Cracking Mechanisms in Asphalt Pavement

Prepared By
Akash Bajaj

University of Illinois at Urbana-Champaign

A report of the findings for

Illinois Asphalt Pavement Association's Scholarship Program

January 2023

TABLE OF CONTENTS

LIST OF FIGURES

To update the List of Figures, right click on the field below and select "Update Field" and then "Update Entire Table." All figure captions using the ICT Figure Caption style will appear in the List of Figures.

LIST OF TABLES

To update the List of Tables, right click on the field below and select "Update Field" and then "Update Entire Table." All figure captions using the ICT Table Caption style will appear in the List of Tables.

CHAPTER 1: INTRODUCTION TO CRACKING IN PAVEMENTS

Failure of transportation infrastructure has always been a concern in the community due to economic, environmental, human and safety factors associated with it. A lot of resources have been utilized to accurately predict the life of highways and pavements in the United States in the 20^{th} century. Design philosophies such as HVEEM and Marshall were the starting points to design the pavements to extend the life of pavements by improving its resistance against distresses like cracking and permanent deformation. Earliest attempts to relate the fatigue life, the number to load repetitions to failure, with the stresses and strains measured in asphalt pavements was by (Monismith et al., 1961) and (Pell, 1962). Stiffness was suggested as a measure of a pavement's life, believed to indicate the resistance of a pavement mix to external forces. The approach gave some mixed results but was generally adopted by people when designing new pavements.

The federal government and highway agencies wanted to improve their understanding about the life of pavements by funding the Strategic Highway Research Program (SHRP) in collaboration with universities and research centers across the country. After the implementation of SHRP recommendations there was a marked improvement in the rutting resistance of pavements but at the same time people observed that cracking across pavements had increase due to creation of more dry, brittle and rut resistant mixes (Harvey et al., 1995; Monismith & Deacon, 1969). Also, people were questioning whether a simple approach can accurately portray the life of a pavement in service (Molenaar, 1984) or if there was merit to move to a better approach which might better to prediction of a pavement life than an empirical one (Aglan & Figueroa, 1993).

One approach gaining traction was to consider an energy approach instead of a stress approach. Fracture energy for asphalt pavements was developed by (Majidzadeh et al., 1971) and (Van Dijk & Visser, 1977). A lot of researchers found success in the application of fracture mechanics when predicting the life pavements (M. Kim et al., 2009; Marasteanu et al., 2012). (Germann & Lytton, 1979) applied the principles of fracture in addition to fatigue to lab testing and showed the usefulness of both theories. Initial use of fracture included mostly Paris law applications (Z. Zhang et al., 2001) but the field developed to include more sophisticated tools to improve the prediction of responses in pavements.

The tools for predicting actual field life from laboratory experiments also got more sophisticated with time. Researchers looked into various specimen geometries (Wagoner, 2006) and loading configurations (Ann Myers & Roque, 2002) which might be able to predict the life of an asphalt mix more accurately. Shift factors from laboratory to field results were developed by (Molenaar, 2007) to address this problem. A great overview of this was given by (Ioannides, 1997). The viscoelastic nature of asphalt was seen to be hard to model in lab specimens of asphalt concrete since researchers also had to take things like healing and relaxation into account (Y. R. Kim & Little, 1990; Roque et al., 2015).

Some researchers tried to use the Weibull survival function to model cracking in asphalt pavements as a stochastic process (Tsai et al., 2003, 2004) although the approach isn't in common use now-a-days. (Roque & Ruth, 1990) also pioneered the critical condition approach where purely using either fatigue or fracture wasn't shown as the correct approach. They argued cycles of loading are not equal in the responses they generate. The effects of factors like temperature, rest periods, age hardening should be taken into effect in a more robust way than it has been till now. (Y. R. Kim et al., 1997) has also shown the effectiveness of another theory , Visco-Elastic Continuum Damage, and a lot of research has been done into its application for field validation (Norouzi et al., 2016) and laboratory testing (Hou et al., 2010).

(National Cooperative Highway Research Program et al., 2010) tried to combine the two most prominent theories, Fracture Mechanics and Visco-Elastic Continuum Damage, to create a more accurate model than each one of them individually. They argue that crack initiation is more accurately portrayed by the Visco-Elastic Continuum Damage theory while once the macrocrack forms Fracture Mechanics gives better results. The approach certainly has shown some promising results and tries to play into the strength of each of the major philosophies.

The field is still progressing with researchers working in cutting edge technologies like Finite Element Modeling (H. Kim & Buttlar, 2009) of asphalt using data collected form the lab or using Digital Image Correlation (Abanto-Bueno & Lambros, 2002) to calculate the strains and stresses being developed in lab specimens during testing. With new challenges like polymer modified binders and its affect on cracking and rutting properties of asphalt concrete sample (Norouzi et al., 2016) researchers are sure to use all the tools available at their disposal.

CHAPTER 2: FACTORS AFFECTING CRACKING IN ASPHALT CONCRETE.

In addition to understanding the mechanisms of cracking in asphalt mixes, one needs to try and see how various factors might influence the cracking potential of asphalt pavements in the field. Considering that conditions in the field will nowhere be near as controlled as in the laboratory, one needs to have a thorough undertesting on how these might reflect on the cracking potential and in turn the life of asphalt pavements.

Research has been going on trying to access these qualitatively as well as quantitatively since the 1960's at-least (Abdel-Raouf, 1967; Monismith & Deacon, 1969) . (Monismith & Deacon, 1969) detailed a list containing various factors they discovered during their project that seems to affect the fatigue properties in asphalt concrete specimens. These parameters can be broadly classified either mixture properties or environment parameters.

MIXTURE PARAMETERS

When designing an asphalt mix one has to take into account the various inputs and materials properties that go along with the design. These are classified in this study as mixture parameters. This broadly covers the properties of the component materials like asphalt binder and aggregates that go into the mix as well as the mixing protocol like the air voids. These have been shown to be very important for good field performance and are easier to control when compared with environmental factors.

One of the primary components that dictate the cracking potential in an asphalt mix is the asphalt binder itself. The binder is responsible for dissipating all the induced loading and associated energy due to its viscoelastic nature. These relaxation properties can be indicated by the viscosity of a binder (Roque & Ruth, 1990). Asphalt binder usually is also usually the weaker component in the mix and therefore most cracks seem to originate around the aggregates in the mix itself (Doll et al., 2017a).

In addition to having good relaxation properties, one also has to insure that these binders perform well in low temperatures as well since the binder properties (Collop & Cebon, 1995) and strength of the mix (S.-S. Kim et al., 2006) has been shown to affect the life of the mix. Selection of an appropriate binder is therefore of paramount importance since (Ali et al., 2019) showed that higher flexibility doesn't always lead to better cracking performance. Some studies have also shown how the asphalt chemistry might affect the pavement performance in the long run utilizing properties such as steric hardening (H. Wang, 2018). To improve the performance of binders there has been an interest in the use of polymer and fiber modifications for neat binders. Researchers have shown that these have in most cases led to increase in cracking performance of these asphalt mixes in both laboratory and field (Lee et al., 2005; Norouzi et al., 2016).

The stiffness needed to resist and distribute loads comes from the aggregates used in the mix. The quality and properties of aggregates also play a big part in the performance of any mix

(Monismith & Deacon, 1969). Even the absorptive nature of aggregates have been shown to affect the cracking properties of a mix (Zhou & Scullion, 2005). Therefore, the quality of the aggregates should be kept in mind when designing a mix.

After selection of both aggregates and binder one needs to consider the proportioning and in turn the air voids and the asphalt content for the mix. There have been various studies that have shown the impact of these properties for fatigue performance. Increasing the asphalt content usually leads to more dissipation of energy and therefore better performance in terms of cracking (M. Jacobs et al., 1996; Mobasher et al., 1997). However, as explained in a later chapter this adversely impacts other distress mechanisms in the pavement and is therefore not a silver bullet strategy. (Harvey et al., 1995) showed that air voids also play a significant role in characterizing the cracking potential. Increasing air voids have been shown to inversely affect the fatigue performance of asphalt pavements by multiple researchers. The addition of air voids introduce weaker points in the binder matrix that leads to an increase in cracking potential and decrease in cohesive energy of asphalt binder (Pirmohammad et al., 2016).

Now-a-days the use of recycled materials in asphalt concrete design for a number of positive reasons has given one more parameter for mix designers to take into consideration. Recycled Asphalt Pavements (RAP) and Recycled Asphalt Shingles (RAS) are the most commonly used recycled materials right now in the field. These materials both possess higher stiffness due to the aging they experience in field. When used in an asphalt mix they tend to make the asphalt mix more stiffer and reduce its energy dissipation properties (Doll et al., 2017b). This increased stiffness is helpful with the strength (Krishna Swamy et al., 2011) and moisture susceptibility (Mogawer et al., 2011) of the mix but adversely impacts its fracture energy potential. These stiffer materials lead to a smaller fracture process zone and therefore reduce the energy dissipation mechanism of an asphalt mix (Behnia et al., 2011; Doll et al., 2017a).

One of the most common ways to balance out, so to say, the effect of these stiffer components in a mix has been to either the use of a softer grade binder than dictated by the design or addition of Warm mix additives (WMA) when preparing the mix. Both these techniques act to increase the viscous nature of an asphalt mix and therefore increase the energy dissipation abilities to improve cracking performance (Behnia et al., 2011; X. Li & Gibson, 2016). Both of these techniques have been show to work well in the field (Q. Li et al., 2018; Mogawer et al., 2011) and are recommended whenever working with RAP/RAS in ones design, however researchers have found that these can only offset the negative cracking impacts until a point (McDaniel et al., 2012) and heavy use of recycled materials should be carefully thought through and tested before incorporating it in the asphalt concrete mix design for field projects since the long term performance of asphalt roads with very high recycled materials is still not known completely and needs to be researched.

ENVIRONMENTAL PARAMETERS

The previously listed parameters have a huge impact on the cracking potential of asphalt roads but as one can see most of them are taken into consideration in the design stage itself and are relatively easy to control for. In addition to that one can also classify a broad group of environmental parameters that affect the pavement life and are more difficult to control for. These factors include the weather and temperature, traffic and loading as well as the constructability and issues thereof that might arise.

Temperature variations in the vicinity of an asphalt pavement tend to greatly affect the properties of the structure. Due to the thermal properties of asphalt, there usually exists a thermal gradient within the pavement structure where layers at the top of a pavement have different thermal stresses that develop. The difference in the coefficients of thermal expansion for the aggregates and the asphalt binder usually leads to this thermal stress that develops as shown by (S.-S. Kim, 2005).These stresses when developed at temperatures lower than those prescribed by the binder characterization might lead to adhesive failure (Chen et al., 2022).

In addition to the stresses, the temperature also impacts the fracture toughness as (Mobasher et al., 1997) showed in his research. This leads to the creation of a stiffness gradient within the pavement structure. These stiffness gradients are also created by the aging of the pavement. Similar to temperature, aging also happens mostly in the top layer of a pavement (M. Kim et al., 2009; National Cooperative Highway Research Program et al., 2010). These gradient act a sources of stress intensity when loads act on them (Germann & Lytton, 1979) and therefore decrease the cracking resistance in pavements.

Even in absence of these stiffness and temperature gradients the thermal cyclic fatigue and load fatigue properties would need to be carefully studied. Studies have shown that the traffic and weather cycles both negatively impact the life of asphalt pavements (Y. Wang et al., 2005).

