FRACTURE CHARACTERIZATION OF THIN BONDED ASPHALT CONCRETE OVERLAY SYSTEMS

BY

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DISSERTATION

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ABSTRACT

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Asphalt overlays provide an economical means for treating deteriorated pavements. Thin bonded overlay (TBO) systems have become popular options for pavement rehabilitation. In addition to functional improvements, these systems ensure a high degree of waterproofing benefits. Conventional asphalt concrete fracture tests were developed for pavements with homogeneous asphalt concrete mixtures, and typically their thicknesses exceed two inches. The use of spray paver technology for construction of TBO leads to continuously varying asphalt binder content, up to approximately one-third of the layer thickness. The graded properties of asphalt concrete and thickness of the TBO (typically less than 50 mm) pose challenges for the use of conventional fracture test geometries. For example, obtaining the beams for SEN[B] specimens from pavement may not practical because of insufficient layer thickness of the TBO or may lead to excessive pavement damage. Applications of the other established test geometries, the DC[T] and SC[B] tests, are limited because of the material nonhomogeneity caused by nonuniform distribution of asphalt binder and smaller as-constructed thicknesses of TBO, which are usually less than 25 mm (1 inch) for gap-graded and 50 mm (2 inch) for dense-graded hot mix asphalt (HMA) mixtures. Both the DC[T] and SC[B] tests simulate movement of the crack fronts in transverse or longitudinal directions in the pavement. Use of these tests on field-procured samples of TBO yields a crack front that encounters nonhomogeneous material through the specimen thickness. The crack moves perpendicular to the axis of material nonhomogeneity, which makes data interpretation and fundamental material fracture characterization challenging. In addition, the crack in the specimens is correlated to a crack channeling across the pavement width rather than a more anticipated bottom-up or top-down direction.
New test procedures for fracture characterization of graded asphalt pavement systems that have significant material property gradients through their thicknesses have been proposed. Suitable specimen geometry and testing procedures were developed using ASTM E399 and ASTM D7313-07 as a starting point. Laboratory tests were performed using an optimized compact tension C[T] test geometry for field cores as well as laboratory-fabricated composite specimens. Laboratory testing using the proposed procedure clearly showed distinction in the fracture characteristics for specimens prepared with varying material compositions. This capability of distinguishing different materials combined with stable crack growth makes the proposed testing procedure ideal for fracture characterization of thin and graded pavement systems. Statistical analysis of test data revealed that the proposed C[T] test procedure is capable of detecting differences in fracture energy results across a wide range of pavement systems and yields a low test variability. Finite element simulations of the test procedure further indicate the suitability of the test procedure as well as demonstrate a procedure for extraction of fundamental material properties. The suitability of the proposed C[T] test in the context of warmer temperatures was also evaluated. Changes in the loading rate were suggested to minimize the creep energy dissipation during the test at different test temperatures.

Composite specimen fabrication procedure has been developed to optimize the design of TBOs. The proposed procedure can also be used to prepared composite specimens for interface bond strength and rutting resistance tests with emulsion and asphalt cement as tack coat material. Suggested wet application of tack coat emulsion on textured base, compacted with heated Superpave gyratory compactor top plate closely resembles field installation of TBOs. Moreover tack coat emulsion permeation effects on mixture fracture and bulk properties were also evaluated in an experimental study. Image analysis technique was utilized to characterize the tack coat emulsion impregnation gradient through the thickness of the overlays. An integrated approach to predict cracking performance of TBOs was presented combining laboratory test results, numerical simulations and early field performance.
IN THE NAME OF ALLAH, THE MOST GRACIOUS AND THE MOST MERCIFUL

This thesis is dedicated to
My Parents
Their love, guidance and encouragement made all this possible!

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CHAPTER 1 - INTRODUCTION

1.1 INTRODUCTION

With the ever escalating cost of construction and pavement materials, pavement preservation continues to gain importance as means to delay costly rehabilitation and reconstruction alternatives. An effective pavement preservation program requires cost-effective and efficient maintenance strategies (Hicks et al., 1999). Several new technologies have been developed and are in practice to address these issues (Moulthrop and Smith, 2000; Corley-Lay and Mastin, 2007). Evaluation of field projects reveals that thin bonded wearing courses represent an efficient treatment option for deteriorated rigid and flexible pavement systems and often hold advantages over other alternatives (Bellanger et al., 1992; Kandhal and Lockett, 1997; Hanson, 2001 and Corley-Lay and Mastin, 2007). Thin bonded wearing courses provide an efficient treatment option for deteriorated rigid and flexible pavement systems. As a surfacing layer placed over existing, deteriorated pavement, the system should optimally be designed to be resistant to various forms of cracking, including: thermal, block, reflective, and top-down. Recent advances in fracture testing and modeling have provided stronger links between materials properties and field performance with respect to crack resistance (Wagoner et al., 2006, Dave et al., 2008). However, little work has been directed towards applying these tools to thin and bonded overlay systems.

This research study focuses on fracture characterization of thin bonded asphalt concrete overlay systems; however, the test procedures described herein are also applicable to other non-homogeneous pavement systems such as aged pavements, pavements with varying material composition, etc. Thin bonded overlays systems are inherently different than the conventional HMA overlays in both composition and their construction. Forensic investigation indicates that TBO systems are graded in nature (effective binder content varies vertically through their thickness) with superior adhesion at the interface. Thin bonded overlay systems have three distinct differences from typical HMA overlay systems. These include; (a) wet application of undiluted asphalt emulsion; (b) its higher application rate (3 to 5 time more than conventional
tack coat), and; (c) a construction process designed to protect the heavy tack coat and to promote upward wicking of the tack coat emulsion into the asphalt mixture being placed immediately afterwards. The spray paver delivery system is designed to apply tack coat and place HMA mixture in single pass. Besides other benefits; like stronger adhesion with existing pavement; this paving system enables the use of polymer modified asphalt emulsion (PMAE) as a tack coat and eliminates its loss during the construction process. A key benefit of wet application of tack emulsion is its upward wicking into the overlay mixture and subsequent enhancement of mixture fracture energy. As will be demonstrated later, the wicking effect is thought to be a thermodynamic process occurring under the screed that relies upon interconnected voids, and is therefore more pronounced in the TBOs with gap-graded mixes. Water carrying minute asphalt droplets in the emulsion phase is attracted upward by the heat of the HMA mixture and the hot spray paver screed, which operates at a temperature of up to 375°F. Emulsion upward migration results in an effective asphalt content gradient through the thickness of the overlay. This upward permeation phenomenon (Figure 1.1) results in a graded overlay with a rich binder content in the lower 1/3\textsuperscript{rd} of the overlay thickness. Binder content variation as function of the wearing course thickness depends upon the HMA mixture design and tack coat emulsion type and its application rate.

Preliminary laboratory testing poses certain challenges in characterizing fracture properties of these thin graded overlay system. Thickness and the graded nature of the overlay system make it a completely different system than conventional asphalt concrete pavement. The ASTM specified asphalt concrete fracture test; disk-shaped compact tension DC[T] test provides a good measure of asphalt concrete fracture resistance (Wagoner et al., [2005b]). But this test configuration along with other popular fracture tests has never been applied to thin, graded asphalt concrete mixtures. This necessitates evaluation of in-practice asphalt concrete fracture tests for their suitability to characterize such graded systems. According to Wagoner (2006), the DC[T] is very sensitive to specimen thicknesses below 50 mm (2 inches) and has a thickness size effect on fracture energy in general. The fact that most of these graded overlays are less than 50 mm thick further supports the need for evaluation of these tests to characterize bonded overlays with varying composition through their thickness.
1.2 PROBLEM STATEMENT

The main objective of this research is to develop a procedure that can quantify the fracture resistance of thin bonded overlay system with acceptable accuracy.

1.3 RESEARCH OBJECTIVES AND SCOPE

In order to develop a test procedure according to the problem statement described above, the objectives of this research were identified as follows:

1. Evaluate the suitability of existing asphalt concrete fracture tests to characterize the fracture resistance of thin bonded overlays.

2. Develop and optimize the selected or new test configuration through laboratory testing and to evaluate its applicability using fracture mechanics principles.

3. Characterize the effective binder content and material property gradient in bonded overlay systems.

4. Develop a laboratory fabrication procedure for thin bonded overlay composite specimens.

5. Compare fracture properties of laboratory compacted specimens with field cores.

6. Predict the cracking performance of TBO systems utilizing numerical simulation.

Figure 1.2 provides an outline of the complete research project. This thesis will not encompass steps 6, 7 and 8, which are being studied separately. The present study includes development of the test procedure and its application for thin overlay systems with a variety of mix designs and tack coat emulsion types/rates. More details on each item within this outline are discussed in detail in subsequent chapters.
Figure 1.1: Typical Pavement Structure and Extent of Upward Permeation of Tack Coat Emulsion through the Overlay Thickness

Figure 1.2: Outline of the Research Study
1.4 HYPOTHESIS

The hypotheses developed to investigate the problem stated above are as follows:

1. Fracture properties of the thin bonded overlay (TBO) systems are significantly different than conventional HMA overlays.

2. TBO systems are graded in nature as the binder content varies through its thickness.

3. Existing asphalt concrete fracture tests have limited applicability for such non-uniform, thin and graded overlay systems.

1.5 THESIS ORGANIZATION

The dissertation has ten chapters and two appendices in total, which are organized as follows:

1. Review of Thin Bonded Overlay Systems and Asphalt Concrete Fracture Tests. A brief synopsis of thin bonded overlay system and review of state of practice and state of art asphalt concrete fracture test are presented in this chapter.

2. Compact Tension C[T] Test for Fracture Characterization of Thin Bonded Overlay Systems. This chapter provides development, optimization and evaluation details of a new compact tension C[T] test to characterize thin, graded wearing courses. The proposed test procedure was evaluated in the context of fracture mechanics guidelines and numerical simulation results confirming its validity as fracture test.

3. Preparation of Thin Bonded Composite Specimens. Details of composite specimen fabrication procedures have been enumerated in this chapter. Wet and cured applications of tack coat emulsion on textured and saw-cut surfaces were compared. This trial matrix compares two HMA mixtures compacted at three tack coat application rates on two surface types for wet and cured emulsion application. Effects of paver screed temperature and compaction effort were also evaluated.

analysis of four thin bonded overlay projects paved with gap-graded mixes are evaluated in this chapter. Plant produced HMA, tack coat emulsions and field cores were sampled at the time of construction of these projects. In addition rutting resistance of composite and mix samples were also compared.

5. Fracture Evaluation of Dense-graded Thin Bonded Overlay Systems. Four dense-graded TBO projects with 48 experimental sections are presented in this chapter. The variable evaluated includes; tack coat application rate, emulsion type and construction process. Moreover comparison of compaction effort for spray paver and conventionally paved overlays is also provided.

6. Cracking Assessment of Thin Bonded Overlay Systems using Compact Tension Test and Links to Early Field Performance. C[T] test results are simulated to predict cracking performance of pavements with thin bonded overlays for three projects and compared with their early performance. This chapter demonstrated the usefulness of an integrated approach to predict cracking performance of TBOs.

7. Effects of Tack Coat Emulsion Permeation on Fracture Resistance of Thin Bonded Overlays. Fracture and bulk properties of mixes with emulsions at five increments were evaluated. Emulsion migration gradient was tracked using image analysis techniques and used to simulate graded overlays. This experimental study provided a qualitative measure of tack coat permeation on HMA fracture and bulk properties.

8. Cracking Evaluation of Asphalt Concrete in the Context of Warmer Temperatures. The suitability of C[T] test to determine fracture properties of asphalt concrete at warmer temperatures is presented. Findings of this limited parametric study suggest that fracture properties of asphalt concrete can be measured with reasonable accuracy at warmer test temperatures.


10. References.

11. Appendices.
CHAPTER 2 – REVIEW OF THIN BONDED OVERLAY SYSTEMS AND ASPHALT CONCRETE FRACTURE TESTS

2.1 BACKGROUND

The use of asphalt as a construction material can be traced back to pre-historic times. It has become indispensable and is the material of choice for construction of roads and airfields and serves as the circulatory system for the world economy (Krishnan and Rajagopal, 2003). Asphalt has been used as the primary surfacing layer for pavements in the United States since 1876 (Roberts et al., 1996). The design of pavement structures has evolved through the years from purely empirical to mechanistic-empirical in nature. However, the design philosophy has always been to minimize the potential failure of the pavement structure due to deterioration or distress. In particular, cracking is a major distress in flexible pavements. Fatigue cracking (due to repeated wheel loads), low temperature cracking (because of thermal stresses), and reflective cracking (propagation of existing cracks through the overlay) are the major cracking distresses in flexible pavements. Although all three cracking distresses (fatigue, thermal, and reflective) have different driving forces, the rate and potential magnitude of cracking in all three cases is heavily influenced by the fracture resistance of the surface layers in the system.

A better understanding of these pavement and overlay deterioration mechanisms will enable improved future design and performance. Pavement preservation continues to gain importance as means to delay costly rehabilitation and reconstruction alternatives with ever escalating cost of materials. In the recent past several new cost-effective and efficient maintenance technologies have been developed and implemented to address these issues (Hicks et al., 1999; Moulthrop and Smith, 2000; Corley-Lay and Mastin, 2007). Evaluation of field projects reveals that thin bonded wearing courses represent an efficient treatment option for deteriorated rigid and flexible pavement systems and often hold advantages over other alternatives (Bellanger et al., 1992; Kandhal and Lockett, 1997; Hanson, 2001 and Corley-Lay and Mastin, 2007). The evaluation of these projects included visual performance for raveling, weathering, and delamination, skid
resistance testing, surface macrotexture depth measurements, surface roughness (IRI), crack counts and transportation related noise measurements. Based on these studies, thin bonded overlays (TBOs), particularly those incorporating gap-graded mixtures, can be considered as a viable alternative for preventative maintenance and surface rehabilitation. TBOs provide a riding surface with a high degree of macro texture, good aggregate retention, and are designed to be well bonded to the underlying pavement. This study is focused on the development of tools for fracture characterization of thin bonded asphalt concrete overlay systems.

The remainder of this chapter contains three sections. The first section provides an introduction of the thin bonded overlay system and their construction, followed by a brief overview of fracture tests for asphalt concrete. The applicability of these tests for fracture characterization of TBOs is then presented.

2.2 SYNOPSIS OF THIN BONDED OVERLAY SYSTEMS

2.2.1 Introduction

The ultrathin bonded wearing course (UTBWC) process was developed in France in the mid 1980s by Screg Routes Travaux Publics (Hanson, 2001). UTBWC/Novachip is one of several treatments that can be categorized under a more general category hereafter referred to as thin bonded overlay (TBO) systems. The TBO systems studied in this research include dense-graded and gap-graded bituminous wearing courses paved on existing flexible (asphalt), rigid (concrete) and composite pavements. This process was introduced in the United States in the early 1990’s as part of projects in Alabama, Mississippi and Texas (Serfass et al., 1991). TBOs consist of hot mix asphalt (HMA) placed in thin lifts, often in conjunction with a polymer-modified asphalt emulsion (PMAE) tack coat applied at a high liquid application rate (volume) per unit area of coverage. Special paving equipment (spray paver) is utilized to place both the tack coat and the HMA in a single pass. This process was developed in an effort to create a relatively thin rehabilitative treatment with good skid resistance, improved aggregate retention, a strong bond to the underlying pavement (reducing de-lamination, shoving and tearing potential), and to provide waterproofing benefits.

Forensic investigation indicates that thin bonded overlay systems are graded in nature and significantly different than conventional HMA overlays. Three distinct differences from
conventional HMA overlays, include: (a) incorporation of uncured/wet polymer modified asphalt emulsion (PMAE); (b) a very high tack coat application rate (3 to 5 times greater than conventional overlays), and; (c) a delivery system designed to protect the tack coat emulsion and to promote its upward wicking into the asphalt mixture being placed immediately afterward. Single pass paving operation eliminates loss of tack coat emulsion due to construction traffic. Wet application of emulsion helps promoting stronger adhesion to the existing pavement surface and its impregnation into the paved overlay. The wicking effect is thought to be a thermodynamic process occurring under the screed at elevated temperature (up to 375°C) that relies upon interconnected voids, and is therefore more pronounced in the TBOs with gap-graded mixtures. The magnitude of the upward migration of the tack coat emulsion, which causes a binder content variation as function of the overlay thickness, depends upon the HMA mix design, tack coat emulsion type, and its application rate. The bottom of the layer is aggressively bonded to the layer below (Hanson, 2001) and its higher binder content results in a waterproof membrane and a binder-rich zone with presumably enhanced fracture resistance.

2.2.2 Construction Process

A specially built paver is used to pave thin bonded overlay systems. The delivery system of this spray paver is designed to apply the tack coat and pave the HMA mix in a single pass. As the paver moves forward, emulsion is sprayed at 50°C to 80°C (120°F to 180°F). Immediately after the emulsion is sprayed, the HMA is placed at 150°C to 165°C (300°F to 330°F) as shown in Figure 2.1. The two materials bond to form a thin surface on the pavement. With conventional construction practices, a significant loss of tack coat may occur in the region of pavement subjected to construction equipment and other traffic prior to the paving operation. The delivery system of a spray paver applies the tack coat and HMA in a single pass, thereby avoiding exposure of the tack coat to construction equipment and allowing mixing of the emulsified tack coat, which is still in the liquid state, with the HMA. The spray paver operation speed ranges from 14 to 36 m/min (45 to 120 ft/min) depending on the mix type, lift thickness and width of the pavement. The paver screed is hydraulically extendable so the process can match varying widths of roadway as required.

In the case of TBOs with gap-graded mixtures, the finished overlay thickness usually ranges from 19 to 25 mm (3/4 to 1 inch), as illustrated in Figure 2.2. The layer thickness is determined
by the nominal maximum aggregate size (NMAS). A minimum of two passes with a steel
double-drum roller in static mode weighing at least 9 metric tons (10 tons) is usually specified
for thin gap-graded mixtures. Immediate compaction of the fresh mat (rolling right up to the
paver) is critical in these systems because of the rapid heat loss in the thin, gap-graded layer.
Typically, compaction is completed before the mix temperature drops below 85°C (185°F) and
the roller can immediately follow the paver as shown in Figure 2.3. Due to the rapid cooling in
the thin mat, interruptions in the paving process can cause problems (bumps) with smoothness.
Therefore, careful attention to logistics is a very important aspect of this paving process. In the
case of TBOs designed with dense-graded mixtures, rolling of the mat follows similar procedures
as those used with traditional HMA overlays.

Figure 2.1: Simultaneous Application of Tack Coat and Hot Mix Asphalt

Gap-Graded Thin Bonded Overlay          Dense-Graded Thin Bonded Overlay

Figure 2.2: Thickness of Compacted Thin Bonded Overlay
2.2.3 Project Selection

The primary function of the layer is to provide a durable, friction-resistant wearing course on an existing flexible, rigid, or composite pavement. For flexible pavements, thin bonded bituminous overlay is not recommended when the longitudinal, block, edge, and reflection cracking exceeds the medium severity level as defined by the Distress Identification Manual for the Long-Term Pavement Performance Program (SHRP-P-338). Any cracks greater than 6.3 mm (1/4 inch) should be cleaned, routed, and sealed. Patches and potholes should not exceed moderate severity levels. All areas with potholes and alligator cracking should be properly repaired. When rutting exceeds 12.5 mm (1/2 inch) the surface should be milled or the ruts filled before placing the thin overlay. For rigid pavements, cracking should not exceed the moderate severity level. Any durability cracking should not exceed the low severity level, and any map cracking or scaling should not exceed 10%. Rigid pavement with blowups or pumping and faulting problems should not be considered as a candidate for rehabilitation using a thin bonded HMA overlay. These are the general guidelines for selection of suitable candidate project sites. However, in some recent field trials, next generation TBOs have been placed on concrete pavements exhibiting durability issues such as alkali silicate reaction and have performed well (after three years of service). The next generation TBOs are dual–lift, spray paver constructed...
overlays, designed to provide a crack resistant rehabilitation option. More details are provided in Chapter 5.

2.2.4 Material Properties

UTBWC HMA mix is gap-graded in nature and requires high quality, uniformly sized crushed aggregates. The crushed aggregates are mixed in a central hot-mix facility to produce a mastic made of sand, filler and asphalt binder (Serfass et al., 1991). Bonded overlay systems studied in this research also include dense-graded wearing courses constructed with regular surface mixtures. Polymer modified asphalt emulsion (PMAE) is usually sprayed as tack coat just inches ahead of the point where the HMA is placed at a temperature of 150°C to 165°C (300°F to 330°F). The tack application rate varies and depends on the HMA mix type and existing pavement surface condition. In some very recent projects the tack application rate varied from 0.45 to 1.35 L/m² (0.1 to 0.3 gal/yd²). The high tack application rate seals the existing pavement surface and provides enough emulsion to rise or ‘wick’ upwards to approximately 1/3rd of the TBO lift thickness. Binder content in these systems usually ranges from 5.0 to 6.0 percent. The selection of the asphalt binder grade depends upon the climate and traffic conditions for the project. Polymer modified binder is preferred over un-modified to provide better aggregate coating and adhesion to the existing pavement surface. Spray paver technology has also been utilized for construction of warm mix asphalt (WMA) overlays. A more complete case study describing a spray paver constructed WMA project is provided in Chapter 6.

2.2.5 Performance Overview

Nationwide research has shown that thin bonded overlays reduce deterioration caused by weathering, traffic loading and provides good skid resistance, reduced rolling noise and hydroplaning (Bellanger et al., 1992; Brousseau, 1997; Kandhal and Lockett, 1997; Hanson, 2001 and Corley-Lay and Mastin, 2007). Early performance of Novachip projects in Alabama, Texas and Pennsylvania as characterized by ride quality, rutting, raveling and skid resistance were studied by Hanson (2001). Hanson reported that bonded wearing courses provide excellent aggregate retention and bonding to the underlying surface. In addition, these systems were shown to provide excellent skid resistance and the high macro texture was found to reduce hydroplaning. Hanson also observed that prior sealing of existing cracks minimizes their
reflection through thin bonded overlays. Novachip, a thin bonded overly with gap-graded mixture, appears suitable for high traffic roads based on its performance in some early projects (Kandhal and Lockett, 1997). Other studies have documented the rutting resistance of TBOs (Scullion et al., 2009; Cooper and Mahommad, 2005) and attributed their minimal rutting potential to their thin structure, packing of coarse aggregate, and high bond strength. Hakimzadeh et al., (2011) evaluated the interface bond strength of thin bonded overlays utilizing an energy based fracture mechanics approach. This study presents interface bond strength results of field procured and laboratory prepared samples. The effect of tack coat application rate, emulsion, and HMA types were evaluated. They observed that the spray paver constructed TBO with PMAE as a tack coat resulted in a stronger interface bond than traditional overlay placement techniques. Most of the performance attributes of TBOs have been adequately investigated and reported in the literature, with the exception of their cracking behavior.

Thermal cracking is a major pavement distress in cold climates and a desirable rehabilitation treatment should minimize this form of distress. Moreover thinner overlays are more prone to reflective cracking as well. Hence, it is important to study the cracking performance of thin bonded overlays. TBOs with inferior fracture resistance could lead to accelerated thermal and reflective cracking damage, thereby reducing or negating the overall benefit of the rehabilitation. Cracks in the pavements can lead to water intrusion, loss of ride quality, and eventually spalling and pothole formation. Thus, the focus of this research is to develop a fracture testing procedure to evaluate the fracture resistance of thin bonded overlays with graded properties.

2.3 OVERVIEW OF ASPHALT CONCRETE FRACTURE TESTS

This section provides a brief overview of asphalt concrete fracture tests available in practice. This section was primarily focused on classical fracture tests, which incorporate pre-fabricated notche, crack mouth and crack tip opening displacement gages, and which lead to the determination of various commonly reported fracture parameters.

2.3.1 Single-Edge Notched Beam

Most of the pioneering work in fracture mechanics was done in the area of metals. One of the most investigated and well documented fracture tests is the single-edge notched beam (SEN[B]) test shown in Figure 2.4 (ASTM 339-08). Application of fracture mechanics concepts
to asphalt concrete mixtures was introduced by Moavenzadeh, (1967) using the SEN[B] test. Majidzadeh et al., (1971) predicted fatigue life of paving mixtures in terms of material constants, geometry, boundary conditions, and the state of stress. They described fatigue life by three processes: damage initiation, crack growth, and final failure. Many studies over the following years investigated the fracture toughness of asphalt concrete using linear elastic fracture mechanics (LEFM). One of their major conclusions was the fatigue life of many types of asphalt concrete mixtures can be characterized from simple fracture tests like SEN[B].

Mobasher et al., (1997) compared low temperature fracture parameters of conventional asphalt mixture to asphalt mixture with rubber modified asphalt cement at -1°C and -7°C. They observed that the asphalt rubber mix has a lower modulus but a higher toughness than conventional asphalt cement. Hossain et al., (1999) also investigated the effect of rubber content on fracture energy. Using three rubber contents (19, 22, 24%), three asphalt cement contents (6, 7.5, 9%), and two temperatures (5°C, 25°C), they found higher values of fracture energy from higher binder contents, irrespective of rubber content.

Wagoner et al., (2005a), reported that the SEN[B] was a promising fracture test based on its crack front development and test repeatability. In their study, they compared three different nominal maximum aggregate sizes with three binders and found that the polymer modified mixture with the smallest aggregate size gave the highest fracture energy values. More recently, Artamendi and Khalid (2007) compared the effect of specimen geometry and loading rate. They compared the SEN[B] with the semi-circular bend SC[B] configuration at 1, 5, and 10 mm/min for stone mastic asphalt (SMA) and a dense bitumen macadam mixture. They investigated the maximum load, critical load, stress intensity factor, and fracture energy. They found that the SEN[B] gives lower fracture toughness and energy than the SC[B] and that the both parameters increase with increasing loading rate. Although the SEN[B] test configuration has been used for testing HMA concrete fracture properties, consistent test specimen dimensions, procedures, and analysis have never been established. Most researchers have used different beam dimensions, test control modes, and analysis procedures. Moreover the larger size of the SEN[B] specimens limits the procurement of the field samples.
2.3.2 Semi-Circular Bend Test

The semi-circular bend (SC[B]) test was first explored by Chong and Kurrupu (1984). They observed fracture toughness values were in agreement with the values of fracture toughness of the same material determined through different tests by other researchers (Chong and Kurrupu, 1988). The SC[B] specimen is a half disc with a notch that is ‘a’ mm long and makes an angle ‘α’ with the central diameter of the disc. This is a convenient geometry for fabricating samples from the Superpave gyratory compactor (SGC), which is the common method of compaction in the laboratory in the United States. The samples are prepared by slicing a SGC compacted sample into 25 to 50 mm discs, cutting the discs in half, and inserting a notch. The notch can be vertical for pure Mode I testing, or set at an angle (α) for Mixed-Mode testing. The setup is schematically shown in Figure 2.5.

