete mix design procedures used by DOTs follow Superpave Level I methodology with some variations
- Most states require mechanical testing to ensure good performance against moisture induced damage, with tensile strength ratio (TSR) test as most widely accepted practice
- From typical pavement distress perspective, performance tests for rutting are most common, with asphalt pavement analyzer (APA) being the test of choice
- Very few DOTs utilize commonly used performance tests for cracking distresses
- Several agencies are requiring a minimum dry tensile strength as a requirement in addition to the tensile strength ratio

4 Effectiveness of Asphalt Performance Tests

4.1 Introduction

This chapter discusses the effectiveness of the performance tests reviewed in Chapter 2. Its goal is to take the most promising of those tests and find their effectiveness in predicting in-field performance. These tests can then be compared to find the most promising test(s) moving forward.

4.2 Methodology and Performance Correlation Strengths

Not all of the performance tests discussed in Chapter 2 are included in this chapter. Only tests considered *potentially viable* were reviewed and evaluated. Potentially viable was defined as a test with published literature relating test results to field performance. A test also needed to have shown a reasonable level of repeatability to be considered. The effectiveness of these tests to predict field performance is discussed in Section 4.3.

The following subsection shows examples of strong, moderate, and weak correlations to field performance. These examples are provided to give distinctions between strong and weak correlations.

4.2.1 Strong Correlation

Disk-Shaped Compact Tension Test

Research by Cascione et al. (2011) aimed to validate good correlations to field performance using a fracture energy threshold of 400 J/m^2. Ten different field sites from various states were evaluated using the DCT to find whether this threshold could sufficiently predict the cracking found in the field. As shown in Figure 18, 400 J/m^2 seems to be a suitable threshold for cracking prediction.

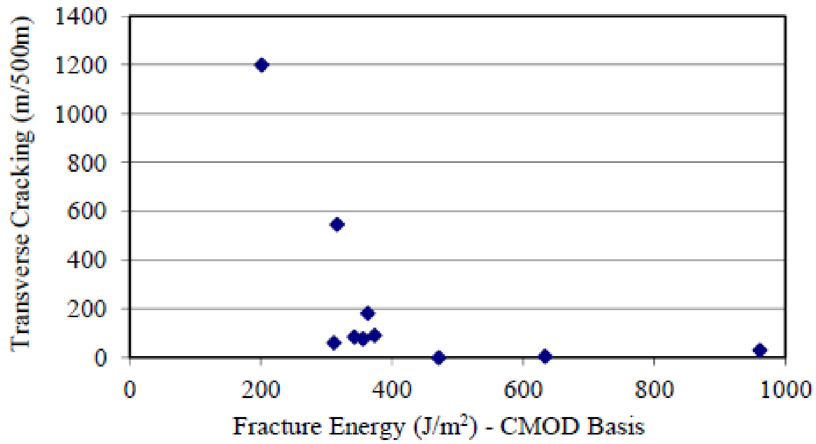

Figure 18 DCT Fracture Energy vs. Field Cracking

Source: Cascione et al. (2011)

Thermal Stress Restrain Specimen Test

Zubek et al., (1996) used TSRST to compare laboratory fracture temperatures to field-collected cracking temperatures. Figure 19 shows five sites from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) where data was collected. Statistical analysis of the data showed an R^2 (goodness of fit) of 0.62. For field-collected data, this is high enough to say (in this case) a strong correlation between TSRST data and field performance is found.

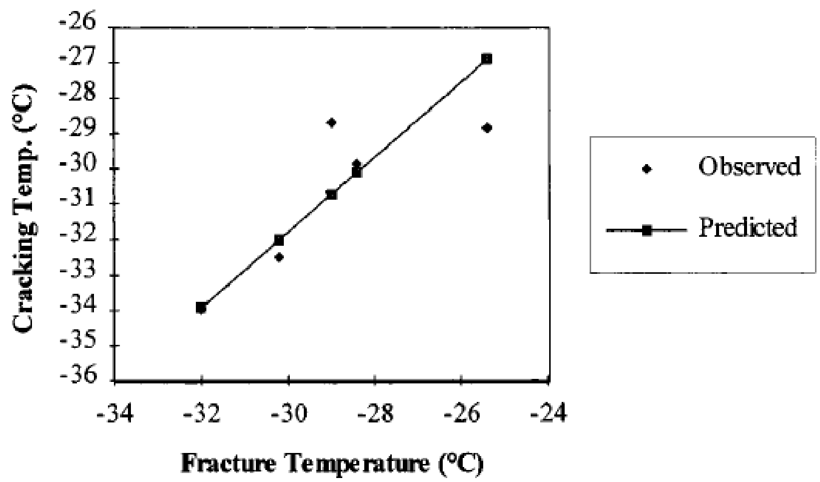

Figure 19 TSRST Fracture Temperatures vs. Cracking Temperatures

Source: Zubek et al. (1996)