When considering the impact of traffic on the life of a pavement one must remember that properties like tire shape, pressure and loading location also play a crucial role in overall fatigue life. With the increase in number of vehicles as well as bigger and bigger vehicles on the market (M. M. J. Jacobs, 1995) showed that different vehicles will have a different impact on the fatigue life of the pavement since they will have different tire properties and loadings. This was further corroborated by (Ann Myers et al., 1999; Ann Myers & Roque, 2002) where the shape of tires and the pressure were considered and shown to have an impact on the life.

The last issue to be tackled here is the construction defects that might happen when laying the asphalt road. There have been multiple studies that show. Presence of these defects can be very detrimental to the overall health of the pavement (National Cooperative Highway Research Program et al., 2010; H. Wang & Al-Qadi, 2010). Not only these defects might act as stress intensifying locations and have subpar properties but they might also retain moisture which will weaken and degrade the section (dos Santos et al., 2014) further and cut short the pavement life considerably. The next section details all the different types of cracks that might occur due to the factors listed above.

CHAPTER 3: ASPHALT CONCRETE CRACKING TYPES

Cracking in asphalt pavement is the mechanism that happens when the stresses reach a high enough level, and the material needs to find a way to get to a lower energy state. With the creation of cracking the stored energy is dissipated by the material via surface energy, heat dissipation and plasticity. Broadly speaking for asphalt pavements, the cracking can be classified as either load related, which is directly affected by the traffic parameters that the pavement endures or as non-load related cracking which encompasses all other factors like the weather, traffic loading, sub-base properties etc. Below some notable cracking types are listed that are seen commonly in asphalt pavements alongside the mechanisms that might cause them

THERMAL CRACKING

In many parts of the United States, asphalt pavement cracking can be caused by low temperatures or high rates of cooling. Due to the extremely low temperatures throughout the winter, pavements in the northern part of the United States are more prone to low temperature cracking. Thermally induced tensile stresses and reduction in stress relaxation capacity in the asphalt layer are the main cause of thermal cracking (Marasteanu et al., 2012).

In the restrained surface layer, contraction induced by cooling leads to the generation of thermal tensile stress. Since there is more constraint in a pavement's longitudinal direction compared to the vertical direction, thermal stress is often greatest along the longitudinal direction of the pavement (S.-S. Kim, 2005), however, for larger airports, runways and taxiways are often very wide and this can result in thermal cracks to develop both in transverse and longitudinal directions. Same is also true for apron areas of an airfield. There might be minor thermal stresses developed in the vertical direction caused due to differential thermal contraction of asphalt and aggregates (K. W. Kim & El Hussein, 1995).

Figure 1 Thermal Cracking

The friction between the asphalt layer and the material underneath it can have an impact on this restraint, with lower friction leading to larger crack spacing. The developed thermal stress might cause slippage to relieve some stress and cause thermal cracking to appear in the longitudinal direction .Furthermore, because the pavement surface temperature is lowest throughout the cooling phase, the thermal stress is typically greatest on the pavement surface (Collop & Cebon, 1995).

The coalescence of thermal cracking leads to the formation of block cracking. A big factor influencing block cracking is the stiffness gradient near the surface of pavement that leads to higher stress concentration on the surface itself and joins the network of thermal cracks to form block shapes. The higher elastic modulus of asphalt layer leads to the curvature in pattern near a cracked boundary (H. Wang, 2018).

REFLECTIVE CRACKING

While developing the overlay tester (Zhou & Scullion, 2005) did extensive research on reflective cracking properties of asphalt pavements. One of the most common rehabilitation techniques used in the united states is placement of an asphalt overlay over a distressed pavement surface. The overlay is usually bonded very well with the underlying layer and any movement of the joints or cracks in the underlying layer leads to highly localized stresses in the overlay above it. These can be caused due to traffic or thermal induced fatigue as shown in Figure 2.

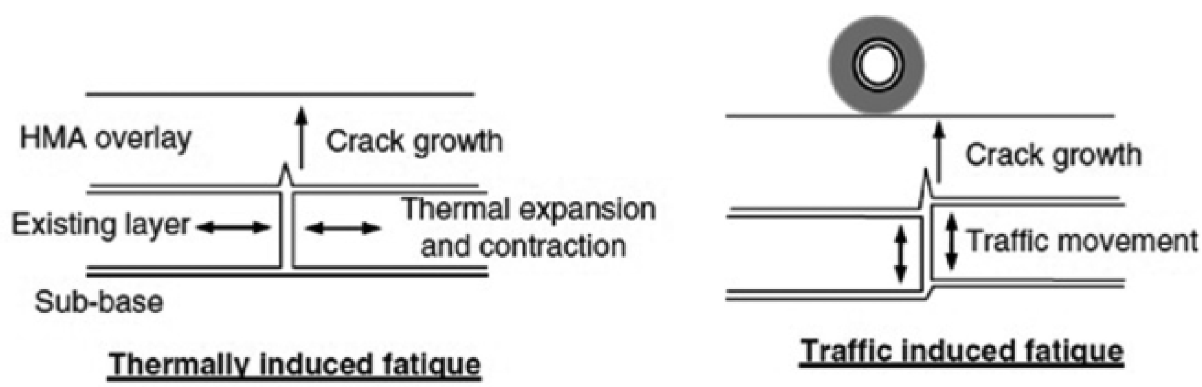


Figure 2 Mechanisms of Reflection Cracking (Nunn, 1989)

These induced stresses are calculated using the relaxation property of the asphalt mix alongside the movement occurring in the joint/crack below and when the tensile stresses exceed the tensile strength of the overlay layer macro-crack initiation and propagation begins. The initiation portion is best evaluated using fatigue methods while the propagation can be better estimated using fracture mechanics principles (Son, 2014).

These cracks can lead to stress localizations on the surface and poor load transfers which make them a precursor to fatigue cracking (Germann & Lytton, 1979) later in the pavement life.

Figure 3 Reflective Cracking

FATIGUE CRACKING

Fatigue cracking is a load-associated distress that results from repeated traffic loading and is one of the top distresses seen in pavements at intermediate temperature. The tensile and shear stresses (mixed mode) are the primary contributors for fatigue cracks in asphalt pavements (Ann Myers et al., 2001; Little et al., 1999). These fatigue cracks can either be adhesive, i.e., form between aggregates and asphalt mastic, or cohesive, i.e., within asphalt mastic.

The tires of vehicles moving on the road lead to complex stress states in the pavement. The tires might exert bending induced surface tension in the longitudinal direction for thinner pavements while for ticker pavements the shear induced near-surface tension might be more critical. Hence one can see that the pavement thickness plays a role in what kind of stresses and therefore cracks develops via fatigue in the pavement (Ann Myers & Roque, 2002; Molenaar, 1984; National Cooperative Highway Research Program et al., 2010). In addition to traffic, age hardening also plays a big factor in fatigue stresses since (Roque et al., 2004) showed the increase in tensile and shear stresses with aging in asphalt due to a decrease in energy dissipative abilities of the sample.

Fatigue cracking can be further divided into subcategories depending on where the initial crack originates and are as follows.

Figure 4 Fatigue Cracking

Bottom-up Cracking

The traditional approach used by (Huang, 1993) and a lot of researches tended to characterize fatigue cracking as mostly bottom-up cracking caused by repeated wheel load application. Miners law was used to measure total fatigue life and the most basic empirical relation was used to correlate field cracking with tensile strains at the bottom of the asphalt layer, which were suspected to be the damage zones. The basic damage was thought to be bending stress induced under the wheel load which will propagate through the asphalt layer. Initial mechanistic design was created using bottom-up cracking as the most prevalent fatigue distress. To improve the resistance to this fatigue the concept of thicker perpetual pavements started to be used.

Top-Down Cracking

With the increasing use of thicker pavement sections there were reports of an increase in top-down cracks in the field. These cracks were shown to be caused by the bending induced surface tension in the longitudinal direction as well as the shear induced surface tension at the tires edge (Canestrari & Ingrassia, 2020; National Cooperative Highway Research Program et al., 2010). The presence of defects or cracks are also shown to be a major influence for this cracking as they lead to redistribution and intensification of stresses and thereby affect crack propagation.

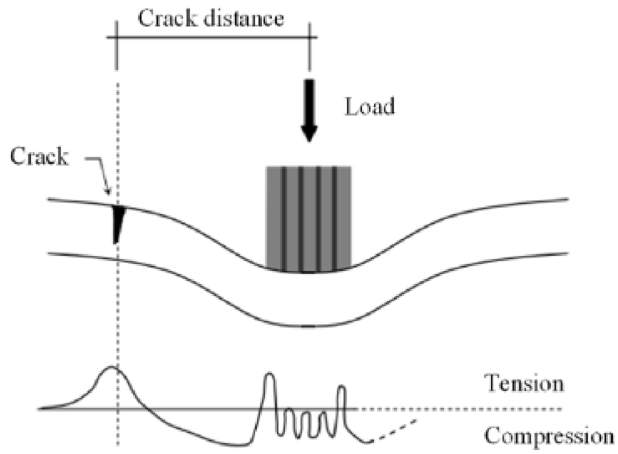


Figure 5 Bending Induced Mechanisms for Top-down Cracking

The likelihood of top-down cracking is shown to increase with increasing temperature and asphalt thickness (Zhao et al., 2018). These cracks initially appear as single cracks in the wheel path or construction joints of pavements but with repeated loading new cracks tend to appear around the vicinity of the original crack and with time they start to form an alligator pattern on the pavement, interlinking with each other (Ling et al., 2019).

Near Surface Cracking

(H. Wang & Al-Qadi, 2010) have also studied the phenomena of near surface cracking that has been observed in the field recently. The shear stresses developed at tire edges at higher temperature lead to distortion and cracking below the surface of the pavement. This region is also shown to be more susceptible to cracking due to the aging and stiffness gradients that occur here. These cracks coalesce below the surface and due to the complex stress states they are subjected to can propagate in both upward and downward directions (H. Wang et al., 2013).

Since the stresses are caused by the shear of the tire the tire contact stresses play a major role and therefore tire acceleration, deceleration and cornering tend to increase the potential for near surface cracking significantly. Also, poor construction and debonding between the asphalt layers would increase the stress intensity factors at these depth levels, leading to near surface cracks being easier to initiate and propagate.

CHAPTER 4: CHARACTERIZATION OF CRACKING IN ASPHALT CONCRETE

Fracture process in asphalt mixtures is complex due to the heterogeneous nature of mixtures (asphalt binder, aggregates, and air voids as primary phases) along with significant temperature and rate dependence response of this material. Multiple previous efforts have demonstrated that a fracture process zone of appreciable size (often more than 15 mm) exists ahead of potential crack path in asphalt mixtures. Thus, theories and tests that are limited to peak stress-based measures are often inapplicable to fully evaluate cracking performance of asphalt mixtures.

BACKGROUND

Depending on the predominant mode of cracking in asphalt materials, often laboratory performance tests are classified into three categories: low temperature cracking tests, intermediate temperature cracking tests and, cyclic degradation or fatigue cracking tests. This chapter presents a summary of literature review on various asphalt mixture cracking tests that have been developed and applied to assess cracking performances of asphalt pavements. A comprehensive literature review has been done to identify cracking tests suitable for routine asphalt mixture designs, such that they can be part of a balanced mix design framework. This section reviews existing laboratory cracking tests which are currently in practice. A summary of all these tests is given at the end of the chapter.