Delft University of Technology pioneered the use of the SC[B] for HMA. Molenaar et al., (2002) found the SC[B] test very promising and used it to determine the tensile stress and resilient modulus of asphalt concrete mixes. Mull et al., (2002) investigated the fracture resistance of chemically modified crumb rubber using the J-integral concept. The chemically modified crumb rubber samples had twice the fracture resistance than ordinary crumb rubber and the control mixtures.

Li and Marasteanu, (2004) used the SC[B] to determine fracture energy of HMA by studying three field sections. They found that the PG binder grade ranked the mixtures appropriately at -30°C and -40°C. As the temperature reaches the low temperature binder grade, the material behaves in a more brittle manner and less energy is required to fracture the specimen. Finally, they used acoustic emissions to successfully monitor the crack propagation. Othman, (2006)
looked at fracture resistance of rubber-modified HMA at room temperature using the J-Integral approach. Fracture resistance decreases as the number of thermal cycles increase, and rubber modification improved the fracture resistance of mixtures. Bayomy et al., (2007) compared 34 asphalt concrete mixtures using the J-integral ($J_c$) fracture mechanics approach. They found that as the binder content increased, the $J_c$ increased as well. In addition, finer aggregate gradations showed a higher resistance to fracture than coarser gradations.

Lastly, Arabani and Ferdowsi (2007) compared the results of the SC[B] test with the Nottingham asphalt tester, the indirect tensile (IDT) test, and the triaxial Hveem test. They found that measured fracture toughness and tensile strengths recorded from different tests were not similar because of the different loading configurations.

![SCB Test Set-up](image1)
![SCB Test Geometry (ASTM 339)](image2)

Figure 2.5: Semi-Circular Bend Test Set-up and Specimen Geometry

2.3.3 Superpave Indirect Tension Test

The Superpave indirect tension (IDT) test was developed under Strategic Highway Research Program (SHRP) to determine creep compliance and tensile strength of asphalt concrete (Buttlar and Roque, 1994; AASHTO T-332). Currently, the Superpave IDT test is widely used to evaluate the tensile properties of asphalt concrete mixtures as shown in Figure 2.6. Roque et al., (1999) began the fracture evaluation using IDT specimen by inserting a hole in the Superpave IDT specimen. This hole was assumed to be a vertical notch for the analysis procedure. They determined that cracks in asphalt concrete grow in a step-like manner and the use of Paris’ law to
describe the crack propagation is not accurate. Therefore, a threshold concept was developed using the dissipated creep strain energy as the limiting factor. This test setup provided a viable approach for determining fracture resistance of asphalt concrete. Zhang et al., (2001) looked at the problem of fatigue cracking and determined that the traditional fatigue approach was not adequate because it did not account for healing or stress redistribution, both of which have a significant effect on fracture energy. By determining the dissipated creep strain energy limit using the energy approach, they showed that the energy limit was an appropriate threshold for asphalt concrete.

Birgisson et al., (2004) applied these concepts to include the analysis of moisture damage. Using the energy ratio, or the dissipated creep strain energy divided by the minimum dissipated creep strain energy, they found that asphalt concrete mixtures conducive to stripping had a lower energy ratio, and that the energy ratio increased with the use of an anti-stripping agent. Roque et al., (2004) extended these concepts to a field study investigating top-down cracking in asphalt concrete. By applying the concept of an energy ratio, they were able to develop an energy-based mixture specification criteria based on the level of traffic. A higher energy ratio is needed for higher traffic levels.

Figure 2.6: Indirect Tension Test Set-up and Specimen Geometry
2.3.4 Disk-Shaped Compact Tension Test

Disk-shaped compact tension (DC[T]) testing using 100 mm (4 inch) diameter discs (Figure 2.7(a)) was first performed on asphalt concrete by Lee et al., (1999). Their experimental design included two binders, an AC-10 and an AC-20, along with two sources of RAP added at amounts of 0, 10, 20, 30, 40, 50, 75, and 100 percent based on total weight of blended asphalt binder. He evaluated fracture toughness using LEFM, at different loading rates and at two temperatures, 0 and 22°C. Brittle fracture behavior was observed at 0°C and the different levels of RAP had no significant effect. At 22°C, fracture toughness increased with the increase of RAP content.

Wagoner et al., (2005b) modified the ASTM E399 DC[T] geometry by increasing disc size and moving the location of the loading holes to reduce failure at the loading holes. In addition, a fracture energy based approach, coupled with a cohesive zone fracture modeling, was developed. A 150 mm diameter disc-shaped specimen was used with a thickness 50 mm (2 inch) and a notch length of 27.5 mm. The increase in overall dimensions was aimed to maximize the fracture ligament area. They investigated the effect of temperature, loading rate and asphalt mixture type on fracture energy. Three temperatures (-20, -10, 0°C) and four loading rates (10, 5, 1, 0.1 mm/min) were investigated. The test was controlled through crack mouth opening displacement (CMOD) gage and fracture energy was computed as the area under the load-CMOD curve normalized by the area of fractured surface. They found that as temperature increased, fracture energy increased, and as loading rate increased, fracture energy decreased in the range of low temperatures investigated. The repeatability of the test was demonstrated by low coefficient of variation (average~10%). Wagoner et al., (2006b) also compared four mixtures; 19 mm NMAS with PG64-22, 9.5 mm NMAS with PG64-22, 9.5 mm NMAS with PG58-22, and 4.75 mm with a polymer modified asphalt binder. They found that softer binders had higher fracture energy and the polymer modified asphalt binder produced the highest fracture energy. They also determined that at higher temperatures, cracks tend to go around aggregate; while at lower temperatures, the crack goes through the aggregate. In addition, they tested three specimen thicknesses (25, 50, 75 mm) and found fracture energy increased as thickness increased. The DC[T] test was incorporated into a testing suite developed for obtaining both continuum and material separation properties from field cores and was standardized through ASTM D7313-07.
Braham et al., (2007) tested 28 mixtures in the DC[T] configuration, with ten asphalt cement binders, two aggregate types, three testing temperatures, two asphalt contents, and two air void levels. They concluded that aggregate, temperature, and asphalt content at high temperatures are significant factors in the set of HMA mixtures tested while asphalt content at low and intermediate temperatures and the air voids were not found to be significant.

Buttlar et al. (2010) presented a comprehensive DC[T] test database, which contains over 700 fracture energy measurements, covering 18 binder types, temperatures ranging from 10 to -42 C, laboratory and field mixes, and spanning across a number of other mixture variables. They observed that test temperature, binder type, binder modification level, air void level, and nominal maximum aggregate size have a significant effect on mixture fracture energy.

Figure 2.7: Disk-Shaped Compact Tension Test Set-up and Specimen Geometries

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<th>Recommended Dimensions (mm)</th>
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<td><strong>Thickness, t</strong></td>
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a. Lee et al., (1999)  
2.3.5 Other Fracture Tests used for Asphalt Concrete

This sub-section summarizes other in-practice tests used to characterize fracture behavior of asphalt concrete. These tests include the thermal stress restrained specimen test (TSRST) (AASHTO TP-10), the Texas overlay tester (OLT) (Zhou et al., 2007), and the dog-bone direct tension (DBDT) test (Roque et al., 2009). Like other tests, these tests also have associated pros and cons for various intended applications. For instance, the thermal stress restrained specimen test requires a thicker specimen size and limits the crack propagation direction. Furthermore, the test provides a critical cracking temperature, rather than fundamental fracture information.

2.4 EVALUATION OF EXISTING ASPHALT CONCRETE FRACTURE TESTS

Each of the reviewed testing procedures offers advantages and disadvantages from the standpoint of practicality as well as their ability to provide reasonably accurate damage and fracture properties. Typically, forensic investigations of in-place pavements are conducted by coring the pavement structure and obtaining properties from the obtained field cores. The graded properties of asphalt concrete and the thickness of the TBO (typically less than 50 mm) pose challenges for the use of certain fracture test geometries. For example, obtaining beams for SEN[B] specimens from a pavement may not be practical because of insufficient layer thickness of the TBO or because the removal of the beam through sawing may lead to excessive pavement damage. In the case of the DC[T] test, transverse crack propagation progresses along the nonuniform/graded properties of the TBO in a channeling fashion, which limit the practicality of the test. The graded nature of TBO limits the versatility of the DC[T] test to capture fracture characteristics in an important direction of crack propagation, that is, upwards through the pavement. This direction of propagation is akin to the direction of propagation in reflective cracking. Figure 3.1 illustrates the orientation of DC[T] geometry with respect to the pavement structure. Another compact fracture test, the semi-circular bend test, (SC[B]), would create a crack propagation direction similar to the DC[T] and thus is also not desirable for graded systems. Furthermore the relatively smaller fractured face area (1500 mm², with specimen thickness of 25 mm) and complex stress state (arch effect arrests crack propagation) also limits the applicability of the SC[B] arrangement to the TBO systems.
Other tests for asphalt concrete that deal with cracking performance of the material, such as the Superpave indirect tension test (IDT) (AASHTO T-332) and the thermal stress restrained specimen test (TSRST) (AASHTO TP-10), also require a thicker specimen size or limit the crack propagation direction. Cracking simulation tests, such as the overlay tester (OLT) (Zhou et al., 2007), that attempt to mimic the formation of reflective cracking in overlays have some applicability to thin and graded systems. However, these tests do not provide fracture properties that can be readily incorporated into discrete cracking models, which are needed for linking test results with pavement performance through mechanistic models. For example, the IDT provides mixture tensile strength, which provides information concerning the peak load (or traction) that can be resisted by the material but does not directly provide information regarding the total energy consumed per unit area of crack propagation. The OLT and TSRST involve simulation-type tests and provide number of cycles to failure and critical cracking temperatures, respectively, as opposed to fracture properties. Therefore the nature of TBO and the limitations of available asphalt concrete fracture tests as applied to TBOs necessitate consideration of other options.
CHAPTER 3 – COMPACT TENSION TEST FOR FRACTURE CHARACTERIZATION OF THIN BONDED OVERLAY SYSTEMS

3.1 INTRODUCTION

This chapter describes the development process of compact tension (C[T]) test and demonstrates its suitability for graded systems such as TBOs. The study was conducted in four main phases, and the organization of this chapter follows in a similar manner. The first section describes existing fracture tests for asphalt concrete and their applicability in the context of thin and graded overlay systems. The next section describes the development and evaluation of the proposed test procedure. Comparisons are made between the proposed procedure and the standardized test procedures for homogeneous material systems. This was done to ensure that the proposed geometry yields fundamental material fracture characteristics with the same rigor as the established tests. The third section describes computer simulations results to gain additional insight into the proposed test procedure. This analysis further demonstrates the suitability of the test procedure and also describes the extraction of local material properties from the laboratory tests. Finally, results are presented for the two pavement systems, each with variables such as tack coat type, application rate, overlay mixture type, etc.

3.2 DEVELOPMENT OF FRACTURE TEST FOR THIN BONDED OVERLAYS

The Compact tension C[T] test, for fracture evaluation of metals is specified by ASTM E399. Manjoine (1965) proposed the C[T] specimen configuration to simulate crack growth in metals and used it to measure fracture toughness. The specimen was attached to the loading frame by threaded grips, and measurements of the crack opening displacement (COD) were made using a clip gauge. Wessel (1968) modified the C[T] geometry, introducing two pinholes, and conducted a comprehensive stress analysis to conclude that the specimen was suitable for determining crack growth rates and measuring the fracture toughness of metals. Collop et al. (2004) introduced a block-shaped (150×150×60 mm with a 60-mm deep notch) C[T] test
configuration to assess crack propagation rate and fracture toughness of asphalt mixtures with a sinusoidal load at 5 Hz, using linear elastic fracture mechanics (LEFM) principles.

Figure 3.1: DC[T] and C[T] Specimens and Their Crack Propagation Orientations with Respect to the Pavement Structure

Orientation of the C[T] geometry with respect to the pavement structure (as illustrated in Figure 3.1) shows that the vertical notch/crack (relative to pavement structure) faces a uniform mixture along the entire width of the specimen. Moreover proposed test configuration represents anticipated bottom up direction of reflective cracking. Researchers have established that the fracture energy approach is more suitable than the LEFM approach for characterization of quasi-brittle materials such as asphalt concrete at low temperatures (Wagoner et al., 2005a, 2005b; Li et al., 2006). An accurate determination of fracture energy requires the use of a valid fracture test, whereby a significant amount of energy dissipation in the test contributes to crack propagation. This requires the presence of a precrack or notch in the specimen. Geometric dimensions of the specimen, loading rate, and test control mode are important parameters associated with the fracture test protocol. For fracture tests, the geometric considerations can be expressed in terms of the ratio between the notch depth and the depth of the specimen in the
direction of fracture, which represents the distance from the centroid of loading to the end of the fracture ligament. Table 3.1 shows recommended values of the ratio and notch width for fracture test specimens in accordance with ASTM E399 (RILEM 5, 1991; Bazant and Planas, 1998). Comparison of these geometric parameters for the proposed C[T], DC[T], and SC[B] tests are also provided in the same table. The proposed C[T] geometry (illustrated in Figure 3.2) fulfills the geometric restrictions on notch-to-depth ratio and notch width based on the preceding recommendations and previous work in the field of fracture mechanics (Song et al., 2008a). The specimen geometry, especially the in-plane thickness \( D \) and the ligament length \( t \), were explored in depth as part of test procedure development. The test results and discussion are presented in a later section of this chapter.

Table 3.1: Pre-crack/Notch Dimensions of Fracture Tests Specimens and Recommended Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DC[T]</th>
<th>SCB</th>
<th>C[T]</th>
<th>Recommended Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notch to depth ratio ((a/W))</td>
<td>0.25</td>
<td>0.25</td>
<td>#0.26 to 0.40</td>
<td>≤ 0.45 (ASTM 399)</td>
</tr>
<tr>
<td>Notch width, (mm)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>≤ 0.5 ( d_a ) (RILEM 5)</td>
</tr>
</tbody>
</table>

\( d_a \) is the diameter of nominal maximum aggregate size (NMAS) in the mixture
# considering overlay thickness from 55 mm to 30 mm

Figure 3.2: Geometric Dimensions of Proposed C[T] Test Specimen
3.3 TEST SETUP

The proposed C[T] test is controlled using a constant rate of crack mouth opening displacement (CMOD). The CMOD rate was selected as 0.017 mm/s (0.00067 inch/s) based on the recommendations for the DC[T] and SEN[B] tests from Wagoner et al. (2005a, 2005b). Stable crack propagation on a predefined path with a reasonably low coefficient of variation (CoV) is expected from a suitable test control mode and loading rate. The results discussed later in this thesis indicate that the recommended control mode and rate yielded a stable crack growth with good test repeatability. Soundness and integrity of the 50 mm (2 inch) thickness of underlying, existing pavement was found to be important, as loading pin holes and the notch are fabricated into this layer of material.

The test set-up and C[T] specimen are shown in Figure 3.3. Typical load verses CMOD data as obtained from the C[T] test is plotted in Figure 3.4. The work of fracture ($S_f$) was evaluated by integrating the imposed load ($P$) and the corresponding crack mouth displacement ($u$). The fracture energy ($G_f$) is determined as the amount of fracture work required to generate a unit cracked surface area, and can be calculated as follows,

$$S_f = \int P. d_u; \quad G_f = \frac{S_f}{D.t}.$$  

where the length of the fracture face is $t$ (ligament length), and the specimen thickness is $D$.

3.4 EVALUATION AND APPLICABILITY OF PROPOSED TEST

3.4.1 Comparison of C[T] and DC[T] Test Results

A range of field projects with TBO systems were selected to study the effect of crack orientation on fracture properties. The projects available for this evaluation had gap-graded (GG) and dense-graded (DG) HMA mixtures paved as thin bonded wearing courses on existing pavements. The gap-graded mixes were paved on asphalt as well as on concrete pavement. Conversely, the dense-graded mixes were paved as TBO on the existing asphalt pavements only. Field cores obtained immediately following the construction of each project were fabricated into DC[T] and C[T] geometries and later tested under the same conditions in accordance with ASTM D7313-07.
Test results shown in Figure 3.5 indicate that test geometry and the corresponding direction of crack propagation had significant effect on the fracture properties of these overlay systems. Cracks propagating in a transverse direction with respect to the direction of vehicular movements (DC[T] test geometry) resulted in lower fracture energy for both types of overlay systems when compared to specimens fabricated to produce cracks propagating in a vertical direction (C[T] test geometry). In the case of the open-graded wearing course, average fracture energies measured in the C[T] test configuration were 72% greater than the DC[T] test results. This observed variation in fracture energies of the same TBO by changing crack orientation merits a thorough evaluation. The following sections discuss whether this observed variation of fracture energies can be attributed to the difference in crack orientation and/or size of the fracture ligament.

![Figure 3.3: C[T] Test Set-up](image)

![Figure 3.4: Typical Load versus CMOD Data Measured During C[T] Test](image)
Figure 3.5: Comparison of C[T] and DC[T] Fracture Energies Measured from Field Cores Specimens

3.4.2 Significance of Crack Orientation

The effect of anisotropy in asphalt concrete has been explored in previous studies (Mamlouk et al., 2002; Underwood et al., 2005; Motola and Uzan, 2007). Given the nature of asphalt pavement construction (considering typical paving and rolling processes), and owing to the fact that HMA is a heterogeneous material comprising aggregates, asphalt cement, and air voids, it is apparent that as-built asphalt concrete pavement layers can display anisotropic behavior. Simply stated, the compaction process, whether in the field via rolling-type compactors or in the laboratory via gyratory or other lab compactor, can create an anisotropic aggregate fabric (i.e., aggregates, which are not perfectly cubical or spherical, can have a non-random distribution of the orientation of the longest axis of the particle). Air void, shape and distribution, mastic distribution, etc., can also be non-uniform as a result of field or laboratory compaction. Therefore, the direction of compaction in relation to the response direction of interest (stress-strain behavior, crack propagation, etc.) should be considered. Wagoner and Braham, (2008) observed that HMA appears to display anisotropic behavior at low temperatures for bulk material properties, such as complex modulus and creep compliance, whereas it does not show consistent, measureable anisotropic behavior for tensile strength and fracture energy. The fracture energy results presented in the previous section suggest that the effect of aging may be more significant
than the anisotropic effect, since a change in crack orientation did not affect the fracture energy of unaged HMA mixes (Wagoner and Braham, 2008).

Testing of field cores in the two configurations described above was conducted and fracture energies were compared to trends obtained by testing laboratory-compacted specimens to further explore the effect of TBO composition on fracture anisotropy. A gap-graded wearing course project paved with a spray paver was selected to study the contribution of the tack coat in improving the fracture properties of the bonded overlay system. Three replicates of field cores were fabricated and tested in C[T] and DC[T] test geometries. A set of six gyratory samples were also compacted from the same plant-produced mix without incorporating tack coat using a Superpave gyratory compactor (ASTM D 6925). The laboratory-compacted samples were compacted to the same air void level as that of the field cores (12 ± 1%). Three C[T] and DC[T] specimens were fabricated from laboratory-compacted gyratory samples. All testing was done inside a temperature controlled chamber at -12°C in CMOD control mode at a loading rate of 0.017 mm/s. Test results shown in Figure 3.6 illustrate the following points:

1. The C[T] test configuration measured 67% higher fracture energy than the DC[T] test in the case of field cores from the same project.
2. The C[T] and DC[T] test results of the laboratory-compacted (without tack emulsion) specimens were not significantly different.
3. A comparison of the fracture results for field cores (composite system) and laboratory-compacted (without tack emulsion) specimens in both test configurations indicated that the measured difference in fracture energies is inherent to the overlay system itself. Fracture energy variations are not a test artifact; both test configurations yielded identical fracture energies for laboratory specimens prepared without tack coat.
4. Laboratory-compacted specimens without tack coat from the same mix had 48% lower fracture energies as compared to the field cores in the C[T] test.
5. The C[T] test seems to capture the effect of material gradation in the TBO constructed using the spray paver. In particular, the test results indicate that the effect of the polymer-modified emulsion and its impregnation or upward wicking into the overlay significantly reduces the potential for cracking in the direction of overlay thickness.

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6. The results also indicate that the use of a spray paver system to apply a high rate of polymer-modified tack coat significantly enhances the fracture resistance of the gap-graded mixtures as measured using the C[T] configuration.

![Figure 3.6: Comparison of DC[T] and C[T] Fracture Energies of Field Cores and Laboratory Compacted Specimens](image)

In summary, the results of this testing suite support the previous finding that asphalt concrete does not display anisotropic behavior for fracture energy at low temperatures (as seen in Figure 3.6). These results suggest that the variation in fracture energy observed in the initial round of testing (Figure 3.5) is attributable to something other than the difference in crack orientation associated with the two tests. Another possible reason for measured fracture energy variations of TBO core specimens in the two tests is fracture ligament size difference, creating a possible size effect of fracture. The next subsection provides details on the effect of fracture ligament size on asphalt concrete fracture properties.

3.4.3 Evaluation of Fracture Ligament Area

Wagoner and Buttlar (2007) observed that the thickness and diameter of DC[T] specimens significantly affect the measured fracture energy of asphalt concrete. A test matrix (Table 3.2) was developed to study the influence of fracture test ligament size on asphalt concrete fracture energy measured through the C[T] test. The four test geometries were tailored to provide a
reasonable range of fracture ligament cross-sectional areas while maintaining a 150 mm (6 inch) diameter for all geometries. In developing this test matrix, the following considerations were also made:

1. C[T] test geometries in the size effect test matrix were proportioned so that fracture properties of thin bonded wearing courses could be obtained from field cores as well as laboratory-compacted samples.

2. The test geometries developed assume that a minimum of 50 mm (2 inches) of underlying pavement material will be present on field cores. This amount was deemed necessary to approximately match the notch and loading hole configuration with the DC[T] test geometry. This also ensured minimal probability for end failures at the loading pin locations.

3. Similarly, a range of C[T] size effect specimen geometries were selected so that the fractured ligament area of the DC[T] test would fall within their range.

4. The approach toward developing this test was to try different ligament lengths that would represent typical bonded wearing course thicknesses as well as to examine the effect of specimen width. The motivation for studying different specimen widths was so that thin overlay systems could be tested with a reasonably high fracture area via the increased specimen width.

The test matrix used included two specimen widths and two ligament lengths, as shown in Table 3.2.

Table 3.2: C[T] Specimen Dimension for Size Effect Test Matrix

<table>
<thead>
<tr>
<th>Specimen Width, D</th>
<th>62.5-mm (2.5-inch)</th>
<th>100-mm (4-inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25-mm (1-inch)</td>
<td>1560-mm² (2.5-inch²)</td>
<td>2500-mm² (4-inch²)</td>
</tr>
<tr>
<td>50-mm (2-inch)</td>
<td>3125-mm² (5-inch²)</td>
<td>5000-mm² (8-inch²)</td>
</tr>
</tbody>
</table>

All specimens were fabricated from gyratory samples using plant-produced 9.5-mm dense-graded HMA mix compacted to 4% air voids. A single testing temperature was used, which corresponded to the Superpave performance-graded binder low temperature grade plus 10°C.
This follows the recommendation given in ASTM D7313 for the establishment of test temperature for fracture energy testing of asphalt concrete, and is believed to produce fracture energy values that correlate well with field cracking performance. Since a PG 64-22 binder was used, a test temperature of -12°C was selected. Three replicates for each specimen size were tested.

Figure 3.7 summarizes the fracture energy values obtained in the C[T] size effect study. The legend shown below each bar on the plot indicates the width (D) and length (t) of the specimens tested (in inches). The average DC[T] fracture energy of the tested 9.5 mm (3/8 inch) dense-graded HMA mix was 347 J/m² with 9% CoV, and the fracture energies obtained through the C[T] test for the same mix ranged from 312 to 408 J/m². The paired t-test was performed on the test data using statistical analysis software (SAS). Statistical results are presented in Table 3.3, and can be summarized as follows:

1. The fracture ligament sizes investigated were found to be significantly different, as indicated by the p-values obtained (0.0050 and 0.0039).
2. The paired t-test p-values (0.5404 and 0.4875) at a 95% confidence interval indicate that C[T] and DC[T] test results are insignificantly different. All C[T] geometries were pooled together as one group to make this comparison.
3. The C[T] specimen dimensions considered in the test matrix were stable and produced repeatable results as indicated by the relatively low CoV values obtained, as shown in Figure 3.7.

<table>
<thead>
<tr>
<th>Comparison of C[T] &amp; DC[T] Test Fracture Energies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance</td>
</tr>
<tr>
<td>Equal</td>
</tr>
<tr>
<td>Unequal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Comparison of C[T] Test Fracture Energies (size variation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance</td>
</tr>
<tr>
<td>Equal</td>
</tr>
<tr>
<td>Unequal</td>
</tr>
</tbody>
</table>
Figure 3.7: Comparison of Fracture Energies of C[T] with Different Fracture Ligaments and DC[T] Specimen Geometry from the Optimization Test Matrix

The C[T] and DC[T] test geometries used herein result in different crack trajectories relative to the orientation of the gyratory specimen; e.g., the DC[T] configuration results in crack which moves across the diameter of a circular projected area of the gyratory, while the C[T] configuration involves a crack which moves in the direction of the axis of symmetry of the cylinder (see Figure 3.1). This suggests that the direction of crack propagation does not significantly affect the fracture energy of laboratory compacted mixture specimens. By comparing this result to those obtained from the testing of field cores (Figure 3.6, for instance), it can be concluded that the differences in fracture energies obtained from tests simulating channeling cracks (DC[T]) and vertically propagating cracks (C[T]) can be primarily attributed to the spatial variation of material properties (fracture properties graded in the vertical direction in the case of spray paver applied overlays).

3.5 NUMERICAL SIMULATION OF C[T] TEST

Ahmed et al., (2010b) presents the details on numerical simulations of the C[T] test. These simulations were aimed to determine the suitability of the C[T] geometry as a fracture test and
also to determine if fracture properties of the asphalt material could be successfully extracted from the proposed test procedure.

The simulated and as-tested load and CMOD curves from Ahmed et al., (2010b) are shown in Figure 3.8. Figure 3.8 also shows the as-measured global fracture energy from the C[T] test (631 J/m$^2$) and the calibrated local fracture energy utilized in the model (490 J/m$^2$), yielding a ratio of about 77% between global and local energies. The 23% difference in energy appears to be predominantly due to dissipation associated with viscoelastic creep. The relatively small difference between measured global energy and local energy input to the finite element model indicates that with minor calibration it is possible to extract a fundamental material fracture property from the proposed test procedure.

Stress contours in the direction of loading (x-direction) are shown in Figure 3.9 at various stages during loading, e.g., at peak load (showing fully formed fracture process zone) and at 75%, 50%, and 25% of peak load during the softening or post-peak portion of the response. Notice that in this test geometry a fully formed fracture process zone is visible (Figure 3.9(a)), and furthermore, the process zone progresses along the crack path as the test continues (Figure 3.9 (b)-(d)). Both of these conditions, formation of a full process zone and its movement during the propagation of cracking, are necessary requirements for a valid fracture test of quasi-brittle materials.

