The Pennsylvania State University

College of Engineering

USE OF SEMI-CIRCULAR BEND TEST TO CHARACTERIZE FRACTURE PROPERTIES OF ASPHALT CONCRETE WITH VIRGIN AND RECYCLED MATERIALS

A Dissertation in

Civil Engineering

by

Xuan Chen

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

August 2019

The dissertation of Xuan Chen was reviewed and approved* by the following:

Mansour Solaimanian
Research Professor and Director of Northeast Center of Excellence for Pavement Technology (NECEPT)
Dissertation Advisor
Chair of Committee

Shihui Shen
Associate Professor, Department of Engineering—Altoona, The Pennsylvania State University

Clifford J. Lissenden
Professor, Department of Engineering Science and Mechanics, The Pennsylvania State University

Tong Qiu
Associate Professor, Department of Civil and Environmental Engineering, The Pennsylvania State University

Patrick J. Fox
Professor and Head of the Department of Civil and Environmental Engineering, The Pennsylvania State University

* Signatures are on file in the Graduate School

ABSTRACT

Cracking in asphalt pavements is a challenging problem and has been the subject of numerous research studies for decades. To properly address this problem, suitable tests must be conducted to capture material behavior in cracking, such testing must be accompanied by proper mechanistic and empirical modeling of the material behavior in cracking. For mixture design and material quality control/assurance purposes, there is not a commonly accepted protocol for testing asphalt mixtures for cracking resistance characterization, due to variability of test results, non-uniformity in test specimens, and overall complexities of the tests that prevent them from being adopted for daily uses. On the other hands, for the tests that are popular for research purposes, the validity and sensitivity of such tests have not been fully witnessed and proven, due to lack of data quantity. Addressing these problems will help improve mixture design procedures and advance quality control and quality assurance of asphalt mixes, especially when complicated components, such as recycled materials and performance enhancing additives, are commonly incorporated into asphalt concrete nowadays.

The overall goal of this research is to characterize the cracking resistance of various types of asphalt concrete mixes via a suitable candidate test. An additional goal is to provide guidelines for performing balanced mixture design on asphalt concrete with virgin and recycled materials when using such a test.

Throughout the research, the selected fracture test, namely the semi-circular bend (SCB) fracture test, was first evaluated by investigating the sensitivity of performance indicators under various test conditions and proposing the most appropriate test conditions using a solid theoretical background. Then, the test was used to study fracture behavior of a wide range of asphalt paving materials including, but not limited to, various virgin asphalt mixes, crumb rubber modified (CRM) asphalt mixes, asphalt mixes with recycled materials such as reclaimed asphalt pavement (RAP), and recycled asphalt shingles (RAS), together with asphalt mixes with recycling agents. Not only were these mixtures prepared in a single laboratory, specimens received from different laboratories and plants were also included in the test matrix to reduce bias and to investigate the variation of the performance indicators. Additionally, a method to conduct the performance-based balanced-design using only the SCB fracture test was explored. Finally, the effect of long-term aging on fracture behavior of asphalt mixes was investigated, in order to build foundations for performance prediction commonly used in asphalt pavement design procedures.

The main contributions of this study are: 1) verification of the sensitivity of the SCB test using asphalt mixtures with controlled variables under the proposed test conditions that are suitable to the commonwealth of Pennsylvania, 2) investigation of the impacts of material variables and conditioning, namely aging process, on fracture behavior of asphalt concretes, 3) exploration of possibility of performing balanced mixture design on asphalt concrete using the SCB test as a stand-alone test. The SCB fracture test procedure is found to be suitable to qualify asphalt mixes to fulfill different traffic demands and pavement structural conditions. Reliable mix design and quality assurance of asphalt pavements with complicated rehabilitation histories and sophisticated material compositions can be performed with confidence using such a test.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1 INTRODUCTION

1.1 BACKGROUND

A considerable amount of federal and state funding is spent annually on construction and maintenance of highways to improve functionality, serviceability, and performance of the roads. The road network is an essential and integral part of our daily life. More than 90 percent of road networks in the United States are paved with asphalt paving materials (Copeland, 2011). Asphalt concrete consists of asphalt binder, graded aggregate, and in some cases other additives and recycled materials. It is viscoelastic and its behavior is highly dependent on the temperature and loading rate. All components in asphalt mixtures play roles in the overall performance of the mix. Pavements in poor condition result in poor ride quality and potential safety concerns.

There are three major distresses in asphalt pavement: permanent deformation (rutting), thermal cracking, and fatigue cracking. All could be reduced through proper mix design (material selection and combination), structural design (thickness selection), and high-quality construction. Fatigue cracking, or in a broader sense, intermediate temperature cracking, which is the focus of this research, refers to independent or interconnected cracks, varying in size, that develop in the pavement structure. It is a result of exposure of asphalt paving materials to repeated traffic or thermal loading after they have been oxidatively aged severely. Propagation of fatigue cracks in asphalt pavement will eventually result in raveling (i.e., loss of fine aggregate), and will allow moisture to infiltrate into the pavement system, deteriorating the pavement structure and reducing its serviceability. Despite the development of many experimental and analytical techniques to tackle the fatigue cracking, this type of distress continues to be a challenging problem requiring more reliable testing and analytical systems, especially during the design and construction stages.

Performance of asphalt pavements with respect to intermediate temperature cracking has been investigated through collection of field performance data and simulation of traffic loads using accelerated loading of full or scaled test tracks. Such procedures are often time-consuming and expensive. Simpler and less costly approaches for characterization of asphalt mix resistance to intermediate temperature cracking include the use of bench scale laboratory tests. Such tests are inferior to full-scale or model-scale accelerated loading tests with respect to simulating loading conditions that resemble actual field conditions more closely. However, they do provide the advantage of a faster and more economical approach, better control of test parameters, and the ability to capture material engineering properties more accurately.

Laboratory fracture tests can be classified into two major categories: monotonic load tests and cyclic load tests. In monotonic load tests, as the name implies, the load is applied on the test specimen in one run at a constant deformation rate. The load is typically increased until failure of the specimen is observed and even continued beyond the failure point. The most common monotonic tests used in asphalt mixture studies are indirect tensile test (IDT) and semi-circular beam (SCB) test. In cyclic load tests, repeated loading cycles (sometimes as many as several million) are applied at either stress control or strain amplitude control modes. Load repetition is continued either until certain failure criteria are met or the total failure of the specimen has occurred. The most common cyclic fatigue tests are four-point bending beam (4PBB) or flexural beam test, uniaxial push-pull (compression-tension) fatigue test, and cyclic IDT test.

Although some of these test methods have been used by researchers for decades, for asphalt mixture design or material quality control/assurance purposes, however, there is no commonly accepted protocol for testing asphalt mixtures for cracking resistance characterization yet, due to variability of test results, nonuniformity in the test methods, and overall complexity and sensitivity, or lack of, of the tests.

1.1.1 Problem Statement

Intermediate temperature cracking in asphalt paving materials is a challenging problem requiring suitable testing and analytical systems. No mechanical test protocol has been adopted for routine mixture design and material quality control/quality assurance purposes at this point, although engineers have been struggling to characterize the fracture behavior of increasingly sophisticated asphalt concretes. A simple, efficient, yet sensitive fracture test is needed to aid engineers for decision making. Addressing these problems will help improving mixture design procedures and advance quality control and quality assurance of asphalt mixes during construction.

Adding the complexity to the asphalt concrete is the inclusion of recycled materials, namely crumb rubber modifiers (CRM), reclaimed asphalt pavement (RAP), and recycled asphalt shingles (RAS). Scrap vehicle tires are a growing environmental problem in the United States. Even though use of CRM, the end product of scrap vehicle tires, in asphalt binder has been researched extensively, there is insufficient information on the effect of crumb rubber in asphalt concrete cracking resistance under a performance-based rational mix design approach. A similar, though lesser, concern exists with the use of other recycled materials such as RAP and RAS. Investigating and understanding the behavior of asphalt mixtures in terms of cracking resistance when recycled materials are used, and incorporating the results in mix design, could lead to better utilization of recycled materials, resulting in significant cost savings and environmental benefits.

1.2 RESEARCH OBJECTIVES

The overall goal of this research was to characterize the intermediate temperature fracture properties of asphalt concretes with virgin and recycled materials via a suitable candidate fracture tests. Additional goals were to provide guidelines for optimizing the rejuvenator dosage for asphalt mixes with recycled materials, and explore possibility of using a single test for balanced mix design for asphalt concrete with virgin and recycled materials.

1.3 SCOPE OF WORK AND RESEARCH APPROACH

The research had a series of well-defined tasks to cover gathering background information, material procurement, specimen preparation, testing, analysis, and finally development of design guidelines. The materials investigated in the research consisted of typical asphalt paving materials and recycled materials used in the Commonwealth of Pennsylvania.

Throughout the research, the selected fracture test, namely the semi-circular bend (SCB) fracture test, was first evaluated by investigating the sensitivity of performance indicators under various test conditions and proposing the most appropriate test conditions using a solid theoretical background. Then, the test was used to study fracture behavior of a wide variety of asphalt paving materials including, but not limited to, various virgin asphalt mixes, crumb rubber modified (CRM) asphalt mixes, asphalt mixes with recycled materials such as reclaimed asphalt pavement (RAP), and recycled asphalt shingles (RAS), together with asphalt mixes with recycling agents. Not only were these mixtures prepared in a solo laboratory, specimens received from different laboratories and plants were also included in the test matrix to reduce bias and to investigate the variation of the performance indicators. Additionally, a method to conduct the performance-based balanced-design method using only the SCB fracture test was explored. Finally, the effect of long-term aging on fracture behavior of asphalt mixes was investigated, in order to build foundations for performance prediction commonly used in asphalt pavement design procedures.

To address the objectives of the research, a three-phase research approach with seven tasks is proposed and shown in Figure 1-1. Details of each task are presented next.

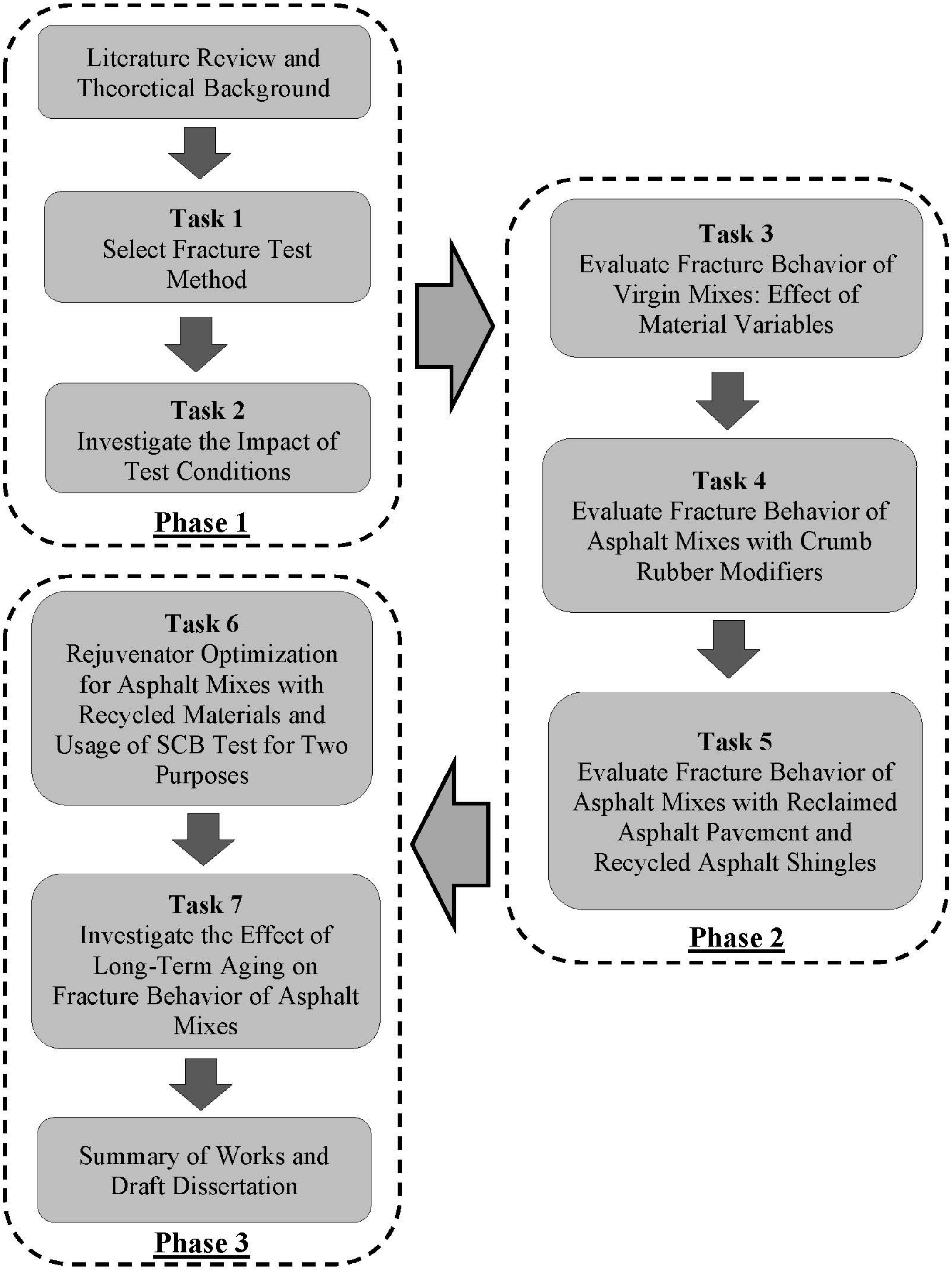


Figure 1-1. Flow chart of the overall research framework.

Literature Review and Theoretical Background

A comprehensive literature review was conducted to gather and summarize information regarding fatigue and intermediate temperature fracture behavior of asphalt mixtures in general, characterization methods and quantifying parameters on asphalt mixtures, and fatigue and intermediate temperature cracking behavior of asphalt mixtures with crumb rubber modifiers and recycled asphaltic materials.

Task 1. Select Fracture Test Method

The semi-circular bend (SCB) fracture test was selected as the most suitable laboratory test for routine mix design and quality control of asphalt paving materials. The decision was based on criteria proposed by previous studies. Different approaches to perform SCB test were introduced next, followed by the details on the test configuration and the final test procedures used throughout this research. This task also included information such as the unique method proposed by the author to calculate performance indicators.

Task 2. Revise and Verify the Selected Test Method

The effect of displacement rate and temperature on the sensitivity of the SCB fracture test was investigated. Numerous asphalt mixes with controlled variables were tested with SCB fracture tests under a range of displacement rates and test temperatures to investigate how performance indicators such as fracture energy, flexibility index, and peak load respond to changing test conditions, and whether these indicators remain sensitive under different test conditions. The temperature and displacement rate sweep tests were also performed on a selected mix to study the fundamental characteristics of performance indicators. Finally, a SCB fracture test condition that is suitable for Pennsylvania was identified.

Task 3. Evaluate Fracture Behavior of Virgin Mixes

For this task, efforts were undertaken to investigate the impact of material variables, e.g., air void, binder content, and binder stiffness, on performance indicators of the SCB fracture test using virgin materials. The fractional factorial test matrix was designed statistically to account for the influence of all material variables. The responses of performance indicators under different material variables were analyzed via statistical approaches. A simple regression expression was proposed to predict performance indicators using the data generated in this study. A general guideline for improving asphalt mixtures' resistance to cracking and the limitation of using flexibility index is proposed as a result of this research.

Task 4. Evaluate Fracture Behavior of Asphalt Mixes with Crumb Rubber Modified (CRM)

This task studied the fracture properties of crumb rubber modified (CRM) asphalt mixes using the SCB fracture test. The focuses were primarily on the effect of gradation, CRM content, virgin binder stiffness, and binder contents. Performance indicators were also compared with binder fatigue test results.

Task 5. Evaluate Fracture Behavior of Asphalt Mixes with Recycled Materials: Effect of Reclaimed Asphalt Pavement (RAP), and Recycled Asphalt Shingles (RAS)

This task examined the fracture properties of asphalt mixtures with recycled materials such as reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) using the SCB fracture test. For this part, the focus was on the types and contents of recycled materials, comparison to virgin mixtures, and the effect of dosage and types of recycling agents, i.e., rejuvenators.

Task 6. Rejuvenator Optimization for Asphalt Mixes with Recycled Materials and Dual Purpose Usage of the SCB Test

The task aimed to propose using a stand-alone fracture test (SCB fracture test), together with two performance indicators, i.e., flexibility index and peak load, to optimize rejuvenator dosages for asphalt mixes with recycled materials. Performance indicators obtained from the mixture fracture test, i.e., the SCB fracture test, were compared with performance indicators measured from binder performance tests. Peak load obtained from the SCB test was also compared with rut depth measured from the Hamburg wheel tracking device to verify the proposition of correlating rut depth measurement from the wheel tracking test with peak load of the SCB test for the purpose of balanced mix design.

Task 7. Investigate the Effect of Long-Term Aging on Fracture Properties of Asphalt Mixes

The SCB fracture test was performed on various asphalt mixes prepared by different laboratories. The effect of long-term aging (LTA) on fracture performance indicators was investigated by comparing performance indicators before and after the mixes were exposed to LTA. The responses of material variables and the effect of recycled materials under LTA were also evaluated.

1.4 RESEARCH CONTRIBUTION

The main contributions of this study are: 1) verification of the sensitivity of the SCB test using asphalt mixtures with controlled variables under the proposed test conditions that are suitable to the commonwealth of Pennsylvania, 2) investigation of the impacts of material variables and conditioning, namely aging process, on fracture behavior of asphalt concretes, 3) exploration of possibility of performing balanced mixture design on asphalt concrete using the SCB test as a sole test.

The SCB fracture test procedure is found to be suitable to qualify asphalt mixes to fulfill different traffic demands and pavement structural conditions. Reliable mix design and quality assurance of asphalt pavements with complicated rehabilitation histories and sophisticated material compositions can be performed with confidence using such a test and the material performance database generated through this research.

1.5 DISSERTATION ORGANIZATION

Chapter two summarizes the literature review. Chapter three analyzes the reasons for selecting the SCB fracture test and details the test procedure, alongside the unique method for parameter calculation. Chapter four discusses the effect of displacement rate and temperature on the sensitivity of the SCB fracture test. Chapter five shows how material variables affect performance indicators of the SCB fracture test using virgin materials. Chapter six presents the fracture behavior of crumb rubber modified (CRM) asphalt mixes. Chapter seven presents fracture behavior of asphalt mixes with recycled materials and recycling agents. Chapter eight discusses how to optimize rejuvenator dosages on asphalt mixes with recycled materials and verification of using the SCB test as the sole test to fulfill the goal of balanced mix design using both binder performance tests and other mix performance tests. Chapter nine presents discussions on the effect of long-term aging (LTA) on fracture properties of asphalt mixes. Finally, chapter ten summarizes the most important observations and conclusions from each chapter and proposed recommendations for future study.

Chapter 2 LITERATURE REVIEW

The contents of this chapter provide a comprehensive framework of fatigue, or a broader term, intermediate temperature fracture behavior of asphalt mixture, characterization approaches, and reported performance of asphalt paving materials. Separate and more detailed literature reviews, however, will be given in each chapter addressing their specific subject.

2.1 FATIGUE BEHAVIOR OF ASPHALT PAVEMENT

Fatigue is a phenomenon in which a pavement is subjected to repeated stress level less than the ultimate failure stress, during which process the damage accumulates in the material (Ghuzlan 2001). The fatigue damage is typically shown in the form of longitudinal or hexagonal crack pattern. The mechanism of fatigue failure can be described as a three-stage process involving the crack initiation, propagation, and final fracture failure. To avoid serious distresses in asphalt pavement, fatigue cracking must be controlled.

2.2 FATIGUE CHARACTERIZATION METHODS

There are four approaches to characterize fatigue behavior of asphalt mixtures using lab testing: the traditional phenomenological approach, the fracture mechanics approach, the viscoelastic continuum damage approach, and the dissipated energy-based approach. In the traditional phenomenological approach, the stress or strain responses and stiffness of asphalt mixtures are related to number of load repetitions to complete failure. The fracture mechanics approach focuses on crack initiation and propagation. Stress intensity factor, fracture energy, and other newly developed parameters such as flexibility index are all used to characterize material's ability to resist cracking. Based on the correspondence principle and work potential theory developed by Schapery (Schapery 1984), the viscoelastic continuum damage approach proposed by Kim (Kim 1988) provides fundamentals of the asphalt mixture fatigue performance. This method shows great potential for sound characterization of asphalt paving materials. The dissipated energy-based approach assumes the fatigue life of asphalt mixtures is related to dissipated energy of each loading cycle. In the past two decades, the concept of rate of dissipated energy change and plateau value have been proposed and developed. These recent parameters have also shown potential for reliable prediction of fatigue life and characterization of fatigue damage.

2.2.1 Phenomenological Approach

In the phenomenological approach, the stress, strain, and stiffness of asphalt concrete mixes are related to the number of load cycles that cause material failure (Van Dijk et al. 1972 and SHRP 1994). The fatigue behavior of asphalt pavements has been intensively studied through the phenomenological approach in the 1960s and 1970s (Monismith and Deacon 1969, Epps and Monismith 1969, Monismith et al. 1985):

2.2.2 Fracture Mechanics Approach

Fracture mechanics better explains the occurrence and development of a crack in the asphalt mixes. Using the fracture mechanics approach, fatigue is studied by monitoring the full stage of crack development and growth, i.e. crack initiation, stable crack propagation, and unstable crack fracture. It usually assumes that the stable crack propagation consumes most of the fatigue life. Paris and Erdogan pioneered this domain with the famous Paris law (1963), which further improved by Majidzadeh et al. (1971).

Lots of researchers employed the stress intensity factor (SIF) concept in the linear elastic fracture mechanics (LEFM) to study the fracture performance of asphalt concrete (Majidzadeh et al. 1971, Ramsamooj 1991, Tseng and Lytton 1990). However, Bazant and Planas (1998) pointed out that the application of LEFM may not yield accurate results for asphalt concrete materials because asphalt materials have the ability to carry load due to aggregate bridging and interlocking as the crack propagate, as exhibited by that phenomenon that a softening curve, instead of a brittle failure, appear after the peak load. On the other hand, the concept of J contour integral (J-integral) (Rice 1968) and fracture energy (G_f) (Bazant and Planas1998) in nonlinear fracture mechanics are also commonly used to characterize the fracture behavior of asphalt mixtures (Mull et al. 2002).

2.2.3 Viscoelastic Continuum Damage Mechanics (VECD) Approach

The work of Kim and Little (Kim and Little 1990) applies Schapery's viscoelastic constitutive theory (Schapery 1986) for materials with distributed damage to describe the behavior of sand asphalt under controlled strain cyclic loading. This work has resulted in a model formulation known as the viscoelastic continuum damage (VECD) theory (Underwood et al. 2012). There has already been much work done in applying this theory to asphalt mixtures (Kim 1988, Kim and Little 1990, Park et al. 1996, Kim and Lee 1997, Lee and Kim 1998, Daniel 2001, Kutey et al. 2009, Underwood et al. 2010, 2012), and the research has shown that material parameters derived from this model can accurately predict damage evolution in asphalt mixtures irrespective of the testing temperature or mode of loading. It is believed that such material parameters represent true material property and are independent of testing methods, loading mode, and other testing conditions.

2.2.4 Dissipated Energy Methods

The area under the loading stress-strain curve represents the input energy to the viscoelastic material. If the loading and unloading curves coincide, all the input energy in material is recovered after the removal of the load. If they do not coincide, then there are energy losses in the form of mechanical work, heat generation, or damage in the material. This phenomenon is called "hysteresis" (Van Dijk 1975). The energy dissipated during each load cycle captures effects not only of the imposed strain but also of the dynamic mix properties (SHRP A-404).

To predict fatigue life and calculate allowable strain in the mix, researchers have proposed and developed: 1) initial dissipated energy approach (Rowe 1993, SHRP A-404), which was found out to be not appropriate for the whole loading range, especially low strain fatigue tests (Shen et al. 2006); 2) cumulative dissipated energy approach (Van Dijk et al. 1972, 1975, 1977, Tayebali et al. 1992); and 3) work ratio ψ approach (Van Dijk 1975, Van Dijk and Visser 1977, Rowe 1993).

According to Carpenter and Janson, the loss of energy in each load cycle due to material mechanical work and other environmental influence remain almost unchanged, only the change in dissipated energy cause damage in materials (Carpenter and Janson 1997). If the dissipated energy started to change dramatically, it means damage started developing. The theory was verified and expanded by Ghuzlan and Carpenter (Ghuzlan and Carpenter 2000) and Carpenter et al. (Carpenter et al. 2003), and further improved based on the research findings by Shen and Carpenter (Shen and Carpenter 2005, 2006). As an energy-based approach, the theory is fundamental and has been demonstrated valid for different testing methods such as flexural bending beam fatigue testing (Carpenter et al. 2003, Ghuzlan and Carpenter 2000, Shen and Carpenter 2005, Ghuzlan 2005) and uniaxial tension testing (Daniel et al. 2002).

2.3 FATIGUE TEST METHODS

2.3.1 Semi-Circular Beam (SCB) Test

The SCB test was first used to test fracture resistance of rock materials (Chong and Kuruppu 1984). Three-point cyclic or static loading is applied on semi-circular shaped specimens with or without an introduced single edged notch. This geometry induces tension at the bottom of the sample resulting in the crack propagation throughout the specimen. Because of several merits such as high repeatability, reproducibility, consistency, and simplicity in terms of specimen preparation and testing, the SCB test has received a growing interest and is considered to be a promising candidate test to characterize fracture properties of asphalt mixtures.

2.3.1.1 SCB Test Analysis

The SCB test results cannot be completely analyzed using simple geometry-based models due to its non-uniform distribution of stress and the heterogeneity of the HMA itself. Chong and Kuruppu provided analytical solutions using the FEM for mode I and mixed mode loading for a very limited range of notch lengths and specimen size (Chong and Kuruppu 1984). ven da Ven et al. first stated an approximate solution for maximum horizontal tensile stress and claimed that to obtain the same maximum horizontal tensile stress as the IDT test, only 1/9 of the applied load is needed (ven da Ven et al. 1997). They also derived equations to calculate maximum horizontal tensile stress in SCB setup and stiffness values using 2-D FEM on steel specimen. The following study of the authors (Smit et al. 1997) employed 3-D FEM and revised the expression to calculate the maximum horizontal tensile stress and stiffness.

Molenaar et al. stated concerns that strain rate is not constant along the height of the specimen and tensile failure might not be the dominant mode in the SCB test, as compressive modes exist (Molenaar et al. 2002). The authors conducted 3-D FE analysis and shown that the dominate failure mode in SCB test is cracking, which indicate that SCB test provide relevant information on tensile characteristics and it is possible to derive the true tensile strength from the SCB test. The authors derived expressions to calculate the maximum tensile stress and stiffness. Hofman et al. used static and cyclic SCB test to assess the resistance against crack growth (Hofman et al. 2003). The maximum force at which the specimen fail during the static load test, is converted into the fracture toughness.

Huang et al. derived an approximate analytical solution to estimate horizontal stresses and strains response in SCB specimen for asphalt mixtures using the theory of elasticity (Huang et al. 2005). Based on their simulation and lab test results, their semi-analytical solution for stress is proved to be variable for calculation. Using both FEM analysis and laboratory tests, another research team (Huang et al. 2009) further verified that a simple form of analytical solution which is used in flexural bending beam test is actual very accurate (maximum error of 2 %), with the basic assumption of basic mechanics that the plane sections remained plane even after bending has taken place in the specimen. The following analytical expression of maximum stress was found out to be very close with the FEM results and can be effectively used to predict the maximum stress:

$$\sigma_{\mathrm{max}} = \frac{6Pl}{tD^2}$$

Where:

σ_{max}: Maximum stress, Pa

P: Load per unit thickness of specimen, N

l: Length of specimen, mm

t: Thickness of the specimen, mm; and

D: Diameter of semi cylinder, mm

2.3.1.2 SCB Test for Fracture Properties

To investigate fracture properties of asphalt mixtures using a performance test such as the SCB method, the linear elastic fracture mechanics (LEFM) and elastic plastic fracture mechanics (EPFM) must be involved. The parameters such as stress intensity factor (SIF) K, fracture toughness K_{IC}, and fracture energy G_{IC}, are commonly used in LEFM analyses, while the critical energy rate J_c and J integral are used for analysis in the EPFM domain (Saha and Biligiri 2016).

Compare to other fracture tests, the SCB specimen has a rather complex geometry, thus it is very difficult to obtain analytical solutions for SIF, which is related to applied load and specimen geometry and is used to explain the stress distribution near the crack tip for linear elastic materials. Chong and Kuruppu provided analytical solutions using the FEM for mode I and mixed mode loading for a very limited range of notch lengths and specimen size (Chong and Kuruppu 1984). Lim et al. expanded these numerical solutions using the FEM to a wide range of SCB specimen geometries and tabulated the normalized SIF. Lim also conducted a 3-D FE analysis and analytical analysis to calculate fracture toughness of SCB tests (Lim et al. 1993). The fracture toughness and fracture energy obtained through multiple methods were found out to be very close with insignificant errors.

Critical energy release rate (G_I) represents the external energy required for a crack to grow which is calculated by considering the area under the load-deformation curve as in the LEFM approach (Saha and Biligiri 2016). J integral, on the other hand, is defined as the critical fracture energy and calculated accounting for the area under the load-deformation curve until the peak load, and then plotted against the notch depth (Saha and Biligiri 2016). A linearly decreasing trend of strain energy can be obtained and thereof the critical fracture resistance is calculated as the slope of the fracture energy curve. Mull et al. evaluated fracture resistance of chemically modified crumb rubber asphalt mixtures using the SCB with three notch depths (Mull et al. 2002). The J integral concept is used instead of SIF to characterize the fracture performance and proved to be effective in quantifying the fracture properties of AC mixtures.

2.3.1.3 Flexibility Index Using SCB Test

Al-Qadi et al. pointed out that fracture energy itself alone is not sufficient to differentiate asphalt materials. The fracture energy is a function of both the strength (defined by peak load) and ductility (defined as the maximum displacement at the end of the test) of the material. If the material displays a high peak load, it may compensate its fracture energy for the lack of ductility in the post-peak region of the load-displacement curve (Al-Qadi et al. 2015). So, they proposed a new fracture potential parameter called flexibility index (FI), which can be a parameter representing process zone size or other property combinations with a good correlation to crack growth speed. The FI is defined as:

$$\mathrm{FI} = \mathrm{A} \times \frac{\mathrm{G_f}}{\mathrm{abs(m)}}$$

Where:
FI: Flexibility index;
A: Calibration factor coefficient, default to be 0.01;
$\mathrm{G_f}$: Fracture energy, $\mathrm{J/m^2}$; and
$\mathrm{abs(m)}$: Absolute value of slope at inflection point after peak load.

2.3.2 Push-Pull (Tension-Compression) Fatigue Test

This test protocol was developed by Drs. Solatani and Di Benedetto at Ecole Nationale Des Travaux Publics de l’Etat (ENTPE) in Lyon, France (Di Benedetto et al. 1996). It unifies controlled stress and controlled strain fatigue test results, by accounting for self-heating and thixotropy of mixes, offer a unique approach for developing more rational fatigue criterion and rigorous analysis for binders and mixtures (Soltani and Anderson 2005a). It is a true homogeneous test in the central part of the specimen (homogeneous stress and strain field), and can be conducted in both true controlled stress and strain mode. It has been used extensively to pair with the aforementioned VECD theory (Underwood et al. 2010, 2012). The advantages of the push-pull fatigue test include (Kutay et al. 2009) (a) the sample can be prepared in the Superpave gyratory compactor; (b) the stress state is simply uniaxial; (c) advanced mathematical theories such as the viscoelastic continuum damage (VECD) can easily be used to analyze the data; and, (d) the tests can potentially be conducted with the new asphalt mixture performance tester (AMPT), which is reachable to many state DOTs and contractors in the United States.