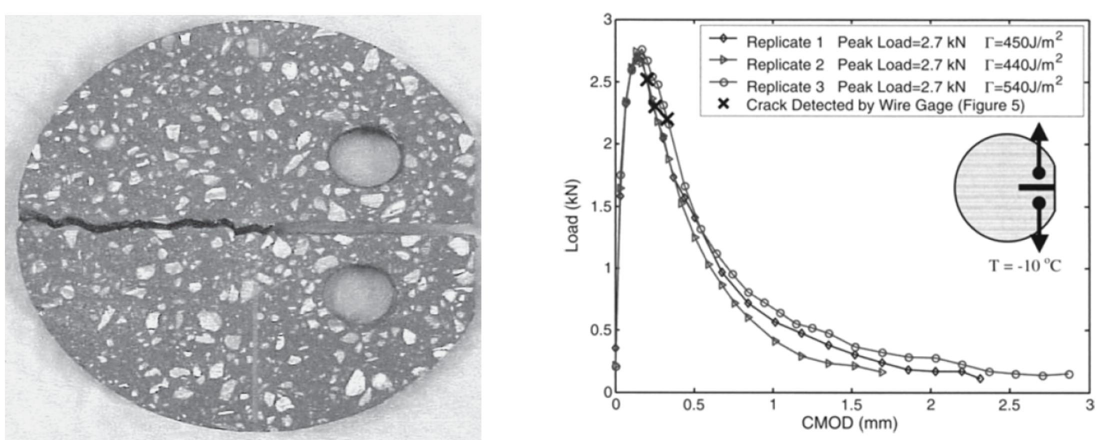
- Disk-Shaped Compact Tension (DCT) Test (ASTM D7313-20, 2020)
- Semi-Circular Bend (SCB) (Low Temperature) Test (AASHTO T 394-21, 2021)
- Indirect Tensile (IDT) Creep and Strength Test (AASHTO T 322, 2007)
- Illinois Flexibility Index Test (I-FIT) (AASHTO T 393-21, 2021)
- Louisiana Semi-Circular Bend (LTRC SCB) Test (ASTM D8044-16, 2016)
- Crack Tolerance (CT) Index Test (ASTM D8225-19, 2019)
- Simplified Viscoelastic Continuum Damage (S-VECD) Fatigue Test (AASHTO T 400, 2022)
- Texas Overlay Test (OT) (Tex-248-F (Revised), 2022)
- Flexural Bending Beam Test (AASHTO T 321, 2022)

THERMAL CRACKING

Disk-Shaped Compact Tension (DCT) Test

The DCT test for asphalt mixtures was proposed by Wagoner (Wagoner et al., 2005) and has been refined through subsequent efforts such as (Marasteanu et al., 2012) to measure cracking resistance of asphalt mixtures at low temperatures. The origin of this test is from the compact tension test that has been originally developed for metals. The test procedure has been refined and revised to make it more suited for routine mix design and production control through efforts supported by the Minnesota Department of Transportation (Dave et al., 2019). (ASTM D7313-20, 2020) covers standard test method to conduct DCT test and the Minnesota Department of Transportation has a modified version with tighter specimen dimension tolerances and test temperature control.

In this test, a disk-shape specimen with a notch (Figure 1) is pulled apart until the post peak level has reduced to 0.1 kN. The DCT test is conducted in a crack-mouth opening displacement (CMOD) controlled mode with an opening rate of 1 mm/min at temperature of 10ºC warmer than the required PG low temperature grade for the study mixture. Figure 1 (b) shows a typical load-CMOD curve obtained from DCT test. The area under this curve represents the fracture energy (Gf) and the ratio of fracture energy to peak strength before the failure is called fracture strain tolerance (FST) parameter (Zhu et al., 2017). Higher values of both parameters indicate the higher cracking resistance of asphalt mixtures. The test can be performed on the gyratory compacted laboratory prepared specimens and specimens obtained from field cores.



(a) (b)

Figure 6 (a) Typical fractured DCT specimen (Wagoner et al., 2005) (b) Typical test curve

Standard test methods:

(ASTM D7313-20, 2020): Standard Test Method for Determining Fracture Energy of Asphalt Mixtures Using the Disk-Shaped Compact Tension Geometry

Test Parameters

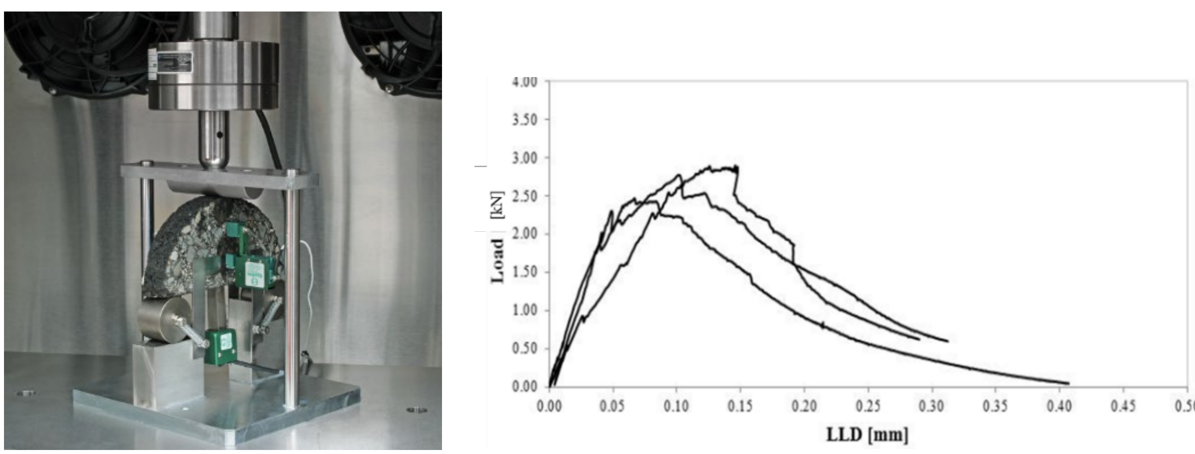
- Specimen geometry: 150 ± 10 mm diameter and 50 ± 3.5 mm thick, two 25 ± 1 mm holes, and a 62.5 ± 5 mm notch
- CMOD opening rate: 1 mm/min.
- Test temperature: low temperature PG + 10 °C

Measured Properties

Fracture energy (Gf), Fracture strain tolerance (FST)

Semi-Circular Bend (SCB) Test

The SCB test for low temperature cracking was developed by (X. (Shaw) Li & Marasteanu, 2004) and subsequently revised by Marasteanu (Marasteanu et al., 2012) to measure cracking resistance of asphalt mixtures at low temperatures. (AASHTO T 394-21, 2021) covers standard test method to conduct SCB test. Similar to the DCT test, the SCB is often conducted in a crack-mouth opening displacement (CMOD) controlled mode with an opening rate of 0.0005 mm/s at 10 ºC warmer than the PG low temperature grade of binder. However, the fracture work measure is determined using the load-line displacement (LLD). Figure 2 shows the SCB test setup and typical test plot of load-LLD curve for three different replicates. Like the DCT test, the SCB test can be easily performed on the laboratory prepared specimens and specimens obtained from field cores. Fracture toughness, K_{IC} is computed as shown in Equation 1. K_{IC} is defined as the stress intensity factor corresponding to the initiation of the crack. The stiffness (S) is calculated as the slope of the linear part of the ascending load-LLD curve.



(a) (b)

Figure 7 (a) SCB test setup and LLD extensometer, and (b) Typical plot of SCB test for three replicates (Marasteanu et al., 2012)

$$K_{IC} = Y_{I(0.8)}\sigma_0\sqrt{\pi a} \quad (1)$$

Where,

K_{IC} = the dimensionless geometric factor,

σ_0 = the applied stress (MPa) = $\frac{P}{2rt}$,

r = specimen radius (m),

t = specimen thickness (m),

a = notch length (m), and

$$Y_{I(0.8)} = 4.782 - 1.219\frac{a}{r} + 0.063\,exp\left[7.045\left(\frac{a}{r}\right)\right]$$

(Dave & Behnia, 2018) utilized low temperature SCB tests conducted in CMOD control with a CMOD rate of 0.7 mm/minute to obtain fracture properties of asphalt mixtures. In this work, they have demonstrated that by use of cohesive zone fracture model, local fracture properties of asphalt mixtures can be extracted, and these are independent of test geometry and CMOD rate. This is shown by extracting local fracture law (cohesive zone model and its parameters) using DCT test and then predicting low temperature SCB test.

Standard test methods:

(AASHTO T 394-21, 2021): Determining the Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB)

Test Parameters

- Specimen geometry: 150 ± 9 mm in diameter and 24.7 ± 2 mm thick, a notch with 15 ± 0.5 mm length and no wider than 1.5 mm
- CMOD opening rate: 0.0005 mm/s
- Test temperature: low temperature PG + 10 °C

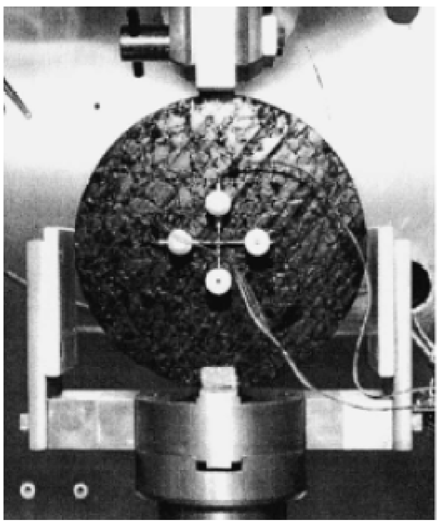
Measured Properties

Fracture energy (Gf), Fracture toughness (KIC), Stiffness (S), Rate-dependent cracking index (RDCI)

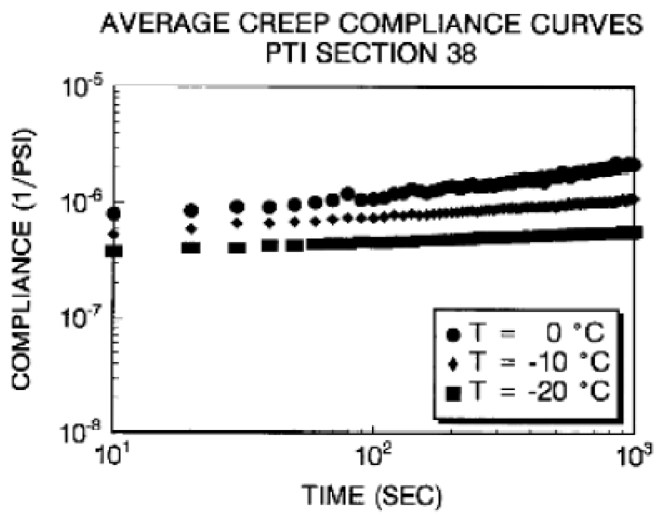
Indirect Tensile (IDT) Test

Roque and co-workers at Pennsylvania State University developed the Superpave IDT test for low-temperature cracking during the Strategic Highway Research Program (SHRP) (Buttlar & Roque, 1994; Roque & Buttlar, 1992). (AASHTO T 322, 2007) covers standard test method to conduct IDT test which measures both creep compliance and tensile strength of asphalt mixtures at low temperatures. AASHTOWare Pavement ME design requires both as an input for prediction of low temperature cracking of asphalt pavements.

A cylindrical specimen with a 150 mm diameter and a thickness of 38 to 50 mm is subjected to compressive load across the diametral plane. The creep test involves holding a load level constant for 1,000 seconds that produces a horizontal deformation of between 0.00125 mm and 0.019 mm. During the loading process, the horizontal and vertical deformations are recorded and used to determine the creep compliance and stiffness as a function of time. In the strength test, the specimen is loaded at a constant LLD rate of 12.5 mm/minute until failure to determine the tensile strength, strength is calculated based on the specimen dimensions and peak load. Figure 3 shows IDT test setup and typical creep compliance curves. The test can be easily performed on the laboratory prepared specimens and specimens obtained from field cores as well.