Figure 3.8: Comparison of Laboratory Results and Finite Element Simulations (Load and Crack Mouth Opening Displacement are shown), (Ahmed et al., 2010)

Measured Fracture Energy = 631 J/m$^2$
Local Fracture Energy = 490 J/m$^2$
Local Strength = 4.6 MPa
Figure 3.9: Stress Contours in x-direction (Loading Direction) from the Finite Element Simulation of the C[T] Test (Ahmed et al., 2010)

3.6 PROPERTIES OF TYPICAL THIN BONDED OVERLAY SYSTEMS

Figure 3.10 provides a comparison of fracture energies of field cores and laboratory-compactted specimens from a field project involving a gap-graded, thin bonded overlay. Laboratory-compactted specimens can be divided into two categories, namely, specimens without tack coat and specimens with tack coat. Specimens that incorporate tack coat are hereafter referred to as “composite” specimens. The results illustrate that field cores have approximately 50% higher fracture resistance than composite, laboratory-compactted samples. Compared to laboratory-compactted composite samples with the same HMA and tack coat emulsion application rate, the TBO field process resulted in a more crack resistant overlay system. Permeation of the tack coat emulsion into the overlay seems to be the primary reason for higher fracture energies in the field TBO. The gap-graded mix fracture energy was 547 J/m², compared to 631 J/m² of the composite laboratory-fabricated specimen. Field core samples resulted in 73%
higher fracture energies than the base mix without tack emulsion. A small CoV supports the repeatability of the C[T] test for the characterization of fracture properties of TBO systems.

![Figure 3.10: Comparison of Fracture Energies of Field Cores, Laboratory Compacted Composite and Mixture-only Specimens of a Gap-Graded TBO Project](image)

The spray paver construction technique was recently applied to dense-graded mixtures in several field projects across the US. Figure 3.11 presents the effects of the construction technique, tack coat emulsion type, and application rate on dense-graded TBO fracture properties. The control section (Sec 1) was constructed with a distributor for emulsion application and a conventional paver using an unmodified SS-1HP emulsion at 0.45 L/m\(^2\) (0.1 gal/yd\(^2\)), where the unit L/m\(^2\) represents the average tack coat application rate of undiluted emulsion, in liters per square meter. The remaining sections were constructed using a spray paver and PMAE at varying application rates. Sections 1 and 2 provide a comparison spray paver (Sec 2) and conventionally paved (Sec 1) overlays. Besides the construction technique, PMAE was applied instead of SS-1HP as a second field test variable. The spray paver applied TBO had 20\% greater fracture energy than the control section. Comparison of all spray paver constructed sections revealed that the optimum tack coat application rate with respect to fracture properties for this dense-graded mix was about 0.9 L/m\(^2\) (0.2 gal/yd\(^2\)). Dense-graded mixtures have limited capacity to absorb tack coat emulsion and higher tack coat application rates have been found to produce negative effects on overlay fracture properties.
3.7 SUMMARY

The C[T] testing configuration was compared to the DC[T] test in the context of thin bonded overlay systems using both gap-graded and dense-graded mixtures. The C[T] test configuration was found to be more sensitive to vertically graded material properties, which are present in spray paver applied, thin bonded wearing courses. It was found that the C[T] test configuration with 100 mm (4 inch) width and a thickness equal to the wearing course thickness of the system under evaluation is a viable geometry. This width is the maximum that can be practically obtained from 150 mm (6 inch) diameter cores/gyratory samples. Moreover, this width compensates to produce a reasonable fracture ligament area in the case of thin bonded wearing courses. A few hundred specimens have now been tested with success using the C[T] configuration proposed in Figure 3.2 for a range of TBO systems (Ahmed et al., 2010). Repeatability of test results provides confidence in the ability to accurately characterize the fracture properties of TBO systems having thicknesses ranging from 19 mm (0.75 inch) to 62.5-mm (2.5 inch), using the 100-mm (4 inch) wide C[T] geometry. Soundness and integrity of the 50 mm (2 inch) thickness of underlying, existing pavement was found to be important, as the loading pin holes and notch are fabricated into this layer of material.
The C[T] test appears to be a viable test procedure for fracture characterization of TBO systems, and can characterize/optimize variables in these systems, such as:

1. Composition of the paved HMA concrete.
2. Type of tack coat emulsion applied.
3. Optimum tack coat application rate in terms of fracture energy maximization.

The C[T] geometry was found to produce stable crack growth during the test. Combined with the fact that low CoV values were obtained when testing a variety of mixture types; the efficacy of the recommended test procedures was thoroughly investigated in this study.

Statistical analysis revealed that the C[T] test captures the resistance of TBO systems to vertically propagating thermal or reflective cracks. Numerical simulations using a cohesive zone model validate the C[T] test procedure as having a fully developed fracture process zone. Moreover this test procedure enables extraction of fundamental fracture properties with a relatively small calibration factor, indicating the benefit of its potential integration with combined modeling/testing studies to predict the performance of bonded overlay systems.
CHAPTER 4 – PREPARATION OF THIN BONDED OVERLAY’S COMPOSITE SPECIMENS

4.1 INTRODUCTION

Ideally, the design of thin bonded overlays would be guided by laboratory-prepared specimens, which suggests the need for fabrication of composite specimens in the laboratory that closely match field-produced materials. Composite specimens have three components; namely the base, the asphalt emulsion tack, and the HMA that represents the overlay. The base represents the existing pavement and should be as representative of an actual pavement surface as possible. The existing pavement surface condition in terms of its texture / voids structure, oxidation, and aggregate absorption capacity affects the emulsion application rate. If possible field cores should be procured from the project site prior to paving and used as bases for designing the TBO, otherwise a fine-graded mixture can be used to prepare the bases (as will be demonstrated in this chapter). Tack coat emulsion type, application rate, HMA mix design and existing pavement condition all significantly affect the overall properties of thin bonded overlays.

A number of techniques to fabricate composite specimens were evaluated using different mixtures, base textures, and varying application rates of tack coat emulsions. A total of four plant produced mixtures and tack coat emulsions sampled from different projects at the time of construction were used in this experimental study. The effect of base texture and emulsion application process were evaluated at four tack coat application rates for a particular mix. Fracture resistance of the fabricated composite specimens were determined using the C[T] test following the test procedure presented in Chapter 3. The composite specimen preparation procedure is described in the next section followed by an evaluation of gyratory compactor top plate temperature and compaction effort on fracture properties of composite specimens. The significance of sample preparation technique, mixture type, tack coat application rate, compactor top plate temperature, and compaction efforts on composite specimen fracture properties is summarized in this chapter.
Four techniques to prepare composite specimens representing thin bonded overlays were evaluated in this chapter. These four techniques include: wet emulsion on saw-cut base (WSB), cured emulsion on saw-cut base (CSB), wet emulsion on textured base (WTB) and cured emulsion on textured base (CTB). As their names suggest, there are two key variables; \textit{emulsion application} (wet versus cured), and \textit{base texture} (saw-cut versus textured). Bases for these composite specimens were prepared with a fine-graded mixture in order to achieve uniform texture after compaction. These 150 mm (6 inch) diameter bases were compacted in a Superpave gyratory compactor (SGC) to 50 mm (2 inch) thickness for textured replicates and 105 mm (4.1 inch) for saw-cut ones. Saw-cut faces were obtained by cutting these 105 mm thick bases in two halves of 50 mm thickness each using a water cooled masonry saw. Each saw cut consumes about 5 mm thickness of the specimen. The rims of the prepared bases were sealed after drying overnight with a building compound material (plaster of Paris) to avoid loss of emulsion. Weighed amounts of the emulsion were applied to match the target tack coat application rate in each case followed by compaction of the loose overlay mix to the desired thickness. In the case of \textit{“wet emulsion application”}, overlay mix at compaction temperature was immediately placed and compacted on the base with uncured emulsion. Whereas bases with applied emulsion were kept at room temperature for 4 hours in the case of \textit{“cured emulsion application”} before compaction of the overlay mix.

During development of the composite specimen fabrication process, it was observed that the SGC top plate temperature has a significant effect on emulsion permeation and curing. Therefore it was proposed to compact the overlay mixture with a heated SGC top plate temperature at 200°C. The emulsion permeation effect expressed in terms of fracture resistance of composite specimens is described in the next section. According to Superpave guidelines, HMA mixture compaction is designed for a particular volume of traffic. Compaction effort may have a significant effect on TBOs properties; considering their smaller thickness and aggregate structure, particularly for gap-graded mixtures. Thus the compaction effect component is also evaluated as part of the composite specimen fabrication process; details are provided in an ensuing section. An illustration of the composite specimen fabrication process using the WTB procedure is provided in Figure 4.1. The provisional specification for \textit{“Preparation of}
“Bituminous Composite Test Specimen by Means of Gyratory Shear Compactor” developed in collaboration with Road Science LLC is attached as Appendix A.

Figure 4.1: Laboratory Compacted Composite (LCC) Specimen Fabrication Process

(a) Base with sealed rim; (b) Application of Emulsion; (c) Placement of a measured quantity of overlay mix immediately after applying the tack coat emulsion; (d) Insertion of heated top plate in the SGC mold; (e) Removal of compacted composite specimen, and; (f) Fabricated Composite Specimen.
In order to evaluate the four sample fabrication techniques, a PG 70-28, 9.5 mm plant produced gap-graded mixture typically known as “Novachip” was compacted to a 30 mm (1.2 inch) thick overlay for all replicates. The overlay thickness of 30mm was selected to match the target thickness of the TBO of the project from which the mixture and emulsion were sampled. Equal thicknesses helped in making comparisons with fracture test results of field core samples. Polymer modified asphalt emulsion (PMAE) at four application rates, 0.45, 0.9, 1.35 and 1.80 L/m² (0.1, 0.2, 0.3 and 0.4 gal/yd²) was applied on all replicates fabricated with above mentioned four techniques. The effect of tack coat application rate was studied against two base textures (saw-cut & textured) and two emulsion application processes (wet & cured). Compacted composite specimens were kept at room temperature overnight before cutting compact tension, C[T], specimens for fracture testing. Sample fabrication, testing, and analysis procedure for the C[T] test is described in Chapter 3. All 54 replicates were conditioned and tested at -12°C using the C[T] test geometry. The test temperature used represents 10°C warmer than the performance graded (PG) low temperature grade at a 98% reliability level for the project location. C[T] test results presented in Figure 4.2 illustrate the following key points:

1. Increases in tack coat application rate result in higher fracture energy of the composite laboratory compacted specimens measured using the C[T] test.

2. Wet application of the emulsion yields more consistent results with higher fracture energy values compared to cured emulsion.

3. Cured emulsion on textured surface resulted in the highest variability of the test data. It is assumed that most of the emulsion residue remains on the textured surface and very little quantity permeates upward to improve overlay mixture fracture properties. Moreover variation of the texture on individual replicates causes a significant effect on emulsion permeation.

Considering the spray paver construction process; wet application of emulsion on a textured surface compacted using heated SGC top plate best represents the spray paver installed thin bonded overlay systems. Textured base provides a better representation of the existing pavement surface and paver screed effect is simulated with the heated SGC top plate. Figure 4.3 provides a close-up view of the C[T] test fracture test performed on a PG 70-28, 9.5 mm gap-graded mixture composite specimen fabricated using the wet emulsion on textured base (WTB)
technique at four tack coat application rates. These results indicate that increases in tack coat application rate result in progressively higher fracture energy for this gap-graded mixture. Similar trends in fracture energy results can be observed in Figure 4.4 for a 9.5 mm PG70-22, dense-graded mixture. It is important to note that the range of tack application rates is narrow in the case of a dense mixture, which is 0.45 to 0.9 L/m² (0.1 to 0.2 gal/yd²). Dense-graded mixtures generally exhibit an optimum tack coat rate beyond which the fracture energy of the TBO decreases (Ahmed et al., 2010a).

Tack coat emulsion rate, emulsion type, mixture properties, existing pavement surface condition replicated as base texture and construction process are factors which may significantly affect TBO properties. Spray paver screed spreads/levels the overlay mate and its elevated temperature facilitates upward emulsion permeation. The effect of screed temperature was simulated using a heated top plate of gyratory compactor and results are discussed in succeeding paragraphs.

![Graph showing fracture energy results for different fabrication techniques.](image)

Figure 4.2: C[T] Test Results of Laboratory Compacted Composite Specimen Using Different Fabrication Techniques for PG70-28 Gap-Graded Mixture Tested at -12°C
Figure 4.3: Effect of Tack Coat Application Rate on Fracture Properties of LCC Specimens with PG70-28 Gap-Graded Mixture Tested at -12°C

Figure 4.4: Effect of Tack Coat Application Rate on Fracture Properties of LCC Specimens Using Dense-Graded Mixture with PG70-22, Tested at -12°C
4.3 SIGNIFICANCE OF SGC TOP PLATE TEMPERATURE

Spray paver screed temperature and its effect of drawing wet emulsion upwards into the overlay mixture were replicated using a heated SGC top plate. The effect of the Superpave gyratory compactor top plate temperature was studied for three mixtures and composite specimens at three temperatures. Figure 4.5 demonstrates the effect of SGC top plate temperature on the fracture properties of composite specimens. A 9.5 mm Novachip mixture manufactured with PG70-28 was used as an overlay on top of wet emulsion applied on textured bases and compacted with a SGC top plate heated to three temperatures, 150°C, 175°C, and 200°C. Fracture properties of these laboratory compacted composite specimens were determined using the C[T] test. Three replicates in each case were tested at -12°C. A significant increase in fracture energy was observed for specimens compacted using a heated SGC top plate for the gap-graded mix. Test results shows a 27% increase in fracture energy comparing composite specimens compacted with 150°C to 200°C top plate temperatures. It is hypothesized that the spray paver screed temperature helps emulsion to permeate into the overlay and, to an extent, the same phenomenon occurs for heated SGC top plates in laboratory fabricated composite specimens.

Temperature conditioning is one of the causes of oxidative ageing of asphalt concrete. Braham et al., (2009) reported that initial / short term aging improves the fracture resistance of asphalt concrete mixtures while longer aging begins to decay the fracture properties. Thus it was considered essential to see whether the heated SGC top plate was causing any changes in the mixture properties. Composite specimens with and without tack coat emulsion were compacted at three temperatures. LCC specimens were prepared with a tack coat application rate of 0.90 L/m² (0.2 gal/yd²), where the mixture specimens had no emulsion (0 gal/yd²) as shown in Figure 4.6. A 9.5 mm gap-graded mixture manufactured with PG70-22 binder was used in this case. Three replicates of each set were tested using the same temperature and loading conditions. C[T] test results in Figure 4.6 illustrate that a heated SGC top plate did not cause any change in asphalt concrete mixture (without tack coat) properties. The average fracture energy of the 9 mixture replicates compacted at three different SGC top plate temperatures is 405 J/m² with an overall CoV of 7%. In the case of composite specimens fabricated with the same mixture, the fracture energy increased with increased SGC top plate temperature. Furthermore, the fracture energy increased from 415 J/m² to 560 J/m² (~ 35%) as the top plate temperature increased from 150°C to 200°C.
The effect of SGC top plate temperature was also studied for a 9.5mm, PG58-28 dense-graded mixture with 25% RAP. A total of eighteen replicates of this mix and composite specimens were compacted at the three temperatures previously used. Results presented in Figure 4.7 illustrates that SGC top plate temperature does not affect any change in the mixture as well as in the composite specimens. Incorporation of the emulsion as tack coat does not change the fracture energy for this dense-graded mixture. These results do not reflect the overall behavior of dense-graded mixtures. Figure 4.4 illustrates that the inclusion of tack coat emulsion improves the fracture energy of LCC specimens for dense-graded mixtures. Detailed evaluation of tack coat application rate and emulsion type on fracture properties of dense-graded TBO is presented in Chapter 6. Since dense-graded mixtures are designed with low air voids, the mixture does not have enough space to accommodate and assist significant permeation of the tack coat emulsion. Finally, besides other parameters, mixture design air void has a significant effect on tack coat emulsion permeation into the overlay system.

![Figure 4.5: Effect of SGC Top Plate Temperature on Fracture Energy of Laboratory Compacted Composite Specimens of Gap-Graded Mixture](image-url)
Figure 4.6: Effect of SGC Top Plate Temperature on Fracture Properties of LCC Specimens and PG70-22 Gap-Graded Mixture, Tested at -12°C.

Figure 4.7: Effect of SGC Top Plate Temperature on Fracture Properties of LCC Specimens and Dense-Graded Mixture with 25% RAP, Tested at -12°C.

4.4 SIGNIFICANCE OF COMPACTION EFFORT

Novachip mixtures are usually paved at 10 to 15% air voids and are gap-graded in nature. The compaction process is designed not to compact the HMA but rather to seat the aggregate for such mixtures. A minimum of two passes with a steel double drum roller in the static mode

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weighing at least 9 metric tons (10 tons) is usually employed (Hanson, 2001). The compaction process for spray paver constructed TBOs has been evaluated for dense-graded mixtures at different tack coat application rates and emulsion types; these findings are documented in Chapter 6. The significance of compactive effort in designing thin bonded overlay systems were evaluated by compacting composite specimens at three gyration levels in the laboratory. A 9.5 mm, PG 70-28 gap-graded mixture and PMAE was used to fabricate 18 composite specimens at two tack coat application rates, 0.9 and 1.8 L/m² (0.2 and 0.4 gal/yd²). Fabricated C[T] specimens were tested at -12°C. Results in Figure 4.8 indicate that 100 gyrations seemed optimal for this gap-graded mix. Fifty gyrations appeared to be too low to provide enough compaction, whereas the aggregate structure started becoming damaged beyond 100 gyrations.

A comparison of fracture energy results measured using C[T] test for field cores and laboratory compacted composite specimens is presented in Figure 4.9. Laboratory specimens were fabricated using the same plant produced mix and emulsion at the same rate (0.2 gal/yd²) as that of field cores on textured bases. Fracture energy of laboratory compacted composite specimens was 32% lower than the field installed TBO system. Though composite specimen fabrication in the laboratory has most of the features to mimic the spray paver construction process, it is still limited by scale of the laboratory fabrication process.

![Figure 4.8: Effect of Compaction Effort on Fracture Energy of Laboratory Compacted Composite Specimens for Gap-Graded Mixture](image-url)
4.5 SUMMARY

Composite specimen fabrication techniques for designing thin bonded overlays have been presented in this chapter. Wet application of the emulsion on textured surface best represents the field construction process of TBO and yielded the most consistent results. It is important to note that the compacted base should have uniform and low texture which can be better achieved with fine mixtures. The effects of SGC top plate temperature and compaction were also studied with a range of mixtures. Provisional specifications for preparing composite specimens were developed to account for different bases and emulsion application processes. The following key points can be drawn from this experiment:

1. Composite specimens fabricated using wet emulsion on uniform and low textured surfaces compacted with a heated SGC top plate at 200°C best represents spray paver constructed thin bonded overlays and can be used as design tool.

2. Superpave gyratory compactor top plate temperature significantly affects the fracture properties of gap-graded mixtures indicating that it mimics the effect of the spray paver screed. However, given differences between the laboratory and field conditions, this effect can only be partially reproduced in the laboratory.
3. SGC top plate temperatures evaluated in this study did not appear to cause aging, as the fracture properties of reference mixtures were found to be insensitive to plate temperature.

4. Gap-graded mixtures displayed increased fracture resistance with increases in emulsion application rate.

5. Tack coat emulsion permeation and its consequential effect to improve fracture resistance of the composite TBO specimens is significantly affected by mixture void structure, especially dense-graded mixes.

6. There is an optimum tack coat rate associated with a particular dense-graded mixture with respect to its fracture properties. Higher application rates do not always yield higher fracture energies for dense-graded TBO systems.

7. Compaction effort is associated with traffic. However, over or under compaction results in weaker composite overlay systems.
CHAPTER 5 – FRACTURE EVALUATION OF GAP-GRADED THIN BONDED OVERLAYS SYSTEMS

5.1 INTRODUCTION

Spray paver constructed thin bonded overlays were introduced in United States as “Novachip” in early 1990s (Serfass et al., 1991). Novachip is a typical gap-graded mix, paved in conjunction with PMAE tack coat. Mixture design specification and gradations for all three types of Novachip are presented in Table 5.1 and Figure 5.1 (Hanson, 2001). Since then, this gap-graded mixture has been placed in almost all climatic regions of the country. Novachip performance with respect to achieving enhance skid resistance, improve aggregate retention, provide strong bond to the underlying surface (reducing de-lamination, shoving and tearing potential) and waterproofing benefits has been well documented (Hanson, 2001; and Corley-Lay and Mastin, 2007). However, the cracking performance of this thin lift system with high air voids (10-15%) has not been thorough investigated.

Four TBO projects paved using gap-graded mixtures through a spray paver in the recent past were selected for evaluation. Field cores, loose mixture, and tack coat emulsion samples were collected at the time of construction of these projects. Laboratory compacted composite and mixture samples with and without tack coat emulsion were prepared following the procedures presented in Chapter 4. C[T] fracture test specimens were prepared and tested utilizing field and laboratory samples in accordance with test procedure introduced in Chapter 3. Fracture testing of field cores, laboratory prepared composite and uniform mix samples will be presented for these projects.

In addition, the effects of tack coat application rate in the context of composite specimen fracture resistance will be illustrated for two selected projects. Permanent deformation behavior of a Novachip mixture and a composite TBO system is documented for one of these projects. The spray paver technology has been recently extended to create a double-lift bonded overlay system. An experimental project involving the double-lift bonded overlay system will also be presented, along with a brief summary of its early performance.
### Table 5.1: Novachip Mix Design Limits - Composition by Weight Percentages

<table>
<thead>
<tr>
<th>Sieve</th>
<th>Type-A 6.2 mm (1/4 in)</th>
<th>Type-B 9.5 mm (3/8 in)</th>
<th>Type-C 12.5 mm (1/2 in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metric (mm)</td>
<td>ASTM</td>
<td>Design Limits (% Passing)</td>
<td>Design Limits (% Passing)</td>
</tr>
<tr>
<td>19</td>
<td>¾ inch</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>12.5</td>
<td>½ inch</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>9.5</td>
<td>3/8 inch</td>
<td>100</td>
<td>85 – 100</td>
</tr>
<tr>
<td>4.75</td>
<td>#4</td>
<td>40 - 55</td>
<td>24 - 41</td>
</tr>
<tr>
<td>2.36</td>
<td>#8</td>
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<td>19 – 32</td>
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<tr>
<td>0.60</td>
<td>#30</td>
<td>10 – 18</td>
<td>7 – 16</td>
</tr>
<tr>
<td>0.30</td>
<td>#50</td>
<td>8 – 13</td>
<td>5 – 13</td>
</tr>
<tr>
<td>0.15</td>
<td>#100</td>
<td>6 – 10</td>
<td>4 – 10</td>
</tr>
<tr>
<td>0.075</td>
<td>#200</td>
<td>4 - 7</td>
<td>4 – 5.5</td>
</tr>
</tbody>
</table>

**Figure 5.1: Comparison of Different Types of Novachip and Traditional Dense-Graded Surface Mix**
5.2 CASE STUDIES

5.2.1 SR-3, Blackford and Delaware Counties, Indiana

*Project Description*

A 9.5 mm (3/8 inch) nominal maximum aggregate sized (NMAS) Novachip type B gap-graded mixture manufactured using PG 70-28 asphalt binder was paved on State Route 3 (SR-3). This project is approximately 12.5 miles long and is located in Blackford and Delaware Counties in Indiana. A thin bonded overlay with a target thickness of 19 mm (3/4 inch) was placed through a spray paver in conjunction with a polymer modified asphalt emulsion (PMAE) tack coat placed at a wet application rate of 0.90 L/m$^2$ (0.2 gal/yd$^2$). The paving of the TBO was initiated on June 17th, 2009 by E&B Paving and took approximately two weeks to complete.

*Existing Pavement Condition*

The existing pavement was an aged, dense-graded hot mix asphalt concrete surface and was last treated in 1993. The pavement condition was assessed in 2007 prior to rehabilitation, which indicated the presence of moderate to severe transverse cracking and some longitudinal cracking. The north end of the project consisted of a higher amount of transverse cracking at regular intervals indicating the possibility of an underlying PCC structure. Exact details on the structure of the underlying pavement are not available.

*Test Results and Discussion*

Field core samples, loose mix and tack coat emulsion were sampled from the project during construction. Using the plant produced mix from the project, laboratory compacted samples with and without tack coat emulsion were fabricated. Laboratory compacted composite (LCC) specimens were fabricated at a tack coat application rate of 0.90 L/m$^2$ (0.2 gal/yd$^2$) to match that used in the field project. All subsequent LCC specimens were prepared in accordance with the procedure outlined in Chapter 4 and mixture samples were compacted using the Superpave gyratory compactor in accordance with the AASHTO T-312 procedure. Field cores and laboratory samples were fabricated into C[T] test specimens. Specimen preparation as well as test set-up for the C[T] test described in Chapter 3 were utilized in all fracture testing reported in this document hereafter. Fracture tests were conducted at -12°C. This test temperature was
selected based on the recommendations of ASTM D7313 test procedure for determining fracture energy of asphalt mixtures. Three test replicates were tested for each set of samples.

Comparison of C[T] test results for field cores, laboratory compacted composite and mixture samples from SR-3 are presented in Figure 4.1. Note that the laboratory compacted mix (LCM) samples were manufactured using mixtures from the same project and composite samples also included tack coat emulsion at the overlay interface. Thus, the primary difference between “Cores”, “LCC” and “LCM” are as follows:

1. Core samples provide the best opportunity to characterize the actual behavior of thin bonded overlays (plant produced, field-placed hot-mix asphalt overlay incorporating tack-coat placed with a spray-paver).

2. LCC samples represent laboratory fabricated TBO (hot-mix asphalt overlay incorporating tack-coat that is prepared in the laboratory using the Superpave gyratory compactor), which has the correct constituents as compared to the field, but which may not capture the full amount of upward wicking effect of tack emulsion achieved in the field.

3. LCM samples contain only HMA and thus represent the behavior of the mixture that was used in the construction of the TBO instead of the entire composite system.

Laboratory compacted mix specimens (LCM) were found to have an average fracture energy (520 J/m²) that was 45% lower than field core samples (948 J/m²). Whereas laboratory compacted composite specimen (LCC) average fracture energy (631 J/m²) was 33% lower than the fracture energy of field installed TBO. These results highlight the following key points:

1. Spray paver constructed overlay systems have superior fracture resistance as compared to the base mix, and superior fracture resistance as compared to laboratory compacted composite samples with same ingredients.