4.2.2 Moderate Correlation

Indirect Tensile Test

The correlation between the IDT and field performance is moderate because of the IDT Strength Test. Although results from the test correlate well with field performance at low temperatures, the test showed an inability to distinguish results at varying temperatures (Raad et al., 1998). As shown in Figure 20, the test results ranging from high test temperatures to low test temperatures are statistically indifferent.

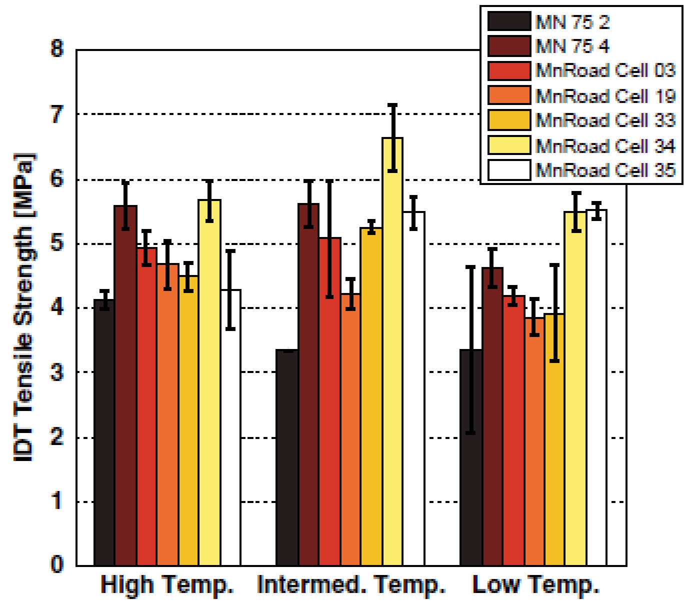

Figure 20 IDT Strength Results at Varying Temperatures

Source: Raad et al. (1998)

Beam Fatigue Test

Because some parameters of the Beam Fatigue Test correlate well with performance and some do not, the 4PB is graded in this report as having moderate correlations with field performance.

Willis and Timm (2011) compared fatigue endurance limits to collected field strains at the National Center for Asphalt Technology's (NCAT) Test Track. The data is shown in Figure 21. Good correlating data would show the data on the left side of the line to be uncracked, and data on the right to be cracked. The figure shows this to not be the case.

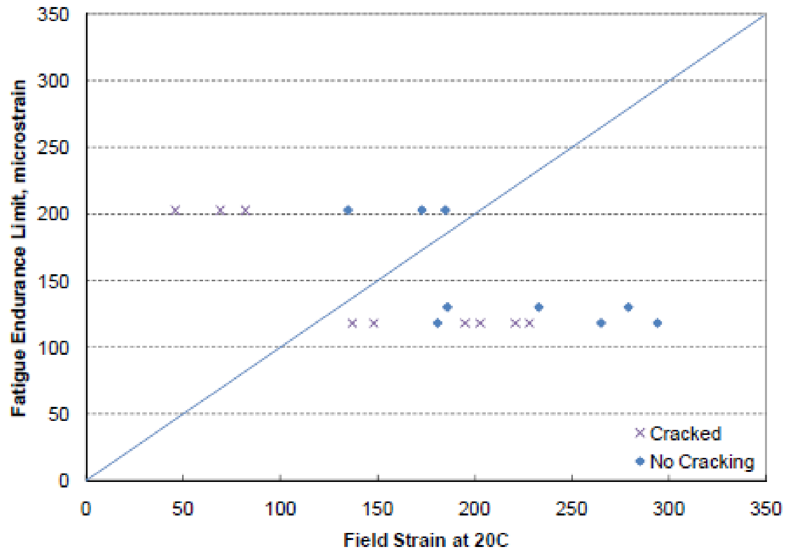

Figure 21 Relative Strain Comparisons

Source: Willis and Timm (2011)

Research by Way et al. (2009) showed a better correlation with field performance by way of number of cycles to failure (N_f). Figure 22 shows a very good correlation (R^2=0.93) between N_f and measured field strains ε_t. In this case as the strains in the field increased, the number of cycles to fail the specimen using the 4PB decreased.