2.3.3 Indirect Tensile (IDT) Test

The indirect tensile test (IDT) is developed simultaneously but independently by Carneiro and Barcello in Brazil and Akazawa in Japan in 1953 (Husdon and Kennedy 1968). Hudson, Hadley, Kennedy and their colleagues (Hudson and Kennedy 1968, Hadley et al. 1969, 1970, Anagnos and Kennedy 1972) first applied this this method into pavement material researches to a great extent in a series of reports and concluded that the IDT is the best practice for operating agencies. The test involves loading a cylindrical specimen with compressive loads distributed along two opposite generators. This condition results in a relatively uniform tensile stress perpendicular to and along the diametrical plane containing the applied load. The failure usually occurs by splitting along this loaded plane (Hudson and Kennedy 1968).

Hondros (1959) derived equations to calculate the stresses along the principle diameter and at the center. Wijk then developed the 3-D solution of stress and strain for IDT configuration (Wijk 1978). The work was further expanded by Wen, who incorporated viscoelastic solutions into the calculation (Wen 2001).

Roque and Buttlar developed a new testing system using IDT mode that uses gauge-point-mounted devices on a specimen to conduct interior measurement only in center region of the testing specimen (Roque and Buttlar 1992). This configuration ensures a rigorous analysis for time and temperature dependent material properties since stress and strain distribution in this region is fairly uniform, measurements obtained in this region would reduce or eliminate the effects of local stress concentration around the loading strip and the rotation of the specimen. In this test configuration, Poisson's ratio can be calculated using measured vertical and horizontal deformation instead of using assumed values, besides, creep compliance can also be calculated. The approach was further improved by Buttlar and Roque (1994) and put it to use to a great extent (Roque et al. 1999). Kim and Wen used fracture energy obtained using such a test to serve as a simple performance indicator to evaluate cracking resistance of asphalt mixtures (Kim and Wen 2002).

2.3.4 Other Fatigue/Fracture Tests

Except the three fatigue/fracture test methods introduced previously, various several other laboratory tests have been developed to investigate fatigue and fracture resistance performance of asphalt mixtures and to predict service life in the field. Those laboratory mechanical tests include (Tangella et al. 1990):

- Simple flexural.
- Supported flexural.
- Triaxial test.
- Wheel tracking testing.

3.4.1 Simple Flexural

The three-point bending (center point) beam and four-point bending beam tests are the most widely used fatigue tests in the United States, while the cantilever loading test is mainly used in Europe. They are all simple flexural fatigue tests. In all these tests, a constant stress or constant strain is applied repeatedly to the specimen until a defined level of failure is reached. Failure is sometimes defined as the point where a specific change in properties of specimens from the initial state is reached. The tested specimen for the three/four-point bending beam test is in rectangular shape with different dimension requirement. The cantilever loading setup is usually conducted in two ways, vertically mounted rotational cantilever beam and sinusoidal loaded trapezoidal beam.

3.4.2 Supported Flexural

This test setup duplicates in-situ loading conditions, especially the stress state and mode of loading. An asphalt mixture beam or slab sits on a rubber material subjected to a load at the center that directly simulates in-situ modes of loading. Concerns about this test setup include high cost, time requirement, unusual sample size, and the need for more complicated test equipment.

3.4.3 Triaxial Tests

Test setup in triaxial test is similar to direct axial (push-pull) fatigue test but with horizontal confinement. Shear strain in this test setup needs to be well controlled, otherwise the predicted fatigue life could be considerably different than the field results.

3.4.4 Wheel Track Testing

Wheel track fatigue test includes laboratory performed wheel track testing and full scale accelerating pavement testing. For laboratory tests, it can be performed using a rolling wheel that moves over an asphalt concrete slab to simulate wheel loading in the field. In full scale accelerating testing, real pavement is built in a circular or longitudinal track. Then the track is loaded at full scale.

Tremendous differences exist among properties obtained using different tests, mainly because of the differences in testing methods, loading conditions, specimen configuration, and environmental conditions during testing. The mechanics of different test methods also differ from each other on loading configuration, stress distribution, load waveform, loading frequency, permanent deformation, and the state of stress. Several reports and thesis (Ghuzlan 2001, Tangella et al. 1990, Zeiada 2001) provided more detailed information regarding these tests including advantages, disadvantages, and application. Especially in SHRP project A-003A and SHRP A-404, the authors (Tangella et al. 1990, SHRP A-404 1994) evaluated all existing fatigue testing methods and ranked them based on their ability to simulate field condition, simplicity, application of test results and field performance correlation.

2.5 CRUMB RUBBER MODIFIED ASPHALT MIXTURES

According to the United States tire manufacturers association, 4.2 million tons of vehicle tires were discarded in 2017. This number keeps increasing due to growing demand of vehicles and traffic. Discarded tires pose a severe environmental problem in the United States. Normally, discarded tires are reused, resold, retreated, or landfilled. Among possible uses of scrap tires, only two methods have shown potential for the greatest benefit: use as combustion fuel and use as crumb rubber modifier (CRM) for paving industry (Heitzman 1992). The ignition of tires produces a large amount of toxic black smoke and is extremely difficult to extinguish (Buncher 1995) unless very carefully controlled. Only the application in paving industry seem to be a wise and heathy choice. CRM use in asphalt paving has a relatively long history and its first use goes back to 1840 (Heitzman 1992). However, a rational approach for use did not come into play until McDonald introduced the wet process in 1960s.

The usage of scrap tire rubber as a modifier in asphalt and asphalt mixtures have been developing for more than 50 years. Prior to 1991, only a few states had experimented with CRM in hot mix asphalt (HMA) and fewer were using it on a regular basis. However, in an effort to reduce the solid waste management problem of scrap tires, United States Congress passed the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) (Buncher 1995). Section 1038 of ISTEA mandates that each state will utilize a certain amount of recycled tire rubber every year in their HMA and/or asphalt binder for federally funded highway projects, or have federal money withheld for future projects. As a result of ISTEA, a surge of interest has developed in CRM technology so states can make technically sound and financially wise decisions.

There are two ways of incorporating grinded or sheared crumb rubber particles into asphalt paving materials, wet process and dry process. The term wet process defines any method that blends the crumb rubber with the asphalt binder at elevated temperature before incorporating the binder into the aggregate, which was first developed by Charles McDonald in 1960s. On the other hand, in dry process, crumb rubber particles will be mixed with the aggregate before they are charged with asphalt binder, which is developed in late 1960s in Sweden (Heitzman 1992) with a trade name Rubit and then in the United States under the trade name PlusRide.

The sole objective of the wet process has always been binder modification. Conversely, the primary reason for using the original dry process system is to replace a portion of the aggregate with granulated CRM particles, achieving a "flexible aggregate" effect (Buncher 1995). The dry process consumes 2 to 4 times the amount of CRM than in wet process, as the CRM particle used in dry process is much coarser than those used in wet process. It also requires more asphalt binder to reach a similar air void level and to produce similar HMA (Abdelrahman 1996). The typical wet process requires special blending equipment to react the CRM with the asphalt binder at elevated temperatures for a specified period of time. In addition, the blending process requires additional manpower for operation. However, wet process produces a much more uniform binder product. As a result, it is favored over dry process for field application in the United States.

2.6 FATIGUE PERFORMANCE OF ASPHALT MIXTURES CONTAINING CRM AND RECYCLED MATERIALS

A great amount of research efforts has put into using CRM in asphalt mixtures; however, limited information is available regarding their fatigue performance. Mohammad et al. conducted a comprehensive study to evaluate the overall laboratory and field performance of crumb rubber asphalt mixtures (Mohammad et al. 2000). The authors concluded that CRM asphalt mixtures behave similarly to conventional asphalt mixtures in laboratory tests. As for field accelerated loading test, CRM mixes as base course shown significant less rut compare to conventional mixes, while CRM mixes as wear course shown similar rut depth compare to conventional mixes. Kaloush et al. conducted the dynamic modulus tests on field cored crumb rubber asphalt mixtures (Kaloush et al. 2003). Master curves of mixtures were obtained using confined and unconfined dynamic modulus tests and compared with conventional HMA at certain temperature and frequency. At both low and high temperature in unconfined test, asphalt rubber mixtures shown lower stiffness which indicate a good resistance to fatigue. However, in the confined test configuration, asphalt rubber mixtures shown relatively higher stiffness which indicate a good resistance to rutting. The crumb rubber modified asphalt binder and mixtures have also been incorporated with other asphalt paving materials such as RAP and WMA technologies (Shen et al. 2006, Xiao et al. 2009) and shown improvement fatigue performance due to its soft nature. Raad and Saboundjian investigated the summarized the experience of using rubber asphalt mixes in Alaska and conducted controlled strain flexural beam fatigue test (Raad and Saboundjian 1998). Comparing to regular mixes, rubber mixes seem to have the ability to dissipate more energy before 50 percent reduction in flexural stiffness compare to conventional mixes. At 20℃, both rubber mixes and conventional mixes shown similar fatigue life, at 0℃, both mixes shown the longest fatigue life while rubber mixes exceed conventional mixes. Mohammad et al. investigated performance of asphalt mixtures with high RAP contents with CRM (Mohammad et al. 2011). Up to 40 percent of RAP was added in the mixes with CRM. SCB test and Superpave IDT were conducted and based on their results, CRM mixtures show the least cracking resistance even though CRM had softened the stiff aged binder. Overall, asphalt mixtures containing CRM tend to show better fatigue performance than conventional asphalt mixtures.

Using RAP and RAS to replace virgin materials may result in paving projects that have lower initial costs or life-cycle costs. Due to aging effect of the binder, the recycled asphalt materials are normally very stiff, thus rutting is not an issue for asphalt mixes with recycled materials. However, fatigue resistance of asphalt mixtures with high volumes of recycled materials could be compromised, and it is the primary concern of using these materials. In addition, recycled materials tend to have higher variability than virgin materials. To better utilize recycled materials that have tremendous environmental benefits, it is very importance to fully understand their behavior, especially their ability to resist cracking.

Timm et al. stated that adding to hot mix asphalt mixtures with 50 percent RAP is a viable option based on the rutting and fatigue cracking test results on their test sections (Timm et al. 2016). Test sections with 50 percent RAP performed equal or even better than control sections. McDaniel et al. tested mixtures of 0%, 15%, 25%, and 40% RAP under the push-pull configuration and shown that 40% RAP mixes exhibited higher fatigue resistance followed by control mix. The mixes with 15% and 25% RAP had similar fatigue lives (McDaniel et al. 2012). Al-Qadi et al. evaluated the stability and durability of asphalt mixtures with up to 50 percent RAP (Al-Qadi et al. 2012). They reported slightly improved fatigue performance when incorporating RAP, and this improved went further when using single-bumped binder grade. Shu et al. studied fatigue characteristics of asphalt mixture containing up to 30 percent RAP using the Superpave IDT and the beam fatigue test (Shu et al. 2008). Decreased dissipated creep strain energy threshold and energy ratio was reported, which indicated a reduction in fatigue life. Contrary to CRM, most reported data shown decreased fatigue resistance when incorporating RAP and RAS in asphalt mixes.

2.7 SUMMARY OF LITERATURE REVIEW

Cracking in asphalt pavement is a severe issue that need to be controlled to ensure a safe and comfortable roadway system. Among four methods to characterize this distress, the phenomenological approach is simple to use and easy to understand, however, it does not account for damage evolution. Mechanistic approach, which consists of dissipated energy approach, fracture mechanics approach, and viscoelastic continuum damage approach, are more complicated but represents fundamentals of asphalt materials.

Numerous test methods have been invented to study cracking resistance of asphalt mixtures. Some are complicated to perform with complicated results for interpretation, some represent specimen performances instead of material behaviors. Only limited number of tests showed potentials to be implemented in routine mix design and quality assurance process with their simple but valid, low cost but high efficiency nature.

Cracking resistance of asphalt mixtures containing CRM are normally better than conventional asphalt mixtures added by the elastic nature of rubber. On the other hand, mixtures include recycled materials normally shown less cracking resistance owing to the higher stiffness.

Given that there are so many laboratory fatigue/fracture tests to choose from, the applications are mostly limited within research or forensic study purposes. With increasing usage of complicated compositions such as recycled materials into asphalt paving materials, it is of great value and importance to adopt performance tests into routine asphalt mixture design practice. Such methodology improves the quality of the construction materials and ensures the durability and serviceability of the pavement. A performance database of asphalt mixtures with CRM and recycled materials is also in need to better utilize these materials for lower costs and better performance.

Chapter 3 LABORATORY FRACTURE TEST SELECTION

3.1 CRITERIA FOR TEST SELECTION

A volumetric or experience-based mixture design method is sufficient when only virgin materials, i.e., virgin aggregate and virgin binder, are used in the asphalt mix. With the increasing usage of sophisticated compositions such as recycled materials, namely reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), and crumb rubber modifiers (CRM), and different performance enhancing additives such as polymer modifiers, recycling agent, and warm mix asphalt (WMA) additives, conventional design methods eventually lose their edge. Performance-based mix design methods are more capable of differentiating high or low quality of the final mixes.

Apart from the field track and model tests, a variety of laboratory tests have been developed to characterize the fracture properties of asphalt mixes due to their simplistic nature and lower costs compared with full- or model-scale testing. Although these laboratory tests have been successfully adopted for research, there is no widely accepted fracture test for routine mix design and material quality control in the United States. An exception is the four-point bending beam (4PBB) cyclic fatigue test being used by the state of California for mixture design. Many studies have attempted to find the most appropriate fracture or fatigue test, one that is simple yet reliable, so that agencies and contractors can implement it into routine mix design and possibly into quality assurance or quality control.

To be successfully used on a day-to-day basis, a candidate fracture test must have the following characteristics (Zhou et al., 2017):

- Testing devices are easily accessible;
- Testing and interpretation of results are not complicated;
- Test results are sensitive to mix variables and have low variability; and
- Test results correlate well to field performance.

Based on these criteria, Zhou and his colleagues summarized some practical and promising cracking tests (Zhou et al., 2017).

Walubita et al. (2011) compared four laboratory cracking tests: overlay tester (OT), direct tension (DT), indirect tension (IDT), and semicircular bending (SCB) test with repeated-loading fatigue test. Based on results obtained from their unique mixes, the four monotonic loading tests were found to be more repeatable and less variable, but less capable of discriminating good- and poor- performing mixes, compared with a repeated loading test. Such a conclusion is contradictory to other studies and propositions, it is probably because the researchers employed tensile strength, which is not a fracture resistance performance indicator to begin with, for performance evaluation. Despite the controversial results, the authors proposed five criteria for selecting a fracture test, similar to previously mentioned criteria:

- Rationality of the test concept and tie to field performance;
- Repeatability and variability;
- Simplicity and practicality;
- Specimen fabrication process; and
- Simplicity of data analysis.

Point one from both criteria is not challenging to follow. The test has to be fundamentally rational with a solid theoretical background. The correlation to field performance is not less important since the ultimate goal of any evaluation system is to ensure long-term field performance of the mixes. Point two ensures the sensitivity of the test. High variation from the test results masks the sensitivity, and thus affects the final decision making, of the test. Low repeatability prevents the test from being widely adopted because of concerns for bias and error. Points four and five tie into point three: To be employed by agencies and contractors, considering the volume of mixes they process on a daily basis, the proposed test has to be easily performed in a short period of time. It means the overall specimen processing time, testing time, and finally data analyzing time have to be minimal, which manifests the importance of simplicity.

From the literature review, reported data, and topics of conferences in the past few years, the SCB test seems to be the overall best choice for the fracture test. First, it is an index-based fracture test with solid theoretical background, which means that performance indicators—in this case, fracture energy, flexibility index, and peak load—could be directly associated with cracking resistance of asphalt mixes. An advantage of such index-based performance indicators is that, comparing to mechanistic-oriented performance indicators, such as creep compliance from Superpave IDT test or damage parameters from viscoelastic continuum damage (S-VECD) and direct tension pull-pull test, which are generally combined with cracking models for performance evaluation, the performance indicators of the SCB test are simpler to understand and easier to analyze requiring minimal training.

A second reason for choosing the SCB test is that a monotonic loading test is naturally less scattered in results and has much higher repeatability. This research and other studies have proven that some performance indicators of the SCB test have extremely low coefficient of variations (COV), a statistical term describing the variability of a data. Even the most scattered performance indicator—flexibility index—has a lower COV compared with indicators from cyclic fatigue tests. Third, numerous studies have proven the high sensitivity of parameters of SCB tests, which means such a test is capable of discriminating between good and poor performing asphalt mixes. Finally, the SCB test is very easy to perform. Test specimens can be cut from gyratory compacted plugs or field extracted cores to start with, meaning there is no extra work beyond specimens that have been extracted using conventional procedures; additionally, there are no procedures associated with gluing or mounting strain measuring devices; the test can be performed on any loading devices that are common in a civil engineering laboratory with a compressive loading capacity as low as 10 KN; and test results can be analyzed in spreadsheet within seconds. In other words, the SCB fracture test is currently the best candidate fracture test for routine mix design and quality screening.

3.2 SEMI-CIRCULAR BEND (SCB) FRACTURE TEST

The SCB test is a laboratory mechanical test used to evaluate the fracture resistance of asphalt mixtures. It was first developed to study the fracture resistance of rock materials (Chong et al., 1984). Later, it was adopted by pavement engineers to investigate fracture characteristics of asphalt mixtures (Molenaar et al., 2002). In the early stage of test implementation, linear elastic fracture mechanics concepts, such as stress intensity factor and fracture toughness, were used to characterize the fracture properties of asphalt mixtures. However, for quasi-brittle materials such as asphalt mixture, assumptions of linear elastic fracture mechanics are not valid because high scale yielding at the crack tip requires consideration of a larger fracture process zone (i.e., the region of damage around the crack tip) for fracture assessment. Mull and his colleagues used the J-integral concept to investigate the effect of crumb rubber additives on the fracture resistance of asphalt mixtures (Mull et al., 2002). In their study, three different notch depths were used on SCB specimens, and the slope of pre-peak fracture energy vs. notch depth plot was used for evaluation. Later, this method was adapted by Mohammad and his team (Mohammad et al., 2004; Kim et al., 2015), and was implemented by Louisiana Department of Transportation. Wisconsin, Oklahoma, and New Mexico have also considered use of the Louisiana protocol (Zhou et al., 2017). Al-Qadi and colleagues developed a new fracture mechanics-based performance index, called “flexibility index” (Al-Qadi et al., 2015; Ozer et al., 2016), which considered the combined effect of fracture energy and post-peak behavior of the material under load in the SCB configuration. Correlation of results from flexibility index to field performance is under investigation, but data generated from initial studies by Al-Qadi and colleagues show promising results (Al-Qadi et al., 2015). The approach proposed by Mohammad et al. (2004), using the critical strain energy release rate, has been found to correlate with field performance (Kim et al., 2015), and has been standardized and available as ASTM D 8044-16. The Flexibility Index approach is still a work in progress and therefore has been the subject of the investigation presented in this paper.

3.2.1 SCB Test Configuration

During the test, a monotonic load (a single time loading process) was applied vertically on the top center of a half cylindrical sample with a notch created at the bottom center (Figure 3-1) until the complete failure of the test specimen (Figure 3-2). The load and displacement were recorded continuously during the test. The specimen was supported by two rods that could slide freely during the loading process (Figures 3-1 and 3-3).

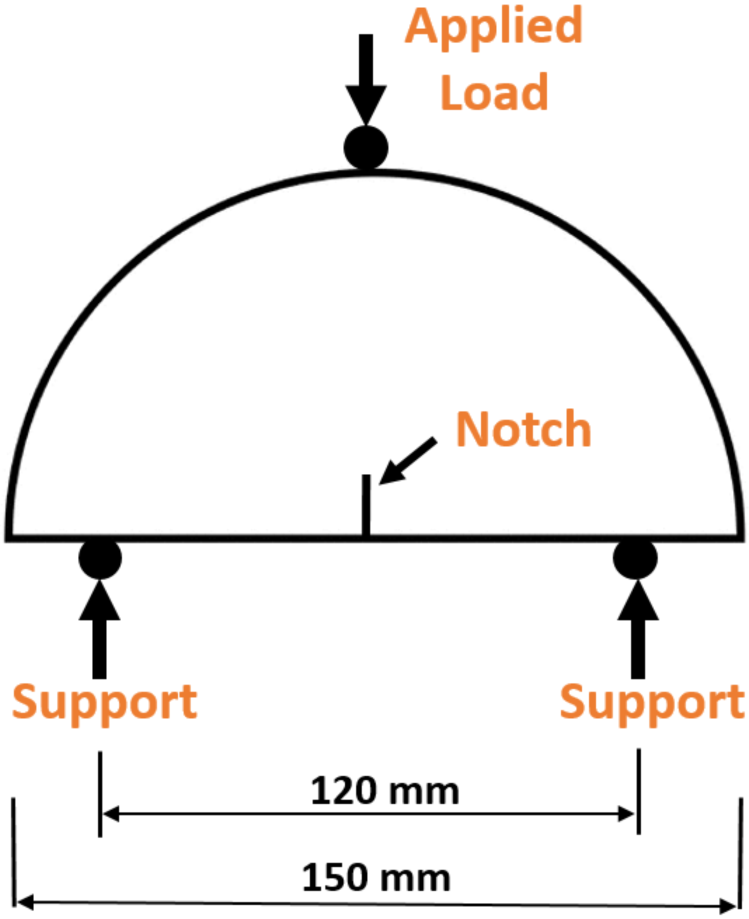


Figure 3-1. Schematic of SCB test configuration

Figure 3-2. A SCB specimen before (left) and after (right) test, demonstration of a crack propagation.

Figure 3-3. A SCB specimen after test (crack at the center of specimen).

3.2.2 Standardized SCB Fracture Test

The standardized SCB fracture test is normally used to evaluate low-temperature and intermediate-temperature cracking resistance of asphalt mixtures. The application in low-temperature evaluation is beyond the scope of this research, and thus will not be discussed. For evaluating fracture resistance of asphalt mixtures at intermediate temperature, however, there are two standardized test methods: ASTM D 8044 and AASHTO TP 124.

ASTM D 8044 adopts the J-integral concept in nonlinear fracture mechanics to evaluate the fracture properties of asphalt mixes. The uniqueness of this test compared with other SCB fracture tests is that it requires three different notch depths to be created: 25 mm, 32 mm, and 38 mm. Because of the difference in ligament area (the area from notch tip to specimen top across the specimen thickness) caused by different notch depths, the strain energy (the area under load-displacement curve until failure) differs by notch depths. Then strain energies are plotted against their corresponding notch depths, and the slope of the curve is calculated as the critical strain energy release rate, i.e., J_c. The higher the J_c, the better the cracking resistance of the mix. Such a test is commonly used in Louisiana.

AASHTO TP124, also known as I-FIT, uses the flexibility index (FI) concept, which, as mentioned previously, is a fracture mechanics-based performance indicator developed at the University of Illinois (Ozer et al., 2016) to quantify the cracking potential of asphalt mixes.

AASHTO TP124 was chosen over ASTM D8044 as the primary reference test employed throughout this research for three reasons. First, TP 124 uses much fewer materials. Assuming three replicates are needed for evaluation, ASTM D 8044 would need three times more materials to complete the evaluation, because it need three replicates for each of its three different notch depths. Considering the volume of mixes evaluated in this research, the difference is significant.

Second, TP 124 has fewer variables in parameter calculation, and all of them are directly obtainable from the test result without further interpretation. The performance indicators used by ASTM D 8044, on the other hand, requires direct measurements plus linear regression to reach the final performance indicator. Specifically, fracture energy, flexibility index, and peak load of TP 124 are directly obtainable from the load vs. displacement curve of SCB test. The final parameter used for performance evaluation in ASTM D 8044 is critical strain energy release rate, which is the regression of strain energies against notch depths, an interpretation rather than direct measurement. Although, the strain energy (referred to in some studies as fracture energy before peak load), is well-known for extremely low variations, the regression process normally increases variation of the data because it does not use real measured data. In addition, creating multiple notch depths increases variation by itself. One final reason for using AASHTO TP124 is that the overall specimen preparation process is much simpler to follow: It requires less cutting, which is ideal for day-to-day application.

3.3 SCB FRACTURE TEST PARAMETER CALCULATION

Figure 3-4 shows a typical load-displacement curve from an SCB test. Peak load (P_{max}), also known as failure load, is the maximum load on the load-displacement curve. It represents the highest load an asphalt mix can sustain before failure under a given test configuration. Work of fracture (W_f) is the area under the load-displacement curve. It can be summed up by adding work of fracture before and after the peak load. These two are the direct measurements from the load-displacements plot.

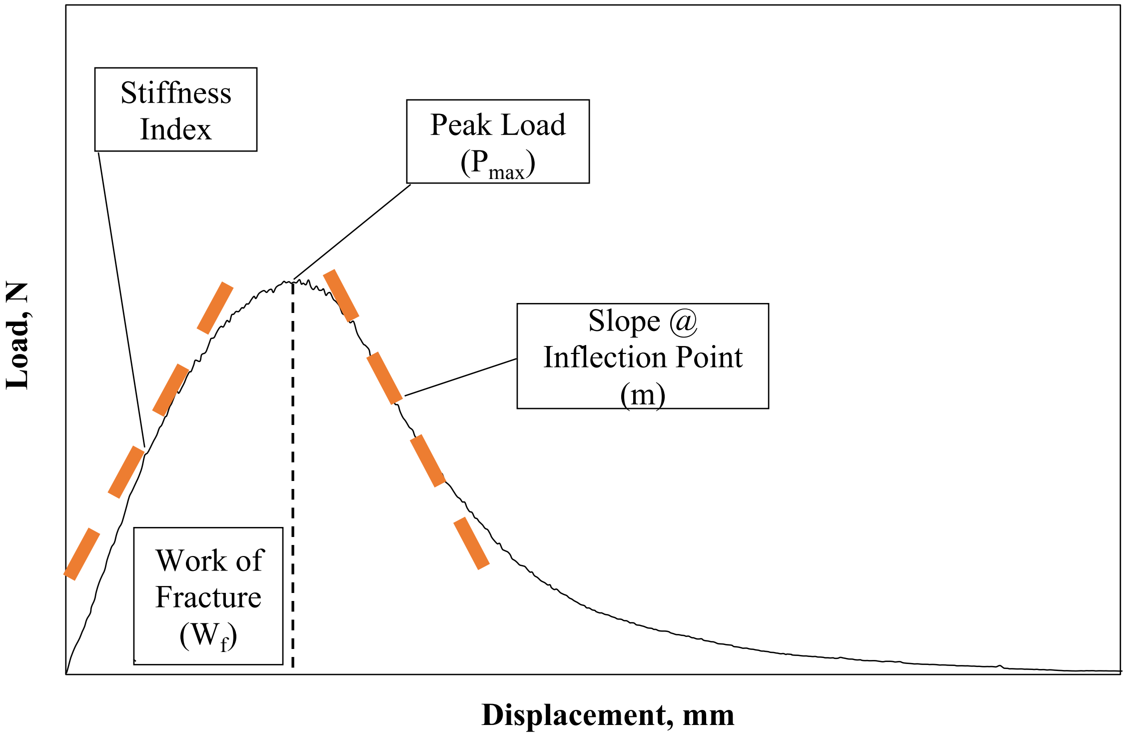


Figure 3-4. Typical load-displacement curve of SCB test and performance parameters in SCB test.

Work of fracture (W_f) is defined as the area under the displacement-load curve. Fracture energy (FE) is then calculated as work of fracture divided by ligament area. Pre-peak fracture energy means the fracture energy value before the curve reaches peak load. Flexibility index is calculated as fracture energy divided by the absolute value of the slope at the inflection point on the post-peak curve, then times a constant 0.01 for scaling (Al-Qadi et al., 2015; Ozer et al., 2016). Finally, stiffness index (Bonaquist et al., 2017) is calculated as the slope at 50 percent peak load on the pre-peak curve. Detailed information can be found in cited references.

FI was first calculated using the I-FIT software provided by the Illinois Center of Transportation (ICT) during the preliminary study phase. The software uses a polynomial equation with a degree of three to fit the pre-peak curve, and an exponential based equation to fit the post-peak curve. Then we performed integral to calculate the work of fracture, and derivative to calculate slope at the inflection point (m-value). It was noticed during the work that the software sometime yields unreliable results (notably, drastically different FI values for two overlapping curves), and is unable to provide any numerical value less than one. Thus, adjustments were made to how the post peak slope is established by using the minimum value of tangent curves of each data point after post-peak as the m value in the FI definition. Work of fracture was calculated using Simpson's rule. This method made it possible to calculate FE and FI without using curve-fitting equations or dedicated software, while in the meantime providing highly accurate results. All FE and FI values presented in this paper thus used this modified approach.

As discussed previously, there are many performance parameters developed for the SCB test and other similar monotonic fracture tests. The main application of these performance parameters has been ranking different mixes. The importance of ranking different mixes is undeniable, however, to be considered and adopted for routine mix design, the requirement for a robust performance indicator is far from simple ranking. Currently, suitable performance threshold values do not exist. It is important to identify appropriate performance indicators and establish design oriented performance derived threshold values, before such test can be confidently adopted into routine practice by material suppliers and agencies.

3.4 SPECIMEN PREPARATION FOR SCB FRACTURE TEST

All SCB specimens were cut from a Superpave Gyratory Compacted (SGC) specimen, i.e., plug, with a diameter of 150 mm and a height of 150 mm as well (Figure 3-5). The compacted specimens were air-cooled overnight before being cut into four slices. The top and bottom slices, with a thickness of 20 mm, were discarded, and the middle two slices, each with a thickness of 50 mm, were further split into four SCB specimens. The rationale behind this approach was to minimize the effect of air void gradient within the specimen on SCB test results. An independent study, described in Chapter Five, was also conducted to ensure that the two middle layers, although differing in relative location in a compacted specimen, deliver the same results statistically. Finally, a notch of 15±0.5 mm in depth and 1.5 mm in width was cut in each SCB specimen, which was then air-dried overnight before measurements were taken of the ligament size and bulk specific gravity.

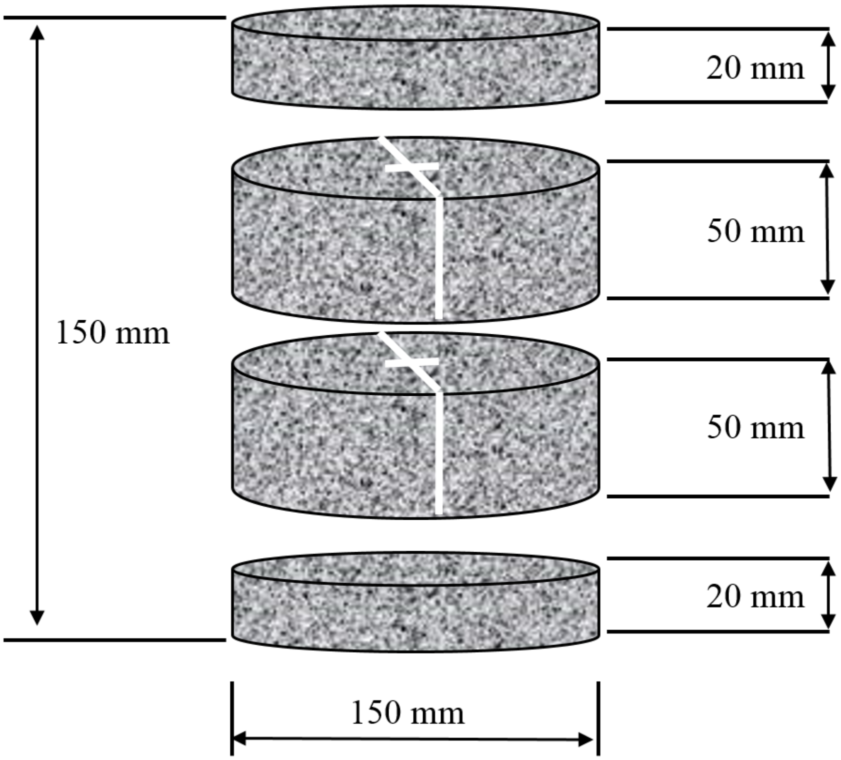


Figure 3-5. Schematic showing four SCB specimens cut from one plug.