2. The process of field constructing TBOs significantly improves the fracture resistance of overlays relative to the base mix; the upward permeation of the tack coat emulsion is hypothesized to cause this improvement.

Hamburg wheel tracking test results of laboratory compacted composite (LCC) and mixture samples are presented in Figure 5.3. LCC specimens were prepared using PMAE tack coat at an
application rate of 0.2 gal/yd² same as that was used on the project. HWT results indicate that the mixture rutting resistance improves by incorporating tack coat emulsion. Higher rutting resistance of LCC samples can be attributed to better compaction and packing/orientation of the aggregates in the presence of tack coat emulsion by limiting movement, and better bond between material layers.

![Figure 5.2](image)

**Figure 5.2:** C[T] Test Results of Mix, Composite and Field Core Specimens from SR-3 Project; Utilizing 9.5 mm PG70-28 Mix Tested at -12°C

![Figure 5.3](image)

**Figure 5.3:** Hamburg Wheel Tracking Test Results of Laboratory Composite and Mixture Samples for SR-3, Gap-Graded TBO Project
5.2.2 SR-114, North Manchester, Indiana

Project Description

This TBO project was constructed in July 2008 by Brooks 1st Construction along a one mile section of SR-114 located in North Manchester, Indiana. The annual daily traffic (ADT) on this stretch of highway was 9,790 with 5% trucks in 2008. A TBO with a target thickness of 19 mm (3/4 inch) was constructed with a spray paver and polymer modified asphalt emulsion (PMAE) was applied as tack coat at a rate of 0.90 L/m² (0.2 gal/yd²). This project was paved with a 9.5 mm (3/8 inch) nominal maximum aggregate sized (NMAS) gap-graded mixture manufactured using PG 70-28 asphalt binder.

Existing Pavement Condition

The pavement consists of two undivided traffic lanes with angled parking in the urban portion of the project. The existing asphalt concrete surface had moderate to severe transverse and longitudinal cracking and was supported on a brick / aggregate base. The pre-construction survey revealed areas of fatigue damage that were repaired using partial depth asphalt patching prior to paving. Extensive crack filling was performed on cracks of 5 mm width or higher.

Test Results and Discussion

Field cores were taken and loose mixture along with PMAE was sampled at the time of construction from the project site. Figure 5.4 provides a comparison of C[T] test results of field cores and laboratory fabricated mix samples. Three replicates were tested in each case at -12°C. The average fracture energy of field cores (886 J/m²) was found to be 46% higher than those of laboratory fabricated mixture specimens (482 J/m²). The two main differences between field and laboratory samples were the presence of tack coat and the spray paver construction process for field core samples.

Laboratory compacted composite specimens were fabricated at four tack coat application rates using PG 70-28, 9.5 mm gap-graded mixture. Three replicates of these LCC specimens for each tack coat application rate were tested at -12°C. The C[T] results presented in Figure 5.5 indicate that increases in tack coat application rate results in progressively higher fracture energy for this gap-graded mixture.
Figure 5.4: C[T] Test Results of Laboratory Compacted Mix, and Core Specimens from SR-114 Project; with 9.5mm PG70-28 mix Tested at -12°C

Figure 5.5: C[T] Test Results of Laboratory Compacted Composite Specimens at Different Tack Coat Application Rates
5.2.3 I-80 West Bound, Grundy County, Illinois

Project Description

A thin bonded overlay was constructed on west bound (WB) lanes of Interstate-80 in Grundy county, Illinois for a stretch of 7 miles between mile markers 105 and 112. The 9.5 mm NMAS Novachip type B mixture for this project was designed with PG70-22 binder and PMAE was used as tack coat at an application rate of 0.90 L/m² (0.2 gal/yd²). WB lanes were paved in July 2009, earlier east bound (EB) lanes on the same site were treated with spray paver applied TBO, using Novachip type C mixture in September 2008.

Existing Pavement Condition

Continuously reinforced concrete pavement (CRCP) exists on this segment of Interstate-80. The existing concrete pavement had low to moderate severity transverse and longitudinal cracks at the time of overlay construction. A distinct grout hole pattern suggests that the CRCP was grout injected at some earlier time as indicated in Figure 5.6, which was later verified through discussion with Illinois Department of Transportation officials. EB lanes on the same site paved a year ago with spray paver constructed Novachip were performing well, with no visible distresses.

Test Results and Discussion

Novachip mix and PMAE were sampled during the construction of this project. Laboratory compacted composite samples were fabricated at utilizing sampled mix and emulsion at three tack application rates; 0.2, 0.3 and 0.4 gal/yd². Range of tack coat application rates were experimented to evaluate its effect on fracture properties of laboratory compacted composite samples. In addition laboratory compacted mix samples were also manufactured without tack coat emulsion to represent the baseline Novachip mix. All samples were prepared with overlay thickness of 30 mm to match the field constructed TBO. Three specimens in each category were tested at -12°C. C[T] fracture test results are presented in Figure 5.7. The maximum increase in fracture energy (475 J/m²) for composite specimens was observed at an application rate of 0.3 gal/yd², which was 22% higher than mixture (392 J/m²). The increase in fracture energy of LCC with higher tack coat application rate is not very significant in this case. As observed in the
earlier projects, laboratory fabrication environments may limit the ability for tack coat emulsion permeation into the mixture.

Figure 5.6: Existing Pavement Condition on I-80 WB, Grundy County, IL in 2009

Figure 5.7: C[T] Test Results of Laboratory Compacted Composite Specimens of 9.5 mm PG70-22 Mix from I-80 WB Project, Tested at -12°C
5.2.4 Christina Parkway/SR-2/SR-4, Delaware

Project Description

This project introduced a double lift spray paver constructed bonded overlay system. The pre-overlay condition of the Christina Parkway necessitated the use of a highly crack resistant treatment. DelDOT’s earlier experience of using 37 mm (1 ½ inch) Novachip bonded wearing course (BWC) with 50mm (2 inch) Superpave overlay in 2006 on a project on SR-1 south of Wilmington provided motivation for the system developed for the new rehabilitation. The double lift treatment on SR-1 was intended to waterproof the existing alkali-silica reaction (ASR) affected PCC pavement and to delay/prevent its further deterioration. Previous attempts of placing traditional 90 mm (3 ½ inch) thick HMA over PCC resulted in failures in 1 year or less on SR-1.

Considering the performance of double lift overlay system on ASR affected SR-1 pavement, another experimental project was designed and constructed on Christina Parkway/SR-2/SR-4 in September 2008. This spray paver applied trial project had three sections; traditional Novachip bonded wearing course, a double lift control section and a higher tack coat application rate experimental section as illustrated in Figure 5.8.

The traditional Novachip BWC section had a 19 mm (¾ inch) thick single lift Novachip mix with PMAE tack coat placed at an application rate of 0.22 gal/yd\(^2\). Both of the remaining sections had two lifts of Novachip mix paved on a milled concrete surface. The 1st lift thickness leveled 1 ½” milled depth of PCC and the 2nd lift matched the thickness of traditional Novachip section in the adjoining passing lane (3/4 inch). The Novachip mixture was manufactured with PG64-22 with 9.5 mm (3/8 inch) NMAS local Delaware aggregates. The typical tack coat application rate for Novachip BWC ranges between 0.13 to 0.2 gal/yd\(^2\). Higher application rate of PMAE tack coat with the double-lift Novachip was intended to make it a crack resistant overlay system. This experimental project was designed to evaluate following:

1. How will a double-lift Novachip BWC system perform on a PCC pavement experiencing significant ASR?

2. Will a single lift of 19 mm (¾ inch) thick traditional Novachip BWC protect the ASR PCC?
3. Will heavier application rates of PMAE create flushing or rutting issues with the Novachip BWC mixture?

4. Will the double application of Novachip® BWC and especially the higher application rates of PMAE create a more crack resistant overlay?

<table>
<thead>
<tr>
<th>Section</th>
<th>PMAE Application Rate</th>
<th>Type B Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional Novachip BWC</td>
<td>0.22 gal/yd²</td>
<td>3/4” Type B</td>
</tr>
<tr>
<td>Double Lift Control Section</td>
<td>0.22 gal/yd²</td>
<td>1 1/2” Type B</td>
</tr>
<tr>
<td>Higher Rate Experimental Section</td>
<td>0.3 gal/yd²</td>
<td>1 1/2” Type B</td>
</tr>
<tr>
<td>Higher Rate Experimental Section</td>
<td>0.18 gal/yd²</td>
<td>3/4” Type B</td>
</tr>
<tr>
<td>Higher Rate Experimental Section</td>
<td>0.25 gal/yd²</td>
<td>3/4” Type B</td>
</tr>
</tbody>
</table>

Figure 5.8: Pavement Section Layout of EB Lanes Christina Parkway/SR-2/SR-4

**Existing Pavement Condition**

The existing pavement varied in condition over the length of the project. Generally the passing lane was in much better condition than driving lane. The pavement was jointed PCC with blowups at transverse joints. At several of the transverse joints, asphalt patches had been placed, especially in the driving lane. Some larger PCC panels had been replaced for the width of the lane and either 6’ or 12’ in length. There were random areas of what appeared to be popouts in the PCC, varying in size and depth. Small popouts were not repaired, but larger ones had been patched. Some patches had been saw cut and filled with HMA patch while others were placed in whatever configuration that had blown out. Most of the surface had a pattern of fine surface cracking, mostly running longitudinal in direction. At the edge of the pavement, there were areas of lane-to-shoulder dropoff approximately 1” in depth. A pictorial view of the pre-repaired pavement condition is shown in Figure 5.10.
Sampling, Test Results and Discussion

A total of sixteen field cores were taken from both double lift sections during the week following the completion of paving, where the cores included the underlying PCC pavement. The cores were shipped to Advanced Transportation Research and Engineering Laboratory (ATREL), Rantoul IL for fracture evaluation of the in-place double lift bonded overlay system. Unfortunately, several of the cores had separated at the PCC and overlay interface during the shipping process. It was noted that the entire set of specimens from the control test section had delaminated. Looking at the bottom of the Novachip BWC cores that had separated (control section), there was visible dust adhering to the asphalt. It was thought that the fine dust from the milling and the lower application rate of PMAE might have caused this issue. The set of specimens from the experimental section with a higher application rate of PMAE resulted in 7 of the 8 specimens being still bonded to the existing PCC after shipping. An extra amount of PMAE might have helped wetting all of the fines to provide better adhesion between the asphalt mix and the PCC.

The C[T] test specimen entails 50 mm of underlying pavement, which was PCC with severe ASR damage. The unsound PCC could not withstand the specimen fabrication and testing process and only one specimen could be tested in the C[T] test. Three DC[T] specimens were tailored and tested from the remaining cores. In addition, DC[T] specimens were prepared utilizing the Novachip mixture sampled during the construction of this project. All fracture testing was conducted at -12°C and three replicates were tested in each case.

Figure 5.9 illustrates fracture test results from both double lift spray paver constructed bonded overlay sections and laboratory compacted Novachip mixture. Test results indicate that the experimental section with a higher application of tack coat emulsion had 28% higher fracture energy compared to the double lift control section (873 J/m²). The experimental section with the higher tack coat rate resulted in 46% higher fracture energy (1215 J/m²) than laboratory compacted Novachip mixture (651 J/m²). The relatively higher coefficient of variation (CoV) in the experimental section is likely due to the fact that the average (1215 J/m²) includes one C[T] and two DC[T] test results with measured fracture energy of 1445 J/m². As demonstrated in chapter 3, C[T] test is the appropriate test to determine fracture properties graded systems such as this one. Other key observations on this project are listed as follows:
1. The higher application of PMAE did appear to provide better adhesion with the milled, dusty and deteriorated PCC.

2. Both double lift sections have performed very well so far. The only form of visible distress is low severity reflective cracking over the transverse joints as shown in Figure 5.11.

3. Traditional single lift Novachip BWC section with a thickness of ¾” has also performed equally well to date. Pre-overlay condition of both lanes is a very important factor to keep in mind while comparing single and double lift sections. The driving lane paved with double lift Novachip was severely damaged and deteriorated relative to the passing lane with traditional single lift Novachip.

4. The applied rate of PMAE in two sections did not create flushing or bleeding at the time of construction and after three years of service.

5. The fracture test results suggest that higher application rates of PMAE tack will improve mixture fracture resistance.

Figure 5.9: C[T] Test Results of Christina Parkway Project with Double-Lift Novachip Manufactured with PG 64-22.
Figure 5.10: Panoramic View of Pre-Overlay Condition on EB Lanes Christina Parkway

Figure 5.11: Recent Pavement Condition with PCI 92 on EB Lanes Christina Parkway
5.3 SUMMARY, FINDINGS AND CONCLUSIONS

Four bonded overlay projects paved with gap-graded mixtures through a spray paver were evaluated in terms of their fracture properties. Field core and laboratory compacted composite and mixture samples were tested and compared. C[T] fracture test results indicated 45% higher fracture energy for spray paver constructed TBO compared to LCM samples and about 30% higher than LCC samples. Tack coat emulsion improved the rutting resistance of the mixture as demonstrated by Hamburg wheel tracking test results.

Both double lift sections of next generation bonded overlays have performed very well since their construction three years ago. A traditional single lift Novachip section with a thickness of 19 mm has also performed reasonably well considering the pre-overlay condition of the passing lane with moderate cracking. The only form of visible distress is low severity reflective cracking over the transverse joints. Laboratory test results and field observation during the construction of gap-graded TBOs lead to following conclusions:

1. Field constructed TBO systems have better fracture resistance properties than the uniform mix, and laboratory compacted composite samples with same ingredients.
2. The spray paver construction process significantly improves the fracture resistance of the overlay; the upward permeation of the tack coat emulsion is hypothesized to cause this improvement.
3. The higher application rates of PMAE tack coat improves the fracture resistance of TBO and provide better adhesion with deteriorated PCC surface.
4. Double lift bonded wearing course can adsorb up to 2.5 L/m² (0.55 gal/yd²) of PMAE tack coat without causing any bleeding or flushing after three years in service.
5. Incorporation of the PMAE tack coat improves the rutting resistance of the bonded overlays.
6. Early performance of the double-lift bonded overlays demonstrates their crack resistance potential. These next generation bonded overlay systems provide a viable rehabilitation option for pavements with severe distresses and durability issues.
CHAPTER 6 – FRACTURE EVALUATION OF DENSE-GRADED THIN BONDED OVERLAY SYSTEMS

6.1 INTRODUCTION

Performance evaluation of several field projects has revealed that thin bonded wearing courses represent an efficient treatment option for deteriorated rigid and flexible pavement systems, and often hold advantages over other alternatives (Corley-Lay and Mastin, 2007; Hanson, 2001; Kandhal and Lockett, 1997; and Bellanger et al., 1992). The spray paver construction process has been limited to gap-graded mixtures (known as Novachip) until recently. The gap-graded nature of the mixture manufactured with modified binder and PMAE tack coat processed through the single paving pass of spray paver helps to achieve enhanced skid resistance, improved aggregate retention, a strong bond to the underlying surface (reducing delamination, shoving and tearing potential) and waterproofing benefits (Hanson, 2001; and Corley-Lay and Mastin, 2007). The present economic situation has motivated the pursuit of innovative solutions for the maintenance and rehabilitation of highways. Extension of the spray paver construction process to pave traditional, dense-graded surface mixes thought to provide some or all of the benefits associated with this paving process. The reduced thickness of TBOs results in lower quantities of paving materials and can lower construction costs in some instances. Moreover, the spray paver construction process may lead to better performance through strong bonding with the underlying surface and improved fracture resistance within the dense-graded TBO system.

Road Science LLC, then SemMaterials introduced the paving of traditional dense-graded surface mixtures through the spray paver in 2007 as a proof of concept trial project in the United States. Considering the ability of the spray paver to successfully process such mixtures, more than 20 trial projects involving a range of mixtures (with RAP, WMA and different gradations), tack coat emulsion application rates and types have been constructed thus far. This Chapter introduces four of these projects with 48 trial sections followed by laboratory test results and their analysis. Field core samples, HMA and emulsions were sampled for material
characterization at the time of construction from all projects. Laboratory tests provide comparison of fracture and rutting resistance of field installed spray paver TBO, laboratory prepared composite and mixtures samples.

6.2 CASE STUDIES

6.2.1 K-156 Finny County, Kansas

Project Description

A PG64-22, 12.5mm nominal maximum aggregate size (NMAS) Superpave, KDOT surface mix at compacted thickness of 38mm (1 ½ inch) was placed through a RoadTec SP-200 spray paver (Figure 6.1) in this trial project. The mixture contained 15% RAP. A total of eight sections spanning across approximately 5.3 centerline miles were constructed on 26 ft wide, two lane undivided state highway K-156, located East of Kalvesta in Finney County KS on October 16-17, 2008. The spray paver applied various amounts of polymer modified asphalt emulsion (PMAE) as a tack coat on bonded overlay sections. The control section was paved using a standard distributor to place a SS-1hP diluted tack coat emulsion and conventional HMA paver. Pavement section layout illustrating tack coat application rate, emulsion type and construction process is provided in Figure 6.2.

The purpose of this trial was to gain more field data on the construction characteristics of dense-graded TBO and to evaluate their field performance with a focus on the following aspects.

1. Is mixture compactability related to the rate of PMAE tack coat application?
2. Is there a difference in the ability to compact the test sections with the PMAE tack compared to the control section with conventional SS-hP tack coat emulsion?
3. Will the PMAE tack rate affect the pavement performance with respect to cracking, rutting, potholing, or centerline joint deterioration?

Existing Pavement Conditions

A pavement condition survey was conducted by ISG Pavements, LLC a week before the construction of the project. A detailed cracking map was made for the entire project area. The existing pavement was asphalt concrete with a 3-4 year old chip seal surface (Figure 6.3).
general condition would be considered poor due to high severity transverse cracking and areas of moderate to high severity fatigue cracking. The chip seal surface displayed flushing in the wheel paths near intersections where traffic was reducing speed and approaching a turn. The pavement also showed some signs of shoving in some locations.

Figure 6.1: RoadTec SP-200 Spray Paver with MTV

Figure 6.2: Layout of Pavement Sections
**Construction of the Project**

This subsection is primarily focused on the compaction process considering the objectives of this field study. Different roller patterns were investigated by the contractor, but two vibratory passes followed by a static pass, a single pneumatic pass and a finish pass with the steel drum in static mode appeared to build density the quickest. There were no signs of the tack coat flushing to the surface or pick up of mix on the roller drums even at an application rate of 1.35 L/m² (0.3 gal/yd²). The QC personnel of APAC Kansas, who were responsible for the roller operation and monitoring of the density, indicated that the spray paver constructed overlay was achieving density faster than the control sections. All of the paving on each test section was done at a paver speed of 45 to 50 ft/minute. For an approximately 500 foot long section within section 8, the paver speed was increased to approximately 60 ft/minute. Using the same rollers and roller pattern, it became more difficult to achieve the target density as measured by the nuclear density gage. The east bound paving width was measured to be 13.25 feet wide and the west bound lane was paved at 12.75 feet wide.

Key points observed during the construction of this trial project include:

1. For this study, there was no change in the roller pattern or number of passes required to achieve the desired density as the application rate of the PMAE tack material was reduced. A possible explanation may be that the positive texture of the chip seal
provided higher friction for the new mix to work against compared to a typical, smooth asphalt pavement surface.

2. Compaction of the control section took relatively more effort to achieve the desired density than what was experienced when placing the same mix through spray paver at any application rate of PMAE.

3. The pavement will be reevaluated with time to validate whether the performance of the pavement has been enhanced through the bonding process and if there are optimum application rates of PMAE depending on what performance factor is of interest.

4. There were no signs of flushing or bleeding at the time of construction at any of the application rates under evaluation.

5. The spray paver had no problems placing the desired thickness of 12.5mm Superpave mixture.

6. Paver travel speed has an impact on the ability to achieve the target density of the overlay. It is thought that excessively high paver speed may not provide the screed enough time to apply adequate compaction effort.

Laboratory Tests and Results

Fracture and rutting tests were performed utilizing field cores obtained from test sections 2, 4, 7 and 8 on November 15th, 2008, approximately one month after the initial construction. Fracture properties of the paved overlay were determined using cores in accordance with ASTM D7313 at ATREL. Rutting evaluation using AASHTO T 324 Hamburg Wheel Tracking method was carried at SemMaterials laboratory in Tulsa, OK. D(T) specimens were prepared and tested at -12°C. The thickness of the cores and unsoundness of the existing underlying flexible pavement limited the test geometry to DC[T] testing only.

Fracture test results are illustrated in Figure 6.4, and indicate that section 2, which was a control section paved with a conventional distributor and paver, resulted in the lowest fracture energy as might be expected. The remaining three sections were paved with a spray paver. The tack coat application rates and emulsion types are shown on the fracture energy plot. Section 4 with the highest tack application rate (0.32 gal/yd²), resulted in the lowest fracture energy of the
three spay paver constructed sections. DC[T] fracture test results suggest that an intermediate

tack coat application rate (0.21 gal/yd$^2$) is most beneficial with respect to cracking resistance of

this mixture.

Figure 6.4: DC[T] Fracture Test Results of KS-156 Cores at -12°C

Figure 6.5 presents the Hamburg wheel tracking test results of field cores, laboratory

compacted composite and mixture samples. Composite specimens were fabricated with the same

mixture and emulsion, sampled during construction of this project. Tack coat application for the

laboratory composite specimens was kept same as that of cores (0.2 gal/yd$^2$). Laboratory samples

were prepared at 7% air voids to match the field densities. All testing was carried out with

submerged samples in a 50°C bath. HWT results indicate that spray paver constructed TBO field

samples are more rut resistant than laboratory prepared composite and mixture samples. Considering 12.5

mm rut depth as failure criteria, core samples failed at 8200 passes compared to 7200 and 4800 passes of composite and uniform mixture specimens. Based on results presented in Figure 6.5; the HWT test for laboratory prepared composite specimens can predict field installed TBO system and can be used as a design tool.
6.2.2 Sedgwick County, Kansas

*Project Description*

This trial project placed two warm mixes of different gradations manufactured using chemically modified binder, CM-90 and a PG64-22 dense-graded (DG) HMA (BM-1) from LaFarge plant Wichita, KS. All the test sections were paved using the Vogele SF-1800 spray paver to place the mix and apply different rates of PMAE in Haysville, Sedgwick County, KS.

The purpose of this trial was to observe construction characteristics of TBO using warm mixes and to evaluate their field performance. Specific questions pertaining to this project included the following:

1. Are there any observed construction or field performance differences between open graded verses gap-graded warm mixes?
2. Can we use the same application rate of PMAE tack coat for different thickness?
3. Can we place 25 mm (1 inch) thick bonded overlay with dense-graded mixture?
4. Does PMAE help build density faster base on its application rate?
Table 6.6: Gradations of DG-HMA (BM-1), Gap-Graded (GG) and Open-Graded (OG) WMA

<table>
<thead>
<tr>
<th>Section 2</th>
<th>Section 4</th>
<th>Section 6</th>
<th>Section 8</th>
<th>Section 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap-graded 1198 yd²</td>
<td>Gap-graded 1111yd²</td>
<td>Gap-graded 1111 yd²</td>
<td>Gap-graded 1111 yd²</td>
<td>Gap-graded 1111 yd²</td>
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<tr>
<td>65 lbs/yd²</td>
<td>80 lbs/yd²</td>
<td>80 lbs/yd²</td>
<td>100 lbs/yd²</td>
<td>100 lbs/yd²</td>
</tr>
<tr>
<td>NB 0.24gal/yd²</td>
<td>NB 0.24gal/yd²</td>
<td>NB 0.12gal/yd²</td>
<td>NB 0.29gal/yd²</td>
<td>NB 0.29gal/yd²</td>
</tr>
<tr>
<td>Target 0.25gal/yd²</td>
<td>Target 0.25gal/yd²</td>
<td>Target 0.25gal/yd²</td>
<td>Target 0.15gal/yd²</td>
<td>Target 0.25gal/yd²</td>
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</tbody>
</table>

<table>
<thead>
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<th>Section 5</th>
<th>Section 7</th>
<th>Section 9</th>
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<tr>
<td>Open graded 1014yd²</td>
<td>Open graded 1111yd²</td>
<td>Open graded 1111 yd²</td>
<td>Open graded 1111 yd²</td>
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<td>65 lbs/yd²</td>
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</tr>
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<td>NB 0.22gal/yd²</td>
<td>NB 0.27gal/yd²</td>
<td>NB 0.23gal/yd²</td>
<td>NB 0.15gal/yd²</td>
<td>NB 0.32gal/yd²</td>
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<tr>
<td>Target 0.15gal/yd²</td>
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<td>Target 0.25gal/yd²</td>
<td>Target 0.15gal/yd²</td>
<td>Target 0.25gal/yd²</td>
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Table 6.7: Test Sections Layout; Bonded WMA Project Sedgwick Co, KS

<table>
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<tr>
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<th>Section 6</th>
<th>Section 8</th>
<th>Section 10</th>
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<tr>
<td>1.25” BM-1</td>
<td>1.25” BM-1</td>
<td>1.25” BM-1</td>
<td>1.0” BM-1</td>
<td>1.0” BM-1</td>
</tr>
<tr>
<td>NB 0.06gal/yd²</td>
<td>NB 0.13gal/yd²</td>
<td>NB 0.24gal/yd²</td>
<td>NB 0.19gal/yd²</td>
<td>NB 0.13gal/yd²</td>
</tr>
<tr>
<td>Target 0.06gal/yd²</td>
<td>Target 0.10gal/yd²</td>
<td>Target 0.20gal/yd²</td>
<td>Target 0.20gal/yd²</td>
<td>Target 0.10gal/yd²</td>
</tr>
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<table>
<thead>
<tr>
<th>Section 1</th>
<th>Section 3</th>
<th>Section 5</th>
<th>Section 7</th>
<th>Section 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25” *BM-1</td>
<td>1.25” BM-1</td>
<td>1.25” BM-1</td>
<td>1.0” BM-1</td>
<td>1.0” BM-1</td>
</tr>
<tr>
<td>NB 0.26gal/yd²</td>
<td>NB 0.29gal/yd²</td>
<td>NB 0.21gal/yd²</td>
<td>NB 0.14gal/yd²</td>
<td>NB 0.31gal/yd²</td>
</tr>
<tr>
<td>Target 0.25gal/yd²</td>
<td>Target 0.30gal/yd²</td>
<td>Target 0.20gal/yd²</td>
<td>Target 0.15gal/yd²</td>
<td>Target 0.30gal/yd²</td>
</tr>
</tbody>
</table>

*BM-1 – Dense-graded hot mix asphalt (DG-HMA)
Existing Pavement Condition

The existing surface was a dense-graded HMA of several years in age. No rutting was apparent. There were some transverse cracks of low to moderate severity, but their frequency was considered to be low. No potholes or patches were noted in the test section area. The test section area was posted at 55 miles per hour speed limit. Traffic conditions appeared to be light, less than 5000 ADT, with low percent of truck traffic. During the harvest season heavy traffic may increase substantially in volume and load level.