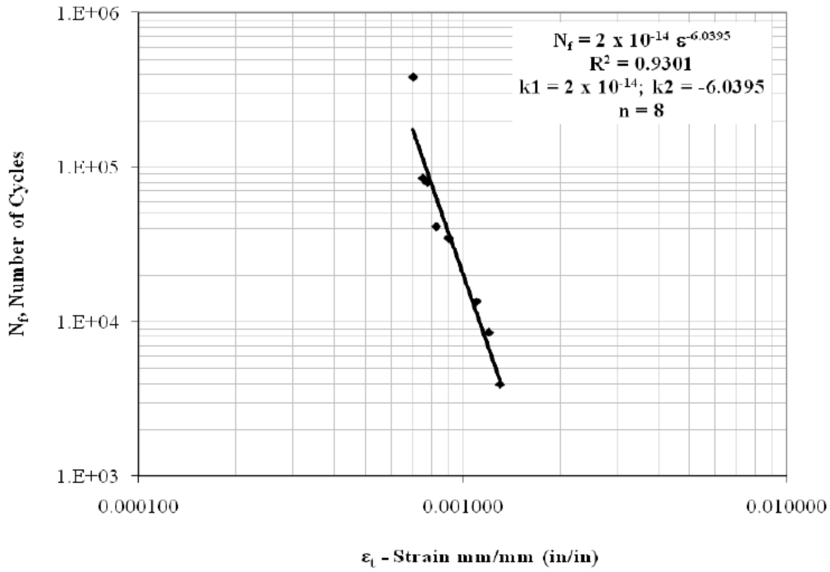

Figure 22 Number of Cycles to Failure vs. Measured Field Strains

Source: Way et al. (2009)

4.2.3 Weak Correlation (Strength-Based)

Superpave Shear Tester

Romero and Mogawer (1998a) compared parameters from the SST to field data from the FHWA's Accelerated Loading Facility (ALF). Figure 23 shows an example of the data they found that showed poor correlations between SST parameters and field performance. In this case, the shear modulus parameter was compared between mixes with different aggregate sizes. What is important to know here, is that the mixtures with different aggregate sizes showed large variations of performance in the field. The figure shows the SST's inability to differentiate between mixtures with varying performance levels. Note: WM in the figure signifies a white marsh aggregate that was designed to be a worst-case scenario aggregate.

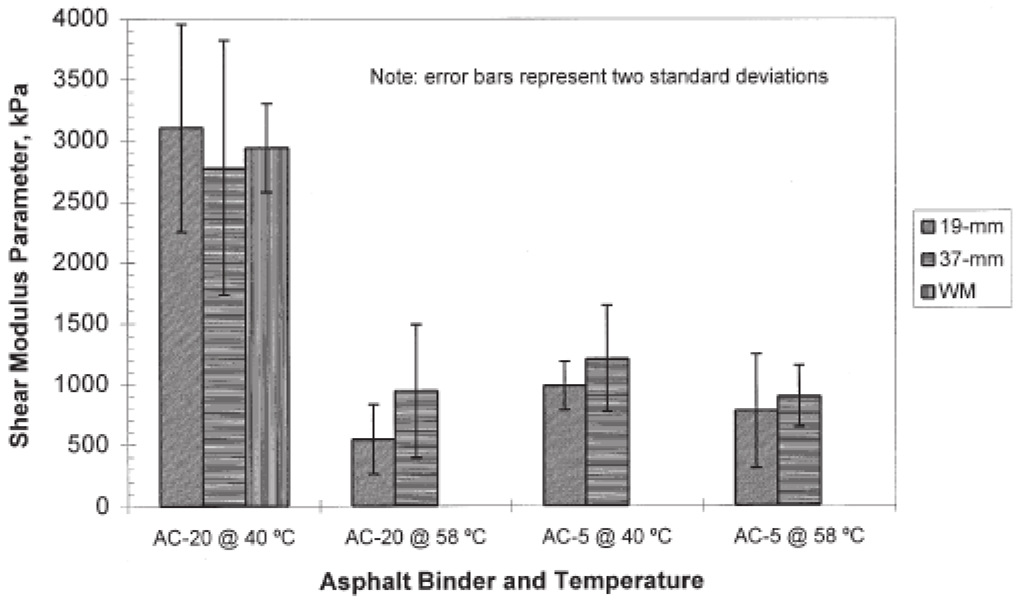

Figure 23 Shear Modulus Using Simple Shear at Constant Height Test Procedure

Source: Romero and Mogawer (1998)

4.2.4 Weak Correlation (Information-Based)

Other tests such as the Semi-Circular Bend Test and the Push-Pull Test showed weak correlations with field performance, but not because poor test performance. In these cases, there was not enough published literature for them to be considered to have strong correlations. For instance, although Kutay et al. (2008) found a strong correlation between the Push-Pull Test and field performance, this was the only published report found relating the test to performance. Therefore, the Push-Pull Test is graded as having a weak correlation.