(a)



(b)

Figure 8 (a) IDT test setup and (b) typical creep compliance curves (Roque & Buttlar, 1992)

Standard test methods:

(AASHTO T 322, 2007): Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device.

Test Parameters

- Specimen geometry: 150 ± 9 mm in diameter and 38 to 50 mm thick
- Loading rate for tensile strength test: 12.5 mm/min

Measured Properties

Creep compliance, Tensile strength

INTERMEDIATE TEMPERATURE CRACKING

Illinois Flexibility Index Test (I-FIT)

Research efforts at the Illinois Center for Transportation resulted in development of the Illinois Flexibility Index Test to determine fracture resistance parameters of an asphalt mixture at an intermediate temperature (Al-Qadi et al., 2015; Ozer et al., 2016). (AASHTO T 393-21, 2021) covers standard test method to conduct I-FIT. The I-FIT setup and typical test outcomes are shown in Figure 4. I-FIT specimens are prepared by cutting the cylindrical disc specimen in half to produce two dimensionally equivalent test specimens. Semicircular specimens shall have smooth parallel faces with a thickness of 50 ± 1 mm and a diameter of 150 ± 1 mm with notch length of 15 ± 1 mm at center as shown in Figure 4. The test is conducted using load line displacement (LLD) control at a rate of 50 mm/minute and the test is stopped when the load drops below 0.1 kN.

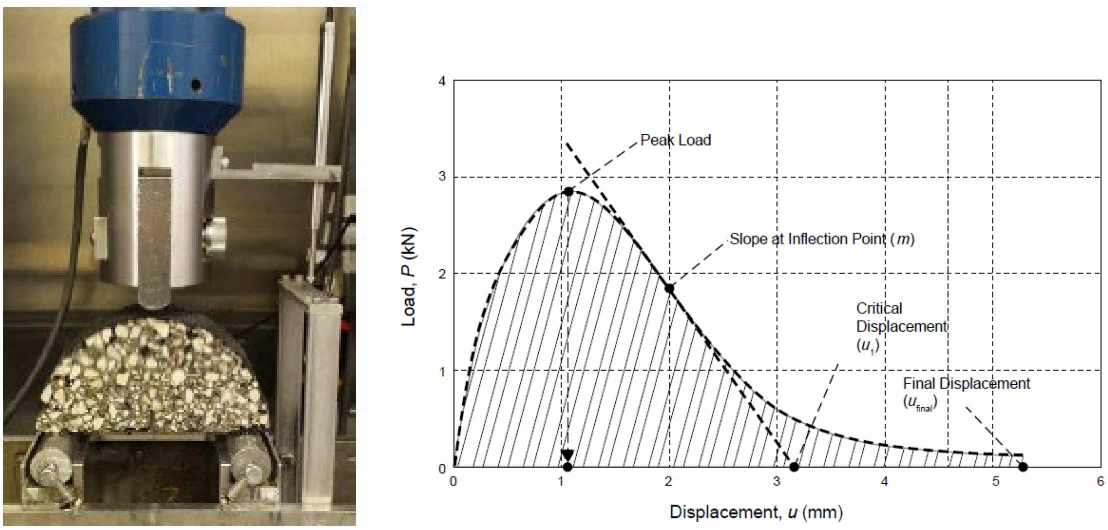


Figure 9 I-FIT setup and typical load vs. displacement plot

The Flexibility Index (FI) of an asphalt mixture is calculated from the obtained fracture parameters fracture energy (Gf) and post peak slope (m) of the LLD curve. FI is defined as the ratio between the fracture energy and the slope of inflection point at post-peak stage of the load-displacement curve. A higher value of FI is generally preferred, indicating a better ability to resist cracking (Al-Qadi et al., 2015). The FI provides a means to identify brittle mixtures that may be prone to premature cracking. FI can be calculated using Equation 2. Higher the FI, higher the crack propagation resistance of HMA mixture for longer time duration under tensile stress. Further, (Nemati et al., 2019) developed the rate-dependent cracking index (RDCI) to better discriminate asphalt mixtures with various mix variables. The calculation of RDCI is shown in Equation 3. This test can be easily performed on specimens obtained from gyratory compacted cylinders or obtained from pavement cores with a diameter of 150 mm.

$$FI = A \times \frac{G_f}{|m|} \qquad (2)$$

Where,
G_f = fracture energy,
$|\mathrm{m}|$ = slope at the post-peak inflection point, and
A = the unit correction coefficient taken as 0.01.

$$RDCI = \frac{\int_{t_{peak}}^{t_{0.1\,peak}} W_C\, dt}{P_{t_{peak}} \times ligament\ area} \times C \tag{3}$$

Where,
$\int_{t_{peak}}^{t_{0.1\,peak}} W_C\ \ dt$ = the post-peak area under the cumulative work versus time curve,
P_{tpeak} = the instantaneous power at peak force,
C = the unit correction factor set to 0.01, and
ligament area = the specimen thickness x the ligament length.

Standard test methods:

(AASHTO T 393-21, 2021): Determining the Fracture Potential of Asphalt Mixtures Using the Illinois Flexibility Index Test (I-FIT)

Test Parameters

- Specimen geometry: 150 ± 1 mm in diameter and 50 ± 1 mm thick, a notch with 15 ± 10 mm

  length and no wider than 2.25 mm

- Loading rate: 50 mm/min using LLD control

- Test temperature: 25 ± 0.5 °C

Measured Properties

Fracture energy (Gf), Post peak slope (m), Flexibility Index (FI) and rate-dependent cracking index (RDCI)

Louisiana Semi-Circular Bend Test

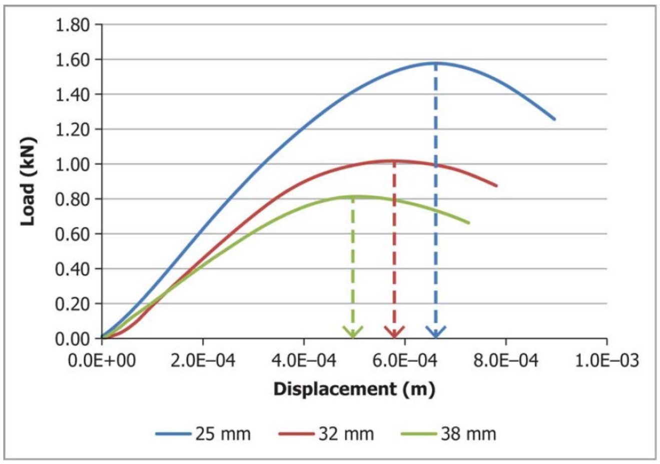
Researchers at the Louisiana Transportation Research Center (LTRC) have proposed the SCB test at intermediate temperature for asphalt pavement’s fatigue cracking performance evaluation (Elseifi et al., 2012; Wu et al., 2005). There are five differences between the LTRC-SCB test and the SCB for low temperature cracking test as per (ASTM D8044-16, 2016), which are as follows:

(1) test temperature: (PG HT + PG LT)/2+4 °C; (2) SCB specimen thickness: 57 mm; (3) three notch depths required: 25, 32 and 37.5 mm; (4) loading rate: cross-head controlled and deformation rate of 0.5 mm/min; and (5) the calculated fracture property: critical energy release rate (J_c).

The LTRC-SCB test setup and typical test outcomes are shown in Figure 5. The critical strain energy release rate is obtained by determining the change in strain energy to failure, U with respect to notch depth, a. The strain energy to failure, U is calculated as the strain energy up to the peak load, which can be calculated as shown in Equation 4. Higher the J_c values, better the fracture-resistance of mixture.

$$J_c = -\frac{1}{b}\left(\frac{dU}{da}\right) \tag{4}$$

Where,
J_c = critical strain energy release rate (kJ/m^2),
b = sample thickness (m),
a = notch depth (m),
U = strain energy to failure (kJ), and
dU/da = change of strain energy with notch depth (kJ/m)



(a) (b)

Figure 10 (a) LTRC - SCB test setup and (b) Typical test result

Standard test methods:

(ASTM D8044-16, 2016): Louisiana Transportation Research Center (LTRC) - SCB method

Test Parameters

- Specimen geometry: 150 ± 9 mm in diameter and 57 ± 1 mm thick, a notch with 15 ± 2.0 mm length and no wider than 1.5 mm
- Loading rate: 0.5 mm/min
- Test temperature: $\frac{PG\ High\ Temperature + PG\ Low\ Temperature}{2} + 4$ (in °C)

Measured Properties

Critical strain energy release rate (Jc)

FATIGUE CRACKING

Direct Tension Cyclic Fatigue (DTCF) Test

The original viscoelastic continuum damage fatigue model and related laboratory tests were simplified by (Underwood et al., 2010) and (Hou et al., 2010), and they renamed it to Direct Tension Cyclic Fatigue (DTCF) test. (AASHTO T 400, 2022) covers standard test method to conduct the DTCF test which characterizes the fatigue performance of asphalt mixtures. Complex modulus (E*) test results are required in order to complete the fatigue damage analysis, even though E* test results are not part of the DTCF test itself. Both E* and DTCF tests can be performed on an asphalt mixture performance tester (AMPT) device (shown in Figure 6) or any other closed-loop control universal test machine. The DTCF test includes a dynamic modulus fingerprint test and two cyclic fatigue damage tests at different strain levels.

The viscoelastic continuum damage parameters, DR (average reduction in integrity up to failure) and Sapp (the accumulated damage when C (pseudo stiffness) is equal to 1-DR), are determined from the test data using the FlexMAT^{TM} software developed through efforts of Federal Highway Administration (FHWA). DR parameter is calculated primarily based on the reduction of the stiffness of sample during the test, thus, is more related to the damage tolerance of the asphalt mixture, while the Sapp parameter is calculated based on the dissipated energy of the sample with increase of cycles, therefore, is more representative of the trade-off between the applied stress and strain, material's stiffness and relaxation capability. DR and Sapp can be calculated using Equations 5 and 6 respectively. Typically, a higher value for both parameters is preferred.

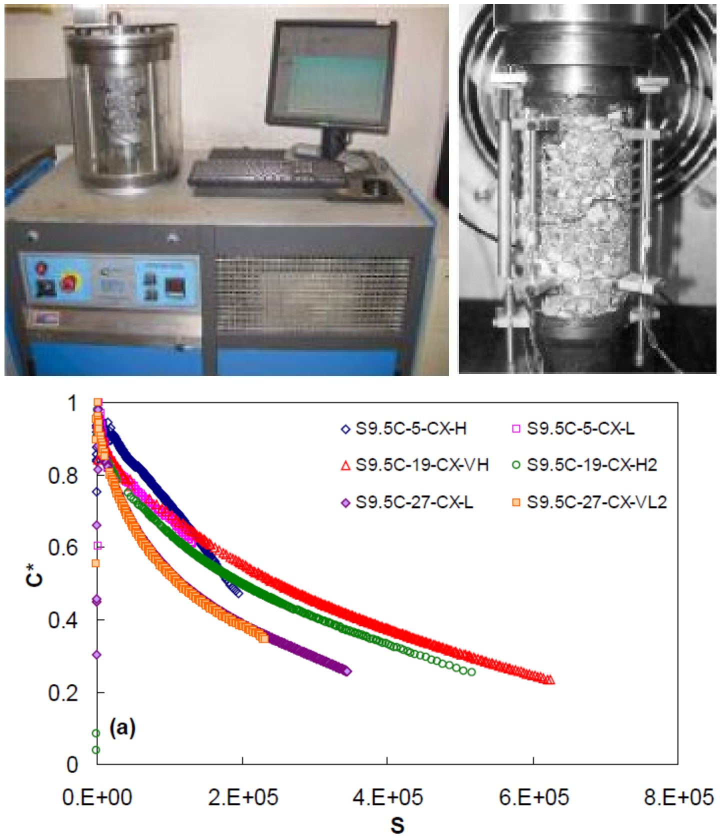


Figure 11 AMPT Apparatus and Specimen with Typical Test Results

$$D^R = \frac{\int_0^{N_f}(1-C)dN}{N_f} = \frac{\sum(1-C)}{N_f} \tag{5}$$

Where,

N = number of load cycles,

N_f = maximum number of load cycles up to failure, and

C = normalized pseudo-stiffness, which decreases from the value of 1 as the damage gets cumulated.

$$S_{app} = \frac{1}{10000} \times \left(\frac{1}{C_1} \times D^R\right)^{\frac{1}{C_2}} \tag{6}$$

Where,

C_1 ,C_2 = the model coefficients in C-S curve determined from S-VECD theory.