Test Variables

CM-90 Warm Mix Test Sections

- Mixture Gradation; Open graded and gap-graded
- Mixture Application Rates; 65, 80 and 100 lbs/yd², corresponds to different thicknesses of the overlay
- PMAE Application Rates; 0.15 and 0.25 gal/yd²

BM-1 DG-HMA Test Sections

- Overlay Thickness; 1” and 1.25”
- PMAE Application Rates; 0.05, 0.1, 0.2, 0.25 and 0.3 gal/yd²

All three mixtures gradations are presented in Figure 6.6. Test section layout is illustrated in Figure 6.7 and Figure 6.8. The information provided in the layout includes; mix type, its application rate, covered area, tack coat emulsion rate and variation from the design target. Each section was approximately 800 feet in length and 13 feet in width.

Construction of CM-90 Warm Mix Test Sections

The warm mix test sections were constructed on June 11th, 2008. CM-90 binder was used in both; gap-graded and open graded WMA at 4% and 4.2% respectively. These mixes were prepared at 190°F and delivered to the spray paver at 150°F to 160°F.

Construction of BM-1, DG-HMA Test Sections

Dense-graded hot mix asphalt (DG-HMA) test sections were paved on June 12th 2008 using the spray paver. The mixture temperature ranged from 285°F to 315°F in the hopper of the paver.
The pattern for rolling was one initial pass for breakdown, followed by a vibratory pass back with a final clean up static pass forward. Mixture densities were measured using nuclear density gage after initial breakdown and final rolling for all sections. Field density results for all emulsion application rates for both overlay thickness (1.0” and 1.25”) are presented in Figure 6.9 and Figure 6.10. Density results indicate that an increase in PMAE tack coat application rate increases the final density of the mixture under equal compaction effort for both experimented thicknesses.

Fracture Test Results and Analysis

- **BM-1 Dense-Graded HMA Sections**

Fracture evaluation of eight sections paved with DG-HMA was carried out utilizing field core samples. The variables studied were two thicknesses and four tack coat application rates for each thickness. Sections 1 to 4 were constructed with TBO thicknesses of 32 mm (1.25 inch), while other sections were constructed at 25 mm (1 inch) thickness. Sampling and testing for this project was conducted in two phases. The first phase of testing was conducted using the DC[T] test. Fracture energy results are presented in Figure 6.11. For the range of tack application rates studied, e.g., from 0.13 to 0.31 gal/yd$^2$, varying fracture energy measurements were obtained. Similar to the other projects involving dense-graded TBOs, the highest fracture energy was associated with an intermediate tack coat application rate. However, in this case, the difference in fracture energy between the various sections was insignificant in most cases. The fracture energies were relatively lower for this project. In case of DC[T] tests, the fracture energy decreases with decreasing specimen thicknesses. Wagener and Buttlar (2007) showed over 40% decrease in the fracture energy measurements for DC[T] specimens of 25 mm thickness when compared with 50 mm thickness. For this project the thickness ranged from 25 to 32 mm. The thickness effect is also visible for Section 1 and 3, which have greater thickness and the higher fracture energy values. Thus, it was difficult to assess whether or not the higher fracture energy values for the intermediate tack coat ranges of 0.26 to 0.29 were due to its optimum value or due to the increased sample thickness for the specimens obtained from these sections and resulting size effect ‘bump’ on fracture energy.

To further evaluate the effect of tack coat rate and to make comparisons between the DC[T] and C[T] test configurations a second phase of testing was undertaken. Samples were procured
from three sections representing the 0.06, 0.13, and 0.29 gal/yd² tack application rates, illustrated as Sec 2, Sec 3 and Sec 4. In this round of testing, all specimens had identical fracture ligament lengths of 32 mm, thus eliminating the potential for variable size effect. Three field core replicates in each case from three sections were tested in both configurations as shown in Figure 6.12. Higher fracture energy values were measured in the C[T] test configuration as compared to the DC[T] configuration. As discussed before (Chapter 3), this difference is anticipated due to the presence of PMAE membrane and material gradation in the vertical direction. Some difference may also arise from the difference in testing mode, and differences in the size of the fracture area, although they were similar. Those differences notwithstanding, both test configurations identified that the highest fracture energies were associated with the tack application rate of 0.29 gal/yd², which concur with the first round of testing.

• **CM-90 Warm Mix Asphalt Sections**

Field core samples from three gap-graded and an open graded spray paver installed WMA TBO sections were procured for fracture testing. Comparison of section 5 and 6 indicates that gap-graded WMA bonded overlay resulted in 31% higher fracture energy (211 verses 161 J/m²) than the open graded section paved with the same tack coat application rate of NB and the same overlay thickness. Results presented in Figure 6.13 indicate that higher tack coat application rate results in greater fracture energy values for this gap-graded mixture for the applied tack coat rates. Similar findings were noticed for gap-graded mixtures in Chapter 5 and Ahmed et al. (2010). The fracture energies for this project were, in general, fairly low as compared to other projects investigated, particularly in the case of the gap-graded mixtures. This WMA may have lower fracture resistance and spray paver construction process can only improve to an extent. Limited experience with fracture characterization of the WMA suggests that warm mix technologies generally leads to higher fracture energies compared to the HMA manufactured with same aggregate structure.
Figure 6.9: Density Versus Tack Coat Application Rate of 1.0” Thick DG-HMA

Figure 6.10: Density Versus Tack Coat Application Rate of 1.25” Thick DG-HMA
Figure 6.11: DC[T] Test Fracture Energy Results for Field Samples from Phase-I Testing of BM-1, Dense-Graded HMA

Figure 6.12: Fracture Energy Results for Field Samples from Phase-II Testing of BM-1, Dense-Graded HMA
An experimental section of thin bonded overlay using 9.5 mm Superpave Arkansas surface mixture was constructed on Route 24 in Chidester, AR on November 3rd, 2009. This study was focused on evaluating the concept of reduced overlay thickness in conjunction with placement by a spray paver using a heavy application of polymer modified asphalt emulsion (PMAE) tack coat. As part of the experiment, different application rates of PMAE were placed for performance evaluation and testing purposes. The entire one mile length of this project was divided into eight sections including a control section, (Figure 6.14). HMA for this project was manufactured utilizing PG70-22 binder. The target average overlay thickness for this experimental section was kept as 29 mm (1 1/8 inch) at HMA delivery rate of 125 lb/yd² as compared to the traditional overlay yield of 200 lb/yd² for this district.

Existing Pavement Condition

The existing surface was a crushed gravel chip seal coat estimated to be 3 – 4 years old, as shown in Figure 6.15. There was measurable rutting (up to 1 ¼ inch) in some of the lower speed areas of the 1 mile test section. Moderate severity transverse cracking was also observed in some
areas. Subsequent coring after construction of overlay revealed that in some test sections, below the chip seal, the HMA displayed signs of stripping.

**Laboratory Testing Results and Discussion**

- **Fracture Tests**

Fracture test results from field core and laboratory compacted composite specimens are presented in Figure 6.16 and Figure 6.17. The fracture energy values measured for this Superpave mixture are relatively higher than all other dense-graded thin bonded overlay projects. This should correlate to improved field performance with respect to thermal induced cracking. These fracture test results are consistent when compared with the comprehensive fracture database (Buttlar et al. 2009). A PG 70-22 Superpave mixture with good quality aggregates tested at -12°C also falls in this range (~550 J/m²). An initial glance at the core sample fracture test results (Figure 6.16) indicates that a tack coat application rate of 0.12 gal/yd² results in highest fracture energy with the tested sections. Subsequently, fracture energy values decreased with an increase in tack coat application rates for sections 4 and 6 (0.15 & 0.20 gal/yd²). This was a common trend for DG mixes, although the optimum tack coat rate from the perspective of fracture resistance through the bulk material has been found to vary depending upon mix characteristics such as voids and VMA.

Laboratory samples were fabricated using the same mixture and PMAE emulsion procured at the time of construction. All laboratory samples were compacted to match the target overlay thickness and tested under same conditions as that of field cores. C(T) test results shows that increase in PMAE tack coat application rate results in higher fracture energy within the evaluated tack coat application range for this Superpave mixture. Thus, the higher fracture energy measured in the section 8 (0.12 gal/yd²) core samples may be attributed to that observed in other studies (Wagoner and Buttlar [2007]), e.g., a thickness size effect where higher thickness leads to higher fracture energy.

- **Rutting Resistance**

Hamburg Wheel Track (HWT) Testing of Compacted HMA and composite specimen was conducted in accordance with AASHTO T 324, to determine the rutting susceptibility of the AR 24 mix. Field mix was obtained from the project and taken to the Road Science Lab in Tulsa,
OK. The field mix and the composite samples were compacted in the SGC to a target of 7% air voids, to simulate the in-place design air voids. Composite samples were fabricated at two tack coat application rates (0.1 and 0.2 gal/\( \text{yd}^2 \)) with same base and overlay thickness of 32 mm (1.25 inch), using the same AR 24 mix. The Hamburg Wheel Tracking testing was performed by the Road Science Laboratory in Tulsa. The tests were performed under water at 122°F (50°C) for 20,000 passes of the steel wheel or 20 mm of rut depth. HWT test results presented in Table 6.1 indicates the rutting resistance of this Superpave mix. The composite specimen made at two different application rates of PMAE tack coat performed slightly better than the homogeneous mixture. Contrary to common thinking; heavy applications of tack did not create a rutting issue and in fact, showed a slight increase in rutting resistance.

**Performance Overview**

Jim Cunningham, an Engineering Specialist for Road Science LLC, reviewed the AR 24 project on April 20th, 2010, approximately 5 ½ months after the paving was completed. Comments, observations and measurements are as follows:

1. No visible cracks were present in the transverse or longitudinal directions.
2. No rutting could be measured at random station locations.
3. The control section displayed two small areas where some debonding has occurred.
4. The ride quality and visual appearance was similar to when it was just paved.
5. Based on a scale of 0-100 pavement condition rating (PCR), this project received a 91 by the rater. The rater would have given a rating of 32 prior to paving.

<table>
<thead>
<tr>
<th>Section</th>
<th>Tack Coat Application Rate</th>
<th>Pave Condition Rating</th>
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<tr>
<td>1</td>
<td>No tack</td>
<td>West 92±10</td>
</tr>
<tr>
<td>2</td>
<td>0.065 gal/( \text{yd}^2 ) PMAE</td>
<td>92±40</td>
</tr>
<tr>
<td>3</td>
<td>0.077 gal/( \text{yd}^2 ) PMAE</td>
<td>96±00</td>
</tr>
<tr>
<td>4</td>
<td>0.154 gal/( \text{yd}^2 ) PMAE</td>
<td>110±00</td>
</tr>
<tr>
<td>5</td>
<td>0.16 gal/( \text{yd}^2 ) PMAE</td>
<td>127±00</td>
</tr>
<tr>
<td>6</td>
<td>0.196 gal/( \text{yd}^2 ) PMAE</td>
<td>141±60</td>
</tr>
</tbody>
</table>

**Figure 6.14: Layout of Experimental Sections on AR 24 Project**
Table 6.1: HWT Test Results of 9.5 mm AR, Superpave Mixture with PG 70-22

<table>
<thead>
<tr>
<th>HWT</th>
<th>Uniform mixture</th>
<th>0.1 gal/yd(^2) PMAE Tack</th>
<th>0.2 gal/yd(^2) PMAE Tack</th>
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<tbody>
<tr>
<td>Rut depth @ 20K passes</td>
<td>7.3 mm</td>
<td>6.6 mm</td>
<td>6.4 mm</td>
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</table>

Chip Seal Surface on AR 24 Close up of Chip Seal Surface Texture

Figure 6.15: Existing Pavement Condition on AR 24

Figure 6.16: C[T] Test Results of Field Core Samples from AR 24 Tested at -12°C
Figure 6.17: C[T] Test Results of Laboratory Prepared Samples Tested at -12°C

6.2.4  Route-T; Franklin County, Missouri

Project Description

A 9.5 mm NMAS dense-graded mix consisting of 15% RAP and PG 64-22 virgin binder was placed on Route T, MO, in October of 2008 by N.B. West Contracting. The target thickness of the overlay was 44 mm (1 ¾ inch) for all test sections. Three variables were evaluated in this project, namely: construction technique; tack coat application rate, and; tack coat emulsion type. A total of 12 sections were paved on this trial project including a control section constructed using a conventional CSS-1h tack applied through a distributor. Other experimental sections were placed using the conventional CSS-1h tack coat emulsion and PMAE tack coat emulsion through a spray paver. The layout of the pavement sections is shown in Figure 6.18.

The purpose of this trial project was to gain more field data on the performance of dense-graded HMA. Specific questions to be answered from this trial included the following:

1. Does the PMAE tack affect the ability to place the mix any differently than the conventional tack?
2. Will the spray paver placement of the conventional tack improve its performance?
3. Will the PMAE tack rate affect the pavement performance with respect to rutting, potholing, or centerline joint deterioration?
Existing Pavement Condition

This project is located in Franklin County, MO on Route-T. The total project consists of a two lane undivided highway 14.5 in miles length, with test sections spanning across 3.5 miles of the project. The existing pavement in the test section area consisted of aged, jointed Portland cement concrete pavement that had been overlaid multiple times with asphalt concrete. The average thickness of old asphalt concrete overlays was estimated to be in the range of 150 to 175 mm. The pavement condition survey conducted prior to TBO construction indicated an aged asphalt surface with moderate to severe transverse cracking and some longitudinal cracking. The west end of the project also showed evidence of wheel path fatigue cracking.

Construction Observations

This subsection summarizes the relative ease or difficulty in achieving desired densities in different test sections during the compaction process. It was observed that as the application rate of the PMAE tack was reduced, there was a corresponding increase in the difficulty to achieve the desired compaction. However, at equal application rates, the PMAE tack created density with less difficulty than the conventional CSS-1h. The traditional tack coat material test sections required the most passes to achieve the desired density. The PMAE tack appears to enhance the mixes ability to be compacted.

Fracture Test Results and Discussion

Field core samples were procured from five sections at the time of construction to evaluate the fracture properties of in-place bonded overlays. Section 1 was paved with conventional paving procedures, i.e., application of conventional unmodified asphalt emulsion (CSS) tack coat using an asphalt distributor. The remaining four sections were constructed with a spray paver, which applied the tack coat and HMA in a single pass. Section 3 and Section 7 had similar target tack coat application rates, 0.45 L/m² (0.1 gal/yd²), but used different tack coat materials. Similarly, Section 5 and Section 9 had similar target tack coat application rates, 0.68 L/m² (0.15 gal/yd²), but were constructed with different tack coat materials.

Fracture energy test results from three C[T] replicates for all five sections are presented in Figure 6.19. A comparison of Section 1 and Section 3 fracture energy results indicates that the spray paver constructed overlay (TBO) had approximately 39% higher fracture resistance as
compared to the conventionally paved overlay with similar materials (both overlay mix and tack coat). Sections paved with PMAE tack coat had approximately 40% higher fracture energy as compared to CSS tack coats. The results also indicate higher fracture energy in overlays constructed with 0.45 L/m² (0.1 gal/yd²) tack rates compared to 0.68 L/m² (0.15 gal/yd²) for both types of emulsions. These results suggest that, unlike the gap-graded bonded systems which exhibit higher fracture energy with higher tack coat application rate, the dense-graded systems may reach a peak fracture resistance at a lower optimum tack coat application rate.

![Figure 6.18: Pavement Sections Layout on Route-T in Franklin County, MO](image)

![Figure 6.19: Fracture Energies for Materials from Route-T](image)
6.3 SUMMARY, FINDINGS AND CONCLUSIONS

An evaluation in the context of constructability, fracture and rutting resistance of 25 pavement sections from four trial dense-graded TBO projects was presented. Field cores, laboratory compacted composite and uniform mixture samples were tested to evaluated fracture and rutting resistance of paved mixtures. Fracture and Hamburg wheel tracking (HWT) test results reveals that spray paver constructed bonded overlay systems are more resistant to cracking and rutting than conventionally paved overlays. Comparison of construction process reveals that conventional paving takes more compaction effort than spray paver constructed bonded overlays with the same thickness. It was also observed during the construction phase that a higher tack coat application rate generally facilitates the compaction process and requires less effort to achieve a given density. Moreover, there were no signs of the tack coat flushing to the surface or pick up of mix on the roller drums even at an application rate of 1.35 L/m² (0.3 gal/yd²) for overlays up to 50 mm in thickness. These field trials also demonstrated that environmental friendly mixtures including RAP and WMA can be paved successfully through spray paver. Based upon field observation during construction and laboratory testing, the following conclusions can be drawn:

1. Spray paver constructed bonded overlays need less compaction effort to achieve desired density than conventionally paved overlays with the same thicknesses.

2. In general, an increase in tack coat application rate of PMAE reduces the compaction effort required for a given thickness and mix type for bonded overlays as compared to conventionally paved control sections.

3. Spray paver installed TBOs with dense-graded mixtures can accommodate 3–5 times more tack coat emulsion than conventional overlays without causing any bleeding and flushing to the surface. The optimum tack coat rate from the standpoint of fracture energy varies from mix to mix and appears to be greatly influenced by the existing pavement conditions and the overlay mixture void structure. In the present study, a range of tack coat application rates (0.06 to 0.30 gal/yd²) were evaluated. It was observed that the highest fracture energy was associated with an intermediate tack coat application rate and varies for different mixtures.
4. Paver travel speed has an impact on the ability to achieve the target density of the overlay and a paver speed of 45 to 50 ft/minute is reasonable for dense-graded mixes. It is assumed that excessive paver speed may not allow the screed enough time to apply adequate compaction effort.

5. HWT results indicate that spray paver constructed TBOs field samples are more rut resistant than laboratory prepared composite and mixture samples.

6. WMA can be paved through spray paver at 150°F lower than HMA. Limited data set suggests that gap-graded WMA bonded overlay are 31% more crack resistant than open graded ones, paved at same tack coat application rate and thickness.

7. Higher fracture energy values were measured in the C[T] test configuration as compared to the DC[T] configuration. As discussed before, this difference is anticipated due to the presence of a material gradation in the vertical direction.

8. Limited data on the early performance of dense-graded mixture TBO is encouraging and the spray paver constructions process seems to improve the overall performance of these mixtures.
CHAPTER 7 – CRACKING ASSESSMENT OF THIN BONDED OVERLAY SYSTEMS USING COMPACT TENSION TEST AND LINKS TO EARLY FIELD PERFORMANCE

7.1 INTRODUCTION

This chapter provides an overview of an integrated approach to predict cracking performance of thin bonded overlays through laboratory measured fracture properties, numerical simulations and comparison to early field performance. A total of three projects with seven field sections constructed in last three years were considered in the evaluation. The four variables studied include; mixture type, construction process, tack coat emulsion type and its application rate. The effects of emulsion type and application rate were evaluated within the context of one field project. The type of asphalt mixtures used include; dense-graded and gap-graded mixes with different binder and aggregate sources. Furthermore, comparisons were also made between the TBO and thin overlays constructed using traditional laydown and compaction equipment. Laboratory fracture evaluation of TBOs was carried out using C[T] test, prediction of cracking behavior through finite element modeling with cohesive zone fracture elements (Ahmed et al., 2010 TRB), and field performance through site visits. The field sections studied herein are now described, followed by a presentation of fracture testing results, numerical simulations and field evaluation.

7.2 PAVEMENT PROJECTS AND FIELD SECTIONS

7.2.1 Brief Overview of the Pavement Projects

A total of three field studies are presented herein. Two projects were constructed using a gap-graded HMA design. Both of these projects are located in Indiana, one on State Route 3 and the other on State Route 114 and are hereafter referred to as SR-3 and SR-114. The third project consists of twelve test sections; five of which are included in this study. The project is located on
Route-T in Missouri, and utilizes dense-graded HMA in both the conventional and spray-paver applied test sections. These projects were introduced in Chapter 5 and 6 as well. More details on pavement conditions prior to construction as well as details on the TBO system materials are now presented.

7.2.2 Gap-Graded TBO Sections (SR-3 and SR-114)

The SR-3 project is approximately 12.5 miles long and is located in Blackford and Delaware Counties in Indiana. The existing pavement was an aged, dense-graded hot mix asphalt concrete surface and was last treated in 1993. The pavement condition was assessed in 2007 prior to rehabilitation, which indicated the presence of moderate to severe transverse cracking and some longitudinal cracking. The north end of the project consisted of a higher amount of transverse cracking at regular intervals. The paving of the TBO was initiated on June 17th, 2009 by E&B Paving and took approximately two weeks to complete. Exact details on the structure of the underlying pavement were not available.

The second project was constructed in 2008 by Brooks 1st Construction along a one mile section of SR-114 located in North Manchester, IN. The annual daily traffic (ADT) on this stretch of highway in 2008 was 9,790 with 5% trucks. The pavement is configured with curb and gutter drainage and consists of two traffic lanes with angled parking in the urban portion of the project. The existing asphalt concrete surface had moderate to severe transverse and longitudinal cracking and was supported on a brick / aggregate base. The pre-construction survey revealed areas of fatigue damage that were repaired using partial depth asphalt patching prior to paving. Extensive crack filling was performed on cracks of 5 mm width or higher.

Both of these projects were paved with a 9.5 mm (3/8 inch) nominal maximum aggregate sized (NMAS) gap-graded mixture manufactured using PG 70-28 asphalt binder. A TBO with a target thickness of 19 mm (3/4 inch) was constructed with a spray paver and polymer modified asphalt emulsion (PMAE) was applied as tack coat at a rate of 0.90 L/m² (0.2 gal/yd²) in both cases. Figure 7.1(a) schematically shows the rehabilitated pavement section.

7.2.3 Dense-Graded TBO Sections (Route-T)

This project is located in Franklin County, Missouri on Route-T. The total project consists of a two lane undivided highway 14.5 in miles length, with test sections spanning across 3.5 miles.
of the project. The existing pavement in the test section area consisted of aged, jointed Portland cement concrete pavement that had been overlaid multiple times with asphalt concrete. The average thickness of old asphalt concrete overlays was estimated to be in the range of 150 to 175 mm (6 to 7 inch). The pavement condition survey conducted prior to TBO construction indicated an aged asphalt surface with moderate to severe transverse cracking and some longitudinal cracking. The west end of the project also showed evidence of wheel path fatigue cracking.

A 9.5 mm NMAS dense-graded mix consisting of 15% RAP and PG 64-22 virgin binder was placed in October of 2008 by N.B. West Contracting. The target thickness of the overlay was 44 mm (1 ¾ inch) for all test sections. Three variables were evaluated in this project, namely: construction technique; tack coat application rate, and; tack coat emulsion type as illustrated in Table 7.1. Section 1 was paved with conventional paving procedures, i.e., application of conventional unmodified asphalt emulsion (CSS) tack coat using an asphalt distributor. The remaining four sections were constructed with a spray paver, which applied the tack coat and HMA in a single pass. Section 3 and Section 7 had similar target tack coat application rates, 0.45 L/m$^2$ (0.1 gal/yd$^2$), but used different tack coat materials. Similarly, Section 5 and Section 9 had similar target tack coat application rates, 0.68 L/m$^2$ (0.15 gal/yd$^2$), but were constructed with different tack coat materials. A schematic of the rehabilitated section is shown in Figure 7.1(b).

<table>
<thead>
<tr>
<th>Gap-Graded TBO</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old AC Overlay</td>
<td>150</td>
</tr>
<tr>
<td>Granular Base</td>
<td>250</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dense-Graded TBO</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old AC Pavement</td>
<td>150 - 175</td>
</tr>
<tr>
<td>PCC</td>
<td>200</td>
</tr>
</tbody>
</table>

a. Rehabilitated Section for SR-3 and SR-114  
b. Rehabilitated Section for Route-T Project

Figure 7.1: Cross-Sectional View of Rehabilitated Pavement Structures
Table 7.1: Summary of Variables Studied for Each Pavement Section of the Route-T Project

<table>
<thead>
<tr>
<th>Pavement Section</th>
<th>Construction Technique</th>
<th>Tack Coat Emulsion Type</th>
<th>Tack Coat Emulsion Rate (L/m²) / (gal/yd²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sec 1</td>
<td>Conventional</td>
<td>CSS</td>
<td>0.36 / 0.08</td>
</tr>
<tr>
<td>Sec 3</td>
<td>Spray Paver</td>
<td>CSS</td>
<td>0.45 / 0.1</td>
</tr>
<tr>
<td>Sec 5</td>
<td></td>
<td>CSS</td>
<td>0.68 / 0.15</td>
</tr>
<tr>
<td>Sec 7</td>
<td></td>
<td>PMAE</td>
<td>0.45 / 0.11</td>
</tr>
<tr>
<td>Sec 9</td>
<td></td>
<td>PMAE</td>
<td>0.68 / 0.14</td>
</tr>
</tbody>
</table>

7.3 EVALUATION USING COMPACT TENSION FRACTURE TEST

7.3.1 Fracture Energy Testing

Fracture energy of a material is indicator of the toughness of the material against the propagation of a crack. When obtained properly, it is a fundamental material property that has been shown to correlate well with the cracking performance of a pavement (Wagoner et al., 2006 and Dave et al., 2008). The disk-shaped compact tension DC[T] and semi-circular bend (SC[B]) are the most commonly utilized test procedures for evaluation of fracture energy of asphalt materials, where the DC[T] procedure is specified as ASTM D7313. In the present study, the C[T] fracture test was utilized for determination of fracture energies of field core as well as laboratory compacted specimens, which is a variation of the DC[T] test that can be run in the same testing apparatus. Chapter 3 described the suitability of C[T] test for evaluation of fracture energy in TBOs. In order to minimize the effect of air void and specimen dimensions on the measured fracture energy the specimen dimensions/overlay thicknesses and air voids for laboratory fabricated samples and field cores were kept the same.

7.3.2 Gap-Graded TBO Sections (SR-3 and SR-114)

Field cores were obtained one day after construction and loose mix was sampled from the project during construction. Using the plant produced mix from the project, laboratory
compacted samples were fabricated. Laboratory compaction was performed using the Superpave gyratory compactor in accordance with the AASHTO T-312 procedure. Field cores and laboratory samples were fabricated into C[T] test specimens. The specimen preparation as well as testing procedure for the C[T] were described in Chapter 3. Fracture tests were conducted at -12°C. This test temperature was selected based upon the recommendations from the ASTM D7313 test procedure for determining fracture energy of asphalt mixtures. Three test replicates were tested for each set of samples.