Before actual testing, each specimen was conditioned at the test temperature for four hours in an environmental chamber. A sitting load of 50 Newtons was applied before starting the actual loading, and the test stopped when the applied load dropped below 100 Newtons.

This chapter discussed reasons why the semi-circular bend (SCB) fracture test was selected as the benchmark test for this research. The details on how to prepare testing specimens, how to perform the test, and the calculation of performance parameters were also introduced. Some limitation of current practice is discussed. In the next chapter, a study to determine the main test condition, i.e., displacement rate, which is the loading velocity of the loading head and test temperature, will be presented.

Chapter 4 THE EFFECT OF TEST TEMPERATURE AND DISPLACEMENT RATE ON SEMI-CIRCULAR BEND TEST

The behavior of asphalt concrete under load is heavily influenced by displacement rate (loading time) and temperature because of its viscoelastic nature. It is the objective of this chapter to investigate the effect of these two factors on performance indicators, or response/characterization parameters, under semi-circular bend (SCB) test. The ultimate goal of this study is to find the most suitable combination of displacement rate and temperature for SCB fracture test to be conducted in northeast region of the United States.

4.1 INTRODUCTION

Fatigue cracking is a major pavement distress which starts from independent cracks and develops into interconnected cracks, it weakens the material greatly and further deteriorates to potholes, the latter of which allow considerable amount of moisture infiltration into the pavement and significantly reduce the strength and durability of the pavement structure. The fatigue cracking phenomenon has drawn considerable attention of research since 1940s. Laboratory tests along with analytical and numerical studies have been applied to tackle this problem. However, more rigorous analysis and testing systems are still in need to solve the fatigue cracking problem due to its complexity.

In spite of recent developments regarding the SCB test, it is yet to be determined which displacement rates and temperatures are the most suitable, and if various rates or temperatures should be used depending on the climatic region and traffic. In current state of practice, the test temperature and displacement rate have been mostly selected based on experience and the ease of operation. Although similar characterizing parameters are being used for analysis, performance data are not comparable among different research groups due to different testing conditions, thus making it difficult to select a unified threshold value for acceptance or rejection of the mix.

4.2 OBJECTIVES

The primary objective of this study is to investigate the effect of testing temperature and displacement rate on SCB test characterization parameters (response parameters). Three individual objectives were pursued: 1) Evaluate the sensitivity of characterization parameters at the common fatigue test temperature of 25℃ under multiple displacement rates, 2) Investigate the sensitivity of characterization parameters at the proposed effective temperature under multiple displacement rates, and 3) Investigate the effect of temperature on characterization parameters at various displacement rates.

For the sake of this study, characterization parameters refer to fracture energy, peak load (failure load), stiffness index, pre-peak fracture energy, and flexibility index. The material variables, or material components, include binder content, binder stiffness, and air void.

4.3 THEORETICAL BACKGROUND

The behavior of many elastic materials is, to a large extent, independent of temperature and duration of loading. An example is the response of steel when subjected to loading under a normal range of temperature change. The strain response of steel is not much affected by changes in temperature (within normal range) or by frequency of loading (or displacement rate). However, asphalt being a visco-elasto-plastic material behaves very different as the temperature and loading frequency change. Specifically, fatigue behavior of asphalt mixtures is highly temperature and time (displacement rate or frequency of load) dependent and this dependency has been the subject of several studies in the past (Pell and Cooper 1975, Tayebali et al. 1992, Al-Khateeb and Ghuzlan 2014, Al-Qadi et al. 2015). Tayebali et al. found that temperature had significant influence on the relationship between cumulative dissipated energy and fatigue life; Al-Khateeb and Ghuzlan reported that fatigue life increases with the increase of loading frequency. However, at the same loading frequency, fatigue life decreases with the increase of test temperature. Research in this respect has been mostly associated with cyclic fatigue tests. Data on the effect of temperature and time on fracture behavior of asphalt under monotonic loading conditions is limited and primarily focused on other purposes such data quality (Nsengiyumva 2015), and hence the motivation for this study. Understanding the effect of temperature and loading frequency on fracture response of asphalt concrete is important so that the right combination of these two parameters is selected to test a mix for use in a specific climate and traffic conditions.

4.3.1 Selection of Test Temperature

For low temperature cracking tests, such as indirect tensile test (IDT) for creep and strength, or the disk-shaped compact tension test (DCT), the test temperature has been selected based on the low temperature grade of the asphalt binder to be used at a specific climatic zone. For permanent deformation (rutting) tests, such as Hamburg wheel tracking, the test temperature is normally set at 50°C or determined by the performance grade of the asphalt binder (Aschenbrener and Currier 1993). For fatigue cracking test, however, there is not a widely accepted method to determine the test temperature. The most commonly used test temperatures for cyclic and monotonic fatigue test are 10°C and 25°C, respectively. These two temperatures have been probably selected to bracket typical range of temperatures associated with fatigue cracking in asphalt pavements.

Al-Qadi et al. conducted SCB fracture tests under a range of temperatures from -30°C to 30°C and a range of displacement rates from 5 to 100 mm/min (Al-Qadi et al. 2015). The authors believed that higher peak value of fracture energy amplifies the difference between mixes, thus proposed to perform SCB fracture test under intermediate temperature (25°C) and a fast displacement rate (50 mm/min), which delivered the highest overall fracture energy values in their study. The other reason for selecting this temperature was to eliminate the need for an additional environmental conditioning chamber, assuming the room temperature could be maintained at 25°C.

Fatigue cracking in asphalt pavement is a complicated phenomenon in regard to the effect of temperature and displacement rate (frequency). Pavement strain response fluctuates during the day as the pavement temperature and truck speed change. Furthermore, the range of these temperature fluctuations is very different in hot climatic regions compared with that in cold regions. Hence, establishing a single test temperature and displacement rate combination for all regions does not seem a reasonable approach. At the same time, finding the most suitable test temperature for various regions will be a daunting task, even though not impossible. It is rational to test the mixture at an effective service temperature as the best representative of the mix overall fatigue performance (Reinke et al. 2004). For example, for a specific location, if the intermediate pavement temperature, at which the majority of fatigue cracking takes place, is 20℃, then all mixes paved for this location should be tested at 20℃ to assess their fatigue resistance, regardless of the binder stiffness. Use of a region-dependent single temperature significantly reduces the testing and analysis efforts in evaluating mixture performance. Such approach would consequently lead to economic advantages (Deacon et al. 1994, El-Basyouny et al. 2009).

The presence of a single temperature at which asphalt mixtures can be evaluated for permanent deformation and rutting has been termed the "effective temperature (T_{eff})" (El-Basyouny et al. 2009), originally proposed in SHRP report A-407 for fatigue cracking (Cominsky et al. 1994). The initial T_{eff} approach considered a comprehensive analytical framework. However, limitations exist in the initial T_{eff} model due to the absence of the traffic-loading frequency effect, and the limited use of a variety of climatic characteristics. Further work by researchers improved this model using a closed-form regression analysis by introducing typical traffic load with corresponding frequency, and more comprehensive environmental terms (El-Basyouny et al. 2009). The researchers also tied the new prediction model to the calibrated performance models found in the Mechanistic-Empirical Pavement Design Guide (MEPDG). The improved effective temperature model for fatigue cracking is shown as:

$$T_{eff} = -13.995 - 2.332 \times (Freq)^{0.5} + 1.006 \times (MAAT) + 0.876 \times (\sigma MAAT) - 1.186 \times (wind) + 0.549 \times (sunshine) + 0.071 \times (rain) \quad [4\text{-}1]$$

$$Freq = 17.6 \times v/[2 \times (a + h_{ac})] \quad [4\text{-}2]$$

Where:

T_{eff}: Effective Temperature, °F;
Freq: Loading Frequency, Hz;
v: Vehicle Speed, mph;
a: Radius of Tire Pressure, in.;
h_{ac}: Thickness of the Pavement, in.;
MAAT: Average Mean Annual Air Temperature, °F;
σMAAT: Standard Deviation of MAAT, °F;
wind: Mean Annual Wind Speed, mph;
sunshine: Mean Annual Percentage Sunshine, %; and
rain: Annual Cumulative Rainfall Depth, in.

For this work, a pavement thickness of 100 mm (4 in.) and vehicle speed of 80 kph (50 mph) were assumed. Quantities of all environmental terms were decided based on data from local weather stations: MAAT = 11.13℃ (52.03°F), σMAAT = 7.85℃ (17.87°F), average annual wind speed = 7 mph, average annual sunshine = 60%, and annual rainfall = 103.9 mm (40.9 in.). Based on this data, the effective temperature for fatigue test for a specific location in the northeast region (In this case, Harrisburg, PA) is calculated as 18.3℃ (65°F). This is also within the range of equivalent temperature reported by Deacon et al. (1994).

4.3.2 Selection of Displacement Rate

The most common displacement rate used for intermediate SCB test is 50 mm/min. There is little evidence in the existing literature establishing the theoretical support for such selection. This displacement rate dates back to 1960s when the indirect strength test (IDT) gained popularity in pavement material research. There is also a strong possibility that the rate was selected to be consistent with the fixed displacement rate used in the Marshall stability tester. Al-Qadi et al. stated that the reason of choosing 50 mm/min was because it delivered the overall highest fracture energy compared with other displacement rates (Al-Qadi et al. 2015); that is the same reason given for choosing 25℃ as the test temperature.

However, reported data (Zhou et al. 2017) has shown that 50 mm/min might be too fast to collect enough data points for reliable calculation of flexibility index in case of brittle mixes. On the other hand, application of too low a displacement rate may also adversely affect test results. At intermediate temperatures, where most fatigue damage happens, extremely low displacement rates (such as 0.5 mm/min) induce creep and corresponding dissipated energy.

Christensen et al. performed a layered elastic analysis and assumed typical structural and material properties, to determine the appropriate displacement rate for the IDT (Christensen et al. 1994). The researchers considered the failure time of about 20 seconds, thus proposed a rate of 3.75 mm/min for the IDT based on Kenlayer results. Later, Christensen et al. proposed a rate of 6 mm/min for IDT low temperature cracking (Christensen et al. 2004), which differed from 12.5 mm/min. as specified in AASHTO T 322. Considering the approximate nature of these analyses, it is the purpose of this research to investigate a range of displacement rates and determine the appropriate rate for the SCB test. The selected displacement rate shows relatively low coefficient of variation, sufficient sensitivity to material variables, and ability to differentiate among various mixes.

4.4 MATERIAL AND EXPERIMENTAL PROGRAM

4.4.1 Material Characterization

The limestone aggregate used in this study came from a local source. The coarse material, i.e., the proportion of aggregates larger than sieve #4 (4.75 mm), with a proportion of 55 percent, has a bulk specific gravity of 2.757. The fine material, i.e., the proportion of aggregates smaller than sieve #4, with a proportion of 45 percent, has a bulk specific gravity of 2.815. A Superpave 9.5 mm mix design was used throughout this study, which means the maximum nominal size of aggregates in this mixture is 9.5 mm. The design binder content for such mix is 5.4 percent, and the design gradation is shown in Figure 4-1.

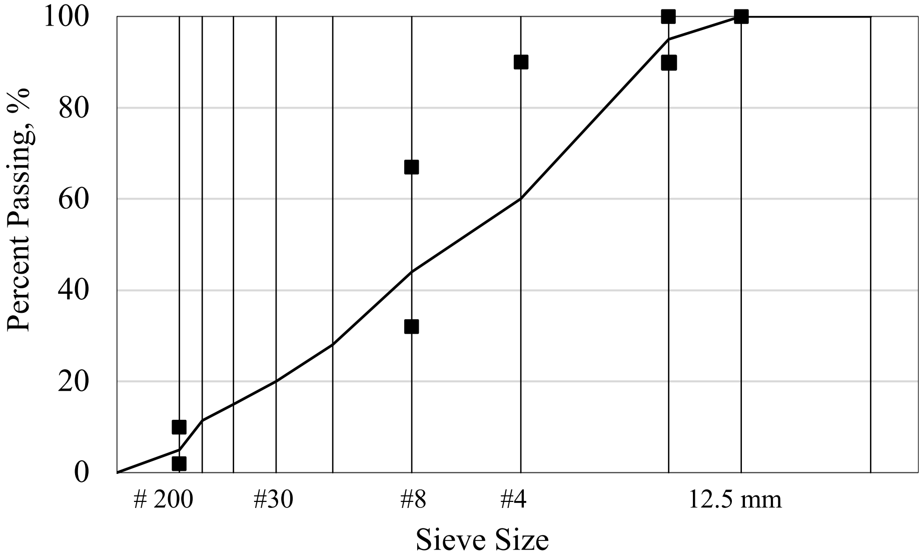


Figure 4-1. Superpave 9.5 mm design gradation.

A total of three binder grades were used in this study: PG 76-22, PG 64-22, and PG 58-28. All aggregates were oven dried and heated overnight at a temperature of 150℃ before mixing. Binders were heated between one hour and one and a half hours at 150℃ before mixing depending on the binder grades.

4.4.2 Specimen Preparation

The theoretical maximum specific gravity (G_{mm}) of mixes, which is used to calculate air void levels of each compacted specimen, with different binder contents were measured using AASHTO T 209. The bulk specific gravity (G_{mb}) of each processed SCB specimen, which is also used to calculate air void levels, were measured using a CoreLok® device.

Immediately after mixing, short term oven aged (STOA) specimens were conditioned at 150℃ for two hours before compaction. STOA refers to the simulated aging process of asphalt mixes using a forced air oven to simulate the high temperature environmental that happens during the mix production in the field. The detail of aging and the impact of aging on SCB fracture test, however, will be discussed further in chapter nine.

A Superpave Gyratory Compactor (SGC) was employed to compact specimens to the desired air void level and at a fixed height of 150 mm. The goal was to ensure final SCB specimens had target air void of 4 and 7 percent at 150°C. Actual final air void of SCB specimens varied in the range of 3.7 and 4.8 percent for the former, and in the range of 6.4 and 7.6 percent for the latter. The compacted specimens were air cooled overnight before being cut into four slices, followed by the process introduced in Chapter three.

4.4.3 Experimental Program

The servo-hydraulic loading system used to perform the SCB tests was enclosed in a small environmental chamber. This chamber itself was enclosed in a walk-in environmental chamber for temperature control and specimen conditioning. With two levels of air voids (four and seven percent), two levels of binder content (design and design + 0.5 percent), and two levels of binder grades (PG58 and PG76), a complete factorial test matrix would have eight combinations. In this study, a half factorial design (four combinations) was used to investigate the sensitivity of the test to mix parameters. The material variables and test conditions used for each objective are summarized in Table 4-1. Three replicate SCB specimens were used for each material variable and test condition combinations. A total of 180 SCB specimens were tested in this study.

Table 4-1. Mix Type and Test Conditions for Each Objective.

Objective	Mix ID	Binder Grade	Nominal Air Void (%)	Binder Content (%)	Test Temperature (℃)	Displacement Rate (mm/min)
1	A	PG58-28	7	5.4	25	1/5/20/50
	B	PG58-28	4	5.4	25	1/5/20/50
	C	PG58-28	7	5.9	25	1/5/20/50
	D	PG76-22	7	5.4	25	1/5/20/50
	E	PG58-28	4	5.9	25	1/5/20/50
	F	PG76-22	4	5.4	25	1/5/20/50
	G	PG76-22	7	5.9	25	1/5/20/50
2	A	PG58-28	7	5.4	18	1/5/20/50
	B	PG58-28	4	5.4	18	1/5/20/50
	C	PG58-28	7	5.9	18	1/5/20/50
	D	PG76-22	7	5.4	18	1/5/20/50
3	H	PG64-22	7	5.4	10	1/5/20/50
	H	PG64-22	7	5.4	18	1/5/20/50
	H	PG64-22	7	5.4	25	1/5/20/50
	H	PG64-22	7	5.4	30	1/5/20/50

Before conducting the test, each specimen was conditioned at the test temperature for at least four hours. The tests were conducted in load-line displacement mode. For displacement rates of 1/5/20/50 mm per minute, sampling rates were 1/5/20/50 per second. Preliminary results showed that the selected sampling rates provide enough data points for analysis (500 points per test). Fracture energy (FE), flexibility index (FI), pre-peak fracture energy (PPFE), peak load (PL), and stiffness index (SI), the calculation of which have been discussed in Chapter three.

4.5 TEST RESULTS AND ANALYSIS

4.5.1 Material Characterization

4.7.1.1 Sensitivity of the Characterization Parameters to Material Variables

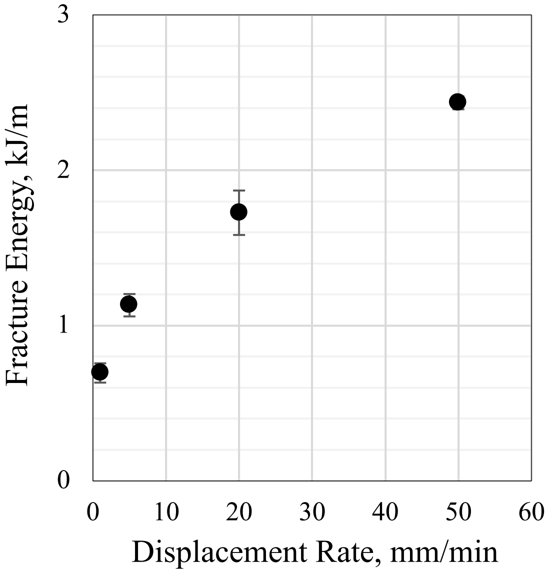
A total of seven different mixes were included in this part of the study (See Table 4-1, objective 1), with the goal of investigating the sensitivity of characterization parameters (FE, FI, etc.) to various material variables. These tests were conducted under different displacement rates but at the constant temperature of 25°C. Analysis of variance (ANOVA) was conducted to determine the significance of the material variables. The p-values of selected characterization parameters for different displacement rates are summarized in Table 4-2.

Table 4-2. Statistical P-Values of Characterization Parameters for Different Mix Variables at Test Temperature of 25°C.

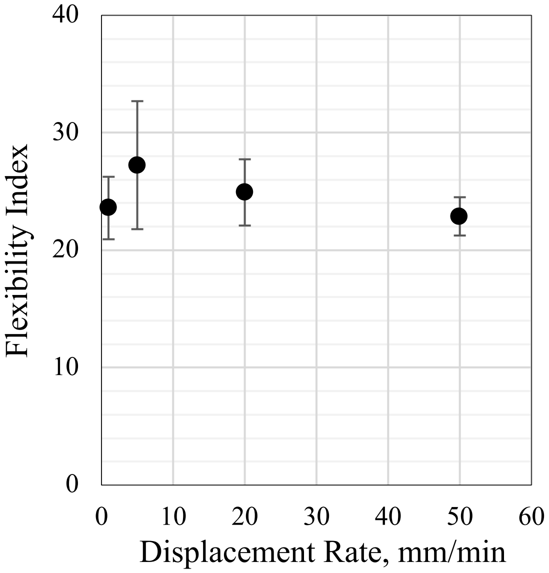
Displacement Rate	**Material Variable**	**Characterization Parameter**				
		Fracture Energy	**Flexibility Index**	**Peak Load**	**Stiffness Index**	**Pre-Peak Fracture Energy**
1 mm/min	Binder Grade	0.000	0.015	0.000	0.000	0.000
	Binder Content	0.049	0.000	0.000	0.000	**0.481**
	Air Void	**0.116**	0.012	0.000	0.000	**0.077**
5 mm/min	Binder Grade	0.000	0.018	0.000	0.000	0.000
	Binder Content	**0.195**	0.000	0.000	0.000	**0.591**
	Air Void	0.003	0.000	0.000	0.000	**0.264**
20 mm/min	Binder Grade	0.000	0.008	0.000	0.000	0.000
	Binder Content	**0.827**	0.000	0.000	0.002	**0.634**
	Air Void	0.003	0.003	0.000	0.000	**0.064**
50 mm/min	Binder Grade	0.000	0.025	0.000	0.000	0.000
	Binder Content	**0.252**	0.002	0.000	0.009	0.032
	Air Void	0.003	**0.282**	0.000	0.000	**0.068**

At 95 percent confidence level, the parameter is statistically significant if the corresponding p-value is smaller than 0.05. For example, at the displacement rate of 1 mm/min, FI, PL, and SI are sensitive to all three material variables, while FE and PPFE are only sensitive to binder grade but not to air void and binder content. Overall, at the test temperature of 25°C, FI, PL, and SI are sensitive to all material variables at all four displacement rates, except that FI did not change significantly for the two air void levels used at 50 mm/min. Both FE and PPFE are capable of differentiating among the three binder grades used based on their stiffness at all displacement rates, but FE appears insensitive to binder content under most displacement rates. Furthermore, the PPFE shows lower sensitivity compared with other parameters.

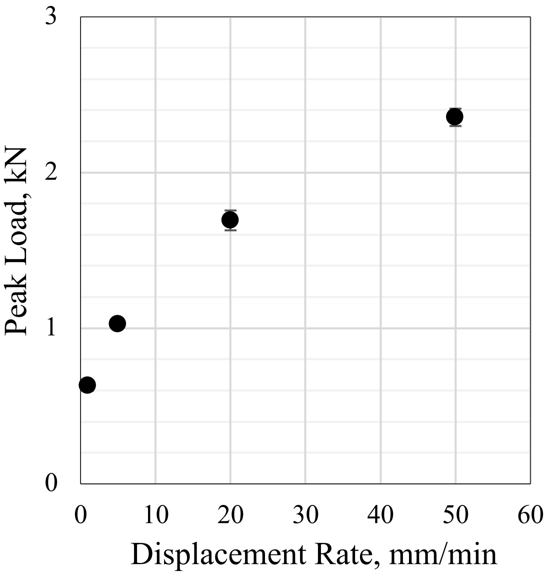
The distribution of characterization parameters (except PPFE) under all displacement rates at 25°C are shown in Figure 4-2. Error bars present the limits for one standard deviation from the mean. This figure presents some examples from test results; similar trends were found for the data.



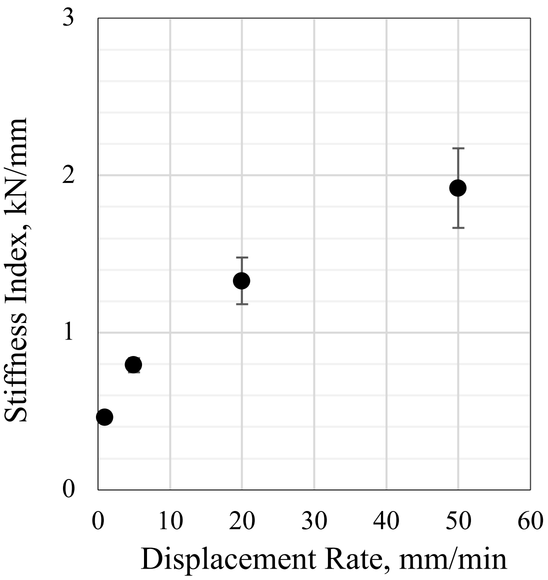
(a)



(b)



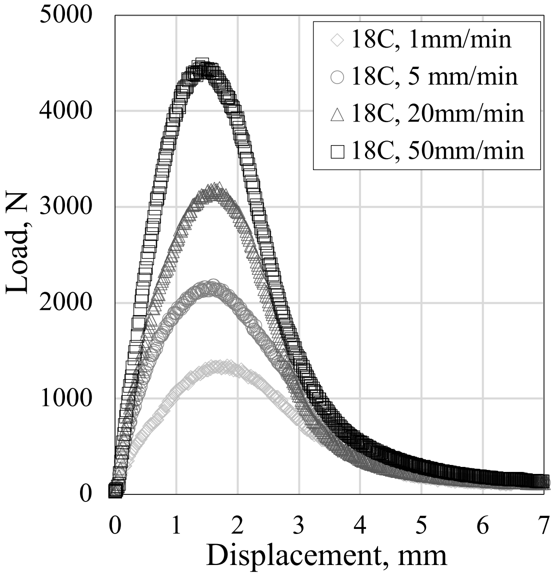
(c)



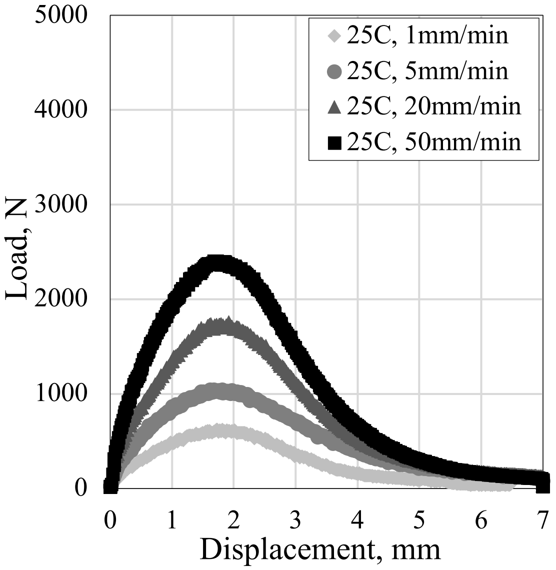
(d)

Figure 4-2. Parameter distribution of mixes with PG58-28 binder, 5.4% binder content, and 7% air void (Mix A). (a) Fracture energy, (b) Flexibility index, (c) Peak load, and (d) Stiffness Index.

The first observation is that FI peaks at 5mm/min at the test temperature of 25℃, then decreases with the increase of displacement rate. The overall trend of FI, however, is relatively insensitive compared with other parameters. The remaining three parameters, on the other hand, are sensitive to the changes in displacement rate, and they all increase with the increase of the displacement rate. The fact that FI is insensitive to displacement rate is the result of the way this parameter is defined. The FI is a dimensionless index which is calculated as the ratio of the total fracture energy divided by the absolute value of the post-peak slope, multiplied by a scaling factor. As the displacement rate increases, both the fracture energy and the slope at inflection point increase (Figure 4-3), but it appears the increase in both is somewhat proportional, resulting in the net effect of the ratio not changing significantly. Furthermore, the remaining three parameters have consistent rankings among different mixes irrespective of displacement rate. One last observation is that PL has the lowest coefficient of variation (COV), followed by FE. FI and SI have relatively higher COV values regardless of displacement rate.



(a)



(b)

Figure 4-3. Effect of temperature and displacement rate on load-displacement curve. (a) At 18°C and (b) at 25°C.

To properly investigate the sensitivity of characterization parameters to mix variables within each displacement rate, Tukey's statistical range test was utilized. Tukey's test is a single-step multiple comparison procedure, and its uniqueness is that it considers all possible pairwise differences of means at the same time. As an example, at a displacement rate of 1 mm/min, Tukey delivers three groups for the means of seven existing mixes, implying that the seven mixes could be separated in three groups, each group of means being significantly different from the other two groups. The overall Tukey test results are shown in Table 4-4.

Table 4-3. Tukey Test Results on All Parameters at 25°C.

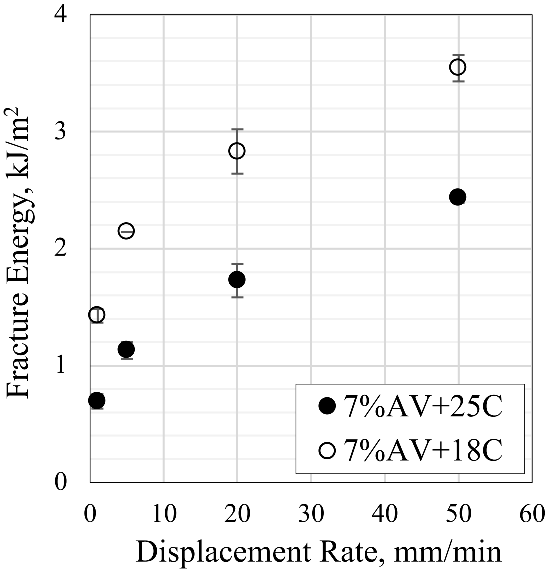
Displacement Rate	**Characterization Parameters**			
	Fracture Energy	**Flexibility Index**	**Peak Load**	**Stiffness Index**
1 mm/min	3 Groups	4 Groups	5 Groups	4 Groups
5 mm/min	3 Groups	3 Groups	5 Groups	4 Groups
20 mm/min	2 Groups	4 Groups	5 Groups	4 Groups

It can be observed that in one case for peak load, this statistical test provides six groups of data, implying significant difference among all means. The more groupings a parameter has, the more sensitive that parameter is to mix variables. For fracture energy, although higher displacement rates (20 and 50 mm/min) gave larger spread of data, lower displacement rates resulted in more groupings, indicating higher sensitivity of this parameter to mix variables at lower displacement rates. For flexibility index, there is no significant difference in terms of the range of values, but overall, displacement rates lower than 50 mm/min returned more groupings, indicating higher sensitivity of FI at lower rates. Peak load showed the highest sensitivity to material variables among these parameters regardless of displacement rates. Displacement rate of 50 mm/min gave six groupings, which provides the rational of choosing this specific displacement rate for strength test. Although high in COV, stiffness index delivered at least three groupings, which makes it slightly more sensitive compared with the fracture energy. Overall, peak load showed higher sensitivity compared to the other three parameters, while stiffness index and flexibility index showed similar sensitivity.

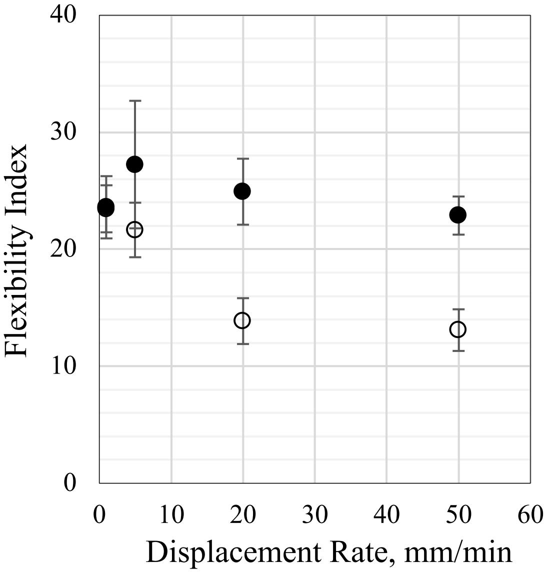
4.5.2 Effective Temperature Study

It was mentioned previously that fracture testing is best to be conducted at the effective fatigue temperature for the region rather than a general temperature for all the regions. Testing was therefore conducted at 18℃, established as the effective temperature for the region of interest, for comparison with the original testing at 25℃.