4.3 Effectiveness

4.3.1 Beam Fatigue Test (4 Point Bending, 4PB)

Varying levels of correlation have been found between the Beam Fatigue Test and field performance. Willis and Timm (2011) found difficulty correlating laboratory fatigue endurance limits and measured strains with field performance. Most of the literature reviewed (SHRP A-404, Way et al., 2009), however, found good correlations with field performance. Research from Pais et al. (2009a) concluded that fatigue parameters evaluated from the test are sufficient predictors of fatigue life.

Although the Beam Fatigue Test seems to have good promise as a predictor of fatigue life, the test does not have the capability of predicting low-temperature cracking. The AASHTO specification for the 4PB calls for the test to be run at 68°F (20°C). The specification does not allow the test to be run at lower or fluctuating temperatures, causing the test to have no correlations with thermal cracking.

The Beam Fatigue Test has some shortcomings in the implementation of running the test. The rectangular beam specimens required for the test are difficult to obtain from the field and fabricate in the lab. Secondly, and more prohibitively, is the extensive amount of work required for running the test. At low strain levels, the test can take a day or more per sample leading to a very lengthy time for performing the test- especially in cases where multiple mix designs are to be tested. Thirdly, the equipment cost of the 4PB is high, reaching into the hundreds of thousands of dollars. Finally, the 4PB requires some input of the pavement's structure properties (base and subbase properties, etc.). This complicates the data analysis by making each test's results site-specific. Tayebali (1996) and Pais (2009b) have provided some laboratory research to improve the test.

4.3.2 Fracture Test- Disk-Shaped Compact Tension Test

Because the Disk-Shaped Compact Tension Test is a relatively new test, vast amounts of research are not available relating DCT results to field performance. However, research by Zofka and Braham (2009), Kim et al (2009), and Dave et al. (2008) aims to relate the DCT to field performance. All available research showed good correlations between the test results and field performance by using computational models such as the Cohesive Zone (CZ) model. Wagoner et al. (2005a) reported the CZ model as "very promising". No available literature could be found reporting poor correlations between DCT results and field performance.

Various research efforts have aimed to validate the DCT's ability to handle mixes with different mixture properties (binder type, aggregate type, etc.). Dave et al. (2008)**,** Wagoner et al. (2005b), and Braham et al. (2007), all showed the DCT's ability to distinguish mixture parameters such as recycled asphalt content, aggregate type, and air voids. Test temperature was also found to be distinguishable across a range of low temperatures. Literature review could not confirm a good correlation of DCT results to high temperature mixes.

4.3.3 Fracture Test- Semi-Circular Bend Test

Although the Semi-Circular Bend test has been criticized because of its complex stress configurations, the test has shown correlations to field performance. Strong correlations to thermal cracking have been shown through fracture energy (Zofka and Braham, 2009, Kim et al., 2009). Critical strain energy release rate has shown weaker correlations to fatigue cracking (Mohammad, 2011).

Much of the academic research relating the SCB to field performance has been in relation to fracture energy. This has often led to comparisons with other fracture energy tests such as IDT and the Disk-Shaped Compact Tension test. Research by Zofka and Braham (2009) and Kim et al. (2009), found the SCB to perform quite similarly to the DCT. Both the fracture tests were found to correlate better with field performance than IDT.

The Semi-Circular Bend test showed favorable results by Li and Marasteanu (2007) when testing laboratory mixtures of different mix designs. This research displayed good repeatability of the SCB. However, Kim et al., (2009) confirmed similar results to other literature, that fracture energy is only valid at low temperatures.

4.3.4 Indirect Tensile Test

Although the Indirect Tensile Test has many different test procedures, this subsection focuses only on IDT Strength and IDT Creep. These tests are commonly run in conjunction with each other to obtain desirable performance parameters. Neither Cyclic Indirect Tensile Test nor Tensile Strength Ratio Test is reported in this section as they were found not to be a viable performance tests.