Comparison of C[T] test results for field cores and laboratory fabricated samples from SR-3 are presented in Figure 7.2. The coefficient of variation (CoV) for each set of test results is also shown on the figure. Note that the laboratory compacted samples (labeled as “LCM”) were manufactured using mixtures from each project location without tack coat emulsion. Laboratory compacted specimens were found to have an average fracture energy (520 J/m\(^2\)) which was 45% lower than field core samples (948 J/m\(^2\)). These results highlight the following key points:

1. TBO field constructed overlay systems have better fracture resistance properties than the base mix, and;

2. The spray paver construction process significantly improves the fracture resistance of the overlay; the upward permeation of the tack coat emulsion is hypothesized to elicit this improvement (Ahmed et al., 2010).

Figure 7.3 presents a comparison of C[T] test results of field cores and laboratory fabricated samples from SR-114. The average fracture energy of field cores (886 J/m\(^2\)) was 46% higher than those of laboratory fabricated specimens (482 J/m\(^2\)). Once again, the two main differences between field and laboratory samples were the lack of tack coat and the spray paver construction process.
Dense-Graded TBO Sections (Route-T)

Fracture energy test results from three C[T] test replicates for all five sections are presented in Figure 7.4. A comparison of Section 1 and Section 3 fracture energy results indicates that the spray paver constructed overlay (TBO) had approximately 39% higher fracture resistance as
compared to the conventionally paved overlay with same materials (both overlay mix and tack coat emulsion). Sections paved with PMAE tack coat had approximately 40% higher fracture energy as compared to CSS tack coats. The results also indicate higher fracture energy in overlays constructed with 0.45 L/m$^2$ (0.1 gal/yd$^2$) tack rates compared to 0.68 L/m$^2$ (0.15 gal/yd$^2$) for both types of emulsions. These results suggest that, unlike the gap-graded bonded systems which exhibit higher fracture energy with higher tack coat application rate (both SR-3 an SR-114 consisted of 0.9 L/m$^2$), the dense-graded systems may reach a peak fracture resistance at a lower optimum tack coat application rate.

![Figure 7.4: Fracture Energies for Materials from Route-T](image)

7.4 CRACKING PREDICTION OF THIN BONDED OVERLAY SECTIONS

Finite element model and simulations results for various pavement sections presented in Table 7.2 were discussed in Ahmed et al., (2011). The results are presented in the form of extent of damage and cracking through the thickness of TBO as predicted by the simulation model. The values in the tables can perhaps be best understood through a simple example. If an overlay with 45 mm thickness is considered and the simulations show that 28% of the thickness is cracked and 72% is damaged, this will indicate that for the given loading conditions the overlay will have a 13 mm long crack through its thickness, and out of the remaining 32 mm, 23 mm (72% of 32 mm) has already begun to undergo damage. Thus only 9 mm of the 45 mm thick overlay is still
intact and undamaged. Based on the extent of damaged and cracked thicknesses predicted, a ranking of predicted cracking performance is also provided for all simulated overlays.

Table 7.2: Summary of Simulation Results (Ahmed et al., 2011)

<table>
<thead>
<tr>
<th>Section</th>
<th>Fracture Energy (J/m²)</th>
<th>Thermal Loading</th>
<th>Thermal + Tire Loading</th>
<th>Predicted Pavement Performance (1=best, 3 =worst)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% Thickness Damaged</td>
<td>% Thickness Cracked</td>
<td>% Thickness Damaged</td>
</tr>
<tr>
<td>Control</td>
<td>350</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>SR-3</td>
<td>948</td>
<td>12%</td>
<td>0%</td>
<td>43%</td>
</tr>
<tr>
<td>SR-114</td>
<td>889</td>
<td>18%</td>
<td>0%</td>
<td>68%</td>
</tr>
</tbody>
</table>

Based on the cracking predictions, it can be observed that, in general, the ranking of pavements follows the same trend as the fracture energy. However, it is also important to notice that although the trends are same, the amount of damage and cracking is not proportional to the fracture energies. This is expected, as the pavement simulation model allows for linking material property with the overall structural response of the system and it also allows for integrating various components of the pavement such as, time dependent non-uniform temperature boundary conditions, viscoelastic material behavior, non-linear fracture behavior, etc. For the gap-graded projects it can be seen that the control overlay is predicted to undergo thermal cracking during the critical event, whereas a limited amount of damage is incurred by the TBOs. Under combined thermal and tire loading cases, the TBO experiences a greater amount of damage as compared to thermal loading only. Simulation results for the SR-114 project indicate low potential for reflective cracking in this type of loading condition, whereas the SR-3 project was predicted to have very low cracking potential. However, in both cases a significant extent of the thickness is predicted to have undergone damage under these critical conditions, primarily due to the reduced
thickness of the overlay. When the tire load is centered over the underlying discontinuity in the deteriorated PCC pavement, the TBOs experience significant straining, the extent of which increases with reduced thickness.

Similar to the case of gap-graded projects, the overall ranking of cracking performance of the dense-graded sections follows the same trend as that of the fracture energies. In the case of this project, significant thermal cracking potential is predicted for Sections 1 and 5. The simulation results indicate that cracks will develop in a bottom-up direction; this type of cracking due to temperature loading is usually prevalent in overlays with PCC in the underlying pavement. Dave and Buttlar (2010) and Dave et al., (2010) explored this type of cracking behavior in asphalt overlays constructed over PCC pavement, which is commonly referred to as “thermal-reflective cracking.” Sections 3, 7 and 9 also show low to moderate potential for thermal-reflective cracking; with Section 3 having the greatest cracking potential and Section 7 having the least. All five sections in this project show some potential for reflective cracking. Sections 1 and 5 showed potential for fully formed reflective cracks during the critical events. Section 7 is expected to have the best reflective cracking resistance of all five sections, followed by Section 9 and then by Section 3. Since each of the sections simulated had some degree of structural deficiency in terms of working cracks in the existing pavement section, it is no surprise that the numerical modeling predicted some degree of reflective cracking potential. As mentioned before, TBOs are not designed to restore a significant amount of pavement structure, given their relatively thin application thickness. However, it is clearly shown that TBOs can be designed to have very high fracture energy, and that higher fracture energy will lead to slower cracking rates.

7.5 FIELD PERFORMANCE OF THIN BONDED OVERLAY PROJECTS

7.5.1 Gap-Graded TBO Sections (SR-3 and SR-114)

In the case of SR-3, the pre-paving survey indicated moderate to severe transverse cracking and some longitudinal cracking on the existing asphalt concrete overlay, as summarized in Figure 7.5(a). No maintenance was performed before paving the thin bonded overlay. After one year of service, the general condition of the pavement was good with no rutting, raveling or potholes. Figure 7.5(b) shows a typical view of the present pavement condition. Low to moderate severity
transverse cracks and a limited number of longitudinal cracks can be found. The location of these cracks suggests that most are reflective cracks, as presented in Figure 7.5.

a. Pre-paving Condition of the SR-3 Pavement Surface

b. Present Pavement Condition

Figure: 7.5 (cont. on next page)
c. Transverse Cracking of Varying Severity at Different Locations

d. Longitudinal Crack at the Outer Edge of the Pavement

e. Transverse Shoulder Crack Leading into the Pavement

Figure 7.5: SR-3 TBO Performance Overview after 1 Year of Service

The existing asphalt concrete surface on the SR-114 project had moderate to severe transverse and longitudinal cracking with areas of moderate fatigue cracking. Areas with severe cracking were repaired with partial depth patching and extensive crack filling was also performed on the cracks prior to TBO placement, Figure 7.6(a). Presently the pavement surface shows signs of low to moderate transverse and longitudinal cracking. Figure 7.6(b) provides a pictorial summary of the pavement condition after three years of service. The cracking pattern follows the pattern of pre-paving cracks, suggesting that these cracks have been reflected from existing distresses and patched areas through the thin overlay system. In no instance was the effect of overlay debonding apparent.
a. Condition of Pavement at the Time of TBO Construction on SR-114

b. Extent of Cracking after Three Years in Service for SR-114

b. (continued) Extent of Cracking after Three Years in Service for SR-114

Figure 7.6: Condition of Pavement at the Time of Construction and after Three Years in Service
7.5.2 Dense-Graded TBO Sections (Route-T)

This project was paved in 2008 on an aged multi-layered asphalt concrete surface over jointed PCC. Pavement condition surveys were performed annually and Figure 7.7 illustrates the performance of various sections in terms of length of cracking in feet per 1000 feet of pavement length. Notice that the cracking amount prior to construction of the TBO is also shown on the plot. At the end of one year in service, Section 1 showed a significant amount of cracking, while Sections 5 to 9 showed minimal cracking. This indicates the difference between sections paved using the spray paver (Sections 3, 5, 7 and 9) when compared to conventionally constructed control section (Section 1). At the end of year 2, the cracking amount indicates that the higher tack coat application rate, especially the sections utilizing PMAE tack coat material, led to a delay in the reflection of underlying cracks.

![Figure 7.7: Extent of Cracking on Route-T Project](image)

### 7.6 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

An evaluation of the cracking potential of thin bonded overlay systems has been presented in the context of seven pavement sections, along with laboratory fracture testing and computer simulation. The laboratory testing and numerical simulation results were found to match reasonably well with the early field performance data. Each of the pavement sections simulated
had some degree of structural deficiency in terms of working cracks in the existing pavement section. Thus, numerical modeling predicted some degree of reflective cracking potential in each section. However, it was clearly shown that TBOs can be designed to have very high fracture energy, and that higher fracture energy will lead to slower cracking rates. Based upon laboratory testing, simulations and field performance, the following conclusions can be drawn:

1. Use of polymer modified asphalt emulsion (PMAE) for tack coat improves the cracking resistance of thin bonded overlays.

2. In general, high tack coat application rate improves the cracking resistance of TBOs. In the present study, application rates up to of 0.90 L/m$^2$ for gap-graded and 0.67 L/m$^2$ for dense-graded mixtures were evaluated.

3. An improvement in cracking resistance at high tack coat application rates is expected for overlays constructed using the spray paver technology. Increased cracking resistance is anticipated from upward migration of tack coat into the overlay during construction.

4. For dense-graded mixtures, a tack coat application rate above 0.45 L/m$^2$ decreased cracking resistance in laboratory testing and simulation results. However, a marginal increase in field performance was observed after two years of service.

5. The use of laboratory testing and simulation results is a viable approach for optimizing the design of thin bonded overlays.

This study was limited to data from seven field sections. Future studies should be conducted to expand on the present study as well as to explore other variables. Based on the findings of this study, the following recommendations are made:

1. TBOs are a viable rehabilitation option for deteriorated pavements. Laboratory testing, numerical simulations and early field data indicate that there is relatively low thermal and reflective cracking potential in these systems.

2. More studies are needed to further explore upon the effect of tack coat application rate on the cracking resistance of TBOs. From this study it is evident that the optimal tack coat rate might vary with the type of overlay mixture, especially based on the type of gradation (gap versus dense). Additionally, the optimum application rate may differ depending upon the characteristic measured, i.e., bulk fracture vs. interface bond vs.
rutting behavior, and a truly optimized system must consider the balance between these performance criteria as guided by traffic, environment and desired performance attributes.

3. Viability of newer asphalt technologies, such as warm mix asphalt for construction of TBOs as well as their performance should be studied.

4. Moisture damage plays an important role in the deterioration of asphalt pavements and overlays. For TBOs, the effect of moisture should be included in future studies.
CHAPTER 8 – EFFECTS OF TACK COAT EMULSION PERMEATION ON FRACTURE RESISTANCE OF THIN BONDED OVERLAYS

8.1 INTRODUCTION

The thin bonded overlay construction process enables application of asphalt emulsion just inches ahead of the mixture placement. As shown in previous chapters, this single pass paving operation results in permeation of the tack coat emulsion into the overlay mixture through a thermodynamic process. The extent of upward migration of emulsion in the overlay thickness direction is influenced by mixture gradation and tack coat emulsion type and application rate. Fracture evaluation of the field installed and laboratory fabricated thin bonded overlays demonstrate the significance of these factors in improving their fracture properties (Ahmed et al., 2010a). However, very little is known about the exact physical nature of this material gradation, which is required in order to accurately model and to optimize this material system.

This chapter provides insight on the physical manifestation of tack coat emulsion permeation through a controlled laboratory designed experiment. Two mixtures with distinctly different gradations were utilized at five application rates of tack coat emulsion. Prepared samples with adjusted emulsion were tested for IDT creep, tensile strength and fracture. Bulk and fracture properties obtained through this testing suite were used as model inputs to simulate cracking behavior in the graded TBO system. Tack coat upward permeation in the field installed TBO was characterized through analysis of digital images using the Image J software. Scanned images of field core samples were processed and analyzed to track gray scale pixel intensity through the thickness of overlay, which were then correlated with emulsion content migration. The characterized TBO gradient was then modeled in numerical simulations using the finite element method in conjunction with cohesive zone fracture modeling. Material properties (bulk and fracture) obtained at varying asphalt contents were assigned through the overlay thickness to simulate the graded material properties that exist in TBOs. Fracture properties obtained through simulations were compared with uniform (without added emulsion) mix samples. This
comparison was designed to help gain a better understanding the phenomenon of tack coat emulsion permeation and also to assess the usefulness of the image analysis technique for this type of application.

8.2 EXPERIMENTAL DESIGN

8.2.1 Material Matrix

Two mixtures sampled from the project sites during construction were used in this experimental study. These mixtures include a 9.5 mm, PG 70-28, gap-graded (GG) mixtures with 5.4% designed asphalt content (AC) and a 9.5 mm, PG 70-22, Superpave dense-graded (DG) mixture with 5.8% AC. Emulsions procured from respective projects were added at five rates and mixed with HMA at mixing temperatures determined for the specific projects. These emulsion adjustment rates are 0%, +0.5%, +1.0%, +1.5% and +2.0% by the weight of the mix. Details on sample preparation are enumerated in ensuing sub-section.

8.2.2 Sample Preparation Process

Plant produced mixtures sampled from the project site during construction were heated in the oven to the mixing temperature. Measured amounts of emulsion at room temperature were added and mixed with the preheated HMA in mixing bucket. Mixture with emulsion was heated back to compaction temperature and compacted using Superpave gyratory compactor (SGC) in accordance with AASHTO T-312. SGC samples were cooled down to room temperature before fabricating test specimens. All 170 mm tall SGC samples were sliced to obtain three test replicates in each case.

8.2.3 Laboratory Testing Suite

Bulk and fracture testing of both mixtures at five asphalt content increments were carried out on laboratory prepared samples. Material creep compliance was determined at three temperatures (PG LT, PGLT+10°C and PGLT+20°C) and tensile strength at PGLT+10°C in accordance with AASHTO T-322. The DC[T] test was utilized to obtain fracture properties of these mixtures at all emulsion adjustment levels at an intermediate temperature (PGLT+10°C) following the ASTM D7313 recommendation. Three replicates were tested in each case.
8.3 TEST RESULTS AND DISCUSSION

8.3.1 Fracture Test Results

Fracture energies of both mixtures at five emulsion increments are summarized in Figure 8.1. Fracture properties of a dense-graded (DG) mixture at -12°C are presented in Figure 7.1. Test results indicate that mixture fracture energies increase with increased emulsion in the mix. For this particular mixture, cracking resistance improved (from 637 to 873 J/m$^2$) by 37% by adding 2% emulsion above the mixture design optimum (5.8%). A similar trend for the fracture properties of the gap-graded (GG) mixture tested at PGLT+10°C (-18°C) was observed. DC[T] test results indicated a 56% increase in fracture energy (from 337 to 590 J/m$^2$) for this gap-graded mixture with 2% increase in asphalt content, Figure 8.3. The gap-graded mixture demonstrated 19% higher improvement in fracture properties compared to the dense-graded mix with the same increase of effective asphalt content. This observation correlates with the general tendency of gap-graded mixtures.

![Fracture Energy Gradient of Both Mixtures at Five Emulsion Increments](image)

Figure 8.1: Fracture Energy Gradient of Both Mixtures at Five Emulsion Increments
Figure 8.2: DC[T] Test Results of 9.5 mm, PG 70-22 Dense-Graded Mixture at Five Asphalt Contents, Tested at -12°C

Figure 8.3: Fracture Properties of 12.5 mm, PG 70-28 Gap-Graded Mixture at Five Asphalt Contents, Tested at -18°C
8.3.2 Bulk Properties

Creep compliance and tensile strength of both mixtures at all five asphalt content adjustment levels were determined in accordance with AASHTO T-322. IDT creep compliance was determined at three temperatures (PG LT, PGLT+10°C and PGLT+20°C) and tensile strength at PGLT+10°C for both mixtures. Compliance master curves are presented in Figure 8.4 and Figure 8.5. Mixture compliance increases with increase in the asphalt content (by adding emulsion) in both cases; however gap-graded mixture is more sensitive to changes in %AC owing to its void structure. Tensile strength results for both mixtures are shown in Figure 8.6 and Figure 8.7. For both mixtures tensile strength reached peak at an intermediate increase in asphalt content and then dropped. For gap-graded mixture peak was observed at 6.4 %AC with an average of 4.68 MPa. Similarly, the dense-graded mix peaked at an average strength of 5.04 MPa at 7.3%AC.

Figure 8.4: Creep Compliance Master Curves of 9.5 mm, PG 70-22 Dense-Graded Mixture at Five Asphalt Contents
Figure 8.5: Creep Compliance Master Curves of 9.5 mm, PG 70-28 Gap-Graded Mixture at Five Asphalt Contents

Figure 8.6: Tensile Strength of 9.5 mm, Dense-Graded Mixture Manufactured with PG70-22 Tested at -12°C
8.4 TRACING TACK COAT PERMEATION USING IMAGE ANALYSIS

The commercially available image analysis software “Image J” (http://rsbweb.nih.gov/ij/) was utilized to trace the tack coat emulsion permeation in thin bonded overlays. This software measures grey scale pixel intensity of the scanned image. Each pixel of the scanned image has a color associated with it, which is translated to grey scale. Gray scale intensity varies from pixel to pixel depending upon its color shade and tone. The potential of Image J to differentiate gray scale intensities of pixels along a line was utilized in the study. Scanned images of field cores were processed to refine the images as shown in Figure 8.8.

Gray scale intensities of pixels along horizontal lines are traced with the “Line Profile Plot” tool. An example is shown in Figure 8.9. This profile plot illustrates that as the gray scale becomes darker its value decreases, as shown in the legend bar in Figure 8.9; black is associated with 0 gray scale value. These gray scale values were determined along a number of horizontal lines at known depths of the overlay utilizing the profile plot tool. The resolution of the scanned image was selected such that a 75 mm (3 inch) length of horizontal line is discretized by approximately 1000 pixels. The average gray scale value of 1000 pixel was calculated and
assigned to the horizontal line. Figure 8.10 and Figure 8.11 show the gradient of gray scale values through the overlay thickness for field core images shown in Figure 8.8. The following points are observed:

1. Gray scale values decrease in the proximity of the interface and are smallest at the interface, indicating darker shading in this region. The dark shade in the proximity of the interface clearly indicates the high content of tack coat emulsion present in this location.

2. The magnitude of gray scale values are significantly smaller for gap-graded TBOs then dense-graded (62 versus 105) at the interface as shown in Figure 8.10 and Figure 8.11.

3. A gray scale gradient can be observed within the lower third of the overlay thickness, indicating the zone of activity of tack coat emulsion permeation. This trend is more significant for gap-graded thin bonded overlays, as shown in Figure 8.11.

4. The average gray scale values remain almost constant in the top $2/3$rd of the overlay for both mixtures.
Gray scale values versus thickness of the overlay for both field installed thin bonded overlays were plotted in Figure 8.12. Linear trend lines through the data indicate that the gray scale gradient is steeper in case of gap-graded TBO as compared to the dense-graded system. The slope of the trend line indicates low gray scale values through the bonded overlay thickness in the lower 1/3rd. This darker gray shade indicates traces of permeated tack coat emulsion.

Figure 8.9: Typical Gray Scale Values of Pixels along Line AA (Figure 8.8)

Figure 8.10: Gray Scale Gradient through the Thickness of Dense-Graded TBO
**Figure 8.11:** Gray Scale Gradient through the Thickness of Gap-Graded TBO

**Figure 8.12:** Comparative Gradient of Pixel Intensities through the Overlay Thickness for Gap and Dense-Graded Mixtures
8.5 PREDICTION OF PAVEMENT CRACKING PERFORMANCE

8.5.1 Modeling of Graded Overlay Structure

Graded overlays structures were modeled with varying asphalt contents through their thickness for both mixes. The variation of the %AC through the overlay thickness represented the emulsion permeation and followed the same gradient as that of pixel intensities shown in Figure 8.12. The asphalt content gradient through the overlay thickness for gap and dense-graded mixtures is presented in Figure 8.13. Material properties; i.e., creep compliance, tensile strength and fracture energy obtained through testing at five emulsion increments were assigned to graded structures following the material gradation through the thickness. Figure 8.14 illustrates the assigned fracture energy profile for graded structures for both mixes. Creep compliance and tensile strength were also assigned according to the measured material gradient from image analysis.

8.5.2 Numerical Simulations

Graded overlays for both mixes were modeled following techniques described by Dave, 2010. Numerical simulation results are presented in Table 7.2 for graded and uniform/homogeneous overlays for both mixes. Homogenous mix overlays represent control sections for both simulation scenarios. These results represent the pavement structure’s response to both thermal and combined (thermal plus tire) loading. The existing pavement structures and simulation model described in Chapter 7 were utilized for these simulations. Cracking performance of graded and homogenous overlays is presented in terms of percent overlay thickness damaged (in post-peak, ‘softening’ range) and cracked (separated crack faces).

The values in Table 7.2 can perhaps be best understood through a simple example. Considering an overlay with 25 mm thickness, the simulations results show that 44% of the thickness is damaged and 0% is cracked. This indicates that for the given loading condition there will be no cracking, and the lower 11 mm of the overlay thickness has undergone damage. Based on the extent of predicted damaged and cracked thicknesses, a ranking of predicted cracking performance is also provided for all four simulated overlays. Comparison of graded and
homogenous overlay cracking predictions clearly demonstrates that tack coat permeation significantly improves the fracture resistance of graded system. Numerical simulation predicts that graded overlay system with dense-graded mixture is more crack resistant than gap-graded, which is obvious in this case. Because dense-graded mixture has higher fracture energy and tensile strength compared to gap-graded mix.

Figure 8.13: Asphalt Content Gradient through the Overlay Thickness for Both Cases

Figure 8.14: Fracture Energy Profile of Graded Overlays for Both Mixes
Table 8.1: Summary of Numerical Simulation Results

<table>
<thead>
<tr>
<th>Section</th>
<th>Thermal Loading</th>
<th>Thermal + Tire Loading</th>
<th>Predicted Pavement Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Thickness Damaged</td>
<td>% Thickness Cracked</td>
<td>% Thickness Damaged</td>
</tr>
<tr>
<td>GG Homogenous Overlay</td>
<td>32%</td>
<td>0%</td>
<td>-</td>
</tr>
<tr>
<td>GG Graded Overlay</td>
<td>20%</td>
<td>0%</td>
<td>76%</td>
</tr>
<tr>
<td>DG Homogenous Overlay</td>
<td>0%</td>
<td>0%</td>
<td>80%</td>
</tr>
<tr>
<td>DG Graded Overlay</td>
<td>0%</td>
<td>0%</td>
<td>44%</td>
</tr>
</tbody>
</table>

8.6 SUMMARY

An experimental study was conducted to provide insight on tack coat emulsion permeation in terms fracture resistance improvement of thin bonded overlays, leading to the following conclusions:

1. Comparison of fracture and bulk properties indicates that added tack coat emulsion for mixtures at optimum AC improves the fracture resistance of the material.

2. The gap-graded mix demonstrated higher improvement in fracture resistance than dense-graded mix when incorporating the same amount of emulsion. This response is attributed to the capacity of the mix to absorb higher amount of emulsion, owing to its void structure.

3. Limited data reveals that image analysis is a useful tool in tracing tack coat emulsion permeation gradient through the TBO thickness. It was observed that emulsion wicks up to approximately 1/3rd of the overlay thickness for the analyzed thicknesses of 30 mm for DG and 20 mm for GG TBOs. It is assumed that the 1/3rd criteria may not hold true for thicker overlays and emulsion would impregnate a limited overlay thickness instead, depending upon the type of mix and tack coat application rate. Considering the air voids and typical tack coat application rate of field constructed TBOs, this thickness may vary from 6 to 10 mm.
4. Image analysis was shown to be a very useful tool for characterizing tack coat emulsion gradient and in formulating graded overlays for numerical simulations.

5. Simulation results clearly illustrated the tack coat emulsion permeation significantly improves the cracking resistance of graded overlay systems.
CHAPTER 9 – CRACKING EVALUATION OF ASPHALT CONCRETE IN CONTEXT OF WARMER TEST TEMPERATURES

9.1 INTRODUCTION

Cracking is a major distress in asphalt concrete pavements and is commonly classified into three main categories. These categories are: fatigue cracking (due to repeated wheel loads), low temperature cracking (caused by thermal stresses), and reflective cracking (propagation of existing cracks through the overlay). Although these cracking distresses (fatigue, thermal, and reflective) develop under different combinations of climatic conditions and applied stress states, the rate and potential magnitude of cracking in all three cracking categories is heavily influenced by material fracture resistance. There are various test procedures to determine fracture properties of asphalt concrete, each with their own advantages and disadvantages. The suitability of the C[T] and DC[T] tests to measure fracture resistance of asphalt concrete at low temperatures has been demonstrated earlier (Ahmed et al., 2010b; and Wagoner et al., 2005b) This chapter evaluates the efficacy of the C[T] and DC[T] to determine fracture properties of asphalt concrete at warmer temperature. The key questions in this context would be: are these tests repeatable at warmer temperatures, and do these qualify as valid fracture tests? The repeatability of the test would be determined by statistical analysis. Whereas, through limited numerical modeling, the validity of the test at warmer temperatures will be explored. Moreover, the effects of loading rate and test temperature on the fracture properties of asphalt concrete mixtures will also be evaluated.

9.2 MOTIVATION

There is a wide array of tests to determine various parameters to predict cracking performance of asphalt concrete, each with varying degrees of repeatability. The present study is designed to determine applicability of the C[T] and DC[T] tests at warmer temperatures. If found suitable; these would enable extraction of material fracture properties at warmer test
temperatures. Fracture properties determined in the warmer temperature regime may be helpful, for instance, in predicting reflective cracking performance of asphalt concrete. This would enable agencies and practitioners to obtain material fracture properties by utilizing quick and repeatable fracture tests that could be evaluated for their use in controlling the cracking behavior of asphalt concrete in a more general sense. To reach that end, the preliminary development work entailed development, calibration and validation of appropriate models with fracture input parameters such as fracture energy and tensile strength and their use in a cohesive zone type fracture model (Paulino et al., 2004; and Song, 2006) to assist in the decomposition of energy dissipation through fracture and creep for fracture tests run at intermediate temperatures. This chapter will provide a starting point in that direction by evaluating suitability of C[T] and DC[T] tests for characterizing the cracking resistance of asphalt concrete at warmer temperatures.