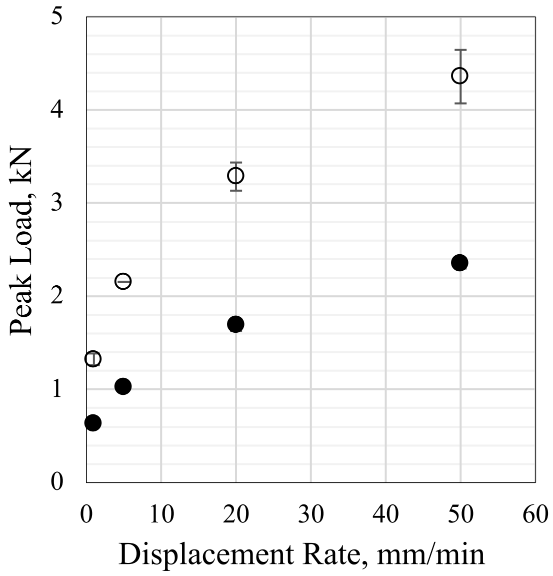
Four different mixes (Mixes A through D) were included in this part of the study. These mixes covered two different binder grades, delivering different moduli at the SCB test temperature. The experiment also covered two air void levels, and two binder contents (See Table 4-1, Objective 2). The objective was to study the sensitivity of characterization parameters to material variables under different displacement rates at a proposed fatigue test temperature. The characterization parameters for both test temperatures, different displacement rates, and different mixes are shown in Figure 4-4. Error bar stands for one standard deviation, and the use of legend is consistent within all figures, so they only appear in Figure 4-4(a). These figures present only examples from test results; similar trends were found for the data not presented due to space limitations.



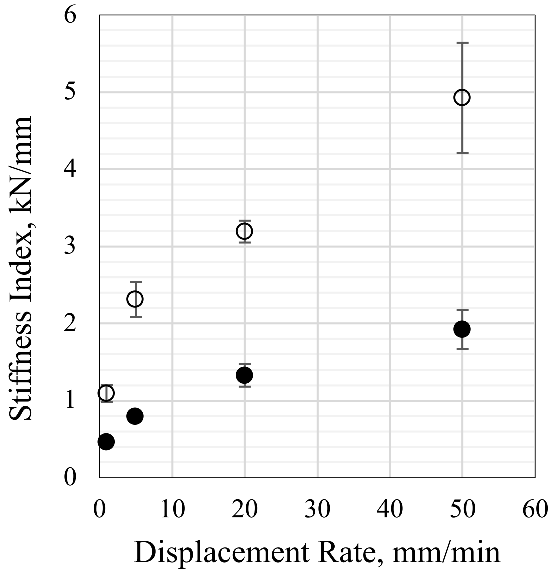
(a)



(b)



(c)



(d)

Figure 4-4. Parameter distribution of mixes with PG58-28 binder, 5.4% binder content and 7% air void under two temperatures. (a) Fracture energy, (b) Flexibility index, (c) Peak load, and (d) Stiffness Index.

All response parameters follow the same trend at 18°C compared with the results at 25°C: FE, PL, and SI all increase with increase of displacement rates at 18°C, while FI decreases with the increase of displacement rate. FI obtained at 18°C are slightly lower than the ones obtained at 25℃, while the remaining parameters are considerably higher at 18℃ than at 25℃. There is also no significant difference in regard to COV values between the two test temperatures.

FE, PL, and SI all show very similar and consistent ranking for different material variables and respond similarly to different test conditions. They all increase with the decrease of air void irrespective of test condition or displacement rate; they all decrease with the increase of binder content under all test conditions with a few exceptions observed in FE plots; and they all increase with the increase of binder stiffness under all test conditions. Moreover, all three parameters increase with faster displacement rate and lower test temperature. The only difference among these three parameters are their COV and spread of data: PL has the lowest COV, followed by FE, while SI has the highest COV, similar to FI.

The flexibility index at both test temperatures, different displacement rates, and different mixes are shown in Figure 4-5. Error bar stands for one standard deviation. Similar plots for other characterization parameters are not shown due to space limitation. Testing mix C at 5 mm/min under 18℃ delivered a strange behavior leading to unusual coefficient of variation, and was considered an outlier (Figure 4-5). Thus, this data point is excluded for further analysis.

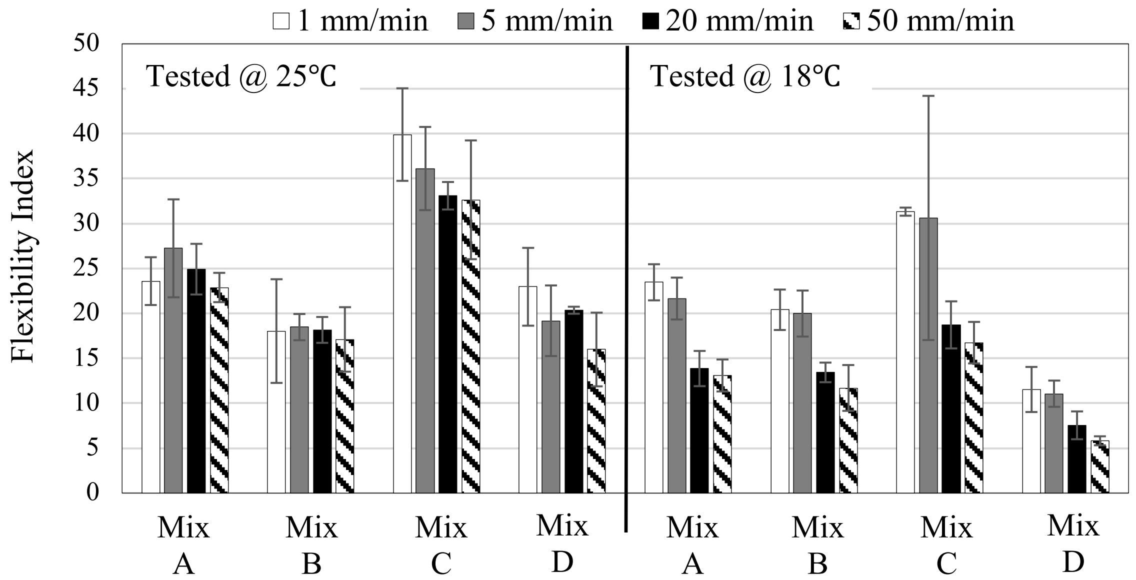


Figure 4-5. Flexibility index distribution of four mixes tested under two temperatures and four displacement rates.

The effect of lower air void on characterization parameters can be observed when comparing results of mix B to A. Similarly, comparing mix C to A presents the effect of higher binder content, and the impact of using stiffer binder can be seen when comparing mix D to A. All response parameters follow the same trend at 18°C compared with the results at 25°C: FE, PL, and SI all increase with increase of displacement rates at 18°C, while FI decreases with the increase of displacement rate. FI obtained at 18°C are lower than the ones obtained at 25°C, especially when displacement rate is higher than 5 mm/min, while the remaining parameters are considerably higher at 18°C than at 25°C. There is also no significant difference in regard to COV values between two test temperatures.

Based on Tukey's test grouping results, the overall sensitivity of fracture energy at 18°C is lower than that at 25°C. FE showed sensitivity to the effect of lower air void at both temperatures and under all displacement rates, but it was not sensitive to the effect of binder content at 25°C. At 18°C, however, the improvement of performance due to higher binder contents was captured by FE. At both temperatures and all displacement rates stiffer binder shows higher FE. Exception is the results of the polymer modified PG 76-22 binder at 50 mm/min and 18°C where a decrease is observed.

4.5.3 Temperature and Displacement Rate Sweep

The final objective of present study was to investigate the effect of test temperature on response parameters at various displacement rates (See Table 4-1, objective 3). This stage of study included a 9.5mm Superpave designed mix with virgin aggregate with PG 64-22 binder. The specimens were made at design binder contents of 5.4 percent and air void of approximately 7 percent. Temperature and displacement rate sweep test results on short term aged specimens in terms of fracture energy, flexibility index, peak load, and stiffness index are shown in Figures 4-6 to 4-9.

At 10°C, the mix shows smaller flexibility index compared to other temperatures regardless of displacement rate. This observation is explained through post peak behavior of the mix. At 10°C, the material tends to be too brittle to show a gradual development of cracks and a soft slope. Rather, an abrupt failure is observed, as shown in Figure 4-6 at 10°C. No post-peak fracture energy can be calculated due to the lack of complete load-displacement curve, and as a result of a very sharp drop in load after the peak. Higher test temperature favors FI since at these temperatures, there is a larger spread of results for FI. For brittle materials, it is impossible to calculate FI since there is no inflection point and the specimen sustains abrupt failure.

The cleanest trend in data shows in stiffness index. The reason could be: 1) Stiffness index is not associated with post-peak softening curve, 2) Stiffness index is calculated at fifty percent peak load, landing it close to the linear range of modulus.

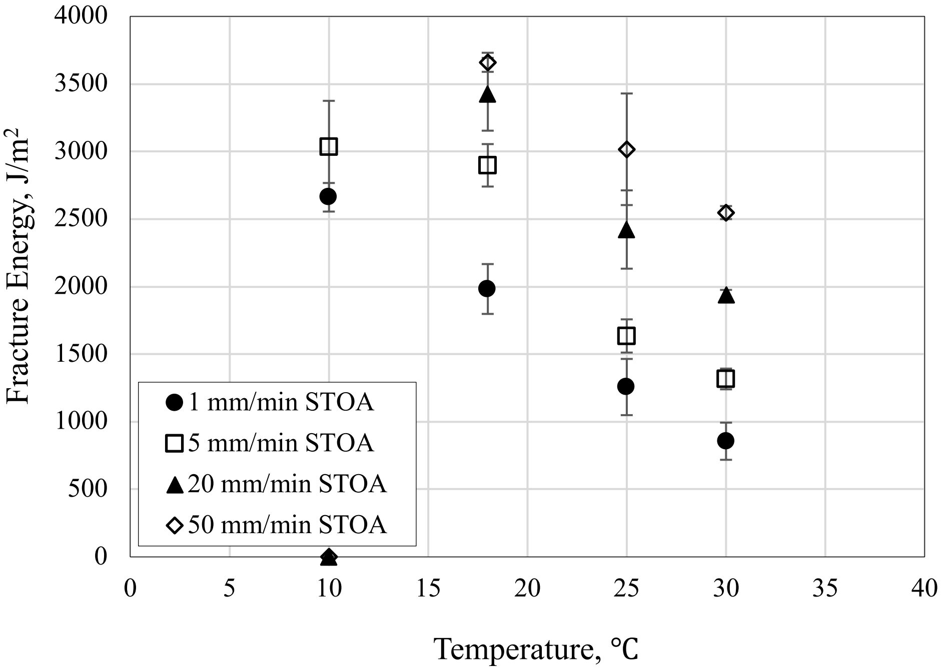


Figure 4-6. Temperature and displacement rate sweep results of fracture energy on short term aged specimens.

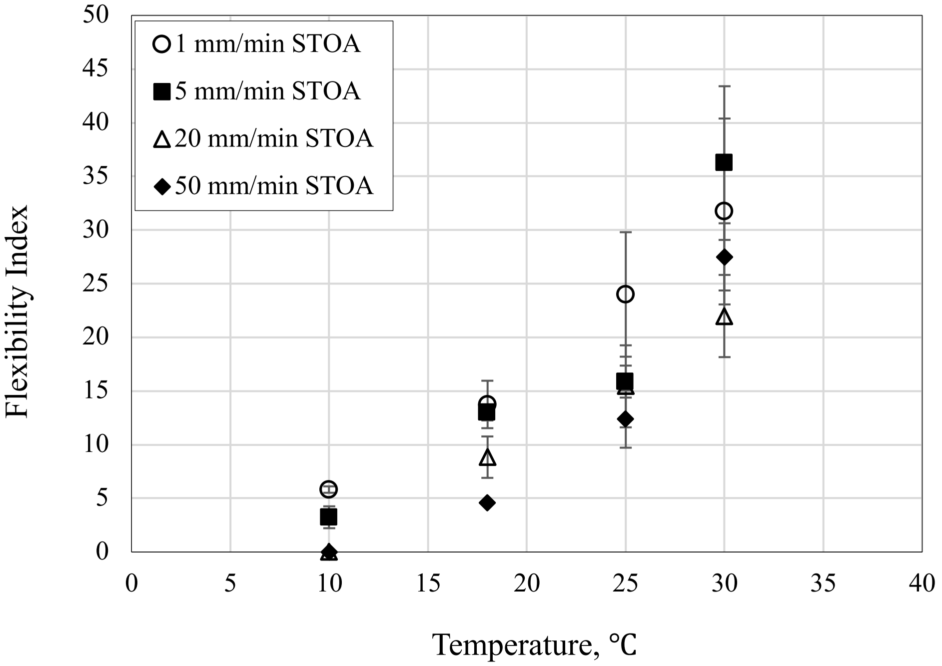


Figure 4-7. Temperature and displacement rate sweep results of flexibility index on short term aged specimens.

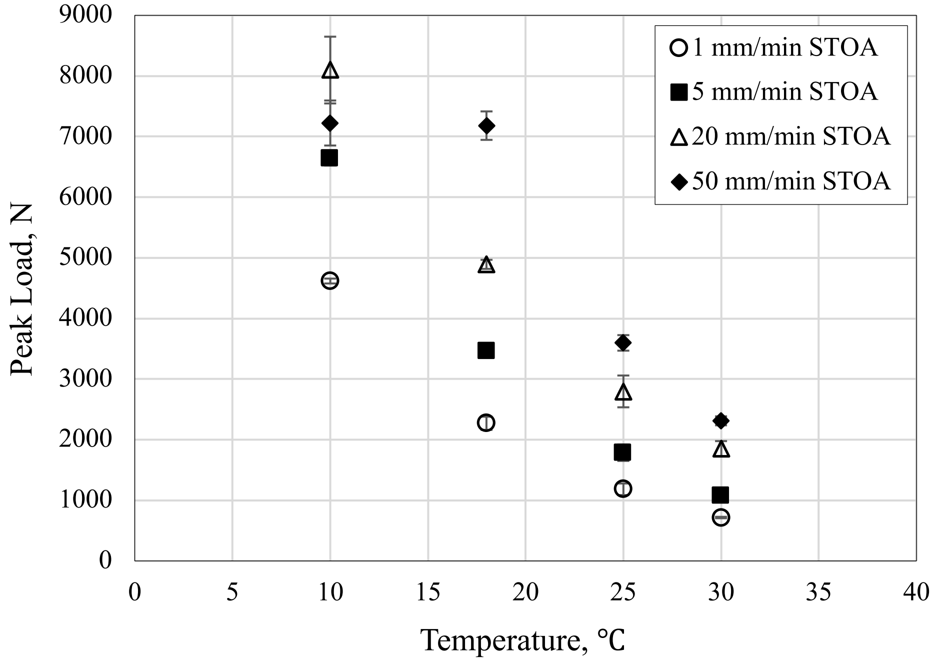


Figure 4-8. Temperature and displacement rate sweep results of peak load on short term aged specimens.

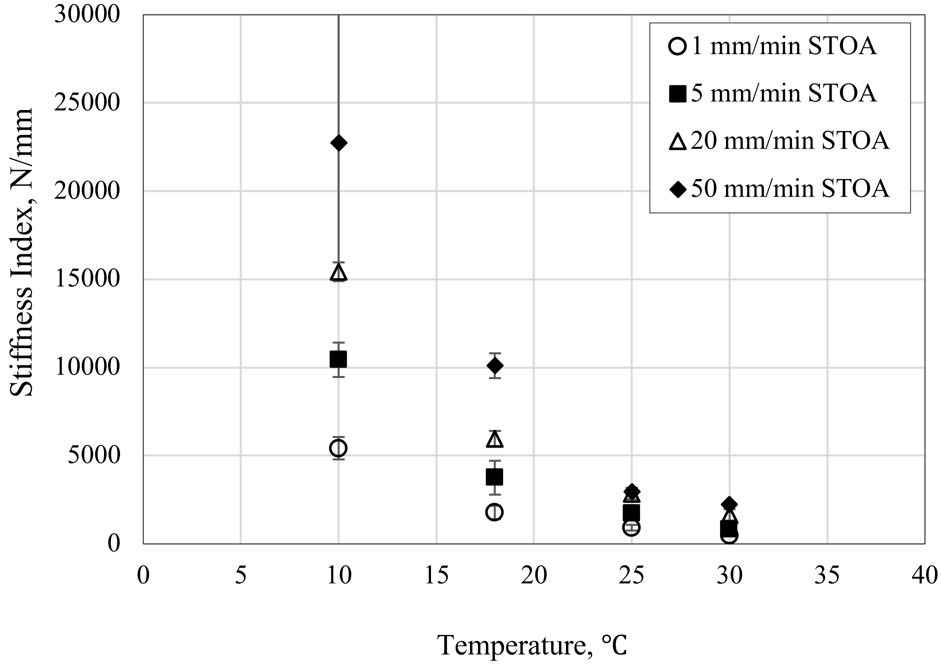


Figure 4-9. Temperature and displacement rate sweep results of stiffness index on short term aged specimens.

4.6 SUMMARY AND RECOMMENDATIONS

Numerous types of laboratory fatigue tests have been proposed to tackle the fatigue cracking problem. Among candidate tests, semi-circular bend (SCB) test was investigated through this study. This test shows some advantages over other tests due to merits such as simplicity, repeatability, and sensitivity to mix parameters.

Effect of displacement rate and test temperature on the SCB test results was investigated in this study. Such study is essential to establish the most appropriate SCB test protocol for routine mix design and material quality control. The experiment included investigating sensitivity of multiple characterization parameters to material variables under different test conditions. Based on test results, following conclusions can be drawn:

1. The SCB test proved to be simple to run and practical for routine mix design. No complicated specimen preparation processes such as coring or gluing are required, and both SGC specimens and field cores can be used for test specimen manufacturing. Four specimen replicates can be tested within a short period of time, and four replicates can be cut from one SGC specimen.
2. The test could be conducted at effective fatigue temperature of the region of interest.
3. Fracture energy and flexibility index exhibit sufficient sensitivity to material variables under most testing conditions. Peak load shows the highest sensitivity to mix variables in every test condition and carries the smallest coefficient of variation among all response parameters.
4. At the test temperature of 25°C, FI peaks at 5 mm/min, then decreased with the increase of displacement rate, but overall trend remains flat compared with other parameters. However, other characterization parameters increased as the displacement rate the increased.
5. FE, PL, and SI increase with the decrease of air void, while FI increases with the increase of air void. The observed increase of FI with air void in the SCB test requires close evaluation and must be considered in combination of with other properties such as strength for proper assessment of the mix ability in regard to cracking resistance.

6. As expected, FI increases with the increase of binder content and decrease of binder stiffness.
7. At the proposed effective temperature of 18℃ for some areas of the northeast region, all response parameters except FI increase with the increase of displacement rate. FI decreased with the increase of displacement rate at this temperature. For other parameters, similar trends were observed at both 25℃ and 18℃.
8. Considering these results and the range of values obtained for FI, it is proposed that testing be conducted at the site effective temperature and a displacement rate between 5 to 20 mm/min.

Further work is needed to establish a reliable correlation between laboratory test results and field performance of asphalt pavement using SCB test and the proposed test protocol.

Chapter 5 THE EFFECT OF MATERIAL VARIABLES ON SCB TEST PERFORMANCE INDICATORS

Chapter four investigated the effect of important test conditions: displacement rate and test temperature, on sensitivity of performance indicators from the SCB test. A combination of 20℃ and 5 mm/min was proposed as they are appropriate test condition for the northeast region of the United States. In this chapter, the effect of material variables, or mixture component, i.e., asphalt binder content, air void, and binder stiffness on performance indicators of the SCB test, are investigated.

5.1 INTRODUCTION

Mixture component plays a major role in the fatigue performance of asphalt mixtures. The most important variables include asphalt content, asphalt stiffness, asphalt volume, aggregate type, aggregate gradation, and air void. Epps and Monismith (1972) reviewed existing literatures, combined with their own study using the flexural beam fatigue test, and summarized the effect of those variables on fatigue performance of asphalt mixtures. Results indicated that mixes with higher air void contents exhibit comparatively shorter fatigue lives, while mixtures with the optimum asphalt binder content, delivering maximum mixtures stiffness showed the best fatigue performance. These two observations were true regardless of loading mode of fatigue tests. However, the effect of binder stiffness appears to be dependent on the loading mode. In the controlled stress fatigue test, as the binder modulus increases, a larger fracture life at a particular stress level might be expected due to increased mixture stiffness. The reverse phenomenon is true for strain-controlled fatigue test.

Fatigue tests in monotonic mode are gaining popularity due to their simplistic nature and the short time of testing. Numerous studies have reported the use of monotonic tests to investigate the effect of mix composition on fatigue performance of asphalt mixes. Ling et al. (2017) investigated the mixture design factors such as percent binder replacement (PRP), binder modification, binder low temperature grade, asphalt binder content, filler content, and aging effect using the I-FIT protocol. As expected, long term aging and increased PRP had negative impact on fracture performance, while the modified binder had an opposite effect. Also reported in this study were that filler content was insensitive neither to FI nor to the peak load. Bonaquist et al. (2017) also employed FI to investigate effects of material variables such as: effective binder volume, virgin binder low temperature grade, recycled asphalt binder content, and polymer modification. From their lab test results, the authors summarized that FI increases with 1) decreasing aging, 2) increasing effective volume of binder, 3) decreasing of low temperature grade of the virgin binder, and 4) increasing level of polymer modification. Among these parameters, effective binder volume and virgin binder low temperature grade are the most significant. The authors also proposed a new index called stiffness index (SI), which was defined as the pre-peak slope of the load-displacement curve at 50 percent of the peak value.

Monotonic tests have been applied to investigate the effect of mix composition on fatigue performance of asphalt mixes. However, for the newly developed test protocols and performance indices, there has not been enough research to investigate the sensitivity of test results to mix composition. Hence, there is not enough test data to support the validity of performance indices over a wide range of material variables, which is completely plausible in the field.

5.2 OBJECTIVES

The overall goal of this study was to determine the effect of asphalt mix composition on the SCB test results, and to investigate whether existing performance indices from SCB test can be used as standalone indicators to quantify fatigue performance of asphalt mixes. It should be noted that the present study is simply focused on sensitive of the SCB test to mix parameters, and is not intended to correlate these indices to pavement performance. It is evident that mix performance in the field depends on the mix itself as well as pavement structure, climate, and traffic. The mix components considered as test variables in this study included binder content (BC), air void (AV), binder stiffness, and the aging duration. Achieving this goal sets the foundation to accomplish several on-going objectives: establish a fatigue performance prediction model using material compositions, and couple FI with other engineering indices as a more reliable indicator of fatigue performance for asphalt mixtures.

5.3 MATERIALS AND TEST PROGRAM

5.3.1 Materials

The dolomite/limestone aggregate used in this study came from a local source, with 55 percent of coarse aggregate and 45 percent of fine aggregate (bulk specific gravities of 2.757 and 2.815, respectively). A Superpave 9.5 mm mix design was used throughout the study with a design binder content of 5.2 percent, the design gradation shown in Figure 5-1. The design binder content was slightly lower than that reported in Chapter four, owing to the slight change in aggregate absorption and density. The gradation was designed as a surface course with the N_{design} of 75. A total of three binder grades were employed in this study: PG 58-28, PG 64-22, and PG 76-22, with corresponding continuous high grades of 60.8/70.5/83.5.

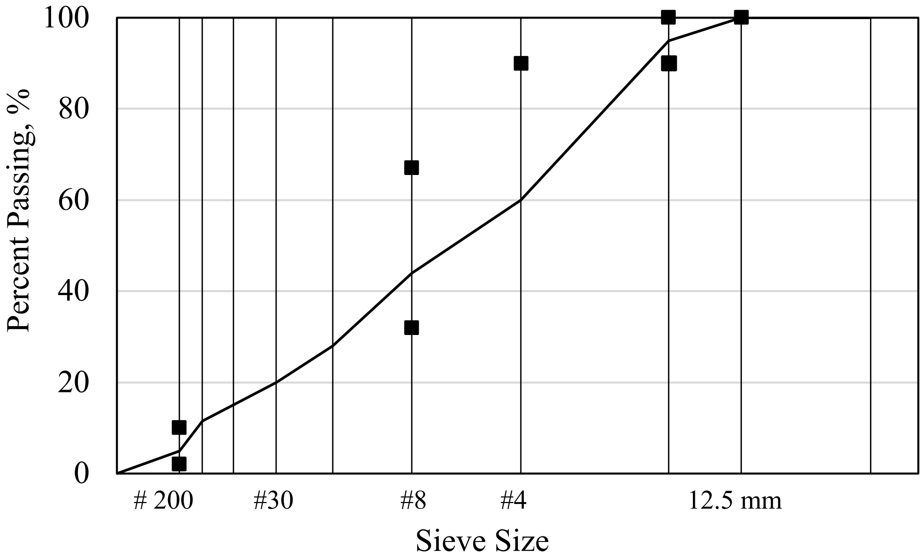


Figure 5-1. Superpave 9.5 mm design gradation.

5.3.2 Design of Experiment

With 4 levels of air voids (2, 4, 7, and 10 percent), 4 levels of binder contents (4.7, 5.2, 5.7, and 6.2 percent), and 3 levels of virgin binder grades (PG 58-28, PG 64-22, and PG 76-22), a complete factorial test matrix with four replicates for each combination would require a total of 192 specimens to be tested for one aging level. The number is doubled when preparing both short- and long-term aged specimens. To make the experiment practical and limit the amount of testing needed, a one half fractional factorial experimental design was conducted. The I-optimal design criterion was employed in lieu of the normally used D-optimal design criterion when selecting the final testing matrix. The D-optimal design criterion focuses on estimating effects, testing for significance, and favors to minimize the variance of the estimated coefficients in the model (JMP Manual). However, since the possible influence of each material variable is known from the past experience, and establishing a prediction model is the goal, the I-optimal design criterion, which focuses on prediction model, suits the objective better. This criterion focuses on predicting a response and determining regions in the design space where the response falls within an acceptable range (JMP Manual). The final test matrix is shown in Table 5-1. To establish a full reference data set, in which at a certain air void level and binder content level, test data are available for all three binder grades, one extra cell was added (7 percent air void and 5.2 percent binder content with PG 76-22 binder). The test matrix is used for both short- and long-term aged specimens, which resulted in testing a total of 200 SCB specimens. Note should be taken that the correlation between results from short- and long-term aged specimens were not the focus of this part of study. The importance and the effect of aging will be discussed extensively in chapter nine.

Table 5-1. Fractional Factorial Test Matrix

Air Void, %	**Binder Content, %**	**Virgin Binder Grades**		
		58-28	64-22	76-22
2	4.7	4[I]		4
	5.2		4	
	5.7		4	
	6.2	4		4
4	4.7		4	
	5.2		4	4
	5.7	4		4
	6.2		4	
7	4.7		4	
	5.2	4	4	**4**
	5.7		4	4
	6.2		4	
10	4.7	4		4
	5.2			4
	5.7		4	
	6.2	4		4
			Total	**100**

NOTE I: Numbers in the cells indicate number of replicates for one aging level.

5.3.3 Specimen Preparation

When preparing aggregate batches for mixing and compacting, batch weight of mixes with different target air voids were slightly adjusted to ensure a fixed compaction height of 150 mm. For short term oven aged (STOA) specimens, immediately after mixing at 150°C, they were conditioned at 150°C for two hours before compaction. For long term oven aged (LTOA) specimens, they were first conditioned at 150°C for two hours after mixing, then followed by 120 hours of long-term aging at 85°C. Finally, the loose mix was conditioned at 150°C for two hours before compaction. During the 120 hours conditioning process, loose mixes were stirred twice to ensure a more uniform aging. The reason of choosing conditioning loose mixes over compacted specimens was to eliminate the effect of aging gradient on test results. A Superpave Gyratory Compactor (SGC) was utilized to compact specimen at 150°C. In spite of using three different binder grades, the mixing/compaction temperatures were sufficiently high to deliver a similar compaction curve and similar number of gyrations for all binder grades. An example of such is presented in Figure 5-2 for short termed conditioned mixes targeting an air void of seven percent at an optimum binder content of 5.2 percent. A similar result was obtained for long term aged mixes.

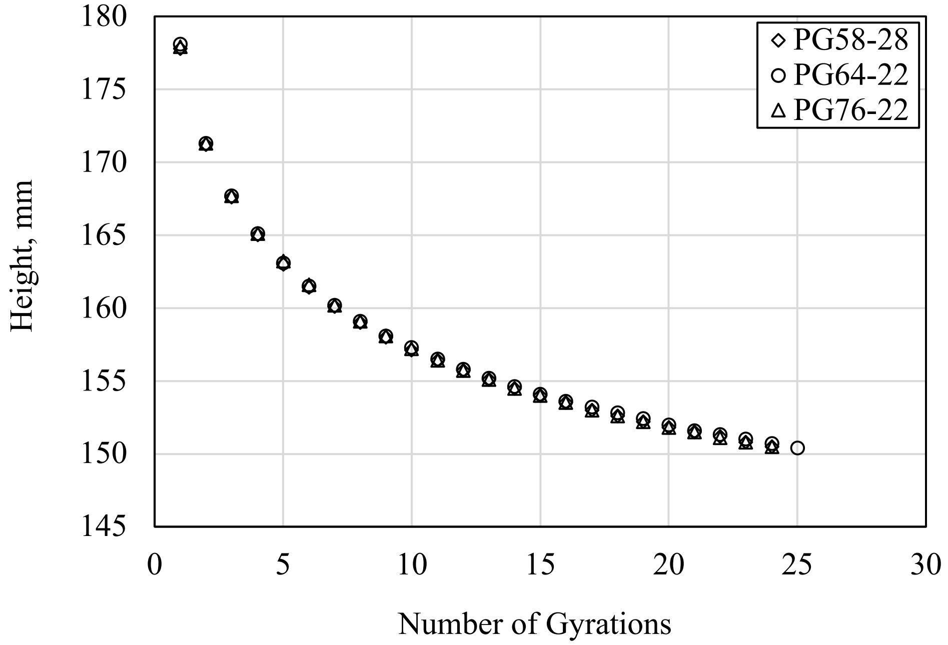


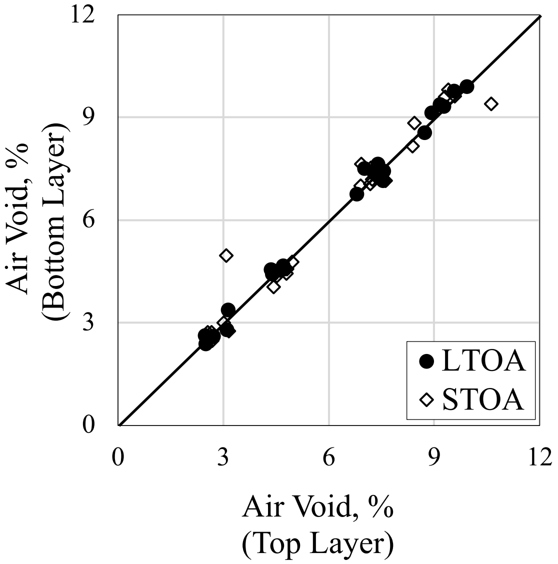
Figure 5-2. Specimen height as a function of number of gyrations for different binders used in this study.

After compaction, the procedures presented in Chapter three were followed precisely to prepare SCB specimens ready for testing.