Standard test methods:

(AASHTO T 400, 2022): Determining the Damage Characteristic Curve and Failure Criterion Using the Asphalt Mixture Performance Tester (AMPT) Cyclic Fatigue Test

Test Parameters

- Specimen geometry: 100 mm in diameter and 130 ± 2.5 mm height
- Loading frequency: 10 Hz at a target strain range of 50 to 75 micro-strain
- Test temperature range: 5 to 25 °C

Measured Properties

Damage characteristic curve, average reduction in integrity up to failure (DR) and the accumulated damage (Sapp)

Texas Overlay Test (OT)

(Germann & Lytton, 1979) initially developed the Texas OT in late 1970s. TxDOT (Tex-248-F (Revised), 2022) and NJDOT (NJDOT B-10, 2007) have both implemented the OT test method that (Zhou & Scullion, 2005) thoroughly updated and standardized later. The key components of the OT device, as shown schematically in Figure 7, consist of two steel plates, one fixed and the other able to move horizontally to simulate the opening and closing of joints or cracks in the old pavements beneath an overlay. The OT test specimens are 150 mm long, 75 mm wide and 37.5 mm thick, which can either be laboratory prepared or specimen obtained from field cores. The Texas OT is a cyclic displacement-controlled test that lasts 10 seconds each cycle and uses a triangle loading wave pattern. Although both test temperature and opening displacement can change, the OT is typically run at room temperature (25 °C) with a maximum opening displacement of 0.06 cm.

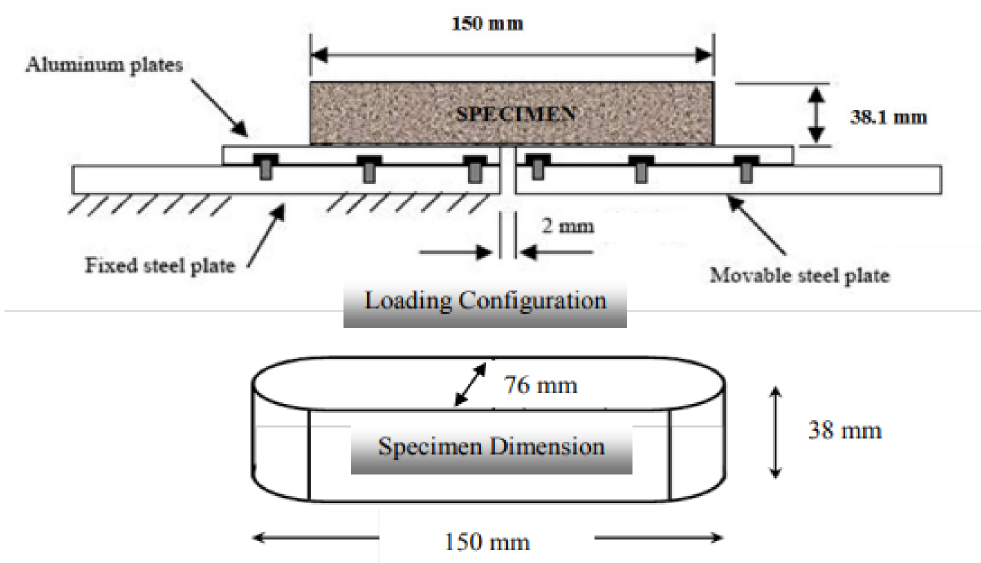


Figure 12 Texas Overlay Tester (OT) setup (Walubita et al., 2012)

The specimen is determined as failed when the cycle peak load drops by 93 percent with respect to the first peak loading cycle or a pre-set value of cycles (e.g., 1000) is reached. The number of load cycles until failure is recorded at the termination of the test. Additionally, the measured load vs. displacement curve can be used to infer the fracture parameters (A and n), if necessary (Zhou et al., 2007). Figure 8 shows the typical result obtained from OT test.

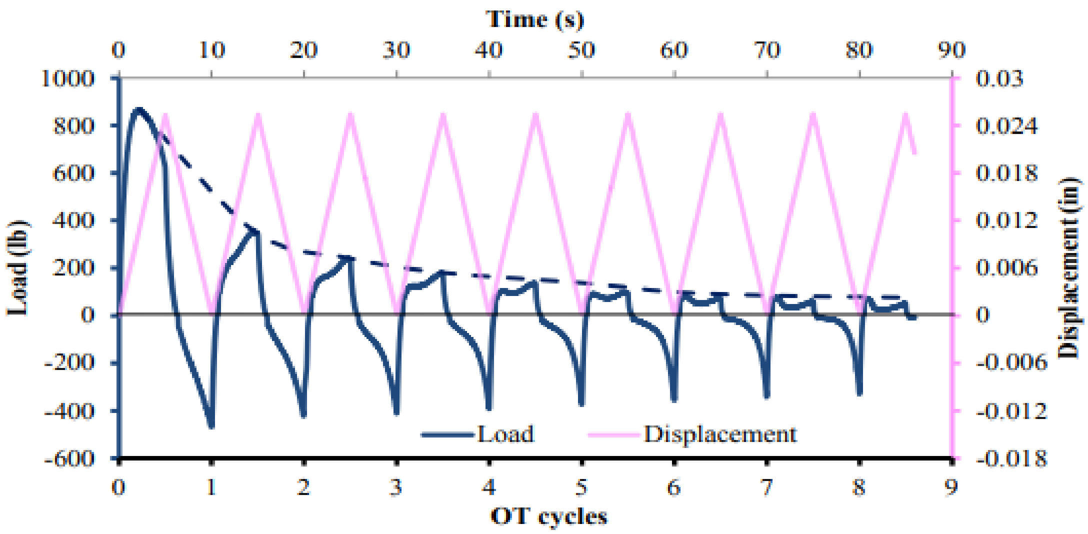


Figure 13 Typical results obtained from OT (Walubita et al., 2012)

Standard test methods:

(Tex-248-F (Revised), 2022): Test Procedure for Overlay Test

(NJDOT B-10, 2007): Overlay Test for Determining Cracking Resistance of HMA

Test Parameters

- Specimen geometry: 150 mm length, 75 mm width, and 37.5 mm thickness
- Loading frequency: 0.1 Hz
- Test temperature: 25 °C
- Maximum opening displacement: 0.06 cm

Measured Properties

Number of cycles to failure

Flexural Bending Beam Test

Monismith and co-workers (Strategic Highway Research Program, 1994) at the University of California, Berkeley, proposed the flexural beam fatigue test under the SHRP A-003A. The current (AASHTO T 321, 2022) is a refined version of this this. The beam specimen is 380×50×63 mm and rate of loading is variable but is normally set at 10 Hz. Generally, the testing is performed at intermediate temperatures, usually 68°F. The test can be conducted in stress- or strain-controlled mode, but the strain-controlled mode is much more widely used because it appears to provide results that are more comparative to field observations. Figure 9 shows a four-point flexural beam fatigue test apparatus. The test involves four clamps holding the beam in place while a repetitive haversine (or sinusoidal) loading is supplied to the two inner clamps and a reaction load is applied to the outside clamps. Consequently, there is a continuous bending moment over the center of the beam between the two inside clamps.

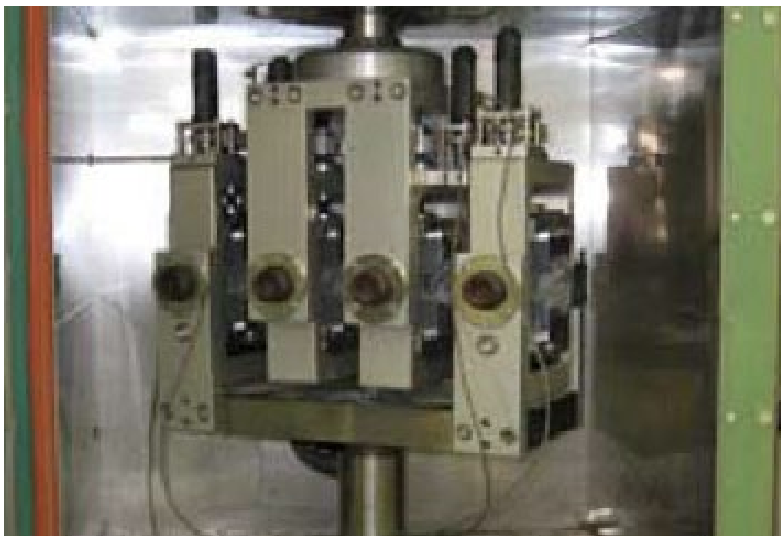


Figure 14 Four-point flexural beam fatigue test apparatus (Su et al., 2009)

Standard test methods:

(AASHTO T 321, 2022): Standard Method of Test for Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending

Test Parameters

- Specimen geometry: 380 mm long, 50 mm wide, and 63 mm thick
- Loading frequency: 10 Hz
- Test temperature: 20 °C

Measured Properties

Number of cycles to failure, Dissipated energy, Fatigue equation

Cyclic Disk-shaped Compact Tension Test

DCT test can also be performed under cyclic loading which is called cyclic DCT test (CDCT) (Chiangmai, 2014). The loading rates for CDCT are generally selected based on peak load obtained during the standard DCT test. CDCT test uses specimens with modified geometry with crack tip opening displacement (CTOD) gage fixed with a 1-cm offset (Figure 10) instead of CMOD gage used in standard DCT test. Currently, there is no standard test method for CDCT. Fracture energy at initial stage (Gf_{ini}), initial and total dissipated energy (IDE and TDE) are fracture parameters which can be obtained from CDCT test. Gf_{ini} is defined as the ratio of released energy dissipated at the 50th cycle (RE_{ini}) to the cracked area of the specimen.