Research for this subsection focused solely on the parameters gained from the Indirect Tensile Test. Many parameters can be obtained from both the Creep and Strength testing methods which can be used in models to predict field performance. The most common parameter found in literature was fracture energy. Fracture energy is calculated from IDT Strength results using the modulus found from IDT Creep. This is different from DCT and SCB in that it is not a direct measurement of fracture energy.

Many research efforts (Witczak et al., 2002, Kim and Wen, 2002) found fracture energy to have good a correlation to field performance. Similarly, other parameters of IDT Creep and IDT Strength were validated by Roque et al. (1993), Zofka et al. (2009), and Flintsch (2005). The IDT Strength Test however, does not have the ability to distinguish results from varying test temperatures (Raad et al., 1998, Zofka et a.l, 2009).

Neither the IDT Creep nor IDT Strength Test was reported to have issues with reliable data collection. Multiple reports previously referenced did, however, note that extra caution needs to be used in the IDT test setup to prevent ensure accurate results.

Parameters obtained from the IDT Creep and Strength tests cannot alone predict field performance. They must be placed in a model to show correlations. The TCMODEL developed during SHRP has become the standard model for thermal cracking. Lytton et al. (1993) aimed to ensure good correlation between the model and field performance. Through their research, it was found that the TCMODEL relates very well to field performance.

4.3.5 Superpave Shear Tester

A good performance tests needs not only to be able to predict field performance, but also must be repeatable. Much of the literature reviewed for the Superpave Shear Tester showed few positives for either case.

The data collected from the SST in most cases is too variable to create consistent conclusions (Anderson et al., 2003, Romero and Mogawer 1998b). Romero (1998) concluded that the SST can differentiate mixes with large variations in performance, but the data was too varied to detect small performance variations. Other research (Romero and Mogawer, 1998a) concluded that when data is averaged, SST still struggles to differentiate between field performance levels.

Test temperature has also been found to be a concern with the SST. Multiple studies, mentioned previously, found the SST couldn't produce reliable results at temperatures over 104°F. Although this is not a large concern for thermal cracking, a test that has lower reliability at warmer temperatures is concerning.

4.3.6 Texas Overlay Tester

The Texas Transportation Institute (TTI), has performed multiple research studies on the effectiveness of the Texas Overlay Tester (OT). In all available studies, it was shown that the Overlay Tester (most commonly the *modified* Overlay Tester) yielded a strong correlation between test results and prediction of fatigue cracking. Fracture properties are used in computational models to predict the susceptibility of fatigue cracking.

Much of the research at TTI looked at field pavements of varying levels of serviceability from very cracked to uncracked. The Overlay Test was performed on cores from these sections to find whether the fracture properties found from the test accurately predicted performance. Separate studies by Zhou and Scullion (2003) and Zhou et al. (2010) showed a very strong correlation between field performance and fracture properties.

Research by Zhou et al. (2006) took a slightly different approach in the data analysis of the Overlay Tester. Instead of using only traditional fracture properties that are found using crack initiation, crack propagation was also studied. The research still successfully verified a correlation between the data and field performance.

As noted in Section 4.2, a performance test must not only be able to predict field performance, but also needs to show repeatability to be considered. A paper by Dave (2008) showed relatively high data variability among test replicates.

4.3.7 Thermal Stress Restrain Specimen Test (TSRST)

Various research efforts have shown that the Thermal Stress Restrain Specimen Test has shown a good correlation between laboratory results and low-temperature cracking. Research by Zubeck et al. (1996), showed a strong correlation with low-temperature cracking using fracture temperatures. It was shown that the laboratory sample fracture temperatures were lower than the field fracture temperatures in sections that did not crack. The opposite was also found: when the laboratory fracture temperature was higher than that of the field's, the sections were cracked.

Sebaaly, et al. (2001) discovered similar findings with their research at the University of Nevada. Twenty-four sections of HMA were chosen in Nevada as suitable samples to test the validity of TSRST. Each sample was reproduced (as closely as possible) to eliminate the variability of in-field mixes as compared to laboratory mixes. In nearly every case, TSRST fracture temperatures showed good correlation of field and laboratory mixes to thermal cracking.

A study by Kanerva et al. (1994) provided comparable findings regarding the use of TSRST as a performance test.

4.3.8 Uniaxial Cyclic Fatigue (Push-Pull) Test

The Uniaxial Cyclic Fatigue Test was developed as an alternative to the 4PB by replacing beam-shaped specimens with cylindrical ones. Research by Soltani et al. (2006) aimed to find whether the Push-Pull Test could produce data similar to the 4PB. The research found that the Push-Pull Test could, in fact, produce similar data.