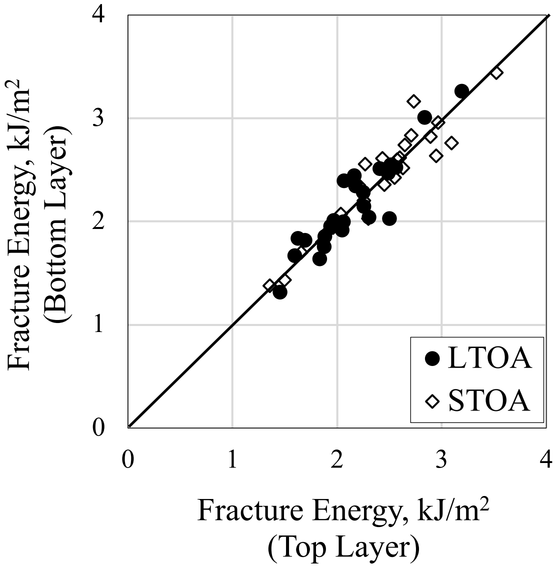
5.4 TEST RESULTS

5.4.1 Top vs. Bottom Specimens

Masad et al. (2002) used X-ray CT system to capture the internal structure of asphalt mixtures. The authors reported that for SGC specimens with a height of 140mm, regardless of compaction efforts, the median size distribution of air void size shows a “bathtub” shape, with fairly uniform size distribution of air voids in the middle 65 to 75 percent of the specimen thickness. Since the middle 100 mm portion of a SCB specimen has relatively uniform air void distribution, then SCB specimen obtained from top and bottom layers should have similar properties and performance as long as specimens are well produced, and segregation is prevented. To ensure that the relative position of a SCB specimen from a complete SGC specimen would not affect test results, comparisons of property and performance between top and bottom layer SCB specimens were conducted. The average values of air void, fracture energy, flexibility index, and peak load of two SCB specimens cut from top layers were plotted against the average values from two SCB specimens obtained from bottom layers, as shown in Figure 5-3.



(a)



(b)

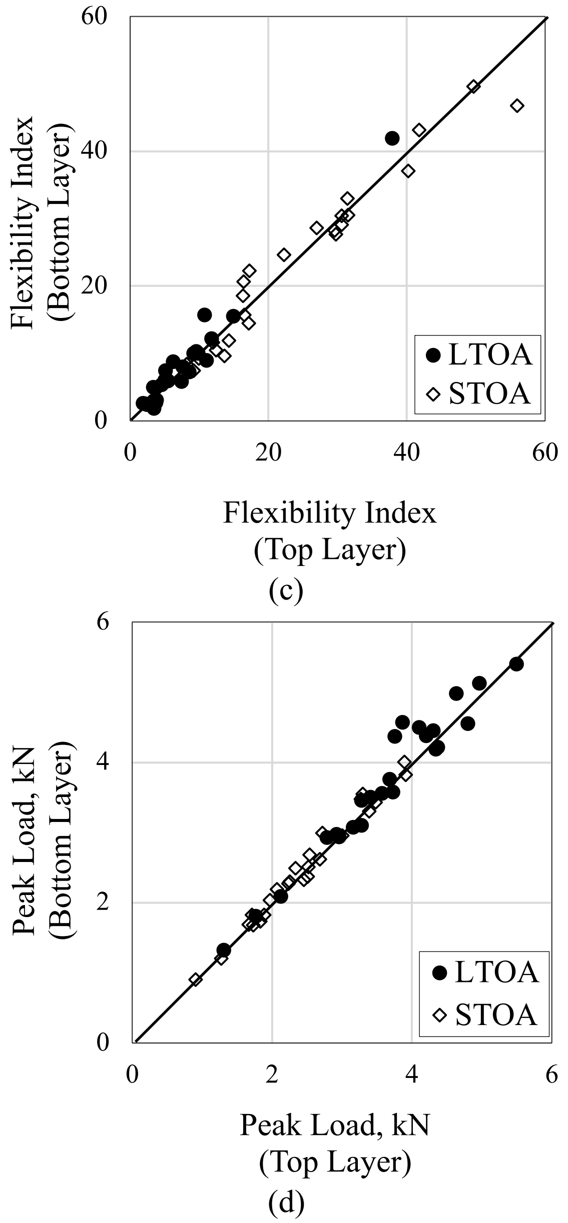


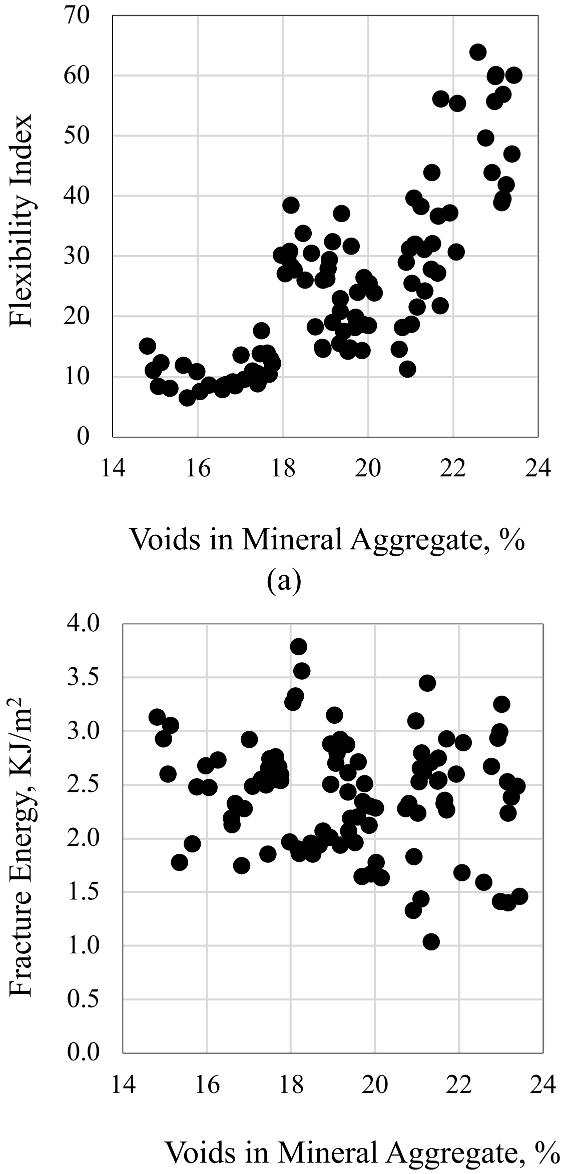
Figure 5-3. Comparison between properties of top and bottom layers: (a) air void, (b) fracture energy, (c) flexibility index, and (d) peak load.

Based on comparison plots shown in Figure 5-3, there are no clear discrepancies between top and bottom layer SCB specimens, regardless of aging conditions. Statistical analysis results further confirm this conclusion: at 95 percent confidence interval, p-value of student t-tests on all properties between top and bottom specimens is larger than 0.05, which indicates that there is no significant difference between properties of top and bottom layers statistically. For properties with relatively low coefficient of variation (COV) such as air void and peak load, data points stay very close to the line of equality. In spite of some slight scatters observed in the fracture energy plot, the overall trend indicates the strong one-to-one relationship between the top and bottom specimens. Part of higher scatter for fracture energy can be explained by the fact that the fracture energy data themselves have relatively higher COVs compared to other parameters. Based on these observations, it is safe to use all four 50mm thick SCB specimens obtained from a single SGC specimen with a thickness of 150mm as independent replicates for testing and analysis. However, caution should still be used to minimize material segregation. SCB specimens cut from one compacted specimen with large air void differences should be discarded and replaced by a new specimen.

5.4.2 Effect of Material Variables

5.4.2.1 Effect of VMA

Voids in the mineral aggregate (VMA) is defined as the void space in the aggregate structure (i.e. summation of volume of voids and volume of effective binder content) as a percent of mix total volume. In the mix design process, adjustments to VMA are always done through adjustments to aggregate gradation. In our study, since only one aggregate source and one aggregate gradation was used, any changes in VMA were simply the result of changes in air void and binder content. In other words, for this study, the effect of VMA on response parameters was simply a measure of the effect of sum of air void and binder content, rather than the effect of aggregate gradation. The impact of VMA on flexibility index and fracture energy is presented in Figure 5-4. Higher values of VMA are the result of higher air void and higher binder content. Therefore, it is not surprising that FI increases as VMA increases, and fracture energy decreases as VMA increases.



(a)

(b)

Figure 5-4. The effect of VMA on (a) flexibility index and (b) fracture energy.

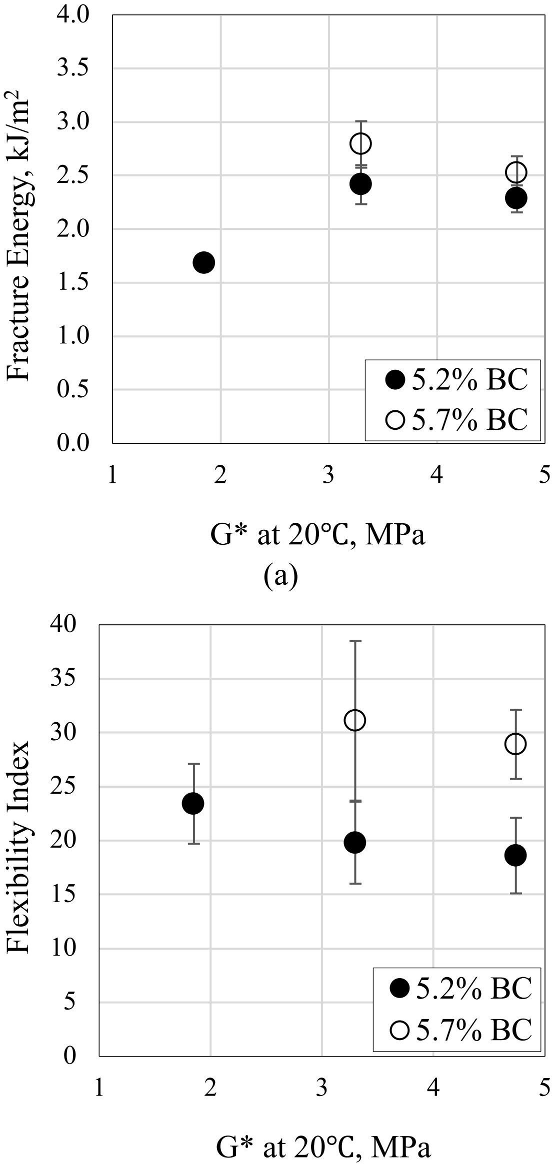
5.4.2.2 Binder Stiffness Effect

Among the variables investigated in terms of the effect on SCB test results was the binder modulus (stiffness). Table 5-2 presents the shear modulus of the three binders used in this study. It can be seen that PG 64-22 binder exhibits higher modulus at 20°C, both for short term and long-term aged conditions, compared with the PG 76-22 binder. While this may seem strange at the first look, one should realize that the higher modulus (G*) of PG 76-22 at higher temperatures (such as at 64°C or 76°C) does not necessarily translate into higher modulus of that binder at 20°C. The PG 64-22 binder has higher stiffness at the low end of temperatures (i.e. at -22°C) compared with the polymer modified PG 76-22 binder and it has a lower stiffness than the PG 76-22 binder at 64°C. Therefore, the PG 64-22 binder is significantly more temperature susceptible than the PG 76-22 binder. The PG 64-22 binder is also more sensitivity to aging. Combination of these two factors is what yields a higher stiffness for the PG 64-22 binder at 20°C.

Table 5-2. Shear Modulus of Binder Used in the Study.

Binder Grade	G* at 20℃ without any aging, KPa	G* at 20℃ after RTFO aging, KPa	G* at 20℃ after PAV aging, KPa
PG 58-28	1016	1850	5792
PG 64-22	4266	4744	12363
PG 76-22	3113	3307	7853

The results shown in Figure 5-5 are plotted for two different binder contents. In general, the graphs indicate that fracture energy increases as the binder modulus (G*) increases but beyond a point, increasing stiffness of binder results in reduction of fracture energy. On the other hand, the figure shows that increase of binder modulus results in reduction in the flexibility index for all three binders. This is an interesting observation as, for example, in the case of PG 58-28 where modulus is low and fracture energy is low, higher ductility in the mix behavior under loading easily compensates for the low fracture energy, resulting in high value of FI. This overall trend was also observed by Bonaquist et al. (2017), since softer grade binder is expected to make the mixture more ductile, and therefore more crack resistant.



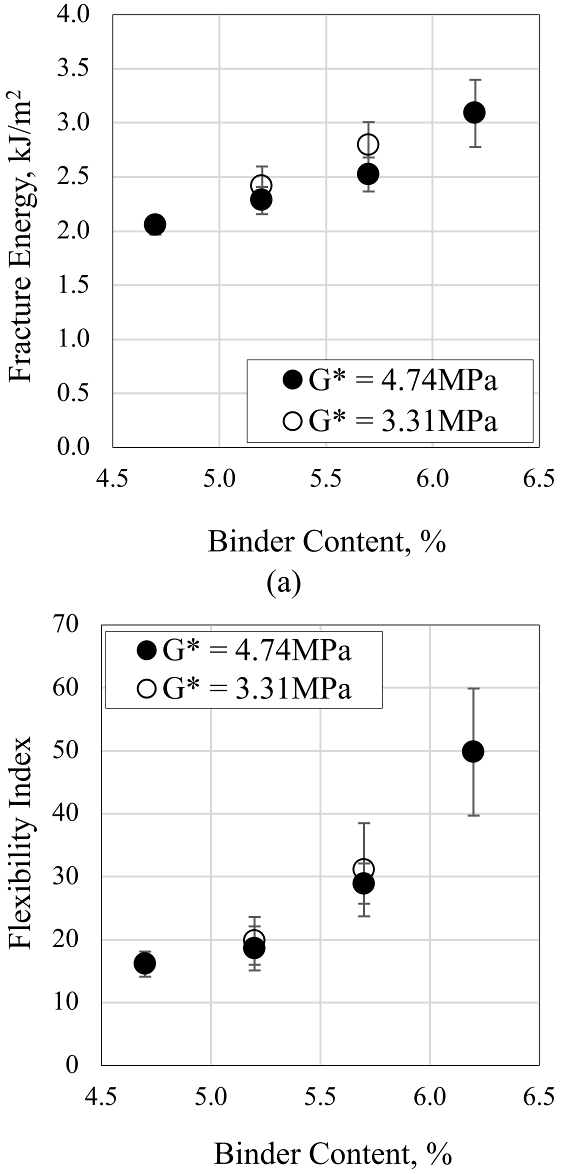
(a)

(b)

Figure 5-5. The effect of binder stiffness on (a) fracture energy and (b) flexibility index at 7% air void.

5.4.2.3 Binder Content Effect

The fracture energy was clearly influenced by the binder content, as shown in Figure 5-6 (a). In general, an increase in FE is observed with increase of binder content. Similarly, flexibility index increases with the increase of binder content, and such increase is more significant than the increase observed in fracture energy. For example, at seven percent air void and as the binder content increases, the fracture energy of PG 76-22 mix increases from 2.4 to 2.8 kJ/m^2, but the flexibility index increases from 20 to 31.



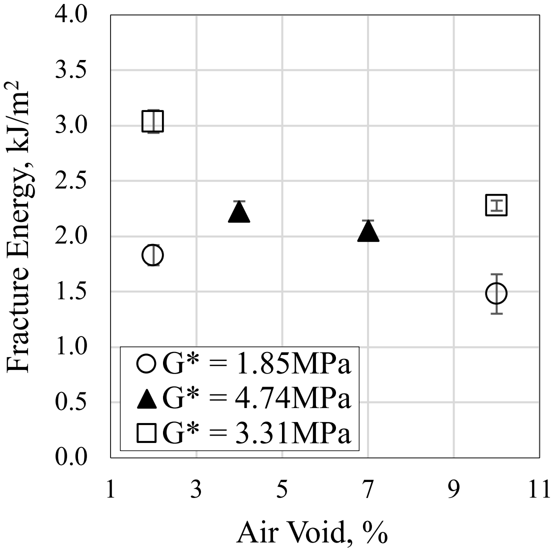
(a)

(b)

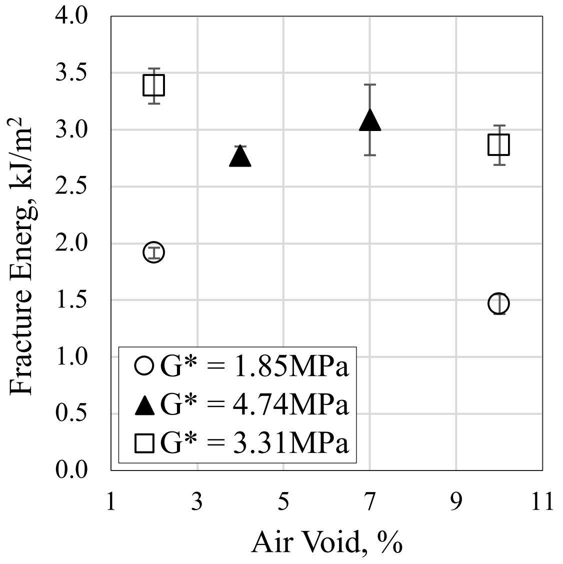
Figure 5-6. The effect of binder content on (a) fracture energy and (b) flexibility index under different binder stiffness and 7 percent air void.

5.4.2.4 Air Void Effect

The fracture energy decreases with the increase of air void level in most cases with a few exceptions. For example, at 6.2 percent binder content with PG 64-22 binder, fracture energy actually increases when air void increases from 4 to 6 percent. However, one of the observations in data needing careful discussion deals with the effect of air void on flexibility index, as shown in Figure 5-7 (b). The results indicate that flexibility index increases significantly as the air void increases. This correlation between air void and FI is consistent with results reported elsewhere (2016). In general, it is well established that high air void levels result in reduction of fatigue life. Therefore, one wonders if FI by itself can be used as a standalone fatigue resistance index considering the fact that higher FI can be found with high air void mixes. Higher FI is desirable when seeking flexibility and fatigue resistance but higher air void content is not.

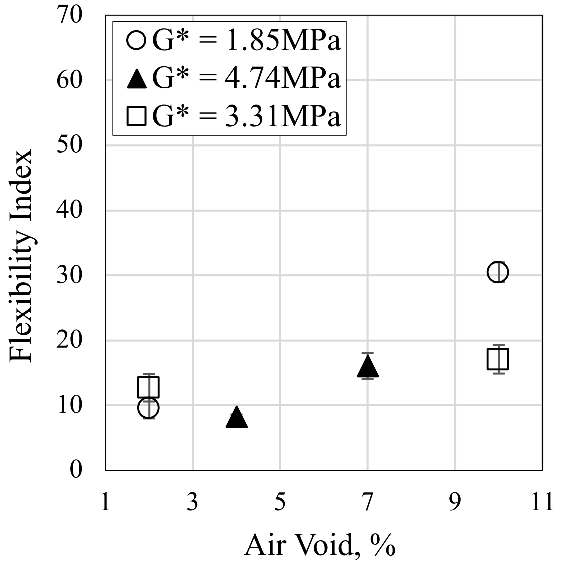


(a)



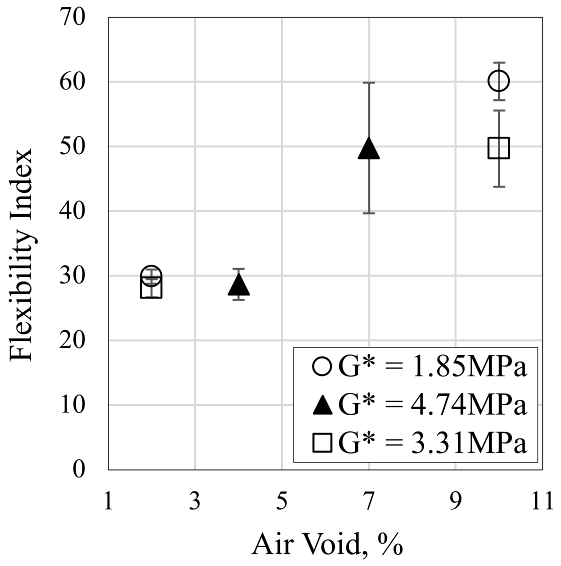
Fracture Energ, kJ/m²
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
3
5
7
9
11
Air Void, %
○ G* = 1.85MPa
▲ G* = 4.74MPa
□ G* = 3.31MPa

(b)



Flexibility Index
70
60
50
40
30
20
10
0
1
3
5
7
9
11
Air Void, %
○ G* = 1.85MPa
▲ G* = 4.74MPa
□ G* = 3.31MPa

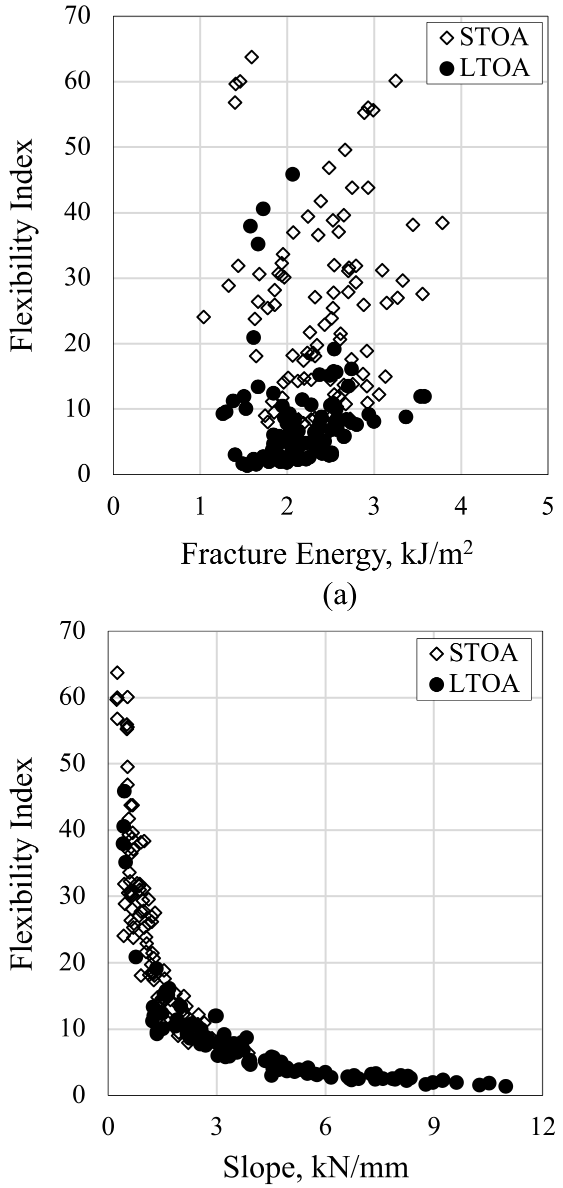
(c)



(d)

Figure 5-7. The effect of air void on fracture energy (FE) and flexibility index (FI) (a) FE at 4.7% binder content, (b) FE at 6.2% binder content, (c) FI at 4.7% binder content, and (d) FI at 6.2% binder content.

To further investigate the root cause of flexibility index, increase with the increase of air void, one should investigate the plot of overall flexibility index against its main calculation components: fracture energy and post peak slope at the inflation point (designated as slope in plots), as shown in Figure 5-8. It is clear that regardless of aging conditions, the value of flexibility index is dominated by the slope, as shown in Figure 5-8 (b), overshadowing the influence of fracture energy on flexibility index.

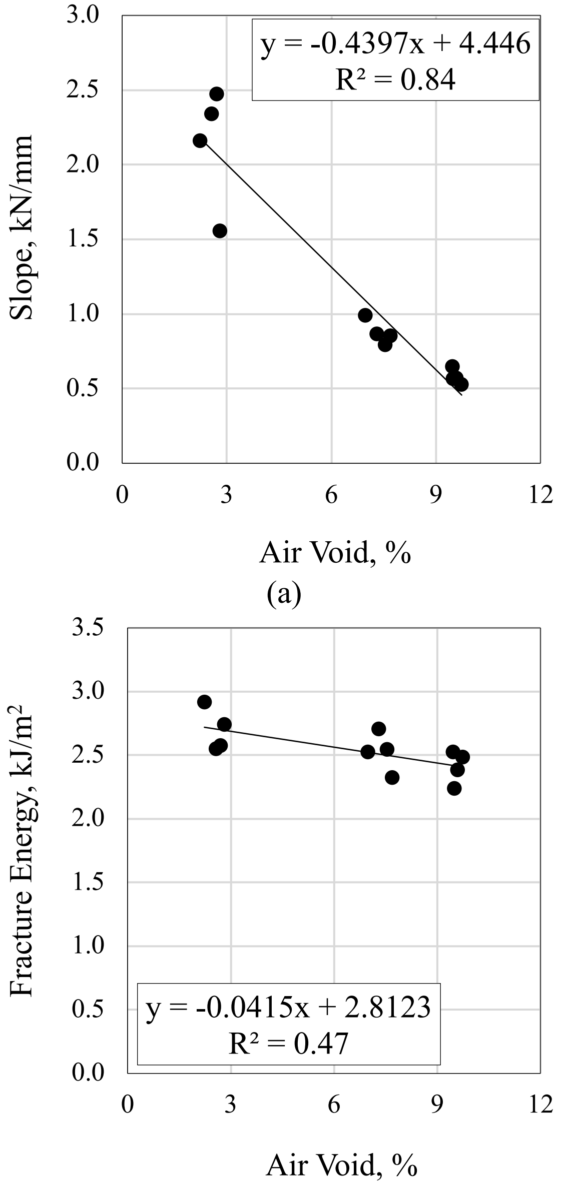


(a)

(b)

Figure 5-8. Flexibility index against its calculation components, (a) fracture energy and, (b) inflation point at the post peak slope.

Although both fracture energy and the post peak slope decrease with the increase of air void (Figure 5-9), the air void has a more significant impact on the slope than on fracture energy. The impact of air void on the post peak slope, which is the denominator in flexibility index calculation, directly results in observing increase of FI with air void. Limited by space, results of only one mix are shown in Figure 5-9, but similar trends are observed for all other mixes researched in this study.



(b)

Figure 5-9. Impact of air void of specimens with PG64-22 binder and 5.7 %binder content, (a) inflation point on post peak slope, (b) fracture energy.

The significant effect of increase in air void on reduction of fatigue life in the field cannot be ignored. Some of the very high air void mixes in this study delivered FI values over 30, but are believed to be highly susceptible to fatigue cracking. Therefore, using the flexibility index as a standalone fatigue performance indicator is questionable. The authors believe FI must be coupled with either a strength index (for example, from the load at failure) or a stiffness index (for example, modulus or pre-peak slope of the load-displacement curve) to ensure the mix is not too weak even though it might exhibit high FI. In other words, FI ensures flexibility of the mix, and the strength or stiffness index ensures the mix bears enough stability against cracking.

To demonstrate the importance of using an additional index, we consider an asphalt mix under a combination of conditions in terms of binder content and air void (Figure 5-10). It can be seen how the increase in air void and binder content results in reduction of peak load, which is an indicator of strength. The graph also shows how increase in these two mix parameters results in increasing the post peak slope. Now, we could have the asphalt mix with a specific combination of air void and binder content to deliver very similar load-displacement curves. Figure 5-11 presents such a case from actual testing. The design binder content for this mix, based on Superpave design, is 5.2 percent at 4 percent air void level. As the binder content is increased, the air void is decreased in such a way that the final load-displacement curve does not change significantly, as observed in the close match of graphs in Figure 5-11. The actual fracture energy and flexibility index values for these two mixes are also almost identical, but these mixes are not expected to behave similarly in fatigue. The mix at higher binder content of 6.2% may be susceptible to rutting but it is doubtful to be susceptible to cracking as much as the lower binder content mix is.

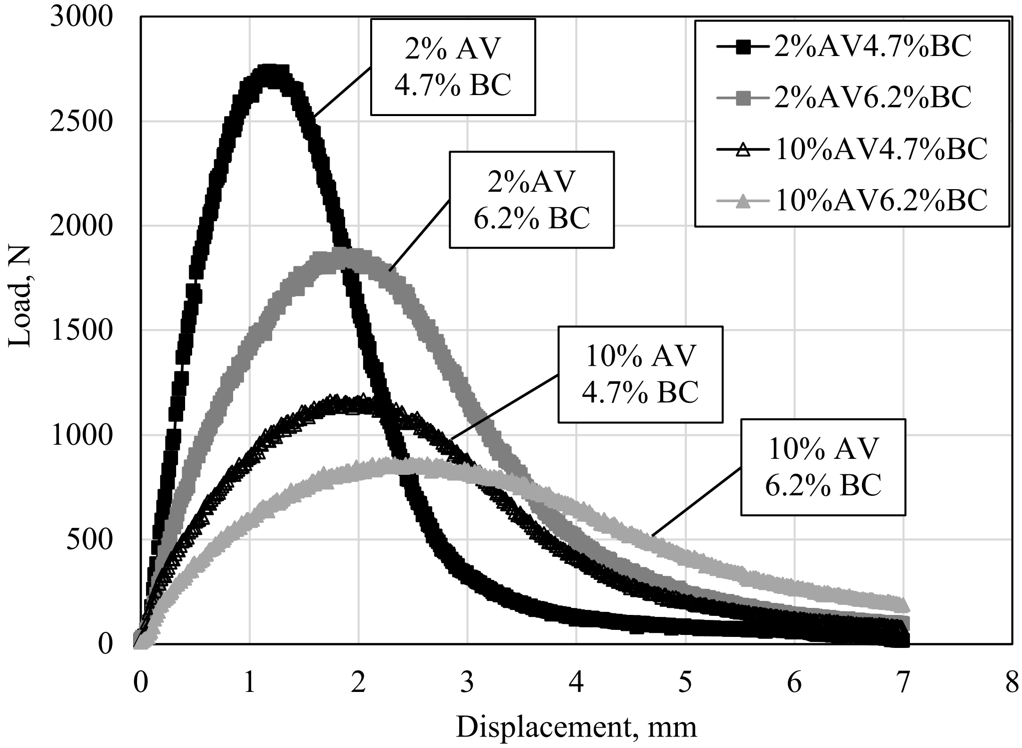
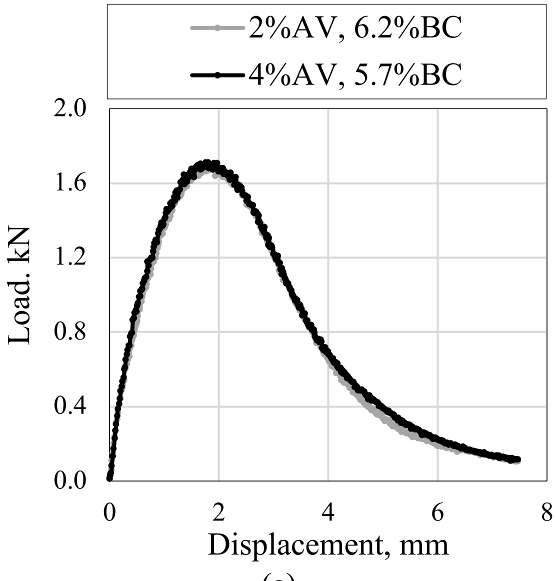
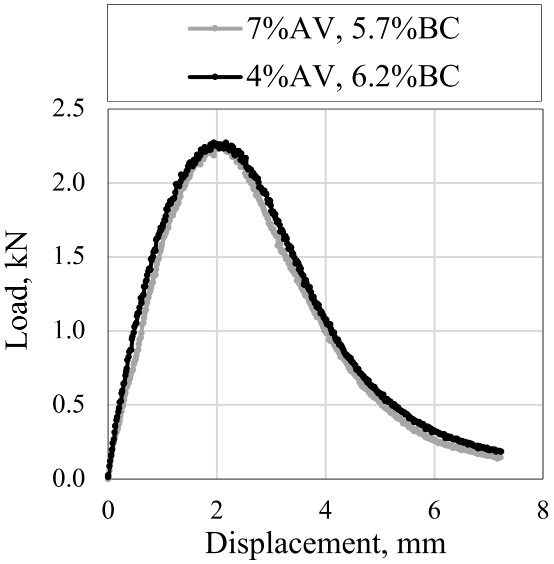


Figure 5-10. Displacement vs. load curves of mixes with PG58-28 binder and multiple binder content/air void combinations.



(a)



(b)

Figure 5-11. Similar load vs. displacement curves from mixes with different material variables, (a) mix with PG58-28, (b) mix with PG64-22.