9.3 EXPERIMENTAL DESIGN

9.3.1 Material Matrix

Two 9.5 mm NMAS fine graded surface mixtures manufactured with PG 64-22 at plant and laboratory were used in Phase-I of this experimental study. Both mixes were prepared using same aggregate and binder with same mix design, with the only difference of production at plant versus preparation in laboratory. These mixtures were compacted at 7% air voids in the laboratory using Superpave gyratory compactor (SGC) in accordance with AASHTO T-312. Thirty 115 mm tall SGC samples were prepared from both mixes with 0.5% variation from design air voids for subsequent testing. The C[T] test was utilized to determine fracture properties of both mixes in Phase-I. Phase-II of the testing involved evaluating loading/CMOD opening rate effects on the ability to measure fracture resistance of asphalt concrete at 20°C with reasonable accuracy. Loading rate dependency was evaluated using the DC[T] test. It is important to reiterate that both test procedures (DC[T] and C[T]) produce nearly identical results (fracture energy values) for non-graded, homogenous/uniform mixes when similar fracture ligament areas are used (Chapter 3).

9.3.2 Laboratory Testing Suite

Indirect tension IDT and C[T] test specimens were fabricated utilizing both mixes for bulk and fracture testing. Creep compliance was determined at three temperatures (-12°C, 0°C and
+12°C) and tensile strength at 0°C in accordance with AASHTO T-322. The C[T] test was utilized to obtain fracture properties of these mixtures at three temperatures (-12°C, 0°C and +12°C) in the first phase of the study. C[T] fracture test specimen fabrication and testing was carried out in accordance with the procedure outlined in Chapter 3. Three replicates were tested in each case. Phase-II fracture testing was carried using the DC[T] and results will be presented and discussed in next section.

9.3.3 Test Results and Discussion

**Bulk Properties**

Material bulk properties, such as creep compliance and tensile strength indicate its viscoelastic response and tensile strength. Creep compliance master curves for both mixes were developed utilizing test data at three temperatures (-12°C, 0°C and +12°C) as shown in Figure 9.1. Plant produced mix was found to be somewhat less stiff than the same mix prepared in the laboratory in this case. IDT tensile strength results of both (plant produced and Laboratory prepared) mixes are presented in Figure 9.1. The average tensile strength of plant produced mix was 2.69 MPa with a CoV of 4%. The laboratory prepared mix averaged at 2.04 MPa with 9% CoV.

![Figure 9.1: Creep Compliance Master Curves for 9.5 mm NMAS, PG 64-22 Laboratory Prepared and Plant Produced Mixtures](image-url)
Figure 9.2: IDT Tensile Strength Results for 9.5 mm NMAS, PG 64-22 Laboratory Prepared and Plant Produced Mixtures

Fracture Test Results

Figure 9.3 and Figure 9.4 presents the C[T] fracture test results of both the mixes at three test temperatures (-12°C, 0°C and +12°C). An increase in test temperature resulted in increased fracture energy for both of the mixes. An increase in test temperature from -12°C to 0°C resulted in 95% higher experimental (global) fracture energy for both mixes, whereas and additional 37% to 56% increase in fracture energy was measured by raising the test temperature from 0°C to +12°C for plant produced and laboratory prepared mixes respectively.

So far, the C[T] test has been successfully utilized at lower temperatures around PGLT+10°C for a range of mixture and field core samples. The test results demonstrate its repeatability and suitability at lower temperatures. The suitability of C[T] and DC[T] tests to measured fracture properties of asphalt concrete at warmer temperatures will be evaluated in the following section.
Figure 9.3: C[T] Fracture Results at Three Test Temperatures for Both Mixtures

Figure 9.4: Fracture Energies of Both Mixes at Three Test Temperatures
9.4 FRACTURE TESTING AT WARMER TEMPERATURE

9.4.1 Loading Rate Dependency

DC[T] and C[T] tests were carried out in displacement control mode at a crack mouth opening displacement (CMOD) opening rate of 0.017 mm/s (1mm/min, 0.00067 inch/s) at colder temperatures (≤ 0°C). At warmer temperatures asphalt concrete is less stiff and testing viscoelastic material at slow loading rates generally results in higher creep energy dissipation. The effect of loading rate on measured load-CMOD response for four replicates is presented in Figure 9.5. Comparison of CMOD and crack tip opening displacement (CTOD) for two loading rates (1.5 and 3.0 mm/min) are also presented in Figure 9.6. CTOD gages are mounted on either face of the specimen at the notch tip and measures the displacements without the bending effect along the notch. Viscoelastic behavior of asphalt concrete at warmer test temperatures usually tends to increase this bending effect. Four CMOD opening rates (1.5, 2.0, 2.5 and 3.0 mm/min) were considered for each of three mixes. Table 9.1 illustrates the load-CMOD response in terms of peak load, $P_p$ and load at 6.25 mm opening of CMOD, $P_{6.25}$. A CMOD of 6.25 mm is the range of the clip-on gage used for asphalt concrete fracture tests in this study. Based on the limited test data at warmer temperatures, the following observations may be made:

1. An increase in CMOD opening rate generally increases the initial stiffness of load-CMOD response, indicating that the more desired quasi-brittle material behavior of asphalt concrete in fracture testing is being induced.

2. $P_{6.25}$, (load at 6.25 mm opening of CMOD) shows the remaining load capacity of the material when the full range of the CMOD gage is reached. An increase in the ratio of $P_{6.25}$ and $P_p$ with decreasing CMOD opening rate shows that the material has undergone damage but still can hold a significant amount of load. For example; the specimen can still hold 85% of the peak load at the full range of CMOD at a 1.5 mm/min loading rate, while it reduces to 16% by increasing the loading rate to 3.0 mm/min.

3. Slope of the post-peak / softening curves becomes steeper at faster loading rate, indicating behavior that is more representative of quasi-brittle material.
4. It was observed that slower CMOD opening rates does not cause discrete crack propagation and material separation ahead of the notch tip, rather it results in localized damage and crack blunting as illustrated in Figure 9.7.

5. While testing all three mixes at a CMOD opening rate of 3 mm/min and 20°C, discrete crack propagation and material separation ahead of the notch tip was observed, indicating that the desired fracture behavior in the quasi-brittle, viscoelastic material state was induced.

6. Comparison of displacements measured at the crack mouth (CMOD) versus crack tip (CTOD) for two loading rates in Figure 9.6 illustrates that the ratio of CTOD/CMOD at the faster loading rate (3 mm/min) is 51% compared to a ratio of 31% at 1.5 mm/min. The relative opening displacements at the notch tip versus crack mouth shows the bending of the notch arms. At slower loading rates, a higher proportion of the applied load (~100-31=69%) is consumed in creep dissipation.

7. Loading rate dependency of the 9.5 mm NMAS mix with PG 64-22 binder at three rates (2.0, 3.0, 4.0 mm/min) at 20°C is presented in Table 9.2. Differences in fracture energy values calculated up to 0.1 kN load and 6.25 mm opening of CMOD show that there is no significant effect of loading rate for this particular mix at 20°C for the two higher loading rates.

8. These observations are based on a test temperature of 20°C, up to the loading rate of 3 mm/min for limited mixes. Testing at higher temperatures (>20°C) and at faster loading rates using variety of mixes is proposed as a follow up to this study.

Table 9.1: Effect of CMOD Opening Rate on Load-COMD Response

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>CMOD Rate, (mm/min)</th>
<th>Peak Load, P_p, (kN)</th>
<th>Load @ 6.25 mm CMOD Opening, P_6.25, (kN)</th>
<th>P_6.25 / P_p</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1_1.5</td>
<td>1.5</td>
<td>0.39</td>
<td>0.33</td>
<td>0.85</td>
</tr>
<tr>
<td>Z2_2.0</td>
<td>2.0</td>
<td>0.92</td>
<td>0.32</td>
<td>0.35</td>
</tr>
<tr>
<td>D1_2.5</td>
<td>2.5</td>
<td>0.78</td>
<td>0.17</td>
<td>0.22</td>
</tr>
<tr>
<td>D2_3.0</td>
<td>3.0</td>
<td>0.93</td>
<td>0.15</td>
<td>0.16</td>
</tr>
</tbody>
</table>
Table 9.2: Effect of Loading Rate on Fracture Energy of PG 64-22, Mix at +20°C

<table>
<thead>
<tr>
<th>CMOD Rate, (mm/min) (a)</th>
<th>Fracture Energy_6.25mm CMOD (J/m²) (b)</th>
<th>Fracture Energy_up to 0.1kN Load (J/m²) (c)</th>
<th>Difference (c-b) (J/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>1178</td>
<td>1289</td>
<td>111</td>
</tr>
<tr>
<td>3.0</td>
<td>1408</td>
<td>1537</td>
<td>129</td>
</tr>
<tr>
<td>4.0</td>
<td>1413</td>
<td>1518</td>
<td>105</td>
</tr>
</tbody>
</table>

Figure 9.5: Load-CMOD Response during DC[T] Fracture Tests at Varying Loading/CMOD Opening Rates

Note: The group of 1st letter and number indicates the mix type followed by a decimal number indicating the loading/CMOD opening rate in mm/min in the legend of Figure 9.5.
Figure 9.6: Load-CMOD/CTOD Responses during DC[T] Tests at Two Loading Rates

Discrete Material Separation Ahead of Notch at Faster CMOD Opening Rates (2.5–3.0 mm/min)
Crack Blunting and Localized Damage at Notch at Slower CMOD Opening Rates (< 2.5 mm/min)

Figure 9.7: Crack Initiation and Propagation Response at Varying CMOD Rates

Discrete Crack

Crack mouth opening of 6.25mm

Localized Damage

Discrete Material Separation Ahead of Notch at Faster CMOD Opening Rates (2.5–3.0 mm/min)
Crack Blunting and Localized Damage at Notch at Slower CMOD Opening Rates (< 2.5 mm/min)
9.4.2 Numerical Simulations of C[T] Test

Numerical simulation results of C[T] at warmer temperatures are presented in this section, details on numerical simulations are discussed elsewhere (Ahmed et al., 2010b). These simulations were designed to evaluate the suitability of the C[T] fracture test in the context of warmer temperatures and also to determine if fracture properties of the asphalt concrete could be successfully extracted from the proposed test procedure at these temperatures. Fracture, creep compliance and tensile strength results of both mixes evaluated in the last section (9.3) were used as material inputs for these simulations. Numerical simulations were performed to extract local fracture energy values at three temperatures (-12, 0 and +12°C). The extracted local properties plotted in Figure 9.8 shows linear trend. In addition the C[T] tests were also conducted at 3 mm/min CMOD opening rate at +20°C. Summary of laboratory measured and simulated C[T] test results in Table 3.3 and Figure 9.9 illustrate the following points:

1. Ratio of the local properties, extracted through simulation and laboratory measured global fracture energy values is more than 0.9 in most cases. The higher ratio indicates smaller creep dissipation, a desired response.

2. Extracted fracture energy values at +20°C matched well (ratio > 0.9) with C[T] test results conducted at 3 mm/min CMOD opening rate. It verifies that faster loading/CMOD rate is more appropriate and ensures a higher ratio of applied load is consumed by the fracture process.

3. Comparison of local versus global response at +10°C with the remainder of the data set in Table 3.3 indicates that an increase in the loading/CMOD opening rate from 1 to 2 mm/min would lead to a decrease in creep dissipation. Similar extrapolation can be proposed for 5 and 10°C.

4. The relatively small difference between measured global energy and local energy input to the cohesive zone model indicates that with minor calibration it is possible to extract a fundamental material fracture property from the proposed test procedure.

5. C[T] test results are repeatable as indicated by the reasonably low CoV values obtained at all four test temperatures. It is interesting to note that the laboratory prepared mixes have relatively higher CoVs than plant produced mixes for the entire test matrix.
6. These findings are based on the two mixes introduced in section 9.3. Both of these mixes are used in a warmer climate and are manufactured with a relatively stiff PG 64-22 binder (that is, the binder is relatively stiff when compared to other PG 64-22 binders). Their measured and simulated responses exhibit their stiff nature with the exceptionally high ratio of 0.9 for local (simulated) versus global (measured) fracture energies. Generally the ratio of measured versus simulated fracture energies is 0.6 to 0.7 for asphalt concrete, even when tested at lower temperatures.

![Figure 9.8: Local Fracture Energy Values of Both Mixes at Different Temperatures](image)

![Figure 9.9: Measured and Simulated Fracture Energies of Both Mixes at Four Temperatures](image)
Table 9.3: Summary of Measured and Simulation Fracture Energy Results at Four Temperatures for Both Mixes

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Test Temperature, (°C)</th>
<th>Peak Load, (kN)</th>
<th>Measured/Global Average Gf, (J/m²)</th>
<th>C/T Test CoV, (%)</th>
<th>Simulated /Local Gf, (J/m²)</th>
<th>GfL /GfG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab Prepared</td>
<td>-12</td>
<td>2.83</td>
<td>241</td>
<td>8</td>
<td>227</td>
<td>0.94</td>
</tr>
<tr>
<td>Plant Produced</td>
<td>-12</td>
<td>2.80</td>
<td>243</td>
<td>8</td>
<td>229</td>
<td>0.94</td>
</tr>
<tr>
<td>Lab Prepared</td>
<td>0</td>
<td>3.05</td>
<td>475</td>
<td>14</td>
<td>437</td>
<td>0.92</td>
</tr>
<tr>
<td>Plant Produced</td>
<td>0</td>
<td>3.27</td>
<td>476</td>
<td>8</td>
<td>438</td>
<td>0.92</td>
</tr>
<tr>
<td>Lab Prepared</td>
<td>+12</td>
<td>1.64</td>
<td>745</td>
<td>4</td>
<td>653</td>
<td>0.88</td>
</tr>
<tr>
<td>Plant Produced</td>
<td>+12</td>
<td>1.43</td>
<td>653</td>
<td>12</td>
<td>561</td>
<td>0.86</td>
</tr>
<tr>
<td>Lab Prepared</td>
<td>+20</td>
<td>1.03</td>
<td>*841</td>
<td>4</td>
<td>800</td>
<td>0.95</td>
</tr>
<tr>
<td>Plant Produced</td>
<td>+20</td>
<td>1.02</td>
<td>*757</td>
<td>11</td>
<td>690</td>
<td>0.91</td>
</tr>
</tbody>
</table>

* Tests at +20°C were carried out at CMOD opening rate of 3 mm/min compared to all other tests at 1mm/min

9.4.3 Additional Exploration and Numerical Simulations of the DC[T] Test

This sub-section will provide numerical exploration of the proposed loading/CMOD opening rate at warmer test temperatures for the DC[T] test. Three distinctly different mixtures were selected to evaluate that a loading/CMOD opening rate of 3 mm/min is appropriate at +20°C for a range of mixtures utilizing DC[T] test. These mixes include; (1) 9.5 mm NMAS gap-graded Novachip mix with PG 70-28 binder, (2) 12.5 mm NMAS SMA with PG 76-22 and (3) 9.5 mm NMAS Illinois surface mix with PG 64-22. Three replicates were tested in each case and DC[T] fracture test results are presented in Figure 9.10. Low values of the statistical parameter, CoV verifies the repeatability of test results under the proposed loading and temperature conditions for a range of asphalt concrete mixtures. The Load-CMOD response of these mixtures is presented in Figure 9.11. Note that test data was extrapolated to 0.1 kN in the post-peak region to calculate fracture energy in accordance ASTM D7313.

The experimental data recorded up to the CMOD opening of 6.25mm was utilized to extract local fracture energies of these three mixes. Numerical simulation results presented in Table 9.4 indicate that local extracted fracture energies (GfL) are in the range 44 to 56% of experimentally
measured global values ($G_{fG}$). The ratio of local versus measured fracture energies are about 10 to 15% lower than the typical values of asphalt concrete at lower temperatures, which indicates the presence of considerable viscous creep strain energy dissipation at warmer temperatures. But more interestingly, there is still significant fracture dissipation (40 to 60% range) noted in these tests. Load-CMOD response presented in Figure 9.12 showed a good match between the simulations and measured test data. It was interesting to observe that the unmodified, PG 64-22 binder had the highest fracture energy and peak load when tested under these conditions, as compared to the gap-graded and SMA mixtures, which contained polymer-modified binder.

Table 9.4: Comparison of Measured and Numerically Extracted Fracture Energies at Loading Rate of 3.0 mm/min and Test Temperature of +20°C

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Extracted Local Fracture Energy, ($G_{fL}$) (J/m$^2$)</th>
<th>Measured Global Fracture Energy, ($G_{fG}$) (J/m$^2$)</th>
<th>Ratio($G_{fL}$)/($G_{fG}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GG_PG70-28</td>
<td>433</td>
<td>927</td>
<td>0.44</td>
</tr>
<tr>
<td>SMA_PG76-22</td>
<td>581</td>
<td>1212</td>
<td>0.48</td>
</tr>
<tr>
<td>IL_PG64-22</td>
<td>793</td>
<td>1408</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Figure 9.10: DC[T] Test Results of Three Mixtures at +20°C at a Loading Rate of 3 mm/min, (Test Data extrapolated up to 0.1 kN)
Figure 9.11: Load-CMOD Response of Three Mixtures at +20°C at a Loading Rate of 3 mm/min, (Test Data extrapolated up to 0.1 kN)

Figure 9.12: Load-CMOD Response of Three Mixtures at +20°C and Fracture Energy Values Corresponds to 6.25 mm opening of CMOD.
Applicability of C[T] and DC[T] tests to characterize asphalt concrete in the context of warmer test temperatures has been presented in this chapter. Asphalt concrete bulk and fracture properties were evaluated at multiple temperatures for two selected mixes. Laboratory measured global fracture properties were compared with numerically extracted local properties obtained through simulation. Laboratory and simulation results demonstrated that asphalt concrete fracture properties can be measured with fair accuracy at warmer temperatures by adjusting loading/COMD opening rate. Effect of loading/CMOD opening rate on ability to measure asphalt concrete fracture properties was illustrated for four mixes. Based upon laboratory testing and numerical simulation results, the following conclusions can be drawn:

1. Fracture properties of asphalt concrete can be measured with reasonable accuracy utilizing C[T] and DC[T] tests up to a test temperature of +20°C.

2. Test temperature and loading rate demonstrated significant effects on the ability to measure asphalt concrete fracture properties. Both fracture tests provide a reliable measures of asphalt concrete fracture resistance at a loading rate of 1 mm/min at low temperatures (≤ 0°C). Following loading rates are proposed at warmer test temperatures to minimize viscous creep strain energy dissipation during the test:
   a. CMOD opening rate of 1.5 mm/min at test temperature of 5°C,
   b. CMOD opening rate of 2.0 mm/min at test temperature of 10°C,
   c. CMOD opening rate of 2.5 mm/min at test temperature of 15°C, and
   d. CMOD opening rate of 3.0 mm/min at test temperature of 20°C.

3. Low CoV values at all test temperatures demonstrates the repeatability of the test procedure at the proposed temperatures and loading rates and may enable researchers, practitioners and agencies to benefit from these findings by conducting the tests at warmer temperatures.

Based on the finding of this ongoing study, the following recommendations are proposed:

1. Proposed loading rates at corresponding test temperatures should be evaluated for more mixes.
2. Considering the potential for significant viscous creep strain energy dissipation at warmer test temperatures, it is proposed to check the formation and progression of the fracture process zone using the numerical simulation scheme presented chapter 3 (Ahmed et al., 2010b), and in the future using digital image correlation experimental techniques.

3. Higher test temperatures and loading rates should also be evaluated.
10.1 SUMMARY

This study introduced new techniques for fracture characterization of spray paver constructed thin bonded overlays and presented research findings across a number of different research thrust areas. These include: (a) a brief synopsis of the TBO paving process and the characteristic tack coat emulsion permeation phenomenon was presented; (b) an overview of the in-practice asphalt concrete fracture tests was presented to determine their applicability for bonded overlays; (c) development and discussion of the potential suitability of the \(C[T]\) test procedure was elaborated for such graded systems, and; (d) the suitability of the proposed fracture test procedure was evaluated to differentiate among the design variables of TBOs. In this context, field cores and plant produced HMA and emulsion samples were collected from a number of projects at the time of construction and subsequently fabricated and tested, leading to additional research results, including: (e) a laboratory composite specimen procedure was developed to represent the field installed TBOs to optimize their design; (f) a parametric study was conducted to demonstrate the effect of tack coat permeation in improving fracture and bulk properties of HMA; (h) application of an image analysis tool to track the emulsion impregnation gradient into the overlay was presented; (i) the applicability of the \(C[T]\) test in context of warmer test temperatures was also presented, and; (j) the efficacy of \(C[T]\) test results in predicting cracking performance was demonstrated utilizing numerical simulation and early field performance of TBO projects. Limited data on the early performance of field installed TBO systems is encouraging and the spray paver construction process seems to improve the overall performance of the mixtures.

The integration of laboratory testing and simulations using finite element based cohesive zone modeling is a viable approach to predict cracking performance of TBO. Numerical simulations results of pavement structure subjected to thermal and tire loading were compared with early performance of several field projects. This approach was used to clearly delineate
between the systems with lower and higher fracture energy levels in terms of extent of damaged / cracked overlay thickness under the simulated conditions.

Based upon laboratory testing, field visits, and numerical simulation results, findings of this study are presented as follows:

10.2 FINDINGS

1. The spray paver construction process renders TBOs significantly different than conventional HMA overlays both in composition and in their construction. Forensic investigation indicates that TBOs are graded in nature (composition varies vertically through their thickness). TBOs have three distinct differences from conventional HMA overlays, namely: (a) incorporation of polymer modified asphalt emulsion (PMAE); (b) a very high tack coat application rate (3 to 5 times greater than conventional overlays), and; (c) a delivery system designed to protect the heavy tack coat and to promote upward wicking of the tack coat into the asphalt mixture being placed immediately afterwards.

2. Tack coat emulsion wicking effect is thought to be a thermodynamic process occurring under the screed at elevated temperature (up to 375°C) that relies upon interconnected voids, and is therefore more pronounced in the TBOs with gap-graded mixes. The extent, amount and rate of the emulsion permeation depend upon HMA mix type, tack coat application rate, emulsion type, and the condition of the existing pavement surface. Gap-graded mixtures demonstrated higher capacity to accommodate tack coat emulsion and PMAE was found to improve the fracture properties more significantly than non-modified emulsions at the same application rate.

3. Composition of the spray paver constructed TBOs vary through their thickness and results in a binder-rich zone in the lower 1/3rd of the overlay. The emulsion migration phenomenon makes the TBOs graded in nature. The bottom of the layer aggressively bonds to the exiting pavement surface (Hanson, 2001; and Hakimzadeh et al., 2011), and the presence of the emulsion residue at the interface results in a waterproof membrane. The binder-rich zone presumably enhances the fracture resistance of the TBO.
4. The graded nature and the thickness of the TBO render the previously available asphalt concrete fracture tests unsuitable for such systems, thus, necessitating an exploration into other viable options to determine fracture resistance of TBOs with reasonable accuracy.

5. The C[T] test appears to be a viable test procedure for fracture characterization of TBO systems and can delineate variables such as; (a) composition of the bonded overlay; (b) type of tack coat emulsion applied, and; (c) optimum tack coat application rate in terms of fracture energy maximization. A provisional ASTM specification for the C[T] test is attached as Appendix A.

6. The C[T] geometry was found to produce stable crack growth during the test. Combined with the fact that low CoV values were obtained when testing a variety of mixture types; the efficacy of the recommended test procedures was clearly demonstrated in this study. Higher fracture energy values were measured in the C[T] test configuration as compared to the DC[T] configuration. As discussed before, this difference is anticipated due to the presence of a material gradation in the vertical direction.

7. Statistical analysis revealed that the C[T] test captures the full potential of TBO systems to resist vertically propagating thermal or reflective cracks. Numerical simulations using a cohesive zone model to validate the C[T] test procedure as having a fully developed fracture process zone. Moreover this test procedure enables extraction of fundamental fracture properties with a relatively small calibration factor, indicating the benefit of its potential integration with combined modeling/testing studies to predict the performance of bonded overlay systems.

8. Fracture properties of asphalt concrete were measured with reasonable accuracy utilizing the C[T] and DC[T] configurations up to an experimental test temperature of +20°C. Test temperature and loading rate demonstrated significant effects on the ability to measure asphalt concrete fracture properties. Both tests (C[T] and DC[T]) provided a good measure of asphalt concrete fracture resistance at a loading rate of 1 mm/min at low temperatures (≤ 0°C). The following loading rates are proposed to be used at warmer test temperatures to minimize the creep energy dissipation during the test:

a. CMOD opening rate of 1.5 mm/min at test temperature of 5°C,
b. CMOD opening rate of 2.0 mm/min at test temperature of 10°C,
c. CMOD opening rate of 2.5 mm/min at test temperature of 15°C, and
d. CMOD opening rate of 3.0 mm/min at test temperature of 20°C.

9. Composite specimen fabrication techniques for designing thin bonded overlays were presented in this study. Wet application of the emulsion on uniform and low textured surfaces compacted with a heated SGC top plate at 200°C closely resembles spray paver constructed thin bonded overlays. This composite specimen fabrication procedure yielded the most consistent results and can be used as a design tool to optimize the TBOs. Moreover composite specimens for interface bond and Hamburg wheel tracking (HWT) tests can be prepared using the same technique. A provisional ASTM specification for composite fabrication (Appendix B) also details the use of emulsions in both forms (wet and cured) and asphalt cement as a tack coat material for composite laboratory specimen manufacture.

10. Evaluation of the several field projects revealed that field constructed TBOs had better fracture resistance properties than the uniform mix and laboratory compacted composite samples with the same ingredients.

11. The cracking resistance of dense and gap-graded TBOs was found to be superior to those of traditionally applied overlays using conventional equipment.

12. Field constructed TBOs, irrespective of the mix type, displayed higher rutting resistance than the uniform mix and composite specimens with the same composition. HWT results indicated that spray paver constructed TBOs field samples are more rut resistant than laboratory prepared composite and mixture samples.

13. In general, high tack coat application rates improved the cracking resistance of TBOs. The higher application rates of PMAE tack coat improved the fracture resistance of gap-graded TBO and provided better adhesion with a deteriorated PCC surface. Gap-graded, thin bonded wearing courses continue to increase in fracture energy even for tack coat rates in excess of 2.5 L/m² (0.3 gal/yd²). On the other hand, there is an optimum tack coat rate associated with a particular dense-graded mixture with respect to its fracture properties. Higher application rates do not always yield higher fracture energies for
dense-graded TBO systems. The dense-graded bonded wearing courses peaked in the range of 0.15 to 0.25 gal/yd$^2$ (depending upon the mixture properties of most dense-graded projects).