In a 2008 research study by Kutay et al. data from the Push-Pull Test was compared against performance data from the Accelerated Loading Facility (ALF). The research used fatigue data found from the Push-Pull Test to populate Viscoelastic Continuum Damage models. The models produced data that accurately predicted field performance from the laboratory samples.

Despite the good correlation found between Push-Pull Test data and field performance by Kutay, very little other data relating the test to field performance could be found in the literature review.

4.4 Effectiveness Summary

The information collected in Chapters 3 and 4 has been summarized into the following tables. Tables 1-3 show how the tests perform in categories deemed important to a good performance test. For each written value, a numerical score was given on a scale from 0-3. The scores from the first 3 tables were combined and represented as road cones () in Table 4. The numerical version of these tables can be found in Appendix B.

Table 1   Strength of Performance Correlation and Test Repeatability

	Correlation to Fatigue Cracking	Correlation to Thermal Cracking	Repeatability
4PB	moderate	unavailable	strong
DCT	unavailable	strong	strong
SCB	weak	strong	moderate
IDT	weak	moderate	strong
SST	unavailable	weak	weak
Texas OT	strong	unavailable	weak
TSRST	unavailable	strong	strong
Push-Pull	weak	unavailable	strong

Table 2   Test Equipment and Specimen Needs

	Equipment Needs	Equipment Cost	Geometry/ Preparation
4PB	exclusive	high	beam-shaped
DCT	non-exclusive	moderate	short cylinder
SCB	non-exclusive	moderate	short cylinder
IDT	non-exclusive	high	short cylinder
SST	exclusive	high	short cylinder
Texas OT	exclusive	moderate	short cylinder
TSRST	exclusive	moderate	beam-shaped
Push-Pull	non-exclusive	high	tall cylinder

Table 3 Performance Correlation Methods and Standardization

	Correlation Method	Standardization
4PB	repetitions to failure	yes
DCT	fracture energy, model	yes
SCB	fracture energy, model	in progress
IDT	tensile strength, fracture energy, model	yes
SST	model	yes
Texas OT	repetitions to failure, model	no
TSRST	fracture temperature	yes
Push-Pull	model	no

Table 4 Test Rankings

	Rank	Cones	
4PB	4	13	
DCT	T-2	19	
SCB	1	20	
IDT	T-2	19	
SST	T-7	11	
Texas OT	T-5	12	
TSRST	T-5	12	
Push-Pull	T-7	11	

4.5 Summary

Eight tests were reviewed in this chapter to discover which were the most promising for cracking prediction. The tests showed varying levels of correlation to field performance and repeatability. When also considering information from Chapter 2, the Disk-Shaped Compact Tension Test, Semi-Circular Bend Test, and Indirect Tensile Test (Strength and

Creep) are the most promising tests available. The Beam Fatigue Test, Superpave Shear Tester, Texas Overlay Tester, Thermal Stress Restrain Specimen Test, and Uniaxial Fatigue (Push-Pull) Test received the lowest marks.

5 Summary and Conclusions

5.1 Summary

This thesis was written to explore the state of the practice and state of the art asphalt concrete performance tests. Its goal is to lay the groundwork to find or develop a performance test that can predict cracking in cold climates.

In Chapter 2, an overview of state of the art performance tests was given. In Chapter 3, fifty-one state Department of Transportation specifications were reviewed to learn what performance tests are currently being specified. The most promising tests from Chapter 2 were explored further in Chapter 4. This chapter looked at how well the tests correlated with in-field performance, and also explored whether the tests showed good repeatability and features that make them suitable for routine usage. All of this information was compiled and analyzed to rank the viability of the tests.

5.2 Conclusions

The key conclusions from this thesis are:

- State Departments of Transportation currently rely heavily on the Superpave Level I volumetric mix design for their specifications. Very few performance tests are specified.
- The list of performance tests is exhaustive. Of the tests reviewed, specimen geometries, preparation procedures, correlation strengths, and repeatability levels vary greatly.

- A ranking method was developed through this thesis that evaluates the suitability of a mechanical test to be used as performance indicator for roadways in colder climates.
- The Indirect Tensile (Creep and Strength) and the Semi-Circular Bend tests are the most suitable performance tests, followed by the Disk-Shaped Compact Tension and Thermal Stress Restrain Specimen tests, which need improvement. The Beam Fatigue Test, Superpave Shear Tester, Uniaxial Fatigue (Push-Pull) Test, and Texas Overlay Tester are not suitable performance tests for cold-climate regions in their current form.