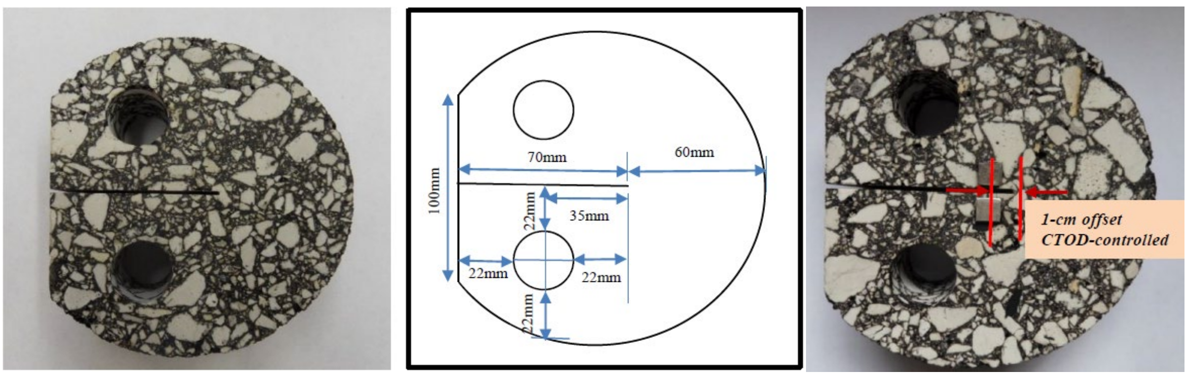


Figure 15 Modified DCT geometry and 1-cm offset CTOD for CDCT test (Chiangmai, 2014)

STRENGTH AND MODULUS APPROACH

Complex (Dynamic) Modulus Test

Complex modulus (E*) is one of the most critical parameters which is used to evaluate both rutting and fatigue cracking distress predictions needed for flexible pavement design using Mechanistic Empirical Pavement Design Guide (MEPDG). (AASHTO T 342, 2022) covers standard test method to determine dynamic modulus of HMA. Mathematically, the complex modulus is the ratio of the peak dynamic stress (σ_o) to the peak recoverable axial strain (ε_o) for a linear viscoelastic material under a continuous sinusoidal loading. The viscous behavior of HMA is indicated by the phase angle (δ), which is the angle by which ε_o lags behind σ_o. The closer is the phase angle to 90°, the more viscous is the material. A sinusoidal (haversine) axial compressive stress is applied to a specimen of asphalt concrete at a given temperature and loading frequency.

A cylindrical specimen with 150 mm diameter and a thickness of 62 mm is subjected to series of cyclic loading at frequencies of 0.1, 0.5, 1.0, 5, 10, and 25 Hz at different temperatures. Figure 11 shows the test setup of dynamic modulus. The applied stress and the resulting recoverable axial strain response of the specimen is measured and used to calculate the dynamic modulus and phase angle. Generally, dynamic modulus values measured over a range of temperatures and frequencies of loading are shifted into a master curve for characterizing asphalt concrete for pavement thickness design and performance analysis.

Figure 16 Dynamic modulus test setup (Y. Zhang et al., 2012)

Standard test methods:

(AASHTO T 342, 2022): Determining Dynamic Modulus of Hot Mix Asphalt (HMA)

Test Parameters

- Specimen geometry: 102 ± 2 mm diameter, and 150 ± 2.5 mm height
- Loading frequency: 0.1, 0.5, 1.0, 5, 10, and 25 Hz
- Test temperature: –10, 4.4, 21.1, 37.8, and 54 °C

Measured Properties

Complex modulus (E*), Phase angle (δ)

Cracking Tolerance (CT) Index Test

(Zhou et al., 2017) have proposed the indirect tensile asphalt cracking test (IDEAL-CT) to characterize fracture resistance of an asphalt mixture at an intermediate temperature. (ASTM D8225-19, 2019) covers standard test method to conduct the CT Index test which characterizes the cracking performance of asphalt mixtures. A cylindrical specimen with 150 mm diameter and a thickness of 62 mm is subjected to compressive load across the diametral plane. The test is conducted using load line displacement (LLD) control at a rate of 50 mm/min and is stopped when the load drops below 0.1 kN. During the testing, the data acquisition system records the time, load, and displacement at a minimum sampling rate of 40 data points per second which can be used for cracking tolerance index (CT_{Index}) calculation. CT_{Index}, which combines total energy dissipation during test with post-peak shape of load-displacement curve, can be calculated using Equation 7. Generally, a higher CT_{Index} value indicates better cracking resistance.

$$CT_{\text{Index}} = \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right)$$
(7)

Where,
G_f = fracture energy (total shaded area under load-displacement curve)
l_{75} = displacement at 75 percent point
$|m_{75}|$ =slope at 75 percent point
D = specimen diameter (mm)

Figure 12 shows CT Index test setup and typical test result. The test can be easily performed on the laboratory prepared specimens and specimens obtained from field cores as well.

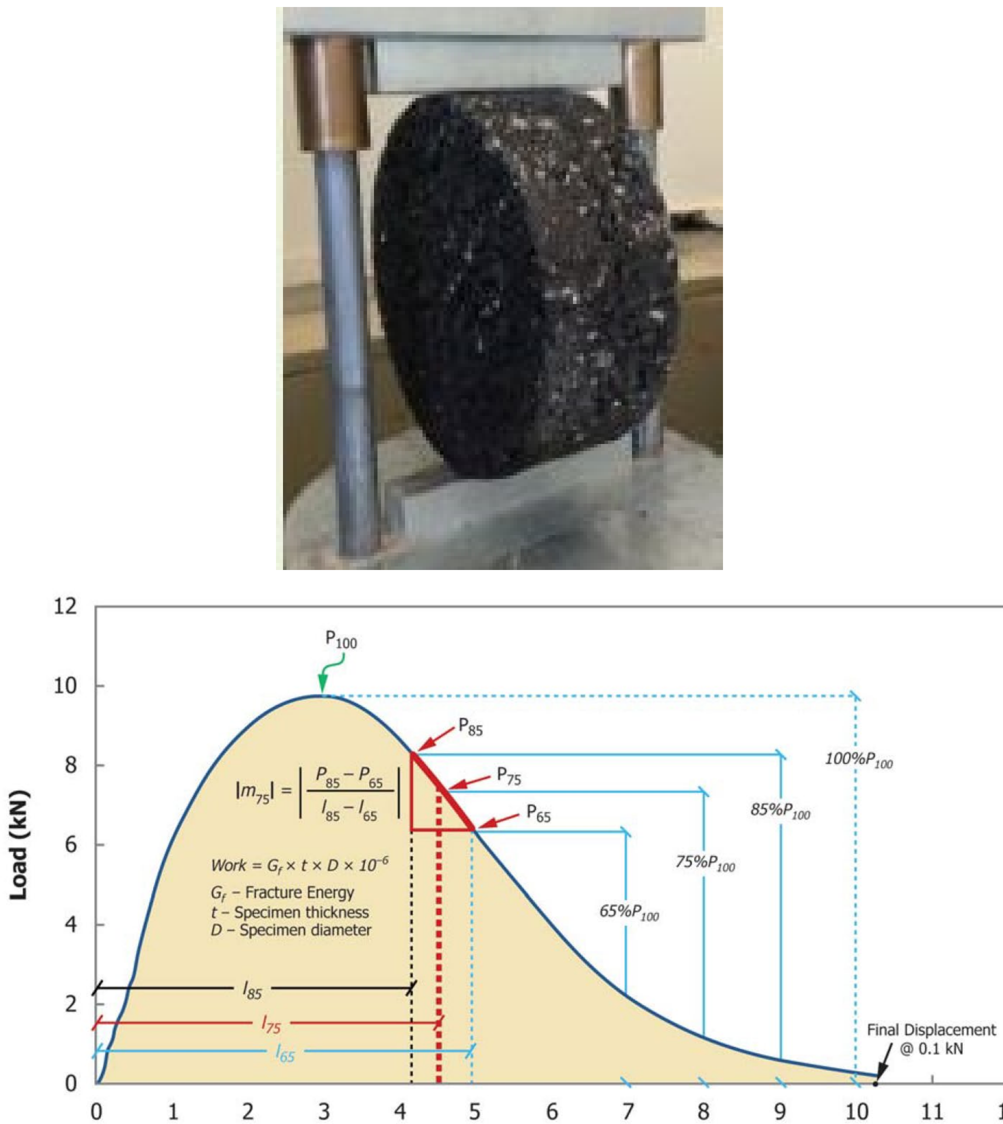


Figure 17 IDEAL-CT apparatus and typical test result

Standard test methods:

(ASTM D8225-19, 2019): Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature

Test Parameters

- Specimen geometry: 150 ± 2 mm in diameter and 62 ± 1 mm height (for NMAS ≤ 19 mm)
- Loading rate: 50 ± 2 mm/min using LLD control
- Test temperature: (PG High Temperature + PG Low Temperature)/2+4 (in °C)

Measured Properties

Cracking tolerance index (CTIndex)

Indirect Tensile Strength Test

Procedure to conduct the IDT test to characterize the strength of HMA mixtures has been explained in the low temperature cracking section of this chapter.

Table 1 Laboratory Cracking Tests Summary

Test name	Test standard	Loading condition	Mode of loading	Notched/ unnotched[1]	Specimen geometry[2]	Test temperature[3]	Test parameter
DCT	(ASTM D7313-20, 2020)	Monotonic	CMOD controlled	N	D: 150 mm T: 50 mm ND: 62.5 mm	LT PG + 10 °C	Fracture energy (G_f), Fracture strain tolerance (FST)
SCB	(AASHTO T 394-21, 2021)	Monotonic	CMOD controlled	N	D: 150 mm T: 24.7 mm ND: 15 mm	LT PG + 10 °C	Fracture energy (G_f), Fracture toughness (K_{IC}), Stiffness (S)
IDT	(AASHTO T 322, 2007)	Monotonic	LLD controlled for strength	UN	D: 150 mm T: 38 to 50 mm	-30 to 10 °C	Tensile strength, Creep compliance
I-FIT	(AASHTO T 393-21, 2021)	Monotonic	LLD controlled	N	D: 150 mm T: 50 mm ND: 15 mm	25 °C	Fracture energy (G_f), Post peak slope (m), Flexibility Index (FI) Rate-dependent cracking index (RDCI)
LTRC SCB	(ASTM D8044-16, 2016)	Monotonic	CMOD controlled	N	D: 150 mm T: 57 mm ND: 15 mm	(HT PG + LT PG)/2 + 4 °C	Critical strain energy release rate (J_c)
CT-Index	(ASTM D8225-19, 2019)	Monotonic	LLD controlled	UN	D: 150 mm T: 62 mm	(HT PG + LT PG)/2 + 4 °C	Cracking tolerance index (CT_{Index})
DTCF	(AASHTO T 400, 2022)	Cyclic	Displacement controlled	UN	D: 150 mm T: 62 mm	5 to 25 °C	Damage characteristic curve, D^R and S_{app}
Texas Overlay Test	(Tex-248-F (Revised), 2022)	Cyclic	Displacement controlled	UN	L: 150 mm W: 75 mm T: 37.5 mm	25 °C	Number of cycles to failure, Paris law crack growth parameters
Flexural Bending Beam Test	(AASHTO T 321, 2022)	Cyclic	Strain controlled (Usually)	UN	L: 380 mm W: 50 mm T: 63 mm	20 °C	Number of cycles to failure, Dissipated energy

[1]N – Notched, UN – Unnotched
[2]D – diameter, W – width, T – thickness, ND – notch depth
[2]LT PG – Low temperature PG, HT PG – High temperature PG

REFERENCES

AASHTO T 321. (2022). *Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending*. American Association of State Highway and Transportation Officials.

AASHTO T 322. (2007). *Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device*. American Association of State Highway and Transportation Officials.

AASHTO T 342. (2022). *Standard Method of Test for Determining Dynamic Modulus of Hot Mix Asphalt (HMA)*. American Association of State Highway and Transportation Officials.

AASHTO T 393-21. (2021). *Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using Illinois Flexibility Index Test (I-FIT)*. American Association of State Highway and Transportation Officials.

AASHTO T 394-21. (2021). *Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB)*. American Association of State Highway and Transportation Officials.

AASHTO T 400. (2022). *Standard Method of Test for Determining the Damage Characteristic Curve and Failure Criterion Using the Asphalt Mixture Performance Tester (AMPT) Cyclic Fatigue Test*. American Association of State Highway and Transportation Officials.