14. Spray paver constructed bonded overlays need less compaction effort to achieve desired density than conventionally paved overlays with the same thicknesses. In general, an increase in tack coat application rate of PMAE reduces the compaction effort for the same thickness and mix of bonded overlays. Spray paver installed TBOs with gap-graded mixtures accommodated 3–5 times more tack coat emulsion than conventional overlays without causing any bleeding and flushing to the surface. The capacity of tack coat adsorption is very subjective and greatly influenced by the existing pavement conditions and the overlay mixture void structure.

15. Paver travel speed has an impact on the ability to achieve the target density of the overlay and paver speed of 45 to 50 ft/minute is reasonable for dense-graded mixes. It is assumed that higher paver speed may not allow the screed enough time to apply adequate compaction effort. Moreover, it is also affected by the thickness and width of the overlay.

16. Warm mix asphalt can be paved through a spray paver at 150°F lower than HMA. A limited data set suggests that a gap-graded WMA bonded overlay is 31% more crack resistant than the traditional open graded overlay system paved at the same tack coat application rate and thickness.

17. Double lift bonded wearing course can adsorb up to 2.5 L/m$^2$ (0.55 gal/yd$^2$) of PMAE tack coat without causing any bleeding or flushing after three years in service. Early performance of the double-lift bonded overlays supports the concept that very high fracture energy at low temperatures is correlated to good overall cracking resistance in the field. These results suggest that double-lift bonded overlay systems may provide a viable rehabilitation option for pavements with severe distresses and durability issues, such as ASR affected PCC.

18. Comparison of uniform and graded mix fracture and bulk properties indicates that tack coat emulsion permeation improves the fracture performance of graded overlays. Gap-graded mix demonstrated higher improvement in fracture resistance than dense-graded
mix by incorporating the same amount of emulsion. This response is attributed to the capacity of the mix to absorb higher amounts of emulsion, owing to its void structure.

19. Limited data reveals that image analysis is a useful tool in tracing tack coat emulsion permeation gradient through the TBO thickness. It was observed that emulsion wicks up to approximately \( \frac{1}{3} \) of the overlay thickness for the analyzed thicknesses. It is assumed that the \( \frac{1}{3} \) criteria may not hold true for thicker overlays and that emulsion would likely impregnate a limited overlay thickness instead, depending upon the type of mix, tack coat application rate, and its type. Considering the air voids and typical tack coat application rate of field constructed TBOs, this thickness will vary from 6 to 10 mm.

20. Image analysis was shown to be a useful tool for characterizing tack coat emulsion gradient in formulating graded overlays for numerical simulations. Using this information, numerical simulation results clearly illustrated that tack coat emulsion permeation significantly improves the cracking resistance performance of graded overlays.

10.3 CONCLUSIONS

Based on the findings, the following conclusions can be drawn from this study:

1. Fracture properties of the thin bonded overlay systems are significantly different than conventionally paved overlays. Improved fracture resistance of TBOs is attributed to upward migration of tack coat emulsion into the overlay thickness. The emulsion permeation makes TBOs graded in nature. The extent, amount and rate of emulsion permeation depends upon, overlay mix type, tack coat application rate, emulsion type and existing pavement surface condition.

2. The graded nature and smaller thickness of TBOs renders the existing asphalt concrete fracture tests unsuitable for spray paver constructed overlays. The proposed C[T] test is a viable fracture test for thin and graded overlay systems. Besides differentiating variables in TBO with low CoV, the numerical simulations validate the recommended test procedure.

3. Spray paver constructed TBO demonstrated higher fracture resistance than laboratory compacted composite specimens with same constituents. The paver screed temperature,
its vibration and the scale effect compared to the laboratory fabrication process is believed to cause this variation. Gap-graded mixtures demonstrated higher capacity to accommodate tack coat emulsion and PMAE was found to improve the fracture properties more significantly than non-modified emulsions at the same application rate.

4. Early field performance of TBO reveals that integrated approach incorporating laboratory test data and numerical simulation results is useful tool to predict cracking behavior of these overlays.

10.4 FUTURE EXTENSIONS

Based on the findings of this study, the following recommendations are made:

1. More studies are needed to further explore the combined effect of tack coat application rate on the interface bond strength, cracking, and rutting resistance of TBOs. This will help in optimizing the overall performance of spray paver applied overlay systems. From this study it is evident that the optimal tack coat rate might vary with the type of overlay mixture, emulsion, and existing pavement surface condition.

2. The C[T] test geometry was tailored to suit 150 mm (6 inch) diameter field cored and laboratory prepared samples. The specimen size effect on the measured fracture energy was studied accordingly. Specimen size effect for larger samples should be evaluated.

3. Viability of newer asphalt technologies, such as warm mix asphalt, for construction of TBOs as well as their performance should be studied in detail. Limited data suggests that WMA can be paved at much lower temperatures through the spray paver with some modifications to the standard spray paving process.

4. Moisture damage plays an important role in the deterioration of asphalt pavements and overlays. For TBOs, and particularly those using WMA, the effect of moisture should be studied.

5. More studies on asphalt concrete fracture response in the context of warmer test temperatures need to be conducted, which encompass a broader array of binders, emulsions, and mix types.
6. Application of advanced technologies such as digital imaging correlation to capture full field displacement will provide better insight of the material property gradient through the thickness of the TBO and should be utilized.

7. Presently, the C[T] test is conducted under a constant CMOD opening rate (monotonic loading). Conducting the test in multiple loading and re-loading cycles within the material tolerance/tensile strength may enable the proposed tests to be used in a more direct way to control various forms of fatigue-type cracking in asphalt and composite pavement systems, and in combined modeling-testing studies.
REFERENCES


2. AASHTO T 312 - Preparing and Determining Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor.


1. **Scope**

1.1 This test method covers the determination of fracture energy \( (G_f) \) of asphalt gradient mixtures using the compact tension geometry. The fracture energy can be utilized as a parameter to describe the fracture resistance of asphalt concrete. The fracture energy using the compact tension geometry can be utilized to test asphalt mixtures. In addition, it may be used to determine the fracture energy of an asphalt gradient mixture. An asphalt gradient mixture in the field may be created by the application of a heavy tack coat material under an asphalt mixture. The sprayed asphalt binder creates higher asphalt content at the interface between the new overlay and the existing pavement.

1.2 The specimen may be in the form of field cores or may be laboratory prepared using the Superpave gyratory compactor and a method for preparing composite specimen.

1.3 The test method describes the testing apparatus, instrumentation, specimen fabrication, and analysis procedures required to determine fracture energy of asphalt concrete and similar quasi-brittle materials.

1.4 The standard unit of measurement for fracture energy is Joules/meter\(^2\) (J/m\(^2\)).

1.5 *This method does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this method to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. **Referenced Documents**

2.1 **ASTM Standards:**

D 8 Terminology Relating to Materials for Roads and Pavements

D 3666 Specification for Minimum Requirements for Agencies Testing and Inspecting Road and Paving Materials

D6373 Specification for Performance Graded Asphalt Binder
D 6925 Test Method for Preparation and Determination of Relative Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor


E 399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness $K_I$ of Metallic Materials

E 1823 Terminology Relating to Fatigue and Fracture Testing

2.2 AASHTO Standard:

AASHTO T322 Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device

2.3 Non-Standard Test Methods:

Preparation of Bituminous Composite Test Specimen by Means of Gyratory Shear Compactor

3 Terminology

3.1 Definitions – Terminologies E 1823 and D 8 are applicable to this test method.

3.1.1 asphalt gradient mixture - an asphalt mixture where the asphalt content changes as a function of the depth of the mixture

3.1.2 crack mouth – portion of the notch that is on the flat surface of the specimen, that is, opposite the crack tip (see Fig. 4)

3.1.3 crack mouth opening displacement (CMOD) – the relative displacement of the crack mouth.

3.1.4 fracture energy, $G_f$ – the energy required to create a unit surface area of a crack.

3.1.5 notch tip – end of notch where the crack will initiate and propagate.

3.1.6 crack tip opening displacement (CTOD) – relative displacement measured at notch tip.

4 Significance and Use

4.1 This test method was developed for determining the fracture resistance of a gradient asphalt mixture. The fracture resistance can help differentiate application rates of liquid binders and types of liquid binders used in a spray paver application of an asphalt mixture, as well as, the asphalt mixtures themselves. The test method is generally valid for specimens tested at
temperatures of 10°C or below. The specimen geometry is readily adapted to 150-mm diameter composite specimens, which can be fabricated in the Superpave gyratory compactor. The specimen geometry can also be adapted to use field cores obtained from existing pavement structures.

5 Apparatus

5.1 Loading – Specimens shall be tested in a loading frame capable of delivering a minimum of 20 kN in tension. The load apparatus shall be capable of maintaining a constant crack mouth opening displacement within 2% of the target value throughout the test. Closed-loop servo-hydraulic or servo-pneumatic test frames are highly recommended, but not required if the CMOD rate meets the specifications listed above. The load cell shall have a resolution of 20 N or better.

5.2 Loading Fixtures – An example of a loading clevis suitable for testing of the specimen and recommended dimensions is shown in Figure A.1. The specimen is loaded through the pins which are allowed to roll freely on the flat surfaces of the loading clevis. Any clevis design may be used if the design demonstrates the ability to accomplish the same result.

5.3 Displacement Gages – Three displacement gages; one at the crack mouth and one each at the crack/notch tip on either face of the specimen shall be used. The CMOD gage shall measure the relative displacement of the crack mouth across two points, initially 5 mm (0.2 inch) apart. Two gages on the crack tip, one on either face shall be used to measure CTOD across two points, initially 12.7 mm (0.5 inch) apart. The gages shall be attached securely to gage points, yet have the ability to be released without damage if the specimen breaks.

5.3.1 A recommended gage would be a clip-on gage, described in Test Method E 399, which is attached to gage points via knife edges. Gage points shall be glued to the specimen so that the clip-on gage is set to the proper gage length, which is typically 5 mm for CMOD gage and 12.7 mm for CTOD gages. Figure A.2(a), Figure A.2(b) and Figure A.2(c) illustrates the gage points and the test set-up with the specimen in the fixtures and clip-on gages attached.

5.3.2 At the beginning of the test, the crack mouth opening displacement gage shall have a minimum displacement of 6.35 mm. The resolution shall be within 0.1% of full scale.

5.4 Data Acquisition - Four channels of data acquisition are required: load, CMOD and two CTODs. The acquisition system shall have the ability to acquire the data at a minimum of 25 data points per second.
6 Test Specimens

6.1 The cylindrical composite specimen as shown in Figure A.3(b), either laboratory prepared or field cored, shall be 150 ± 10 mm in diameter. The sides of the specimen shall be trimmed to leave parallel sides spaced 100 ± 10 mm apart as shown in Figure A.3(a).

6.2 Test specimens shall be fabricated in accordance with the dimensions shown in Figure A.4 and Figure A.5.

6.2 Specimen Fabrication – The equipment used for specimen fabrication shall utilize diamond-impregnated cutting faces and water-cooling to minimize damage to the specimen.

6.2.1 Specimen Thickness – The bottom layer of the specimen must be at least 45 mm in height to allow for the fabrication and the proper functioning of loading holes. For field cores, the bottom asphalt mixture or concrete may be trimmed to 50 ± 5 mm in height. The thickness of the asphalt mixture for which the fracture energy is being measured, may be from 20 to 100 mm.
The thickness, B, shall be measured at two points on each side of the specimen and shall not vary more than 2.5 mm.

6.2.2 Notch – The starter notch shall be fabricated in the bottom layer of the specimen and in a direction perpendicular to the overlay. The notch shall be no wider than 1.5-mm with a narrower notch being highly recommended.

Note 1 – The fabrication of the notch is a critical step in obtaining valid fracture energy. If the notch varies significantly between replicates, then the value of the fracture energy will be influenced. The notch length is also critical since providing a fatigue crack of a known length, as recommended by Test Method E 399, is difficult to produce in these materials. However, a notch which is relatively narrow compared to the maximum aggregate size will produce satisfactory results.

6.2.3 Loading Holes – The loading holes shall be fabricated 90 ± 5° to the flat faces of the specimen. The location of the loading holes shall not be greater than 5 mm from the specified locations.

6.2.4 Initial Ligament Length (W-a) – Measurements shall be taken on both sides of the specimen to the nearest ± 0.5 mm and averaged.

![Schematic of the CMOD Gage Point](image1)

![Schematic of the CTOD Gage Point](image2)

Figure: A.2 (cont. on next page)
(c) Attached Gage Points and Clip-on Gages

Figure A.2: C[T] Test Set-up with Gage Points and Clip-on Gages Attached

(a) Specimen Top View with Sides Trimmed to Leave 100-mm Width

(b) Core or Laboratory Prepared Composite Asphalt Specimen Dimensions

Figure A.3: Core or Laboratory Prepared Composite Asphalt Specimen Dimensions
Figure A.4: C[T] Specimen Dimensions

Figure A.5: Isometric View of Fabricated C[T] Fracture Test Specimen
7 Procedure

7.1 Conditioning – The specimen shall be placed in a temperature controlled chamber for a minimum of 2 h and a maximum of 16 h at the desired test temperature. The temperature shall be within ± 0.2°C throughout the conditioning and testing times. A suggested test temperature of 10°C greater than the low temperature performance grade of the asphalt binder, as defined in Specification D 6373, is recommended.

7.2 After temperature conditioning, insert the specimen in loading fixtures and apply a small seating load of no greater than 0.2 kN.

7.3 Perform the test with a constant crack mouth opening displacement rate of 0.017 mm/s.

7.4 The test is complete when the post-peak level has reduced to 0.1 kN. The validity of the test is a function of the ability to reach the specified post-peak load level.

Note 2 – The complete failure of the specimen, that is, complete separation of the specimen into two pieces, is not feasible due to the closed-loop control through the CMOD. If the specimen fails without maintaining careful control, test equipment could be damaged. Therefore, a minimum load limit was established to provide satisfactory test results. At higher test temperatures, the load level may never reduce to this value within the typical range of a CMOD transducer due to the crack blunting (notch tip opening without crack growth). In this case, the fracture energy may not be the dominant source of energy consumption and the test analysis methods presented in this specification would not be valid.

8 Interpretation of Fracture Energy

8.1 Variability of the test results can be reduced by data smoothing or elimination of extraneous electronic noise captured during the test. The following procedures are suggested to reduce the electronic noise associated with the CMOD data.

8.1.1 Plot CMOD versus time (see Figure A.6).

8.1.2 Use least squares regression (Equation A.1) to fit a line through the data to determine the slope ($a_1$) and intercept ($a_0$).

$$[Y] = [a][X]$$  \hspace{1cm} \text{(A.1)}

where:
\[ [Y] = \text{CMOD Data} \]
\[ [X] = \text{Time} \]
\[ [a] = \text{Regression Parameters} (a_0, a_1) \]

8.1.3 Using the regression parameters from Equation 1, create a smooth line to represent the CMOD data by using Equation A.2.

\[ CMOD_{fit} = a_1 \times \text{Time} \quad (A.2) \]

where:
- \( CMOD_{fit} \) = Smoothed CMOD data
- \( a_1 \) = Slope of line

8.1.4 For a valid test, the rate (\( a_1 \)) shall be within 2\% of the expected rate

8.2 Plot and Load \(-\) \( CMOD_{fit} \) data and compute the area under this curve (See Figure A.7). A suggested technique is using the quadrangle rule as shown in Equation A.3.

\[ AREA = \sum_{i=1}^{n} (x_{i+1} - x_i) \times (y_{i+1} - y_i) + 0.5 \times (x_{i+1} - x_i) \times (y_{i+1} - y_i) \quad (A.3) \]

where:
- \( AREA \) = Area under \( Load \) \(-\) \( CMOD_{fit} \) and \( Load \) \(-\) \( CTOD_{fit} \) curves
- \( x = CMOD_{fit} \) and \( CTOD_{fit} \)
- \( y = \text{Load} \)
8.3. Compute fracture energy, $G_f$, measured by CMOD and CTOD may be calculated using the following equation with respective AREA under the curves:

$$G_f = \frac{\text{AREA}}{B \times (W-a)}$$  \hspace{1cm} (A.4)

where:

$G_f = \text{CMOD/CTOD Fracture Energy}$

$\text{corresponds to Area under Load } - \text{CMOD}_{fit}$ and $\text{Load } - \text{CTOD}_{fit} \text{ curves (Equation A.3)}$

$B = \text{Specimen Thickness}$

$W - a = \text{Initial Ligament Length}$

9 \hspace{1cm} \textbf{Report}

9.1 Report the following information:

9.1.1 Material tested (that is, nominal maximum aggregate size, asphalt binder type, etc),

9.1.2 Thickness, $B$, to the nearest 0.5 mm.

9.1.3 Initial ligament length, $(W-a)$, to the nearest 0.5 mm.

9.1.4 Fracture energy, $G_f$, to the nearest 1 J/m$^2$.

9.1.5 Peak load, to the nearest 0.1 kN.

9.1.6 Time at peak load, to the nearest 0.1 s.

10 \hspace{1cm} \textbf{Precision and Bias}

10.1 The precision and bias have not been determined for this specimen configuration.
APPENDIX B - PREPARATION OF BITUMINOUS COMPOSITE TEST SPECIMEN BY MEANS OF GYRATORY SHEAR COMPACTOR

1. Scope

1.1 This practice covers the preparation of 150-mm or 100-mm composite bituminous test specimens. A composite specimen is the result of a two stage compaction process. The bituminous mixtures in the composite specimen may be of different types or of the same mixture. A field core of bituminous pavement may also be used as the base for the composite specimen.

1.2 The values stated in SI units are to be regarded as the standard.

1.3 This method does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this method to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:

D 6925 Preparation and Determination of the Relative Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor

D 979 Sampling Bituminous Paving Mixtures

D 6997 Distillation of Emulsified Asphalt

3. Significance and Use

3.1 This practice is used in the laboratory to prepare bituminous composite specimen. Specimen may be prepared in the laboratory during the design phase of an overlay project.

3.1.1 The bottom layer of the composite specimen may be a laboratory compacted specimen or a core taken from the actual project to be overlaid.
3.1.2 The specimen may be used to determine the interface bond strength, the rutting resistance or the cracking resistance of composite bituminous mixtures by specified methods.

4. **Apparatus**

4.1 Compaction apparatus shall be accordance with Standard Practice D 4013

4.1.1 Superpave gyratory compactor (SGC)

4.1.2 Specimen Molds

4.1.3 Mold Plates and Ram Heads

4.1.4 Thermometers

4.1.5 Balance

4.1.6 Ovens

4.1.7 Miscellaneous

4.2 Silicone rubber mold, 150-mm or 100-mm inside diameter

4.3 Masonry Saw

5. **Test Specimens**

5.1 The SGC may be used to compact a bituminous paving mixture to be used as a base for the composite specimen. After the compacted specimen is allowed to cool to room temperature, it may be placed back in the gyratory mold and another bituminous paving mixture placed on top of it and compacted using the SGC. A tack coat material may be applied to the base before placing the surface mixture on top of it for compaction.

5.2 A composite specimen may be created starting from a 150-mm core taken from the road to be overlaid. The core can act as the base for the overlay. The bottom of the core may be trimmed with a masonry saw to make the base to the correct height when fabricating the composite specimen. A tack coat material may be applied to the surface of the core before placing the surface mixture on top of it for compaction. The core is placed in the mold for the gyratory compactor and the overlay mixture may be placed on top of it. The SGC is then used to compact the composite specimen.
5.3 A coring procedure may be used to cut 100-mm samples from the larger 150-mm specimen if 100-mm specimens are to be used for specified tests.

5.4 An alternate method for creating 100-mm specimen is to use the 100-mm gyratory mold size for compacting the specimen in the SGC. Field cores of similar size may also be taken to be used as a base for the composite specimen.

6. **Procedure**

6.1 Laboratory prepared compacted mixtures used as a base for the composite specimen

6.1.1 Prepare the mixture following sections 6.2 through 6.5 of Test Method D 6925.

6.1.2 Target the design air void content for the compacted mixture. Adjust the specimen weight as necessary to result in a final height of 62 ± 3-mm.

6.1.3 Compact the mixture following sections 6.6 through 6.10 of Test Method D 6925. Remove the mold from the SGC. After a suitable cooling period, extrude the compacted specimen from the mold. Remove the paper disk from the specimen. Allow the specimen to cool to room temperature on a flat surface.

6.1.4 A water-cooled masonry saw may be used to create a smooth, saw cut face on the diameter of the compacted base. Cut the base to a height that is suitable for the desired test on the composite specimen. The saw cut face of the compacted base or the textured surface of the specimen may be used as the surface for preparing the composite specimen.

6.2 Field mixed, laboratory compacted mixtures used as a base for the composite specimen

6.2.1 Follow the same procedure as in 6.1 but do not condition the loose mix prior to compaction.

6.3 Field cores used as a base for the composite specimen

6.3.1 Field cores should to taken using a 150-mm inside diameter coring bit. Use a masonry saw to trim the bottom of the core to create a finished core height of 50 ± 3-mm.

6.4 Preparation and application of a tack coat material

6.4.1 The amount of binder or emulsion should correspond to the anticipated tack coat application rate to be used in the field. If a field application rate is not known, a range of
application rates may be used to create specimens for further tests to determine an optimum tack coat application rate.

6.4.2 For a hot binder tack material, preheat the silicone rubber mold in a 135°C oven for 7 ± 2 minutes. Pour the hot binder into the appropriate size silicone rubber mold based on the specimen size to be prepared. Place the silicone rubber mold on a level shelf in the 135°C oven for 10 ± 2 minutes to allow the binder to self level. Remove the mold from the oven, place on a level surface and allow the mold to cool to room temperature.

6.4.3 Follow the procedure in section 6.8 to complete the preparation of a composite test specimen.

**PREPARATION METHOD A**

6.5 Cured film procedure – This method describes the procedure for preparing an emulsion tack material as a cured film in the preparation of a composite specimen.

6.5.1 Pour the emulsion into the appropriate size, room temperature, silicone rubber mold based on the specimen size to be prepared. Place the silicone rubber mold on a level surface and allow the emulsion to cure at 25°C for one hour. Following the initial curing, place the silicone rubber mold on a level shelf in a 60°C oven and allow the emulsion to cure for an additional four hours.

6.5.2 Remove the silicone rubber mold from the oven and while the tack coat binder is still hot, place the room temperature, compacted asphalt mixture base, as described in sections 6.1, 6.2 or 6.3, in the silicone rubber mold. Place the compacted asphalt mixture to where the tack coat binder or residue will be deposited on the top surface of the specimen. Allow the weight of the base specimen to remain on the silicone rubber mold and the specimen to cool for a minimum of 30 minutes. Invert the base specimen to where the silicone rubber mold is on top of the specimen. Slowly remove the silicone rubber mold depositing the tack coat binder on the specimen surface.

6.6 Preparation of the composite test specimen

6.6.1 Place the compaction mold and the top mold plate in an oven at the required compaction temperature ± 5°C for a minimum of 30 minutes prior to compaction.
6.6.2 Place the compacted specimen to be used as a base for the composite specimen in a 40°C oven for 45 minutes. Place a room temperature base plate and a paper disk in the bottom of the compaction mold. Insert the composite base specimen in the gyratory mold.

6.6.3 Prepare the overlay mixture following sections 6.2 through 6.5 of Test Method D 6925.

6.6.4 Target field air void content for the compacted mixture unless otherwise specified. Adjust the specimen weight as necessary to result in a target height as anticipated in the field application.

6.6.5 Quickly place the mixture into the compaction mold taking care to minimize segregation. Place a paper disk on top of the mixture followed by a heated top mold plate. Load the compaction mold into the SGC and initiate the compaction process.

6.6.6 At the end of the compaction process, remove the mold assembly from the SGC. After a suitable cooling period, extrude the compacted specimen from the mold. Remove the paper disk from the specimen. Allow the specimen to cool to room temperature on a flat surface.

**PREPARATION METHOD B**

6.7 Wet procedure – This method describes the procedure for applying an emulsion tack material in the preparation of a composite specimen.

6.7.1 Prepare a Plaster-of-Paris mixture at approximately 1:1 ratio of plaster to water. Use your finger to apply a thin film of the Plaster-of-Paris solution to the outer edge of the compacted base near the end of the specimen that will be used as the interface of the final composite specimen. The plaster should be spread to approximately 12 mm below the intended interface around the entire circumference of the specimen. Allow the plaster to set at least one hour. The plaster will act to seal the outer edge of the specimen and prevent loss of the emulsion tack from the interface area.

6.7.2 Place the compaction mold in an oven at the required compaction temperature ± 5°C for a minimum of 45 minutes prior to compaction. Warm the compacted specimen to be used as a base for the composite specimen in a 40°C oven for 30 minutes before inserting it back in the SGC mold. Pour the measured amount of emulsion tack on the surface of the base and distribute evenly over the surface using a spatula or other suitable device.

6.8 Preparation of the composite test specimen
6.8.1 Place the top mold plate in an oven at the 200°C for a minimum of 45 minutes prior to compaction.

6.8.2 Prepare the overlay mixture following sections 6.2 through 6.5 of Test Method D 6925.

6.8.3 Target field air void content for the compacted mixture unless otherwise specified. Adjust the specimen weight as necessary to result in a target height as anticipated in the field application.

6.8.4 Quickly place the mixture into the compaction mold taking care to minimize segregation. Place a paper disk on top of the mixture followed by the heated top mold plate. Load the compaction mold into the SGC and initiate the compaction process.

6.8.5 At the end of the compaction process, remove the mold assembly from the SGC. After a suitable cooling period, extrude the compacted specimen from the mold. Remove the paper disk from the specimen. Allow the specimen to cool to room temperature on a flat surface.

7. **Report**

7.1 Report the following information:

7.1.1 The mixture composition and binder grade used in the base of the composite specimen

7.1.2 The saw cut, smooth face of the base or the textured surface of the base was used to make the composite specimen.

7.1.3 The mixture composition and binder grade used in the surface of the composite specimen

7.1.4 The preparation method (method A or Method B)

7.1.5 The application rate of the tack coat binder/emulsion

7.1.6 If an emulsion tack is used, report the method of preparation of the tack (wet or cured film)

8. **Precision and Bias**

8.1 The precision and bias have not been developed for this method.
AUTHOR'S BIOGRAPHY

The author, Sarfraz Ahmed, was born in Pakistan on 10\textsuperscript{th} April, 1970. After obtaining his Faculty of Science degree from Government College Lahore, he joined Pakistan Army in 1990. He received his Bachelor of Science degree in Civil Engineering from Military College of Engineering, Risalpur in 1993 and was commissioned in the Pakistan Army Corps of Engineers after completing his military training at Pakistan Military Academy in 1994.

He served on various command, staff and civil engineering project assignments during his military service in various capacities. In addition, he served as an Engineer officer in United Nations mission in Sierra Leone. During one year stay in Africa most of his assignments were related to rehabilitation of paved and unpaved roads. He joined University of Illinois at Urbana-Champaign in August 2006 and received his Master of Science degree in Civil Engineering in May 2008. His doctoral research was completed under the supervision of Professor William G. Buttlar in February 2011.