5.3 Recommendations

The overall goal of this research is to begin the process of finding a single performance test to accurately predict asphalt concrete cracking in cold-climate pavements. Future research on this topic should investigate following:

- More extensive and direct relationships between test results and field performance to improve correlation. This may include data from previous testing and through future laboratory and field studies.
- Further evaluation of three most viable tests (DCT, SCB, and IDT) to decide if any could be developed into the optimal performance test for cracking prediction.
- Correlations between the viable performance tests and mix parameters (binder types, volumetrics, recycled fractions etc.).
- Effect of newer asphalt technologies (such as warm-mix) on viable performance tests.

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Appendix A: Review of State Department of Transportation Specifications

The mechanical testing requirements as required by the material specifications for each State DOT are listed:

(1) Alabama:

AASHTO T 283: TSR

(2) Alaska:

AASHTO T-245: Marshall Flow and Stability

(3) Arizona:

Method Based Material: AASHTO T-245: Marshall Stability and Flow.

End Result Materials with Marshall Method: Marshall Stability and Flow plus Tensile Strength (AASHTO T-283). 60% retained strength in TSR (70% if mix is placed above elevation of 3500 ft).

End Result Material with Superpave Method: TSR and Wet or Conditioned TSR and Wet or Conditioned Tensile Strength (AASHTO T-283). 60% retained strength in TSR (70% if mix is placed above elevation of 3500 ft).

(4) Arkansas:

ATHD 480: Loaded Wheel Tester (a.k.a. Asphalt Pavement Analyzer).

Link: http://www.arkansashighways.com/materials_division/A--FIELDMAN.pdf

ATHD 455 (Water Sensitivity): Marshall Stability determined using modified Lottman moisture conditioning procedure.

Link: http://www.arkansashighways.com/materials_division/A--FIELDMAN.pdf

Optional QC test: AASHTO T 245: Marshall Stability

(5) California:

2006 Specifications: Moisture Swell Test CTM 305 Link:

http://www.dot.ca.gov/hq/esc/ctms/pdf/CT_305.pdf

Moisture Vapor Susceptibility in Stabilometer CTM 307 Link:

http://www.dot.ca.gov/hq/esc/ctms/pdf/CT_307.pdf

Hveem Stabilometer CTM 366 Link:

http://www.dot.ca.gov/hq/esc/ctms/pdf/CT_366.pdf

2010 Specifications: Stabilometer Value CTM 366 Link:

http://www.dot.ca.gov/hq/esc/ctms/pdf/CT_366.pdf

AASHTO T-283: TSR

(6) Colorado:

AASHTO T-283: TSR

(7) Connecticut:

AASHTO T 245: Marshall Stability and Flow

(8) Delaware:

AASHTO T 245: Marshall Stability and Flow (For Marshall Mixes)

For Superpave Mixes no mechanical test is required.

(9) Florida:

AASHTO T-283: TSR.

Minimum Indirect Tensile Strength (unconditioned sample): 100 psi

FM 1-T 283 (TSR) Link:

http://www.dot.state.fl.us/statematerialsoffice/administration/resources/library/publications/fstm/methods/fm1-t283.pdf

(10) Georgia:

Beam Fatigue Testing: AASHTO TP 8-94 (fatigue testing, not mandatory but may be imposed)

Asphalt Pavement Analyzer: GDT 115: Determining Rutting Susceptibility Using the TSR: AASHTO T-283. Link:

http://www.dot.state.ga.us/doingbusiness/TheSource/gdt/gdt066.pdf

(11) Hawaii:

Marshall (Stability and flow) or Hveem Stabilometer Test (contractor's choice)

(12) Idaho:

AASHTO T-165: Effect of Water on Cohesion of Compacted Bituminous Paving Mixtures as determined using Hveem Deformation and Cohesion Device

Note: Asphalt Film Thickness is used for mix design

(13) Illinois:

TSR: Modified AASHTO T-283 (no freezing)

Minimum unconditioned indirect tensile strength

(14) Indiana: TSR: AASHTO T-283 (Loose mixes will be oven aged using AASHTO R 30 method).

(15) Iowa:

TSR: AASHTO T-283

(16) Kansas:

TSR: AASHTO T-283

(17) Kentucky:

TSR: ASTM D 4867 (Mix saturated to approximately 65% prior to Freezing)

(18) Louisiana:

TSR: LADOTD Procedure (similar to AASHTO T-283), 55 – 80% saturation prior to freezing.