5.4.2.5 Statistical and Regression Analysis

Statistical analysis was conducted to investigate the level of influence of material variables on performance indicators. When the design of experiment was conducted at the beginning of the study (Table 5-1), air void was considered as a factorial element, same as binder content and binder stiffness. However, due to the inhomogeneous nature of asphalt mixture specimens after cutting, the specimens showed different air void levels. For example, the nominal target air void level was 4 percent, but the actual air void of specimens varies in the range of 4 to 4.7 percent. The mixes for each nominal target air void produced results within the expected range and were clustered together. To make sure the statistical analysis is valid based on existing design of experiment air void data was considered as a factorial element, except in the regression model analysis where it was treated as continuous data. Table 5-3 shows the test statistics for the material variables for performance indicators. It is shown that all material variables, including stiffness index, binder modulus at 20℃, and air void are statistically significant with p-values smaller than 0.05, at a confidence level of 95 percent. In other words, fracture energy and flexibility index of asphalt mixtures tested using the SCB test are sensitive to the material variables included in this study.

Table 5-3. Significance of Material Variables to Performance Indicators

Aging Conditions	**Performance Indicator**	**Binder Content**	**Binder Modulus at 20℃**	**Air Void**
Short Term Oven Aged	Fracture Energy	3.21e-07	2e-16	8.82e-08
	Flexibility Index	2e-16	8.28e-06	2e-16
Long Term Oven Aged	Fracture Energy	2e-16	6.24e-11	7.37e-10
	Flexibility Index	2.71e-16	1.58e-11	2.23e-08

Stepwise regression analysis was conducted using statistical analysis program R for fracture energy and flexibility index, to quantify the effect of each material variable and serve as a prediction model for the specific material sources used in this study. Eighty percent of data sets were used for model generation, and the remaining twenty percent were used for model verification. The regression model includes all three independent variables and their interactions if the term is statistically significant. Final regression models were selected using the Akaike Information Criterion (AIC), which is an estimator of the relative quality of statistical models for a given set of data. Lower AIC value means a better fitted model.

For short term aged mixes:

$$FE = 3759.2 - 0.75 \times G - 55.1 \times AV - 340.41 \times BC + 0.18 \times BC \times G$$

$$FI = -33.12 + 8.29 \times BC - 0.00232 \times G - 6.01 \times AV + 1.75 \times BC \times AV$$

For long term aged mixes:

$$FE = -2749 + 0.0162 \times G + 310.5 \times AV + 938.2 \times BC - 69.01 \times BC \times AV$$

$$FI = -66.95 + 11.81 \times BC + 0.0074 \times G - 4.07 \times AV + 1.41 \times BC \times AV$$

Where

FE = Fracture energy, J/m^2;

FI = Flexibility index;

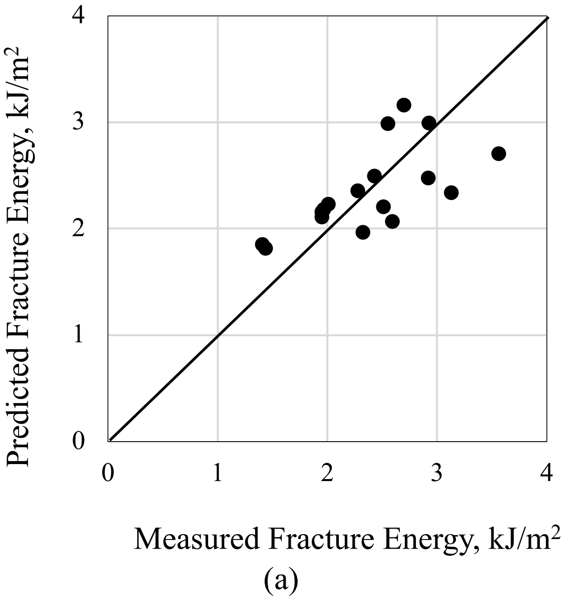
AV = Air void, %;

BC = Binder content, %; and

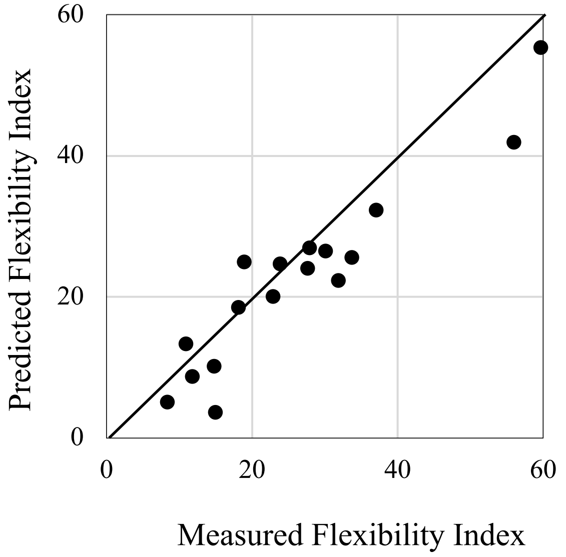
G = Binder Modulus at 20℃, kPa.

Adjusted R-square values for the four models presented above are found to be 0.53, 0.86, 0.79 and 0.76, respectively. The interaction terms in the regression models, even though difficult to explain from engineering perspective, could not be discarded as they were shown to be statistically significant. Moreover, no transformations on predicted and response variables were needed based on the Box-Cox transformation analysis results, which is a common procedure to determine the most appropriate transformation for prediction and response variables, in order to improve the prediction model.

The predicted performance responses versus measured values are plotted in Figure 5-12 for short term aged materials. Similar results can be found for long term aged mixes. Overall, data points stay very close to the line of equality. However, prediction models can be further improved by adding more data points and introducing more material variables that did not included in the model development. In addition, this model is only valid for the aggregate size and type used in this study.



(a)



(b)

Figure 5-12. Comparison between measured and predicted (a) fracture energy and (b) flexibility index for short term aged mixes.

5.5 SUMMARY AND CONCLUSIONS

The fatigue of asphalt mixtures has long been a complicated and unresolved problem. Among many laboratory tests developed to characterize fatigue performance of asphalt paving materials, the SCB test has been recently promoted as a good candidate. The test can be utilized on a routine basis due to its various merits including ease of testing and specimen preparation, ease of analysis, and its sensitivity to mix parameters. To investigate the effect of asphalt mix composition on the SCB test result, a series of SCB tests were performed using a modified SCB test procedure. Material variables included: binder content, air void level, binder stiffness, and aging condition. Based on the laboratory test results and statistical analysis, the conclusions are as follows:

1. The proposed SCB test procedure, with a displacement rate of 5 mm/min and a test temperature of 20℃, is adequately sensitive to capture the effect of all investigated material variables.
2. Once specimens are prepared and ready to be tested, a suite of tests with 4 replicates can be finished within a short period of time (for example, in less than 10 minutes).

The 20°C fatigue testing temperature was established for Pennsylvania using the effective temperature concept for fatigue.

3. There is no significant difference between SCB specimens cut from the top and bottom layers of the specimen in terms of their air void distribution and mechanical properties, as long as the material is uniformly compacted with no segregation. Four specimens cut from a single SGC can be used as independent replicates.
4. Fracture energy increases with the increase of binder content and binder stiffness, but beyond a point, increasing stiffness of binder results in reduction of fracture energy. Fracture energy was also observed to decrease with the increase of air void. These trends match the ones observed in stress controlled cyclic fatigue tests. On the other hand, flexibility index increases with the increase of binder content, and decreases with the increase of binder stiffness. These trends match the ones observed in controlled strain cyclic fatigue tests. To differentiate the effect of binder content, FI is more sensitive than FE. The relationship between binder stiffness and SCB test parameters reported here is limited to materials used in this study. Further work is needed to verify the potential correlation between binder stiffness/modulus and SCB test parameters using broader selection of materials.
5. FI increases with the increase of air void level. Analysis shows that the value of flexibility index is dominated by the slope, overshadowing the influence of fracture energy. The authors believe FI must be coupled with either a strength index or a stiffness index to ensure adequate strength of the mix.
6. Prediction models for FE and FI using material composition variables and their interactions yield reasonable accuracy. However, a broader selection of material variables is needed to enhance the prediction model. Further work is also needed to investigate the influence of interactions between variables.

Chapter 6 FRACTIRE PROPERTIES OF ASPHALT MIXTURES WITH CRUMB RUBBER MODIFIERS

The effect of material variables on performance indicators of SCB fracture test was investigated and analyzed in the last chapter. In this chapter, the fracture resistance of crumb rubber modified (CRM) asphalt mixtures are evaluated using the proposed SCB fracture test protocol. The focus of this study is on the impact of CRM content, gradation, binder content, and binder stiffness.

6.1 INTRODUCTION AND BACKGROUND

Millions of used vehicle tires are disposed each year and this number keeps increasing due to growing demand of vehicles and traffic. Discarded tires pose a severe environmental problem in the United States. Normally, discarded tires are reused, resold, retreated, or landfilled. Among possible uses of scrap tires, only two methods have shown potential for the greatest benefit: use as combustion fuel and crumb rubber modifier (CRM) for paving industry (Heitzman 1992). CRM use in asphalt paving has a relatively long history and its first use goes back to 1840 (Heitzman 1992). However, a rational approach for use did not come into play until McDonald introduced the wet process in 1960s. Due to its huge potential benefits to the environment and improving performance of asphalt mixtures. It has been gradually gaining popularity. Several states such as California, Arizona, Georgia, Texas, and Florida have been using crumb rubber modified asphalt concrete for decades.

There has been extensive research on CRM binders within the last several decades (Bahia and Davies 1994, 1995, Airey et al. 2003, Putman and Amirkhanian 2006, Neto et al. 2006). Bahia and Davies (1994) studied the performance of CRM asphalt binder using three grinding processes: ambient shredding, cryogenic grinding, and special extrusion process with additives. The extrusion process was used to produce rubber particles with a maximum particle size of one millimeter. The authors mixed 15 percent rubber with four different asphalt binder sources, differing in asphaltene content, aromatic content, average molecular weight, and rheological properties. Performance of crumb rubber modified asphalt binder was evaluated at high, intermediate, and low temperatures. The authors reported increased viscosity of binder at mixing and pumping temperatures, increased rutting parameter ($G^*/\sin\delta$), increased strain at failure, marginal change in $G^* \cdot \sin\delta$, creep stiffness and creep rate, and a decrease of stiffness at low temperature. In their following research (Bahia and Davies 1995), they expanded material sources and rubber contents and observed similar trends.

Numerous studies have reported promising performance of CRM binders when incorporated into asphalt mixes as well (Takallou et al. 1997, Mohammad et al. 2000, Venudharan et al. 2017). Takallou et al. employed Superpave® volumetric design procedure for CRM mixes and conducted a series of performance tests (1997). They claimed that the optimum binder contents for CRM mixes as designed in the laboratory are significantly higher than binder contents successfully used in the field. Mohammad et al. conducted a comprehensive study to evaluate the overall laboratory and field performance of crumb rubber asphalt mixtures (2000). They used conventional, SBS modified, and crumb rubber modified asphalt binders to prepare mixes. The authors concluded that CRM asphalt mixtures behave similarly to conventional asphalt mixtures in laboratory tests. In the field, CRM mixes showed significantly less rutting compared with the conventional mixes when used as base course, and similar rutting compared with conventional mixes as wearing course.

Reported research indicates that most CRM asphalt mixes exhibit superior fracture and fatigue performance compared with conventional asphalt mixes (Raad and Saboundjian 1998, Mull et al. 2002). Mull et al. evaluated the fracture resistance of chemically modified crumb rubber asphalt mixtures (CMCRA) using the SCB test (2002). A control binder, a plain crumb rubber binder, and a CMCRA were used in this study. The authors introduced three notch depths and used J-integral concept to describe fracture resistance of mixtures. The results indicated that with the same rubber and binder source, CMCRA presented twice the critical fracture resistance. Raad and Saboundjian conducted controlled strain flexural beam fatigue test at a range of temperatures on field cut specimens in surface layer and lab produced asphalt rubber mixes (1998). At -29℃, asphalt rubber mixes showed fatigue resistance similar to that of regular AC-5 mixes at -12°C. Moreover, rubber mixes seemed to have dissipated more energy before reaching 50 percent reduction in flexural stiffness compared with conventional mixes. At 20°C, both rubber mixes and conventional mixes presented similar fatigue life. At 0°C, both mixes showed the longest fatigue life compared to other temperatures, while rubber mixes exceeded performance of conventional mixes at this temperature.

Although CRM mixes and binders have been investigated extensively, limited research is available evaluating such mixes using the latest developed test protocols, especially the Illinois Semi-Circular Bend test (I-FIT). This study was planned to implement this newly developed concept and evaluating the fracture performance of CRM mixes.

6.2 OBJECTIVE AND SCOPE OF WORK

The primary objective of this study was to investigate the fracture properties of CRM mixes in the SCB test. The study included one type of aggregate, three types of virgin binder, and one type of crumb rubber. A number of aggregate gradations and binder contents were considered, and Superpave® volumetric mix design was conducted for various mixes.

6.3 SPECIMEN PREPARATION AND EXPERIMENTAL PROGRAM

6.3.1 Material and CRM Preparation

The dolomite/limestone aggregate used in this study came from a local source. Two different aggregate structures, based on 9.5mm nominal maximum aggregate size, were used in the study: dense graded and gap graded. One source 30-mesh ambient shredded crumb rubber was used to manufacture CRM binders in the lab with PG58-28 and PG64-22 binders. All gradations are illustrated in Figure 6-1.

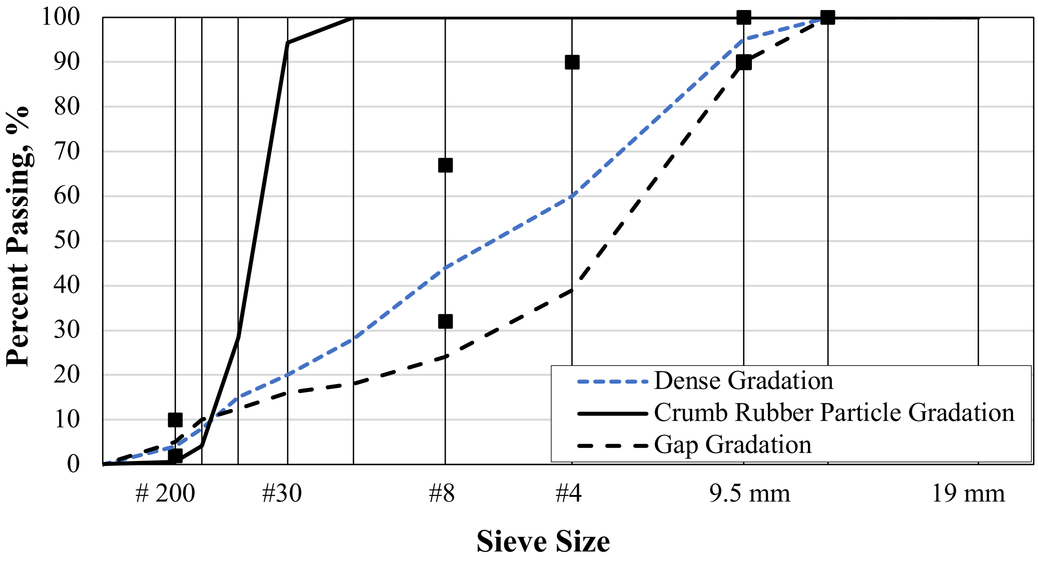


Figure 6-1. Aggregate gradation and crumb rubber particle gradation.

The following procedure was followed to prepare CRM binders:

1. Heat virgin binder at 150°C for 60 to 80 minutes.
2. Continue heating virgin binder in a temperature-controlled container until it stabilizes at 165°C.
3. Add crumb rubber particles into the heated virgin binder gradually and within a period of five minutes. Blending occurs at 3000 RPM while rubber particles are added.
4. Agitate the CRM binder for an hour at a reduced shear rate of 700 RPM after all rubber particles are added.
5. The blended CRM binder is cooled to room temperature.
6. Heat the modified binder for one and half to two hours before usage.

The temperature of the blending container was maintained at 170±2 °C for the entire shear blending process. The CRM binder was used no later than one day after manufacturing. Finally, all specimens were mixed and compacted at 150°C regardless of CRM binder type, although the pre-heating durations for CRM binders varied from 90 to 120 minutes depending on the binder stiffness. CRM binders were stirred carefully to ensure homogeneity before mixing with aggregate.

Three different CRM binders were employed in the study: PG58-28 with 10 percent rubber, PG58-28 with 15 percent rubber, and PG64-22 with 10 percent rubber. The percentage refers to the mass of the crumb rubber as a percent of the mass of the modified binder (i.e. mass of the neat binder and the crumb rubber combined). The CRM for PG64-22 was limited to 10 percent since during a preliminary study it was found that the high temperature performance grade of PG64-22 with 20 percent rubber binder was over 90°C and the binder was barely workable due to high viscosity.

6.3.2 Selection of Study Cases

To capture the effect of gradation and CRM binder type on fracture performance of CRM mixes, five different cases were included in this study (Table 6-1). Binder contents shown in Table 1 are the optimum amount based on the mix design process, targeting 4 percent air void content.

Case 1 was considered the reference mix using dense graded virgin aggregate and virgin binder (PG58-28 and PG76-22). The four additional cases covered various what-if scenarios. For example, two cases were considered for dense graded aggregate: one with adjusting dense gradation to compensate for addition of crumb rubber (cases 2 and 3) versus no adjustment of gradation (case 4). The difference between cases 2 and 3 was that the binder content for the former was optimized based on CRM mix design whereas for case 3, the binder content was the same as virgin mix (case 1). This was done to address the question of what happens to a mix when a virgin binder is replaced with a crumb rubber modified binder adjusting the aggregate gradation but without changing the design binder content. Case 4 was used to address the question of what happens to a mix when a virgin binder is replaced with crumb rubber modified binder without adjusting gradation or binder content of the original virgin mix. Therefore, one can see that for cases 3 and 4, no mix design is conducted, and the binder content designed for case 1 is simply used in cases 3 and 4. Finally, case 5 is used to introduce a gap gradation for CRM mixes. The reason for including case 5 was because the gap graded aggregate structure is the most commonly used type of gradation for CRM mixes.

Table 6-1. Different Cases of Mixes and Binder Content Used in this Study.

Case	Binder	Gradation	Binder Content (CRM Content), %
1	Virgin	Dense	5.2 (0)
2	CRM	Dense with adjustment for rubber	5.5 (10), 5.7 (15)
3	CRM	Dense with adjustment for rubber	5.2 (10/15)
4	CRM	Dense without adjustment for rubber	5.2 (10/15)
5	CRM	Gap	6.2 (15)

6.3.3 Specimen Preparation and SCB Test

The specimen preparation discussed previously in chapter three was followed strictly. All final SCB specimens were prepared to reach the target air void level of 5.5±0.5 percent in order to remove the effect of air void as one of the variables. This target was set to match the most common air void in the field. In a previous study (Chen and Solaimanian 2018), it was found that the air void had an impact on fracture performance indices such as flexibility index. As a result, specimens with air void outside the target range were discarded and new batches were made to achieve the target.

The same test conditions: a displacement rate of 5 mm/min and test temperature of 20℃ were maintained throughout the study. Fracture energy (FE), flexibility index (FI), and peak load (PL) were calculated for each specimen.

6.3.4 Linear Amplitude Sweep Test and Dynamic Shear Rheometer Test

In order to establish reference data and try to correlate mixture fracture performance data to binder fatigue behavior, the fatigue resistance of CRM binder was evaluated using the Linear Amplitude Sweep (LAS) test through cyclic loading employing systematic, linearly increasing load amplitudes (AASHTO 2016). This test consists of two parts: a frequency sweep and an amplitude sweep. The former provides rheological properties, and the latter provides input for damage analysis. The undamaged material properties of the binder were determined by means of frequency sweep tests conducted at 0.1 percent strain level, and at frequencies ranging from 0.2 to 30 Hz. Afterwards, the binders were loaded using the strain amplitude sweep. 100 cycles were applied at a range of strain levels from 0.1 percent to 30 percent at a frequency of 10 Hz. A 35 percent reduction in the loss modulus (i.e. $G^* \cdot \sin\delta$) of the material is used to calculate the number of load cycles to fatigue failure (N_f) at various strain levels. The LAS test was performed at 25°C for all binders. The test results were analyzed using the viscoelastic continuum damage (VECD) approach, the detailed theoretical background and analysis procedure of which have been discussed extensively and can be found elsewhere (Johnson and Bahia 2010, Hintz et al. 2011, Underwood 2016).

In addition to LAS test results, Glover Rowe (G-R) damage parameter ($G^* \cdot \cos(\delta)^2/\sin\delta$) was used to evaluate cracking characteristics of all CRM binders after they were exposed to both rolling thin film oven (RTFO) and pressure aging vessel (PAV) aging. The G-R parameter considers binder stiffness and embrittlement and offers an indication of binder cracking resistance at intermediate temperature. Dynamic shear rheometer (DSR) tests were conducted to determine complex modulus (G*) and phase angle (δ) of all binders after PAV aging via frequency sweep tests (angular frequency range from 0.1 to 100Hz) at 5°C, 15°C, and 25°C under a peak to peak strain amplitude of 0.1 percent to ensure linear viscoelasticity. The Christensen-Anderson (CA) model (Christensen and Anderson 1992) was then used to construct the master curve for each binder, from which the G* and δ at 15°C and 0.005 rad/s was extrapolated to calculate the G-R parameter. The calculated G-R parameter values were compared with two separate G-R damage thresholds: one with G-R parameter value at 180 kPa while the other at 450 kPa (Anderson et al. 2011, Rowe 2011), which represent cracking onset and significant cracking, respectively.

6.4 RESULTS AND ANALYSIS

6.4.1 Design of CRM Mixes

Mix design using different binders was performed following AASHTO M323-17. The results are presented in Figure 6-2. The design binder content is defined as the percent binder in total mix to deliver 4 percent air void at design number of gyrations when compacted in a Superpave® gyratory compactor. The design binder content for virgin mixes, regardless of binder grade, was established as 5.2 percent. As expected, increase of rubber content results in an increase in design binder content. The base binder PG58-28 when modified with 10 percent crumb rubber indicates an increase of 0.3 percent in design binder content, shifting from 5.2 to 5.5 percent. At 15 percent crumb rubber modification, the design binder content is 5.7 percent, yielding an increase of 0.5 percent. Another observation is that both PG58-28 and PG64-22, when modified with 10 percent rubber, delivered design binder content of roughly 5.5 percent. This finding indicates that binder stiffness has less impact on design binder content than rubber content.

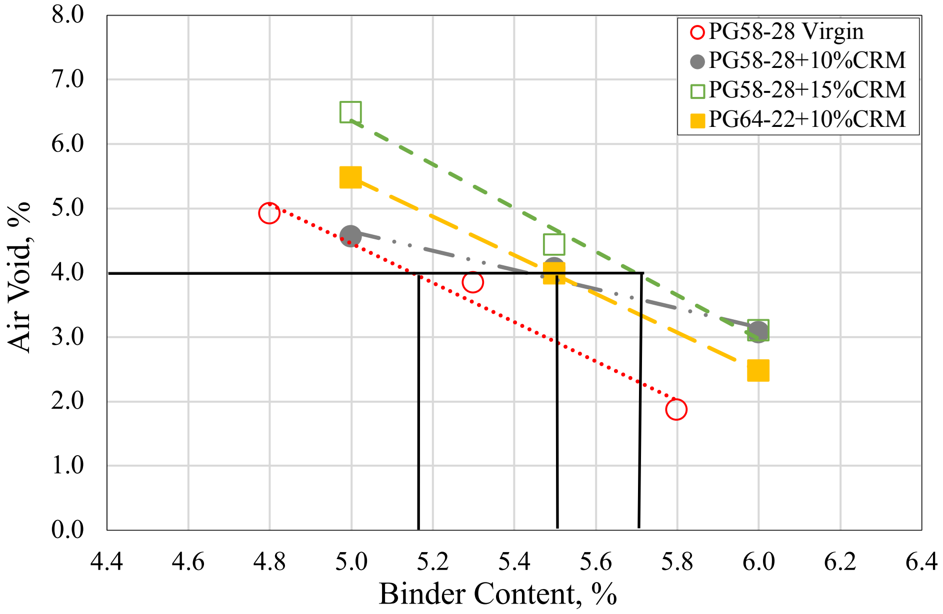


Figure 6-2. Binder content to air void relationship for all mixes.

Void in mineral aggregate (VMA) and void filled with asphalt (VFA) values play a significant role in determining mechanical properties of asphalt mixes. Volumetric results of all mixes at the design binder content are presented in Table 6-2. For a design ESAL of 0.3 to less than 3 million, all VMA values at design binder content passed the minimum threshold and all VFA values fall within the target range.

Table 6-2. Design Binder Content and VMA & VFA Values.

Binder Type	Binder Content, %	VMA, %	Requirement on VMA, %	VFA, %	Requirement on VFA, %
PG58-28 & PG76-22	5.2	16.6	> 15	77.0	65 - 78
PG58-28 + 10% CRM	5.5	17.6		76.9	
PG58-28 + 15% CRM	5.7	17.9		77.5	
PG64-22 + 10% CRM	5.5	17.3		77.0	

6.4.2 Effect of Crumb Rubber Content and Binder Grade on Properties

6.4.2.1 Initial and Post Peak Stiffness.

A plot of load-displacement from the SCB test is presented in Figure 6-3. An obvious observation is that mixes with CRM and PG58-28 as base binder has lower initial stiffness and lower post peak stiffness compared to all other mixes including the mix with PG58-28 virgin binder. This is indeed an interesting observation showing the combined effect of the crumb rubber content and binder content in increasing the mix ductility. The graph also shows that the mix with PG76-22 and the mix with 10 percent CRM and PG64-22 binder have the highest stiffness compared to other mixes.

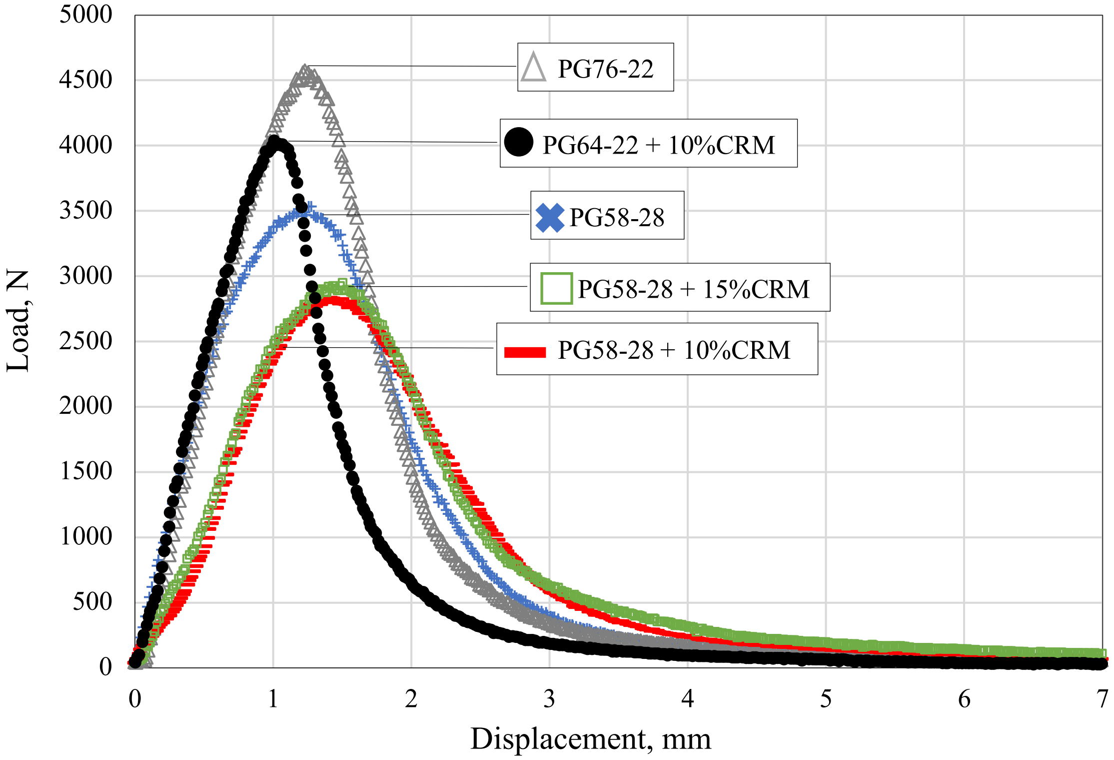
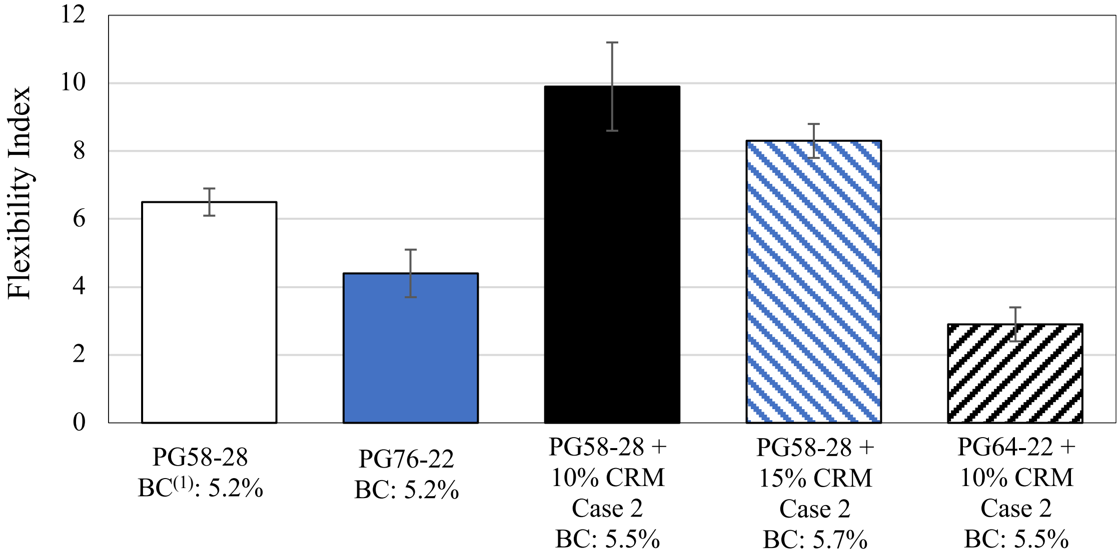


Figure 6-3. Load displacement curves for some of the specimens tested in SCB test.

6.4.2.2 Flexibility Index.

The flexibility index (FI) is presented in Figures 6-4 and 6-5. Error bar stands for one standard deviation. Figure 6-4 shows the effect of binder grade and increasing the rubber content for mixes as designed to deliver 4 percent air void. Figure 6-5 indicates how FI changes as gradation of aggregate is adjusted or design binder content changes in a dense graded mix. Once again, it must be noted that the results are for mixes which have been long term conditioned in the oven.



Note (1): BC is short for Binder Content.

Figure 6-4. Flexibility index distribution of all SCB specimens.

There are several findings from the results presented in Figure 6-4. One is that the CRM mix with PG58-22 at 10 percent rubber content has the highest FI. The mix with virgin binder PG58-28 delivers an average FI of 6.5 while the mix with 10 percent rubber modified binder delivers an average FI of 10. Part of this increase is attributed to the increase in binder content (from 5.2 to 5.5 percent), and the other part is due to the use of crumb rubber. It can also be noticed that further increase in rubber content from 10 to 15 percent results in slight decrease of flexibility, in spite of the fact that the binder content is increased from 5.5 to 5.7 percent. This is an important observation indicating that in dense graded mixes, higher percent crumb rubber does not necessarily result in higher flexibility.