Abanto-Bueno, J., & Lambros, J. (2002). Investigation of Crack Growth in Functionally Graded Materials using Digital Image Correlation. *Engineering Fracture Mechanics*, *69*(14), 1695–1711. https://doi.org/10.1016/S0013-7944(02)00058-9

Abdel-Raouf, A.-G. (1967). *Brittle Behavior and Crack Propagation in Asphaltic Mixtures* [Dissertation, University of Illinois Urbana Champaign]. http://hdl.handle.net/2142/60334

Aglan, H. A., & Figueroa, J. L. (1993). Damage-Evolution Approach to Fatigue Cracking in Pavements. *Journal of Engineering Mechanics*, *119*(6), 1243–1259. https://doi.org/10.1061/(ASCE)0733-9399(1993)119:6(1243)

Ali, U. M., Hernandez, J., Al-Qadi, I., & Ozer, H. (2019). Three-Dimensional Balanced Mix Design for Asphalt Concrete. *Airfield and Highway Pavements 2019*, 178–188. https://doi.org/10.1061/9780784482452.018

Al-Qadi, I. L., Ozer, H., Lambros, J., Khatib, A. E., Singhvi, P., Khan, T., Rivera-Perez, J., & Doll, B. (2015). *Testing Protocols to Ensure Performance of High Asphalt Binder Replacement Mixes Using RAP and RAS* (FHWA-ICT-15-017). Illinois Center for Transportation.

Ann Myers, L., & Roque, R. (2002). Top-Down Crack Propagation in Bituminous Pavements and Implications For Pavement Management. *Journal of the Association of Asphalt Paving Technologists*, *71*. https://trid.trb.org/view/698756

Ann Myers, L., Roque, R., & Birgisson, B. (2001). Propagation Mechanisms for Surface-Initiated Longitudinal Wheelpath Cracks. *Transportation Research Record*, *1778*(1), 113–122. https://doi.org/10.3141/1778-14

Ann Myers, L., Roque, R., Ruth, B. E., & Drakos, C. (1999). Measurement of Contact Stresses for Different Truck Tire Types To Evaluate Their Influence on Near-Surface Cracking and Rutting. *Transportation Research Record*, *1655*(1), 175–184. https://doi.org/10.3141/1655-23

ASTM D7313-20. (2020). *Standard Test Method for Determining Fracture Energy of Asphalt Mixtures Using the Disk-Shaped Compact Tension Geometry*. American Society for Testing and Materials.

ASTM D8044-16. (2016). *Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures*. American Society for Testing and Materials.

ASTM D8225-19. (2019). *Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature*. American Society for Testing and Materials.

Behnia, B., Dave, E. V., Ahmed, S., Buttlar, W. G., & Reis, H. (2011). Effects of Recycled Asphalt Pavement Amounts on Low-Temperature Cracking Performance of Asphalt Mixtures Using Acoustic Emissions. *Transportation Research Record*, *2208*(1), 64–71. https://doi.org/10.3141/2208-09

Buttlar, W. G., & Roque, R. (1994). Development and evaluation of the strategic highway research program measurement and analysis system for indirect tensile testing at low temperatures. *Transportation Research Record*, *1454*, 163–171.

Canestrari, F., & Ingrassia, L. P. (2020). A Review of Top-Down Cracking in Asphalt Pavements: Causes, Models, Experimental Tools and Future Challenges. *Journal of Traffic and Transportation Engineering (English Edition)*, *7*(5), 541–572. https://doi.org/10.1016/j.jtte.2020.08.002

Chen, A., Airey, G. D., Thom, N., Li, Y., & Wan, L. (2022). Simulation of Micro-Crack Initiation and Propagation under Repeated Load in Asphalt Concrete using Zero-Thickness Cohesive

Elements. *Construction and Building Materials*, *342*, 127934. https://doi.org/10.1016/j.conbuildmat.2022.127934

Chiangmai, C. N. (2014). *Experimental evaluation of monotonic and cyclic fracture behaviour using disk-shaped compact tension test and released energy approach*. University of Illinois at Urbana-Champaign.

Collop, A. C., & Cebon, D. (1995). A Theoretical Analysis of Fatigue Cracking in Flexible Pavements. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *209*(5), 345–361. https://doi.org/10.1243/PIME_PROC_1995_209_163_02

Dave, E. V., & Behnia, B. (2018). Cohesive zone fracture modelling of asphalt pavements with applications to design of high-performance asphalt overlays. *International Journal of Pavement Engineering*, *19*(3), 319–337. https://doi.org/10.1080/10298436.2017.1353393

Dave, E. V., Oshone, M., Schokker, A., & Bennett, C. E. (2019). *Disc Shaped Compact Tension (DCT) Specifications Development for Asphalt Pavement* (MN/RC 2019-24). Department of Civil and Environmental Engineering University of New Hampshire. http://dot.state.mn.us/research/reports/2019/201924.pdf

Doll, B., Ozer, H., Rivera-Perez, J., Al-Qadi, I. L., & Lambros, J. (2017a). Damage Zone Development in Heterogeneous Asphalt Concrete. *Engineering Fracture Mechanics*, *182*, 356–371. https://doi.org/10.1016/j.engfracmech.2017.06.002

Doll, B., Ozer, H., Rivera-Perez, J. J., Al-Qadi, I. L., & Lambros, J. (2017b). Investigation of Viscoelastic Fracture Fields in Asphalt Mixtures using Digital Image Correlation. *International Journal of Fracture*, *205*(1), 37–56. https://doi.org/10.1007/s10704-017-0180-8 dos Santos, S., Partl, M. N., & Poulikakos, L. D. (2014). Newly observed effects of water on the microstructures of bitumen surface. *Construction and Building Materials*, *71*, 618–627. https://doi.org/10.1016/j.conbuildmat.2014.08.076

Elseifi, M. A., Mohammad, L. N., Ying, H., & Cooper, S. (2012). Modeling and evaluation of the cracking resistance of asphalt mixtures using the semi-circular bending test at intermediate temperatures. *Road Materials and Pavement Design*, *13*(sup1), 124–139. https://doi.org/10.1080/14680629.2012.657035

Germann, F. P., & Lytton, R. L. (1979). *Methodology for Predicting the Reflection Cracking Life of Asphalt Concrete Overlays* (FHWA-TX-79-09 & 207-5; p. 147). https://trid.trb.org/view/142495

Harvey, J. T., Deacon, J. A., Tsai, B.-W., & Monismith, C. L. (1995). *Fatigue Performance of Asphalt Concrete Mixes and its Relationship to Asphalt Concrete Pavement Performance in California* (RTA-65W485-2).

Hou, T., Underwood, B. S., & Kim, Y. R. (2010). Fatigue Performance Prediction of North Carolina Mixtures Using the Simplified Viscoelastic Continuum Damage Model. *Journal of the Association of Asphalt Paving Technologists*, *79*, 35–80.

Huang, Y. (1993). *Pavement Analysis and Design*. Prentice Hall.

Ioannides, A. M. (1997). Fracture Mechanics in Pavement Engineering: The Specimen-Size Effect. *Transportation Research Record*, *1568*(1), 10–16. https://doi.org/10.3141/1568-02

Jacobs, M., Hopman, P. C., & Molenaar, A. A. A. (1996). Application of Fracture Mechanics Principles to Analyze Cracking in Asphalt Concrete. *Journal of the Association of Asphalt Paving Technologists*, *65*, 1–39.

Jacobs, M. M. J. (1995). *Crack Growth in Asphaltic Mixes* [Dissertation]. Delft University of Technology.

Kim, H., & Buttlar, W. G. (2009). Multi-Scale Fracture Modeling of Asphalt Composite Structures. *Composites Science and Technology*, *69*(15), 2716–2723. https://doi.org/10.1016/j.compscitech.2009.08.014

Kim, K. W., & El Hussein, H. M. (1995). Effect of Differential Thermal Contraction on Fracture Toughness of Asphalt Materials at Low Temperatures. *Journal of the Association of Asphalt Paving Technologists*, *64*, 474–499.

Kim, M., Buttlar, W. G., Baek, J., & Al-Qadi, I. L. (2009). Field and Laboratory Evaluation of Fracture Resistance of Illinois Hot-Mix Asphalt Overlay Mixtures. *Transportation Research Record*, *2127*(1), 146–154. https://doi.org/10.3141/2127-17

Kim, S.-S. (2005). Direct Measurement of Asphalt Binder Thermal Cracking. *Journal of Materials in Civil Engineering*, *17*(6), 632–639. https://doi.org/10.1061/(ASCE)0899-1561(2005)17:6(632)

Kim, S.-S., Wysong, Z. D., & Kovach, J. (2006). Low-Temperature Thermal Cracking of Asphalt Binder by Asphalt Binder Cracking Device. *Transportation Research Record*, *1962*(1), 28–35. https://doi.org/10.1177/0361198106196200104

Kim, Y. R., Lee, H.-J., & Little, D. N. (1997). Fatigue Characterization of Asphalt Concrete Using Viscoelasticity and Continuum Damage Theory. *Journal of the Association of Asphalt Paving Technologists*, *66*, 520–569.

Kim, Y. R., & Little, D. N. (1990). One-Dimensional Constitutive Modeling of Asphalt Concrete. *Journal of Engineering Mechanics*, *116*(4), 751–772. https://doi.org/10.1061/(ASCE)0733-9399(1990)116:4(751)

Krishna Swamy, A., Mitchell, L. F., Hall, S. J., & Sias Daniel, J. (2011). Impact of RAP on the Volumetric, Stiffness, Strength, and Low-Temperature Properties of HMA. *Journal of Materials in Civil Engineering*, *23*(11), 1490–1497. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000245

Lee, S. J., Rust, J. P., Hamouda, H., Kim, Y. R., & Borden, R. H. (2005). Fatigue Cracking Resistance of Fiber-Reinforced Asphalt Concrete. *Textile Research Journal*, *75*(2), 123–128. https://doi.org/10.1177/004051750507500206

Li, Q., Chen, X., Li, G., & Zhang, S. (2018). Fatigue Resistance Investigation of Warm-Mix Recycled Asphalt Binder, Mastic, and Fine Aggregate Matrix. *Fatigue & Fracture of Engineering Materials & Structures*, *41*(2), 400–411. https://doi.org/10.1111/ffe.12692

Li, X., & Gibson, N. (2016). Comparison of Laboratory Fatigue Characteristics with Full-Scale Pavement Cracking for Recycled and Warm-Mix Asphalts. *Transportation Research Record*, *2576*(1), 100–108. https://doi.org/10.3141/2576-11

Li, X. (Shaw), & Marasteanu, M. (2004). Evaluation of the low temperature fracture resistance of asphalt mixtures using the semi circular bend test. *Journal of the Association of Asphalt Paving Technologists*, *73*, 401–426.

Ling, M., Luo, X., Chen, Y., Hu, S., & Lytton, R. L. (2019). A Calibrated Mechanics-Based Model for Top-Down Cracking of Asphalt Pavements. *Construction and Building Materials*, *208*, 102–112. https://doi.org/10.1016/j.conbuildmat.2019.02.090

Little, D. N., Lytton, R. L., Williams, D., & Kim, Y. R. (1999). An Analysis of The Mechanism of Microdamage Healing Based on The Application of Micromechanics First Principles of Fracture and Healing. *Journal of the Association of Asphalt Paving Technologists*, *68*, 501–542.