(19) Maine:

No mechanical testing requirement

(20) Maryland:

TSR: AASHTO T 283

(21) Massachusetts:

No mechanical testing requirement (Volumetrics only)

Note: Specifications have not been updated since 1995; there are supplemental specs from 2006 and 2010.

(22) Michigan:

TSR: AASHTO T 283

(23) Minnesota:

TSR: AASHTO T-283

(24) Mississippi:

TSR: AASHTO T-283

Boiling Water Stripping Test. Link:

http://www.gomdot.com/Divisions/Highways/Resources/Research/pdf/Reports/InterimFinal/SS167.pdf

(25) Missouri:

TSR: AASHTO T-283

(26) Montana:

Hamburg Wheel Tracking Test (Used for determination of moisture damage/ stripping)

(27) Nebraska:

TSR: AASHTO T-283

(28) Nevada:

TSR: AASHTO T-283 (Nev. T341)

Minimum Unconditioned Indirect Tensile Strength (T-283), 50-65 psi

Hveem Stabilometer Value (Nev. T303)

(29) New Hampshire:

TSR: AASHTO T-283

(30) New Jersey:

TSR: AASHTO T-283 (only if required by ME)

(31) New Mexico:

No mechanical testing requirement.

(32) New York:

TSR: AASHTO T-283

(33) North Carolina:

TSR: AASHTO T-283

(34) North Dakota:

Marshall Mixes: AASHTO T 245: Marshall Stability and Flow

Superpave Mixes: TSR: AASHTO T-283

(35) Ohio:

Marshall Mixes: AASHTO T 245: Marshall Stability and Flow

Superpave Mixes: TSR: AASHTO T-283

(36) Oklahoma: TSR:

AASHTO T-283

APA: AASHTO TP 63 (OHD L-43)

(37) Oregon:

TSR: AASHTO T-283

APA: AASHTO TP 63 (If required for the project)

(38) Pennsylvania:

TSR: AASHTO T-283

(39) Rhode Island:

AASHTO T 245: Marshall Stability and Flow

AASHTO T 182: Static Water Immersion (Boiling Water Stripping Test)

(40) South Carolina:

TSR: Modified AASHTO T-283 (SC T 70)

Indirect Tensile Strength of Wet Conditioned Samples (SC T 70)

Asphalt Pavement Analyzer: AASHTO TP 63

(41) South Dakota:

TSR: AASHTO T-283

Asphalt Pavement Analyzer: AASHTO TP 63

(42) Tennessee:

TSR: AASHTO T-283

Asphalt Pavement Analyzer: AASHTO TP 63 (Only for SMAs, not required but if material is available the DOT Central Lab will conduct test)

(43) Texas:

Method Specification: Indirect Tensile Strength (Low and High Limit)

Boil Test

QC/QA Specification: Indirect Tensile Strength

Hamburg Wheel Test

Boil Test

Special Provisions: Texas Overlay Tester for Overlay Mixes

(44) Utah:

Hamburg Wheel Test

(45) Vermont:

Marshall mixes: AASHTO T 245: Marshall Stability and Flow

Superpave Mixes: TSR: AASHTO T-283

(46) Virginia:

TSR: AASHTO T-283

Asphalt Pavement Analyzer: AASHTO TP 63

(47) Washington:

TSR: AASHTO T-283

(48) Washington D.C.:

TSR: AASHTO T-283

For Stone filled sheet asphalt: AASHTO T-245: Marshall Stability and Flow

(49) West Virginia:

TSR: AASHTO T-283

(50) Wisconsin:

TSR: AASHTO T-283

(51) Wyoming:

TSR: AASHTO T-283

Appendix B: Numerical Scores for Chapter 4 Performance Tests

	Correlation to Fatigue Cracking	Correlation to Thermal Cracking	Repeatability
4PB	2	0	3
DCT	0	3	3
SCB	1	3	2
IDT	1	2	3
SST	0	1	1
Texas OT	3	0	1
TSRST	0	3	3
Push-Pull	1*	0	3

*Due to lack of data

	Equipment Needs	Equipment Cost	Geometry/ Preparation
4PB	1	1	1
DCT	3	2	2**
SCB	3	2	3
IDT	3	1	3
SST	1	1	3
Texas OT	1	2	2**
TSRST	1	2	1
Push-Pull	3	1	2

**Due to specimen preparation

	Correlation Method	Standardization
4PB	2	3
DCT	3	3
SCB	3	3
IDT	3	3
SST	1	3
Texas OT	3	0
TSRST	2	0
Push-Pull	1	0