Along the same line is the result for PG64-22 binder, which when used with 10 percent rubber, delivers a low FI possibly due to significant increase in stiffness of the binder.

6.4.3 Effect of Gradation Adjustment in Dense Graded Mixes

It can be seen from Figure 6-5 that in a CRM dense graded mix, slight adjustment of gradation to allow space for rubber does not significantly impact the mix flexibility. For example, compare Case 3, in which gradation is adjusted to allow space for crumb rubber, with Case 4, where no adjustment in gradation is made. Both cases have the same binder content of 5.2 percent. The values for flexibility index from these two cases are not significantly different. Case 2 delivers significantly higher FI for PG58-28 with 10 percent CRM binder most possibly because of higher binder content (5.5 versus 5.2 percent) rather than slight adjustment in gradation. Note should be again made that the results are presented for dense graded mixes, and adjustment to gradation has been only through reducing the amount of fine aggregates at the same size and amount of rubber particles.

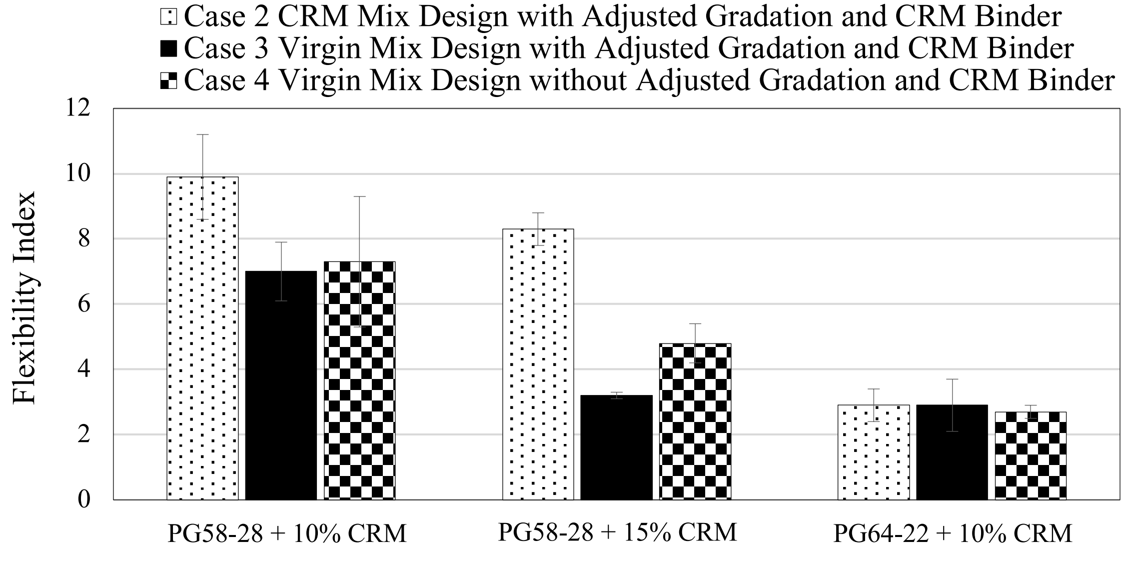


Figure 6-5. The effect of gradation adjustment on flexibility index for dense graded CRM mixes.

6.4.4 Effect on Other Response Parameters

The results for fracture energy (FE) and peak load (PL) data are presented in Figures 6-6 and 6-7.

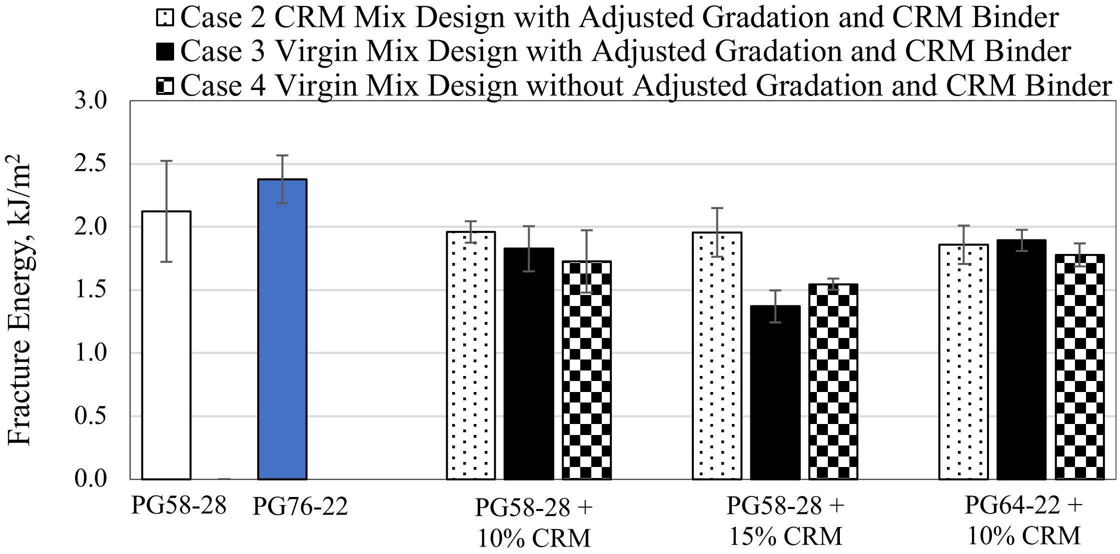


Figure 6-6. Fracture energy for different mixes tested in SCB.

It can be seen that mixes with CRM binders delivered lower fracture energy (FE) compared with mixes with virgin binders. The CRM mixes, however, are not significantly different from one another. The exception is Cases 3 and 4 with PG58-28 binder and 15 percent rubber, which delivered lower FE values compared with case 2. From the results presented for FI and FE, it is reasonable to believe that FI presents a significantly higher sensitivity to mix changes compared with FE. Statistical analysis that follows supports this conclusion.

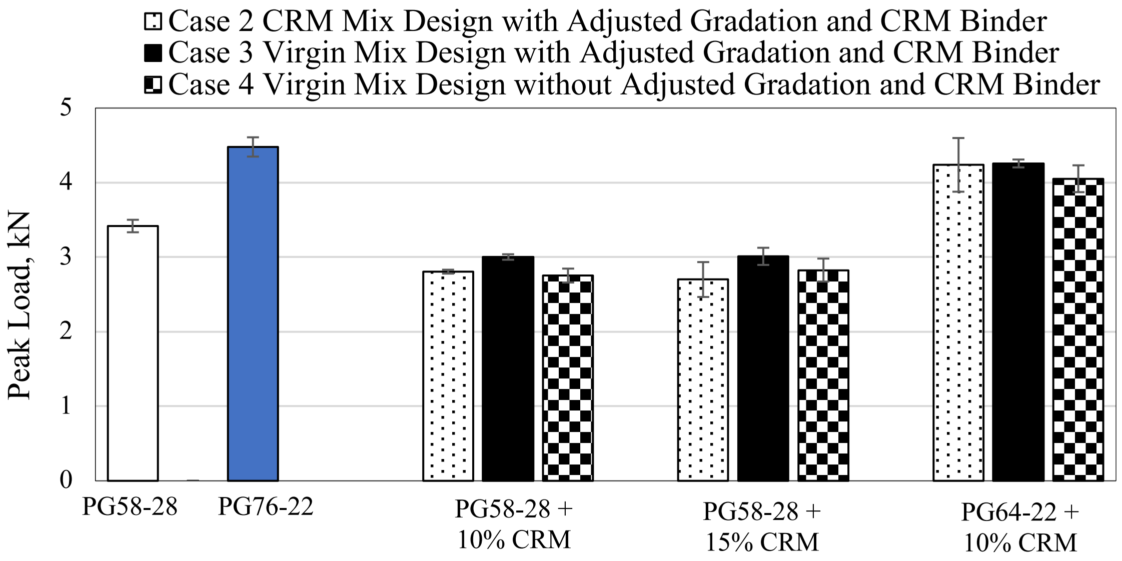


Figure 6-7. Peak load for different mixes tested in SCB.

Figure 6-7 indicates that for the mixes made with virgin binder, the mix with the binder that has the higher shear modulus at 20℃ (PG76-22) yields higher strength (higher peak load) compared with the mix that has binder with lower shear modulus at intermediate temperature (PG58-28). This trend is also true for CRM mixes, where the PG64-22 CRM mix yields considerably higher strength compared with PG58-28 CRM mixes. There is not much difference observed between mixes made with PG58-28 binder at 10 percent CRM and mixes made with PG58-28 binder at 15 percent CRM. What is more interesting, however, is that the CRM modified PG58-28 mix yields lower strength than the mix made with virgin binder PG58-28, even at the same binder content. It was discussed previously that based on the load-displacement curves shown in Figure 6-3, the PG58-28 CRM mixes have lower stiffness both before reaching the peak load (initial stiffness) and after the peak load (post peak slope). This reduction in mix stiffness is the reason for increasing FI in spite of the loss in strength. If the strength results presented in Figure 6-7 are analyzed in the light of FI results presented in Figure 6-5, one can conclude that, in general, mixes yielding lower strength (peak load) are those delivering higher flexibility (FI). A balance between strength and ductility must be pursued to reach the overall best performance.

In summary, adding crumb rubber to dense graded asphalt mixes enhanced fracture resistance and ductility, in the meantime it reduced the mix strength slightly, compared with the mixes with virgin binders.

6.4.5 Statistical Analysis of Data

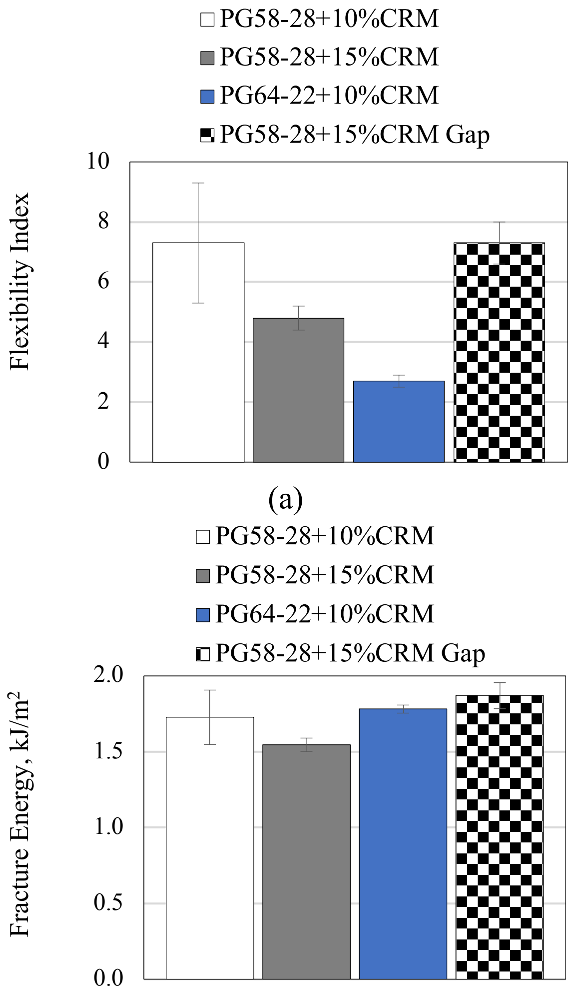
To properly investigate the sensitivity of characterization parameters to mix variables within each displacement rate, Tukey's statistical range test was utilized. Tukey's test is a single-step multiple comparison procedure, and its uniqueness is that it considers all possible pairwise differences of means at the same time. The overall Tukey test results are shown in Table 6-3. For each characterization parameter, mixes that do not share the same letter have statistically different means. In the meantime, materials having the same letter are statistically equivalent. For example, for cases 2 and 4 of PG58-28 with 10 percent CRM, the FI are different (A vs. B), but the PL of these two are the same (E vs. E). The observation applies to the material with multiple letters too. For instance, the case 2 of PG58-28 with 15 percent CRM has two letters of A and B for FI, implying that FI of this mix may be equal to FI of both PG58-28 with 10 percent CRM (case 2) and PG58-28 with 10 percent CRM (case 4).

Table 6-3. Tukey Test Results on All Virgin and CRM Dense Mixes.

Characterization Parameters	**Binder Type and Cases**										
	PG58-28	**PG76-22**	**PG58-28 + 10%CRM**			**PG58-28 + 15% CRM**			**PG64-22 + 10%CRM**		
			Case 2	**Case 3**	**Case 4**	**Case 2**	**Case 3**	**Case 4**	**Case 2**	**Case 3**	**Case 4**
FE	AB	A	BC	BCD	CDE	BC	E	DE	BCD	BCD	BCD
FI	BCD	DE	A	BC	B	AB	E	CDE	E	E	E
PL	D	A	E	DE	E	E	DE	E	BC	BC	C

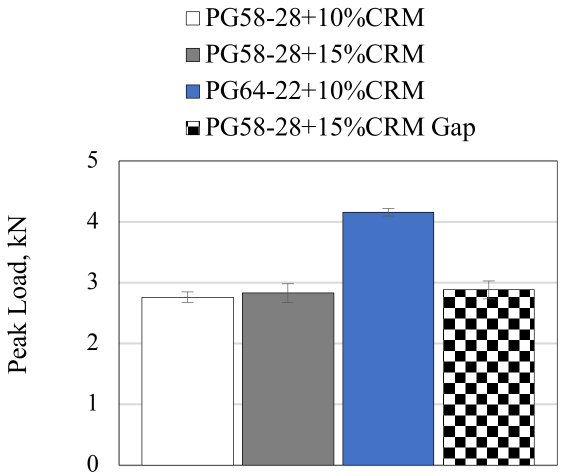
6.4.6 The Effect of Gap Gradation versus Dense Gradation

To evaluate the effect of gradation on fracture performance of CRM mixes, one gap gradation with PG58-28 and 15 percent CRM was included in the study. The mixes for this gradation were also prepared at 5.5 percent air void and exposed to long term oven conditioning, similar to dense graded mixes. The FI, FE, and PL data for this gap-graded mix, in comparison with dense graded mixes, are shown in Figure 6-8. The dense graded mix in Figure 6-8 presents the mix of Case 4 previously discussed. Therefore, all dense mixes in Figure 6-8 had a binder content of 5.2 percent. The binder content for the gap graded mixes was 6.2 percent.



(a)

(b)



(c)

Figure 6-8. (a) Flexibility index, (b) fracture energy, and (c) peak load distribution of dense and gap graded CRM mixes.

It is clear from Figure 6-8a that as the binder stiffness increases, FI decreases in dense graded mixes. However, the gap graded mix, at 15 percent rubber content (i.e. stiffer binder), provides FI similar to that of the dense graded PG58-28 mix at 10 percent rubber content. Obviously, the major contributor to boosting FI for the gap graded mix is the higher binder content, but the mix is also benefitting from the gap in gradation combined with inclusion of CRM.

The figure shows that the fracture energy levels, however, are not significantly different among different mixes (Figure 6-8b). The CRM mix with PG64-22 and 10 percent rubber had the highest peak load (Figure 6-8c). This mix is the stiffest among the dense graded mixes shown in Figure 6-8 and therefore, having the highest peak load is expected.

6.4.7 Fracture Resistance based on Binder Tests

Fracture resistance of binders used to prepare specimens for SCB tests were further investigated independently through two previously introduced binder tests: The Linear Amplitude Sweep (LAS) test that characterizes damage and predict fatigue life, and Dynamic Shear Rheometer (DSR) test that yield Glower-Rowe (G-R) damage parameters. The purpose of conducting stand-alone binder tests is to see if agreement, in terms of fracture resistance of binder materials, between binder tests and mixture mechanical test can be reached. Binder tests results will be presented and analyzed first, and the ranking of all binder and mix tests will be compared and discussed later.

6.4.7.1 LAS Test Results

VECD model fitting coefficients (C_0, C_1, C_2) of all binders are summarized in Table 6-4, along with the predicted fatigue life as determined under two strain levels (2.5 and 5 percent total strain). Fatigue life in Table 6-4 refers to number of cycles to failure at the specified test strain level. Failure is defined as the material integrity indicator ($G^{*}\cdot \sin\delta$) dropping to 65 percent of its original value.

Table 6-4. Amplitude Sweep VECD Coefficient and Predicted Fatigue Life of All Binders at 25°C.

Binder Type	**Parameters**				
	$\mathbf{C_0}$	$\mathbf{C_1}$	$\mathbf{C_2}$	**N_f @ 2.5% Strain**	**N_f @ 5% Strain**
PG58-28	5.204	0.128	0.464	15687	433
PG76-22	6.764	0.147	0.451	18133	246
PG58-28 + 10% CRM	3.705	0.136	0.424	30639	501
PG58-28 + 15% CRM	3.359	0.132	0.419	36924	581
PG64-22 + 10% CRM	6.765	0.136	0.461	19760	289

As shown in Table 6-4, at both strain levels, most of CRM binders show longer predicted fatigue life, especially PG58-28 with 15 percent rubber. It doubled the fatigue life of PG76-22 at both strain levels. PG64-22 with 10 percent rubber also showed superior fatigue life compare to virgin binders.

The predicted fatigue life of PG58-28 with 15 percent rubber is far longer than that of PG64-22 with 10 percent rubber, although two shares similar high temperature performance grading. On the other hand, the fatigue life of PG76-22 virgin binder is very similar to that of PG64-22 with 10 percent rubber, as they also share very similar high temperature performance grade. It seems that the predicted fatigue life using the VECD approach does not necessary correlate to high temperature performance grade of binder. It is expected because one parameter (fatigue life) is used to quantify material properties at intermediate temperature, while the other one (high temperature performance grade) reflects binder's behavior at high temperature range.

Overall, predicted fatigue life increases with the increase of rubber content when using the same base virgin binder. As shown in Table 6-4, regardless of strain level, the increase in fatigue life is significant when the added rubber content increased from 0 to 15 percent.

6.4.7.2 DSR Test Results

The black space diagram for the preceding five binders is shown in Figure 6-9. Comparing PG58-28 virgin binder to the two CRM binders with PG58-28, it is obvious that CRM binders shifted to the left of the spectrum because of the reduced phase angle, while maintaining similar shear modulus. Such a shift indicates that CRM binders show more elastic behavior compared to their base virgin binder (PG58-28). The increased elastic behavior is further enhanced with the increase of CRM content. All binders with PG58-28, regardless of CRM content, fall within the area below cracking onset line, an indication of improved fracture resistance.

The other two binders; PG76-22 and PG64-22 with 10 percent CRM, however, rest in the area between cracking onset and significant cracking line. Observation of this data implies that these two binders have less cracking resistance compared to the three binders discussed previously. It appears that base virgin binder plays an important role in determining the G-R parameter of a CRM binder. In other words, CRM binder with softer virgin base binder (PG 58-22) and higher CRM content (15%) has higher cracking resistance compared with the stiffer base binder (PG 64-22) and lower CRM content (10%). This comparison is based on G-R parameter value.

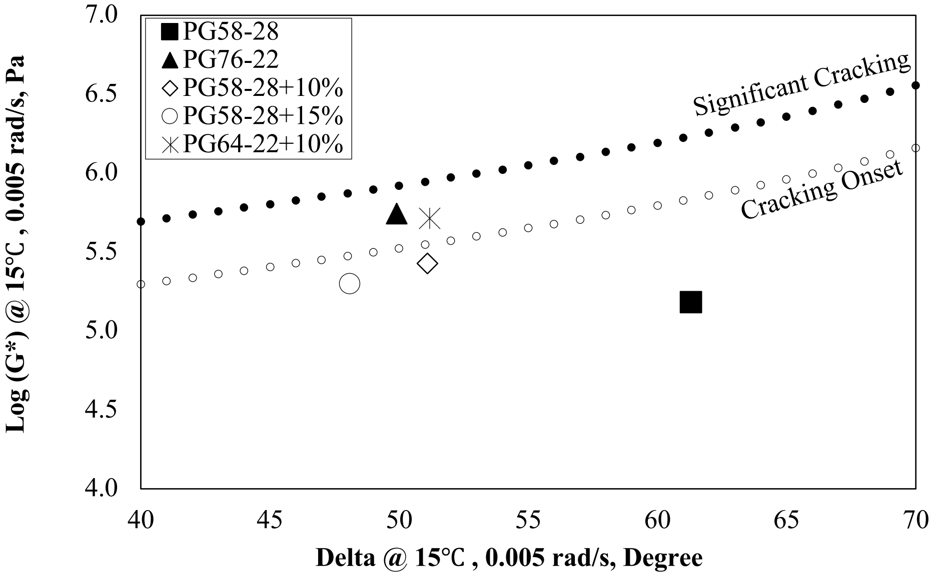


Figure 6-9. Black-space diagram of all binders.

6.4.8 Comparison of Fracture Resistance of Binders versus Mixtures

The ranking of fracture performance (designated using flexibility index) from SCB test, predicted fatigue life from LAS test, and G-R parameter are presented in Table 6-5. It is clear that the rankings are not consistent. What is in common, however, is that both fracture test and binder fatigue test at two strain levels, favor the performance of PG58-28 with 10 and 15 percent rubber. While G-R parameter, on the other hand, favors virgin PG58-28 binder. Additionally, they all agree that virgin PG76-22 was outperformed by almost all other binders tested in this study.

Obviously, the correlation between mix cracking test and binder fatigue tests cannot be established at this point. There are several explanations for this discrepancy. The first one being that aside from binder properties, mixture volumetric properties also have tremendous impact on fracture performance of the final mix, which is not accounted for in binder tests. The other possible reason is that binder and mixes were aged differently, in which binders went through RTFO and PAV aging, while mixes were exposed to forced air oven aging. Despite the fact that both are standardized long term aging protocols, binders undoubtedly reactivated differently under diverse aging environments, thus causing the discrepancies in performance rankings.

However, one conclusion that the rankings do agreed upon is that soft base virgin binder (i.e. PG58-28), regardless of CRM contents, out-performed the polymer modified virgin binder (PG76-22) and CRM binder with stiffer virgin binder (PG64-22), both in terms of binder fatigue properties and mix fracture performance.

Table 6-5. Fatigue Performance Ranking from Mix and Binder Tests.

Binder Type	**Performance Index**			
	Flexibility Index	**N_f @ 2.5% Strain**	**N_f @ 5% Strain**	**G-R**
PG58-28	3	5	3	1
PG76-22	4	4	5	5
PG58-28 + 10% CRM	1	2	2	3
PG58-28 + 15% CRM	2	1	1	2
PG64-22 + 10% CRM	5	3	4	4

6.5 SUMMARY AND CONCLUSIONS

The effect of several material parameters such as CRM content, virgin binder stiffness, binder content, and aggregate gradation on fracture performance of CRM mixes was investigated in this study. Superpave® volumetric mix design was performed on all CRM mixes. Long term oven aged (LTOA) specimens were exposed to the semi-circular bend (SCB) fracture test, and analyzed using flexibility index, fracture energy and peak load. Corresponding binders were subjected to LAS and DSR tests. The following conclusions can be drawn from the laboratory investigation:

1. The optimum binder content to reach 4 percent air void is higher for CRM asphalt mixes compared with mixes made with virgin binder. In addition, higher CRM content results in higher optimum binder content.
2. Using the same CRM binder, the gap graded mix required higher binder content to reach 4 percent air void at design number of gyrations compared with dense graded CRM mixes.
3. CRM mixes showed reduced initial stiffness and post-peak stiffness compared with mixes manufactured with the same base virgin binder or virgin binder at the same

performance grade. This observation indicates that rubber particles in CRM binder increase elasticity and ductility of asphalt mixes.

4. At design binder content, CRM mixes had higher flexibility index compared with mixes produced with the same base virgin binder or virgin binder at the same performance grade. This higher flexibility results from both the increase in binder content and increase in ductility due to the use of crumb rubber. However, in dense graded CRM mixes, higher percent crumb rubber does not necessarily result in higher flexibility. Some CRM mixes in this study delivered low flexibility possibly due to significant increase in binder stiffness.
5. CRM mixes showed lower fracture energy and peak load compared with mixes with the same base virgin binder or virgin binder with the same performance grade. This observation is expected as, in general, CRM mixes have lower pre-peak and post-peak stiffness. This lower stiffness yields in a stretched low-peak displacement-load curve, resulting in reduced fracture energy and peak load. Similar to flexibility index, the difference of fracture energy and peak load among CRM mixes with the same binder, but slightly adjusted gradation, is negligible.
6. For the same CRM binder, using gap graded mixes showed significantly improved flexibility index and fracture energy, in the meantime similar peak load values compared with the one with dense graded mix. Thus, it is recommended that CRM binder be used with gap graded mixes rather than dense graded mixes.
7. CRM binders outperformed virgin binders at the low strain level in LAS test; in the meantime, CRM binders also outperformed their base virgin binder at high strain level in LAS tests. The predicted fatigue life increases with the increase of CRM contents when using the same virgin binder as base binder.
8. CRM binder with PG58-28 as base binder showed strong cracking resistance based on their G-R parameter value. CRM binder with PG64-22 as base binder and PG76-22 virgin binder presents less cracking resistance due to higher stiffness.
9. There is no agreement between the rankings of SCB tests and binder tests at this moment. However, soft base virgin binder modified with 10 to 15 percent rubber have high possibility of out-perform the modified virgin binder both in terms of binder fatigue performance and mix fracture properties.

Chapter 7 FRACTURE PROPERTIES OF ASPHALT MIXTURES WITH ASPHALT RECYCLED MATERIALS

The fracture behavior of crumb rubber modified (CRM) asphalt mixes was discussed in the last chapter. The focus in this chapter will be shifted to fracture behavior of asphalt mixes with asphalt recycled materials, i.e., reclaimed asphalt pavement (RAP), which is the recycled asphalt paving materials from existing pavement, and recycled asphalt shingles (RAS), which are recycled roofing materials.

7.1 INTRODUCTION

Incorporating reclaimed asphalt pavement (RAP) and recycled asphalts shingles (RAS) into asphalt mixtures is economically and environmentally attractive, as it reduces demands on new materials and saves landfill space. Use of recycled materials in pavement construction has been implemented extensively since 1970s. Pavements with recycled materials, when properly designed and constructed, have been shown to perform as well as those made with purely virgin materials (McDaniel and Anderson 2001).

During manufacturing, construction, and through years of service, the binder becomes aged and hardened due to interaction with oxygen (McDaniel and Anderson 2001). This aged stiff binder may cause brittle behavior of the asphalt mix when RAP/RAS is incorporated into the mix. The stiffness and brittleness of the binder directly impacts mechanical properties of the final asphalt mix, especially when RAP/RAS contents are high. Asphalt mixes with recycled materials are normally less susceptible to permanent deformation, but prone to cracking. Sabouri et al. studied fatigue performance of asphalt mixes containing up to 40 percent plant produced RAP using viscoelastic continuum damage (S-VECD) theory and fatigue and Texas overlay tests (Sabouri et al. 2015). They found that most mixes with 40 percent RAP had decreased fatigue life, and mixes with more than 20 percent RAP showed significant drop in the number of cycles to failure in the Texas overlay tester. In addition, all mixes with RAP performed worse than virgin mixes. Ozer et al. investigated fracture properties of asphalt mixes containing RAP using semi-circular bend test and a fracture energy-based performance index called "Flexibility Index" (Ozer et al. 2016). They reported decreased flexibility indices of mixes with higher RAP content, indicating increased brittleness and decreased fracture performance. Yan et al. evaluated cracking performance of surface mixes containing up to 40 percent RAP via the Superpave Indirect Tensile Test (IDT) and the concept of dissipated creep strain energy to failure ($DCSE_f$) (Yan et al. 2016). Their results illustrated decrease in failure strain, fracture energy density, and $DCSE_f$ values when RAP content increased. However, all mixes passed the $DCSE_f$ threshold value of 0.75 kJ/m^3, indicating that well designed RAP mixes satisfy performance requirements. Numerous studies have proven that regardless of testing and analyzing methods, mixes with higher RAP content always lead to reduced crack resistance and fatigue performance without incorporation of rejuvenators or soft binders.

Researchers have proposed different methods to reduce stiffness of RAP/RAS binder to improve fracture properties of asphalt mixes with recycled materials. Zhou et al. proposed four approaches to improve fracture resistance of asphalt mixes containing RAS: 1) reduce RAS content, 2) use rejuvenator, 3) use softer binder, and 4) decrease design air void (Zhou et al. 2013, 2015). Their test results showed improvement in Texas overlay cycles when they used softer binder and reduced design air void; field performance data also verified these improvements. The same approach applies to mixes containing RAP as well, especially using rejuvenator and softer binder (West et al. 2017). McDaniel et al. recommended using softer binder to compensate the increased mixture stiffness and help improving fatigue cracking resistance (McDaniel et al. 2000). Li et al. demonstrated higher fracture resistance of RAP mixes at low temperature when softer binder was used (Li et al. 2008). Ozer et al. reported improved fatigue performance and increased fracture energy on RAS mixes (Ozer et al. 2013) and RAP mixes (Ozer et al. 2016) when using softer binder. For the two RAP/RAS mixes used by Johnson et al., softer grade virgin binder decreased mix stiffness both in the lab and in the field (Johnson et al. 2010). Apart from using softer binder and limiting the amount of recycled materials in the mix, Bennert et al. proposed using performance-based specification for high RAP content mixes (Bennert et al. 2014). Based on results from field trial and plant produced RAP mixes, they stated that using softer binder did not improve crack propagation resistance based on Texas overlay test and showed mixed results according to flexural fatigue test. The authors also reported that fatigue performance of one field project using RAP mixes far exceeded that of virgin mixes, when the performance-based specification was used. Judging by these results, using softer binder is clearly a viable approach to mitigate brittleness of high RAP content asphalt mixes.

Another popular method to reduce stiffness of recycled materials is to use rejuvenators. Mogawer et al. showed improved cracking performance of RAP/RAS mixes using rejuvenators tested through Texas overlay test (Mogawer et al. 2013). Later, Mogawer et al. investigated effect of rejuvenators via beam fatigue test and S-VECD theory (Mogawer et al. 2015). They reported that the effects of rejuvenator were material specific and strain level dependent. To standardize rejuvenator usage, Zhou et al. proposed a project-specific mix design method for rejuvenator/RAP/RAS mixes that considers balanced performance specifications (Zhou et al. 2015). The main steps include: 1) select rejuvenator type, 2) select rejuvenator dosage to meet binder specification and aging characteristics, and 3) verify rutting and cracking performance of the mix. Kaseer et al. recommended to optimize the rejuvenator dosage by matching the continuous performance grade of asphalt binder (Kaseer et al. 2018). Using this methodology, their mix showed equivalent or better cracking resistance compared with control mixes based on flexibility index, regardless of aging conditions.

Another challenge when using high content of recycled materials is selection of a proper mix design approach. Superpave® volumetric mix design is the most common method used in the United States for RAP mixes, including those with more than 20 percent RAP (Copeland 2011). McDaniel and Anderson provided a step by step mix design procedure for asphalt mixes containing RAP using Superpave®. They recommended performing a series of characterization evaluation on RAP materials before conducting volumetric evaluation (McDaniel and Anderson 2001). Similar recommendations were given by West et al., who stated that current standard for Superpave® mix design is applicable to high-RAP content mixes (West et al. 2013). The major addition to the typical mix design approach was evaluation of RAP binder performance grade and deciding the grade of the virgin binder grade.

7.2 OBJECTIVE

The objectives of this study were to evaluate fracture resistance of asphalt mixes with asphalt recycled materials, and the effectiveness of rejuvenator in improving cracking resistance of those mixes.