Majidzadeh, K., Kauffmann, E. M., & Ramsamooj, D. V. (1971). Application of Fracture Mechanics in the Analysis of Pavement Fatigue. *Journal of the Association of Asphalt Paving Technologists*, *40*, 227–246.

Marasteanu, M., Buttlar, W., Bahia, H., Williams, C., Moon, K. H., Teshale, E. Z., Falchetto, A. C., Turos, M., Dave, E., Paulino, G., Ahmed, S., Leon, S., Braham, A., Behnia, B., Tabatabaee, H., Velasquez, R., Arshadi, A., Puchalski, S., Mangiafico, S., … Kvasnak, A. (2012). *Investigation of Low Temperature Cracking in Asphalt Pavements National Pooled Fund Study – Phase II* (Report MN/RC 2012-23). Minnesota Department of Transportation. http://conservancy.umn.edu/handle/11299/135177

McDaniel, R. S., Shah, A., & Huber, G. (2012). *Investigation of Low- and High-Temperature Properties of Plant-Produced RAP Mixtures* (FHWA-HRT-11-058). https://rosap.ntl.bts.gov/view/dot/41731

Mobasher, B., Mamlouk, M. S., & Lin, H.-M. (1997). Evaluation of Crack Propagation Properties of Asphalt Mixtures. *Journal of Transportation Engineering*, *123*(5), 405–413. https://doi.org/10.1061/(ASCE)0733-947X(1997)123:5(405)

Mogawer, W. S., Austerman, A. J., Bonaquist, R., & Roussel, M. (2011). Performance Characteristics of Thin-Lift Overlay Mixtures: High Reclaimed Asphalt Pavement Content, Recycled Asphalt Shingles, and Warm-Mix Asphalt Technology. *Transportation Research Record*, *2208*(1), 17–25. https://doi.org/10.3141/2208-03

Molenaar, A. A. A. (1984). Fatigue and Deflection Cracking Due to Traffic Loads. *Journal of the Association of Asphalt Paving Technologists*, *53*, 440–474.

Molenaar, A. A. A. (2007). Prediction of Fatigue Cracking in Asphalt Pavements: Do We Follow the Right Approach? *Transportation Research Record*, *2001*(1), 155–162. https://doi.org/10.3141/2001-17

Monismith, C. L., & Deacon, J. A. (1969). Fatigue of Asphalt Paving Mixtures. *Transportation Engineering Journal of ASCE*, *95*(2), 317–346. https://doi.org/10.1061/TPEJAN.0000023

Monismith, C. L., Secor, K. E., & Blackmer, E. W. (1961). Asphalt Mixture Behavior in Repeated Flexure. *Association of Asphalt Paving Technologists Proceedings*, *30*, 188–222. https://trid.trb.org/view/728292

National Cooperative Highway Research Program, Transportation Research Board, & National Academies of Sciences, Engineering, and Medicine. (2010). *Top-Down Cracking of Hot-Mix Asphalt Layers: Models for Initiation and Propagation* (p. 22935). Transportation Research Board. https://doi.org/10.17226/22935

Nemati, R., Haslett, K., Dave, E. V., & Sias, J. E. (2019). Development of a rate-dependent cumulative work and instantaneous power-based asphalt cracking performance index. *Road Materials and Pavement Design*, *20*(sup1), S315–S331. https://doi.org/10.1080/14680629.2019.1586753

NJDOT B-10. (2007). *Overlay Test for Determining Crack Resistance of HMA*. New Jersey Department of Transportation.

Norouzi, A., Kim, D., & Richard Kim, Y. (2016). Numerical Evaluation of Pavement Design Parameters for the Fatigue Cracking and Rutting Performance of Asphalt Pavements. *Materials and Structures*, *49*(9), 3619–3634. https://doi.org/10.1617/s11527-015-0744-x

Nunn, M. (1989). A model for top-down reflection cracking in composite pavements. *Proc., 1st International RILEM Conference on Reflective Cracking in Pavements, Assessment and Control*.

Ozer, H., Al-Qadi, I. L., Lambros, J., El-Khatib, A., Singhvi, P., & Doll, B. (2016). Development of the Fracture-Based Flexibility Index for Asphalt Concrete Cracking Potential using Modified Semi-Circle Bending Test Parameters. *Construction and Building Materials*, *115*, 390–401. https://doi.org/10.1016/j.conbuildmat.2016.03.144

Pell, P. S. (1962). *Fatigue Characteristics of Bitumen And Bituminous Mixes*. *203*(1), 43–58. https://trid.trb.org/View/717074

Pirmohammad, S., Khoramishad, H., & Ayatollahi, M. R. (2016). Effects of Asphalt Concrete Characteristics on Cohesive Zone Model Parameters of Hot Mix Asphalt Mixtures. *Canadian Journal of Civil Engineering*, *43*(3), 226–232. https://doi.org/10.1139/cjce-2014-0504

Roque, R., Birgisson, B., Drakos, C., & Dietrich, B. (2004). Development and Field Evaluation of Energy-Based Criteria for Top-Down Cracking Performance of Hot Mix Asphalt. *Journal of the Association of Asphalt Paving Technologists*, *73*, 229–260.

Roque, R., & Buttlar, W. G. (1992). Development of a measurement and analysis system to accurately determine asphalt concrete properties using the indirect tensile mode. *Journal of the Association of Asphalt Paving Technologists*, *61*, 304–332.

Roque, R., & Ruth, B. E. (1990). Mechanisms and Modeling of Surface Cracking in Asphalt Pavements. *Journal of the Association of Asphalt Paving Technologists*, *59*, 396–421.

Roque, R., Zou, J., & Hernando, D. (2015). Cracking Mechanisms in Asphalt Mixtures. In *Advances in Asphalt Materials* (pp. 135–167). Elsevier. https://doi.org/10.1016/B978-0-08-100269-8.00005-2

Son, S. (2014). *Development Of a Phenomenological Constitutive Model for Fracture Resistance Degradation of Asphalt Concrete with Damage Growth Due to Repeated Loading* [Dissertation, University of Illinois Urbana Champaign]. http://hdl.handle.net/2142/49825

Strategic Highway Research Program. (1994). *Fatigue Response of Asphalt-Aggregate Mixes* (SHRP-A-404; p. 309). National Research Council. https://trid.trb.org/View/405685

Su, K., Maekawa, R., & Hachiya, Y. (2009). Laboratory evaluation of WMA mixture for use in airport pavement rehabilitation. *Construction and Building Materials*, *23*(7), 2709–2714. https://doi.org/10.1016/j.conbuildmat.2008.12.011

Tex-248-F (Revised). (2022). *Test Procedure for the Overlay Test*. Texas Department of Transportation.

Tsai, B.-W., Harvey, J. T., & Monismith, C. L. (2003). Application of Weibull Theory in Prediction of Asphalt Concrete Fatigue Performance. *Transportation Research Record*, *1832*(1), 121–130. https://doi.org/10.3141/1832-15

Tsai, B.-W., Harvey, J. T., & Monismith, C. L. (2004). Two-Stage Weibull Approach for Asphalt Concrete Fatigue Performance Prediction. *Journal of the Association of Asphalt Paving Technologists*, *73*, 623–655.

Underwood, B. S., Kim, Y. R., & Guddati, M. N. (2010). Improved calculation method of damage parameter in viscoelastic continuum damage model. *International Journal of Pavement Engineering*, *11*(6), 459–476. https://doi.org/10.1080/10298430903398088

Van Dijk, W., & Visser, W. (1977). Energy Approach to Fatigue for Pavement Design. *Journal of the Association of Asphalt Paving Technologists*, *46*, 1–40.

Wagoner, M. P. (2006). *Fracture Tests for Bituminous-Aggregate Mixtures: Laboratory and Field Investigations* [Dissertation, University of Illinois Urbana Champaign]. http://hdl.handle.net/2142/83316

Wagoner, M. P., Buttlar, W. G., Paulino, G. H., & Blankenship, P. (2005). Investigation of the Fracture Resistance of Hot-Mix Asphalt Concrete Using a Disk-Shaped Compact Tension Test. *Transportation Research Record*, *1929*(1), 183–192. https://doi.org/10.1177/0361198105192900122

Walubita, L. F., Faruk, A. N., Koohi, Y., Luo, R., Scullion, T., & Lytton, R. L. (2012). *The Overlay Tester (OT): Comparison with Other Crack Test Methods and Recommendations for Surrogate Crack Tests* (FHWA/TX-13/0-6607-2). Texas A&M Transportation Institute.

Wang, H. (2018). *Investigation on the Mechanisms of Block Cracking in Asphalt Pavements* [Dissertation]. University of Illinois Urbana Champaign.

Wang, H., & Al-Qadi, I. L. (2010). Near-Surface Pavement Failure under Multiaxial Stress State in Thick Asphalt Pavement. *Transportation Research Record*, *2154*(1), 91–99. https://doi.org/10.3141/2154-08

Wang, H., Ozer, H., Al-Qadi, I. L., & Duarte, C. A. (2013). Analysis of Near-Surface Cracking under Critical Loading Conditions Using Uncracked and Cracked Pavement Models. *Journal of Transportation Engineering*, *139*(10), 992–1000. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000562

Wang, Y., Mahboub, K. C., & Hancher, D. E. (2005). Survival Analysis of Fatigue Cracking for Flexible Pavements Based on Long-Term Pavement Performance Data. *Journal of Transportation Engineering*, *131*(8), 608–616. https://doi.org/10.1061/(ASCE)0733-947X(2005)131:8(608)

Wu, Z., Mohammad, L. N., Wang, L. B., & Mull, M. A. (2005). Fracture Resistance Characterization of Superpave Mixtures Using the Semi-Circular Bending Test. *Journal of ASTM International*, *2*(3), 1–15. https://doi.org/10.1520/JAI12264

Zhang, Y., Luo, R., & Lytton, R. L. (2012). Characterizing Permanent Deformation and Fracture of Asphalt Mixtures by Using Compressive Dynamic Modulus Tests. *Journal of Materials in Civil Engineering*, *24*(7), 898–906. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000471

Zhang, Z., Roque, R., & Birgisson, B. (2001). Evaluation of Laboratory-Measured Crack Growth Rate for Asphalt Mixtures. *Transportation Research Record*, *1767*(1), 67–75. https://doi.org/10.3141/1767-09

Zhao, Y., Alae, M., & Fu, G. (2018). Investigation of Mechanisms of Top-Down Fatigue Cracking of Asphalt Pavement. *Road Materials and Pavement Design*, *19*(6), 1436–1447. https://doi.org/10.1080/14680629.2017.1303394

Zhou, F., Hu, S., Scullion, T., Chen, D.-H., Qi, X., & Claros, G. (2007). Development and Verification of the Overlay Tester Based Fatigue Cracking Prediction Approach. *Journal of the Association of Asphalt Paving Technologists*, *76*, 627–662.

Zhou, F., Im, S., Sun, L., & Scullion, T. (2017). Development of an IDEAL cracking test for asphalt mix design and QC/QA. *Road Materials and Pavement Design*, *18*(sup4), 405–427. https://doi.org/10.1080/14680629.2017.1389082

Zhou, F., & Scullion, T. (2005). *Overlay Tester: A Rapid Performance Related Crack Resistance Test* (FHWA/TX-05/0-4467-2). Federal Highway Administration. https://trid.trb.org/view/760186

Zhu, Y., Dave, E. V., Rahbar-Rastegar, R., Daniel, J. S., & Zofka, A. (2017). Comprehensive evaluation of low-temperature fracture indices for asphalt mixtures. *Road Materials and Pavement Design*, *18*(sup4), 467–490. https://doi.org/10.1080/14680629.2017.1389085