7.3 MATERIAL AND TEST PROGRAM

7.3.1 Materials and Specimen Preparation

The dolomite/limestone virgin aggregate, reclaimed asphalt pavement (RAP), and recycled asphalt shingles (RAS) used in this study came from local sources. Rejuvenator A is the primary source used in the study, as it was added into asphalt mixes by various dosage rates. It is made of 100 percent proprietary modified vegetable oil, with a viscosity of 122 mPa.s at 20°C.

Following ASTM D2172 and ASTM D5404 tests, residual binder content of RAP and RAS materials were found to be 6.4 and 21.0 percent, respectively. Five mixes were used as benchmarks: virgin mix, mix with 25 percent RAP, mix with 35 percent RAP, mix with 5 percent RAS, and mix with 25 percent RAP plus 5 percent RAS; numbers refer to percent weight of recycling material with respect to the weight of total mix. Final gradations for all mixes were close and presented in Figure 7-1. For virgin mixes, two difference virgin binders: PG58-28 and PG76-22, were used. The former was also applied to other mixes with recycled materials. Rejuvenators were only incorporated into mixes with 35 percent RAP by various dosage rates to investigate its effectiveness.

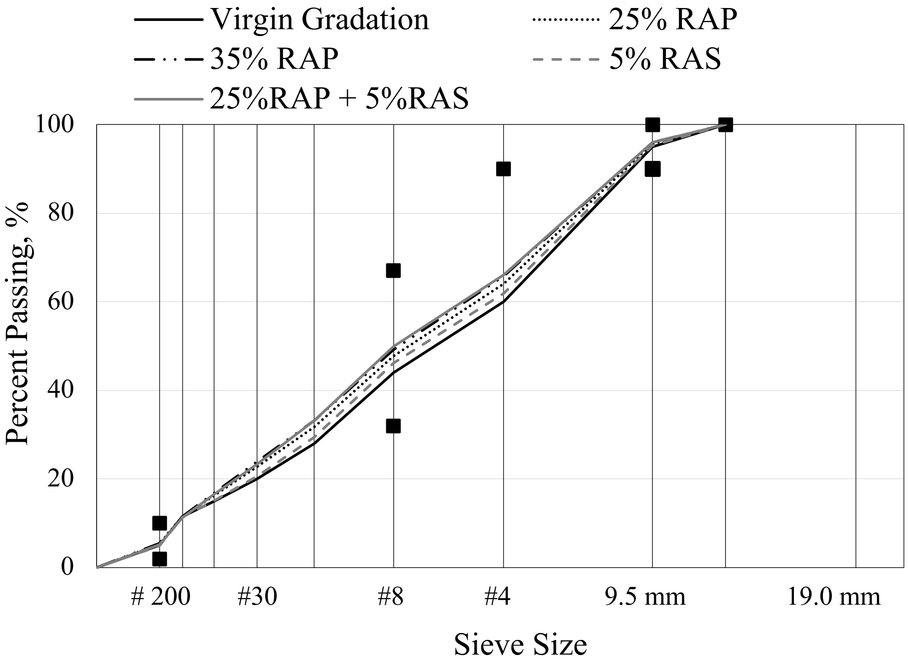


Figure 7-1. Gradation of benchmark mixes.

7.3.2 Test Program

The SCB test was again utilized to evaluate fracture properties of asphalt mixes at intermediate temperature. Specimen preparation and test procedures were strictly followed as introduced in chapter three. Although not the focus of this study, specimens were grouped into two subsets: short term oven aged (STOA) and long-term oven aged (LTOA). More detailed analysis regarding aging can be found in chapter nine.

7.4 Results and Analysis

7.4.1 Results on Benchmark Mixes

7.4.1.1 Volumetric Mix Design

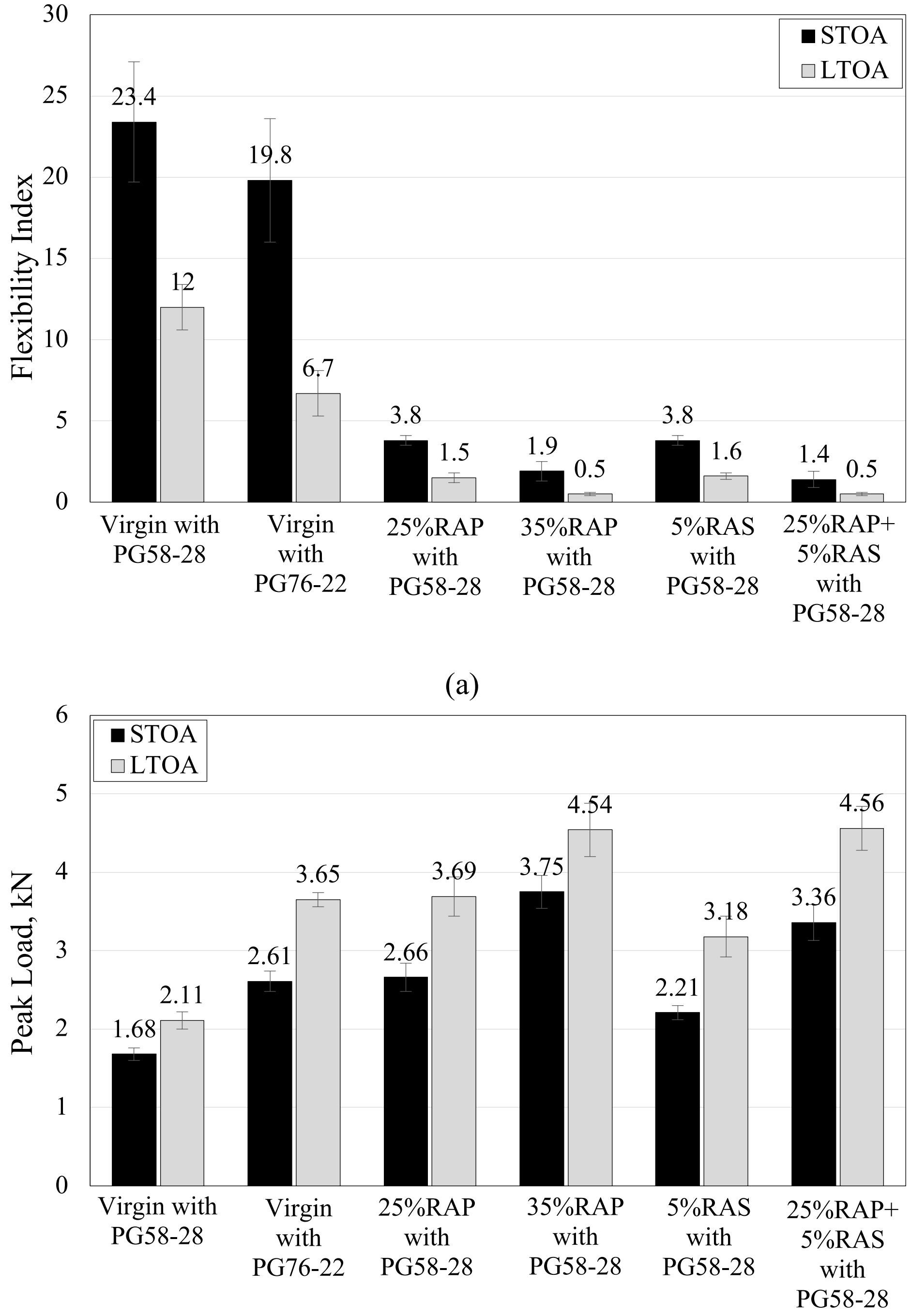
Design binder content to reach the target 4 percent air void and corresponding volumetric parameters from benchmark mixes are listed in Table 7-1. It must be noted that the design binder content here does not mean the total binder content, rather it refers to the added virgin binder content. It can be seen from the table that the mix with higher RAP content required less amount of virgin binder to achieve design air void of 4 percent. Obviously, this is expected due to higher amount of RAP binder contribution. In comparison, the mix with 100 percent virgin aggregate and the same gradation had a design binder content of 5.2 percent, which is higher compared with all other benchmark mixes. Incorporating recycled materials reduces design binder content, which is true both in terms of virgin binder and total binder content (assuming full blending). The voids filled with asphalt (VFA) of all mixes fall within target range for a design ESAL of 0.3 to 3.0 million. The mixes with RAP did not meet the minimum required level of voids in the mineral aggregate (VMA) requirement for a 9.5mm mix. Despite VMA difference, no further adjustment to gradation of RAP mixes was made so that the gradation of all mixes could be maintained close to one another.

Table 7-1. Mix Design Parameters of Benchmark Mixes.

Mix Type	Design Binder Content, %	VMA, %	Requirement on VMA, %	VFA, %	Requirement on VFA, %
25% RAP	3.75	14.9	> 15	74.0	65 - 78
35% RAP	2.60	14.5		72.5	
5% RAS	4.00	15.4		74.8	
5% RAS + 25% RAP	2.45	15.3		75.0	

7.4.1.2 SCB Test Results of Benchmark Mixes

Flexibility index and peak load values of all benchmark mixes from SCB tests are presented in Figure 7-2, error bar stands for one standard deviation.



(a)

(b)

Figure 7-2. (a) Flexibility index and (b) peak load plot of all benchmark mixes.

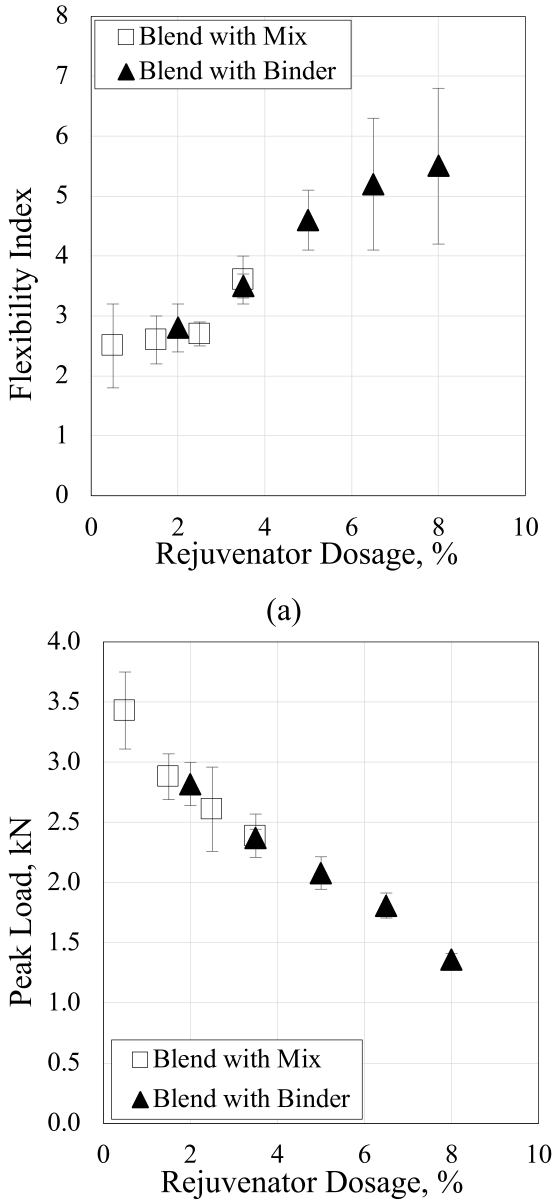
The first observation from Figure 8-2 is that LTOA drastically reduces flexibility index and increases peak load at the same time for all mixes. This observation is expected because LTOA stiffens asphalt mixes, makes them less compliant and thus more susceptible to cracking. This observation is blind to recycled materials, since it applies to all benchmark mixes. Specifically, in most cases, the flexibility index of LTOA mixes drops to less than half of that for the corresponding STOA mixes. Moreover, the peak load for LTOA mixes exceeds that of STOA mixes by almost 30 percent. Differences between flexibility indices of STOA and LTOA mixes as well as peak loads are statistically significant.

The second observation is that incorporating recycled materials reduces flexibility index significantly; while the impact on peak load is less severe, but noticeable. Using the same PG58-28 binder, adding 25 percent RAP decreases flexibility index of STOA mixes from 23.4 to 3.8. The reduction is even more significant as flexibility index drops to 1.9 when 35 percent RAP is used in the mix. Similar trend applies to LTOA mixes as well. Comparing mixes with 25 percent versus 35 percent RAP, and mixes with 5 percent RAS against 5 percent RAS plus 25 percent RAP, one can tell the additional stiffening effect of adding more recycled materials. The results indicate that the selected test protocol (20℃ and 5 mm/min) is capable of distinguishing among mixes with different contents of recycled materials. The peak load in the test also detects stiffening effect of adding more recycled materials. Results indicate increase in the peak load as the amount of recycled material is increased. Overall, flexibility index and peak load correlate negatively, which means that mixes with higher peak load deliver lower FI. All mixes in this study complied to this trend.

7.4.1.3 Effect of Blending Methods on the Effectiveness of Rejuvenator

Use of rejuvenators is a widely adopted approach to mitigate stiffness and brittleness of asphalt mixes with recycled materials. When incorporating a rejuvenator into asphalt mixes, two approaches are commonly used: blending it with binder first, or directly incorporating it into the blend of aggregates and binder. The first step of our investigation was to see if the blending method would impact the effectiveness of rejuvenators.

These two blending methods were applied to the mix with 35 percent RAP. Dosage rates of 0.5/1.5/2.5/3.5 percent of rejuvenator A were applied by directly blending with the mix (aggregate and virgin binder) in the bucket mixer. In parallel, dosage rates of 2/3.5/5/6.5/8 percent rejuvenator A were used when blending the rejuvenator into the virgin binder (PG 58-28). Such blending was carried for 2 minutes, before the blend was applied to the aggregate. The percentage refers to the rejuvenator mass as a percent of total binder mass. After STOA, all mixes were subjected to SCB tests. The test results for flexibility index and peak load are presented in Figure 7-3. Error bar stands for one standard deviation.



(a)

(b)

Figure 7-3. Rejuvenator blending methods comparison in (a) flexibility index and (b) peak load.

It is evident that higher rejuvenator content enhances flexibility index and reduces peak load. Increased flexibility index and reduced peak load fits expectations. From the results, it can also be inferred that there is not a significant difference between the results from the two blending methods. For the range of dosage rates applied, results from both methods follow the same relationship. At a dosage of 3.5 percent, both methods have statistically equivalent results.

7.4.1.4 Effect of Rejuvenator Dosage on Fracture Properties of Asphalt Mixes

Figure 7-4 demonstrates the effect of rejuvenator dosage rate on flexibility index and peak load of mixes with 35 percent RAP. These results are obtained from a combination of two blending methods and increasing the dosage rate at 1.5 percent intervals. Error bar stands for one standard deviation.

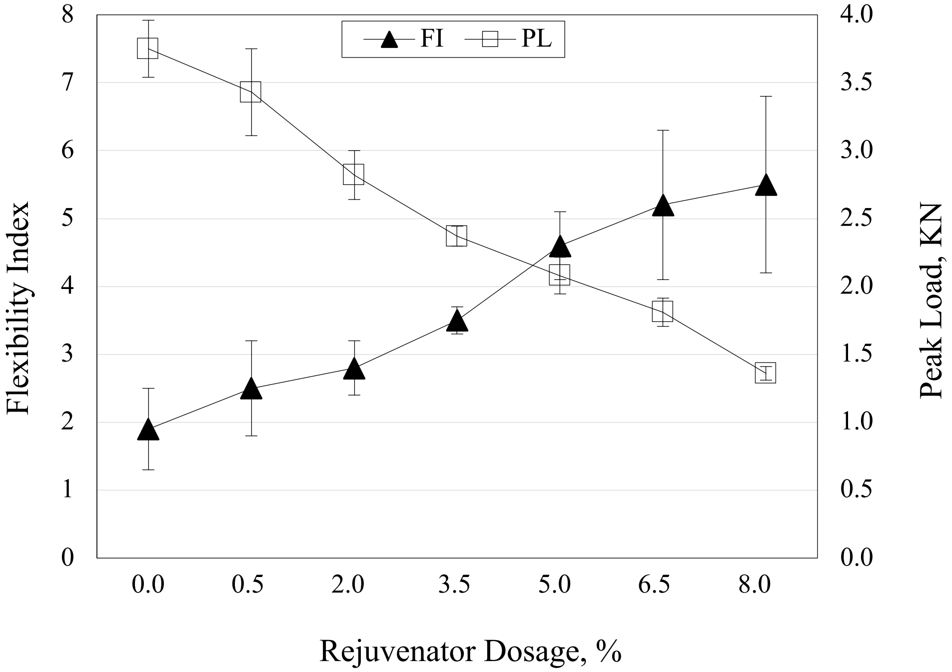


Figure 7-4. Effect of rejuvenator dosage on flexibility index and peak load.

The effect of rejuvenator is most dominant in the range of 2 to 5 percent, as it raises flexibility index at the highest percentage within this range. It is obvious that at high dosage rates, flexibility is increased but it comes at the cost of losing strength.

Figure 7-4 resembles a lot to the typical plots used for balanced mix design. When one variable (normally binder content) changes, two responding performance indices, normally a fatigue/fracture indicator and a rutting indicator, develop into opposite trends. Based on specified performance thresholds, one could determine an appropriate range of the changing variable that satisfies both performance thresholds for fatigue/fracture and rutting performance. In Figure 7-4, when rejuvenator dosage increases, flexibility index (fracture indicator) and peak load (strength indicator) develop into opposite trends. If peak load has the potential to serve as a rutting index, then the SCB test or similar monotonic fracture test could potentially be used as a stand-alone test for balanced mix design in lieu of two independent tests (fracture test and rutting test). As a matter of fact, such proposition is not new, Christensen and Bonaquist proposed to use IDT strength test to evaluate rut resistance of asphalt mixes and reported reasonable results (Christensen and Bonaquist 2002). Bennert et al. demonstrated good correlation between IDT strength and asphalt pavement analyzer (APA) rutting (Bennert et al. 2018). Of course, further work is needed to ensure the mix strength can be used as a good indicator of the mix rutting potential.

7.5 CONCLUSIONS AND RECOMMENDATIONS

An experimental study was undertaken to evaluate the fracture behavior of asphalt mixes containing RAS and high percent of RAP. Based on the presented test results and discussion, following conclusions can be drawn:

1. Adding RAP/RAS into asphalt mixes reduces design binder content. Specifically, incorporating recycled materials into asphalt mixes not only reduces virgin binder demand because of residual binder contribution, but also lowers total binder content compared with similarly structured virgin mixes.

2. Long term aging notably decreases flexibility index and increases peak load of asphalt mixes. Incorporating RAP/RAS materials also significantly lowers flexibility index and raises peak load values of the final mixes. Normally, mixes with higher peak load deliver lower flexibility index.
3. Blending methods (blend with binder first, or directly add into aggregate) do not affect effectiveness of rejuvenators. No statistical difference was discovered in the study when comparing results obtained using two blending methods.
4. Adding rejuvenator into RAP mixes linearly increases flexibility index. It also linearly decreases peak load (mix strength).

Further work is needed to establish performance threshold for mix fracture test. Threshold values should not be a single number. Rather, traffic, climatic, and most importantly, the structure of pavement should be accounted for when proposing such thresholds.

Chapter 8 OPTIMIZING REJUVENATOR CONTENT AND USING THE SEMI-CIRCULAR BEND TEST FOR BALANCED MIX DESIGN

The fracture behavior of asphalt mixes with asphalt recycled materials has been investigated and discussed in the last chapter. It was observed that introducing rejuvenators into such mixes mitigates the stiffening effect of aged and oxidized binder. In addition, flexibility index and peak load plot resembles the typical plot of a balanced mix design. Hence, a study was undertaken to verify such resemblance and explore the possibility of using one mechanical test instead of two for performance based balanced mix design.

8.1 INTRODUCTION AND BACKGROUND

One challenge when using high content of recycled materials is selection of a proper mix design approach. Superpave® volumetric mix design is the most common method used in the United States for RAP mixes, including those with more than 20 percent RAP (Copeland 2011). McDaniel and Anderson provided a step by step mix design procedure for asphalt mixes containing RAP using Superpave®. They recommended performing a series of characterization evaluation on RAP materials before conducting volumetric evaluation (McDaniel and Anderson 2001). Similar recommendations were given by West et al., who stated that current standard for Superpave® mix design is applicable to high-RAP content mixes (West et al. 2013). The major addition to the typical mix design approach was evaluation of RAP binder performance grade and deciding the grade of the virgin binder grade.

Asphalt mix design is rapidly moving beyond the conventional volumetric mix design, with inclusion of performance-based mix testing and balanced mix design. The idea of balanced mix design is to develop an optimal mix based on performance testing to satisfy both rutting and crack resistance. Various performance tests have been used for this purpose. For example, Zhou et al. used the Hamburg Wheel Tracking Device (HWTD) and Texas Overlay Tester (Zhou et al. 2007, 2012). As a result, it becomes extremely important to establish the pass/fail criteria to establish proper design. For example, Im et al. recommended a limit of 9.5 mm rut depth in HWTD in lieu of number of cycles to failure for balanced mix design (Im et al. 2016). Ozer et al. used the semi-circular bend (SCB) test and HWTD test for balanced mix design of RAP mixes and proposed 6 for flexibility index and 12.5 mm for rutting depth as performance thresholds (Ozer et al. 2016).

It was discussed that mixes with high RAP content tend to be brittle and prone to cracking, hence triggering the need to use soft binders and rejuvenators. However, the beneficial effect of rejuvenating or softening to encounter cracking should not come at the cost of making the mix susceptible to rutting and shoving. An important finding from recent work on balanced mix design of high RAP mixes has been the discrepancy between expected mix performance and the established binder grade (Kaseer et al. 2018, Xie et al. 2018). The problem has been that rejuvenators have been successfully used at the right proportion to reduce the binder stiffness and meet the target performance grade, but mixes with such binder could still fail mix performance specifications. This important observation raises concerns of using binder with rejuvenators that satisfy performance grade directly without any verification of mix acceptance through performance tests.

The objectives of this study were to optimize the mix design for asphalt mixes with recycled materials and rejuvenators via binder tests and mixture mechanical tests. It was not the purpose of this study to develop or evaluate the tests themselves. Rather, the authors were trying to compare performance test results from binder and mixes, locate discrepancies, and recommend viable adjustments. Note should be also made that low temperature cracking indices were not included in this study. The focus was only on mix and binder performance indicators at intermediate and high service temperatures. In addition, two parameters from the SCB test were compared with indicators from other performance tests to see whether such test can be used to serve the requirements at the two ends of the balanced mix design approach.

8.2 MATERIALS AND TEST PROGRAMS

8.2.1 Materials

Materials introduced in chapter seven were employed here again. In the first stage of study, only rejuvenator A was added in 0/2/5/8 (to total binder) percent. Unlike in the previous study, more than one type of rejuvenators was incorporated to the asphalt mixes to expand the database. Unlike rejuvenator A, rejuvenator B and C were added at a single dosage rate: the former is a bio-based rejuvenator agent that offers maltenes without aromatic contents; the latter is a hydrolene product made of aromatic petroleum oil. Rejuvenators were only incorporated into mixes with 35 percent RAP.

8.2.2 Hamburg Rutting Test

Apart from the SCB fracture test, Hamburg wheel tracking device (Figure 8-1) was also employed in this study as part of the balanced mix design to investigate the mix resistance to permanent deformation. AASHTO T 324 was followed strictly to conduct the test at 50℃ on two replicates (60 mm in height) for each mix.

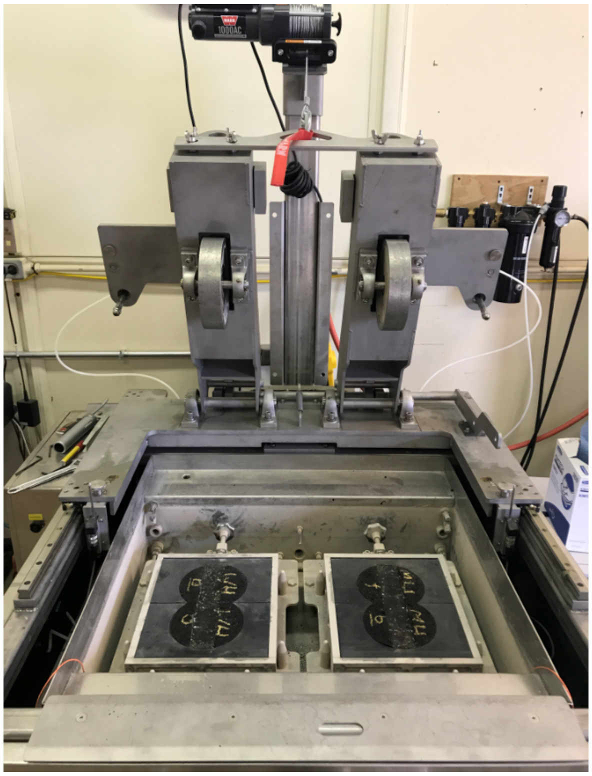


Figure 8-1. Hamburg Wheel Tracking Device used in the study.

8.2.3 Binder Test

For rheological testing of binder, extracted and recovered RAP and RAS binders were blended with virgin binder. Such blending was conducted at the same proportions in the asphalt mixes, assuming full blending. For example, the binder contribution from RAP in a mix with 35 percent RAP and residual binder content of 6.4% in the RAP was 2.24% of the mix mass (i.e. 35%×6.4%=2.24%). If the added virgin binder to the mix was 2.65%, the percentage of residual binder to total binder was then calculated as 2.24%/(2.24%+2.65%) = 45.8%. This ratio was held when blending the virgin and extracted binders.

Intermediate and high temperature properties of asphalt binder were obtained to pair with those of asphalt mixes. For the binders that were aged for 20 hours in the pressure aging vessel (PAV), Glover Rowe (G-R) damage parameter ($G^{*}\cdot\cos(\delta)^{2}/\sin\delta$) was used to evaluate their cracking characteristics. The G-R parameter considers binder stiffness and embrittlement and offers an indication of binder cracking resistance at intermediate temperature. Dynamic shear rheometer (DSR) tests were conducted on 4 mm diameter samples to determine their complex modulus (G*) and phase angle (δ) via frequency sweep tests (angular frequency range from 0.1 to 100Hz) at 5°C, 15°C, and 25°C under a peak to peak strain amplitude of 0.1 percent to ensure linear viscoelasticity. The Christensen-Anderson (CA) model (Christensen and Anderson 1992) was then used to construct the master curve for each binder, from which the G* and δ at 15°C and 0.005 rad/s was extrapolated to calculate the G-R parameter.

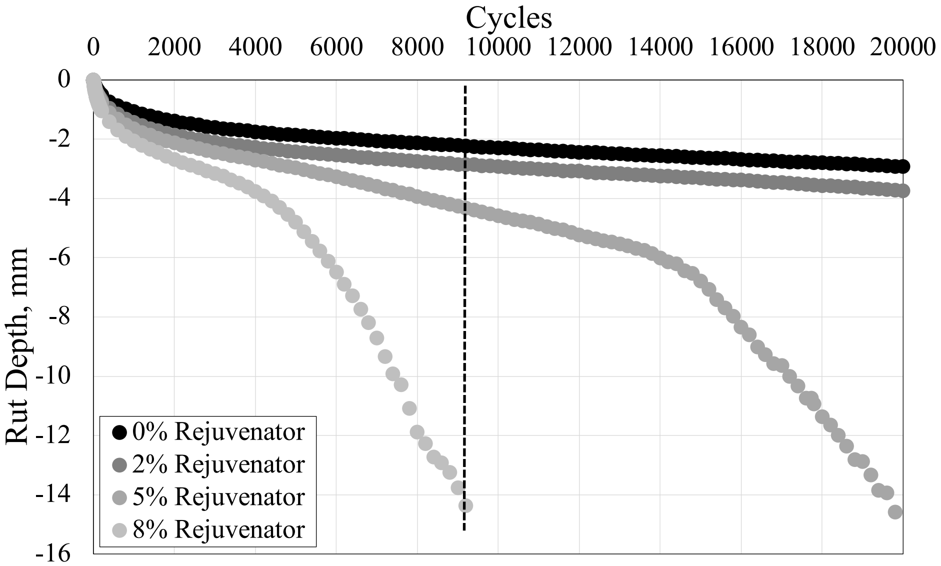
The calculated G-R parameter values were plotted in a black space diagram containing two separate G-R damage parameter curves–one with G-R parameter value at 180 kPa while the other at 450 kPa. It was proposed that binders with G-R values in the zone above the 450kPa curve are prone to significant cracking; while those in the zone below the 180kPa curve have not initiated cracking (Anderson et al. 2011, Rowe 2011). Apart from extrapolated G-R parameter, a separate direct measurement of shear modulus (G*) at 20°C using 10 rad/s and 1 percent strain was also conducted.

The Multiple Stress Creep Recovery (MSCR) test was performed to determine the non-recoverable creep compliance (J_{nr}) of binders under different strain levels. J_{nr} has shown to be an indicator of the resistance of an asphalt binder to permanent deformation under repeated load (AASHTO 2014). In this study, the MSCR test was carried out on rolling thin-file oven (RTFO) aged binders at 64°C. The loading was done in ten cycles at 100 Pa followed by ten cycles at 3,200 Pa. The average J_{nr} value was then calculated at the end of the one second creep plus nine second recovery time. J_{nr} is considered as an alternative to the $G^*/\sin\delta$ based specifications. The ability of J_{nr} to characterize the stress dependency of polymer modified and neat asphalt binders makes it a more discriminating specification parameter that is blind to modification (D'Angelo and Dongré 2009).

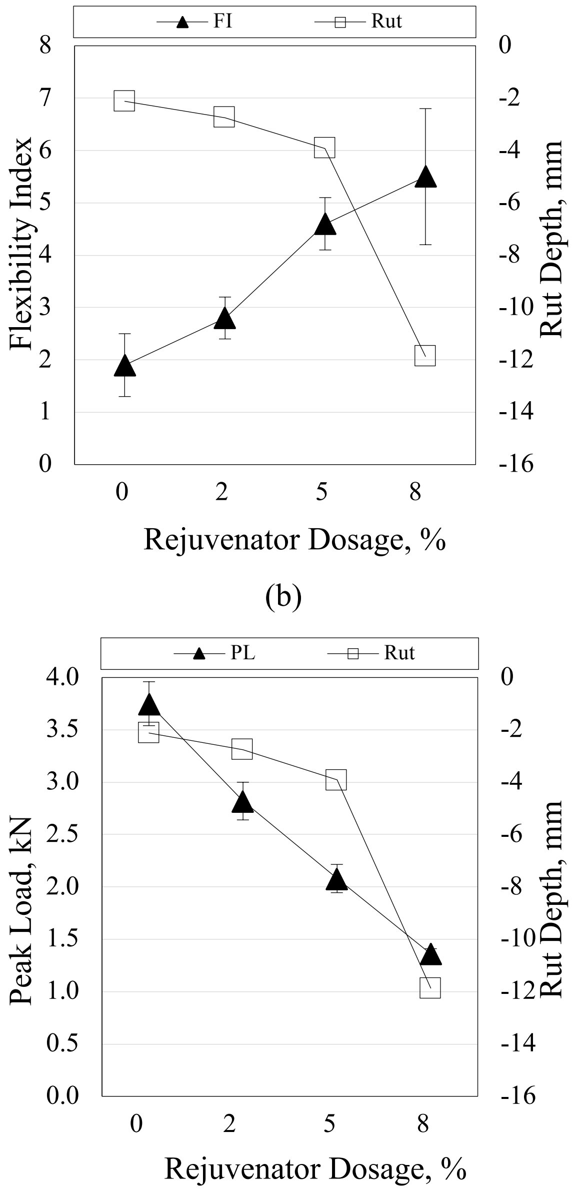
8.3 OPTIMIZE REJUVENATOR CONTENTS FOR HIGH RAP MIXES

8.3.1 Design Using SCB and HWTD

The 35 percent RAP mixes were prepared for HWTD testing at dosage rates of 0/2/5/8 percent using rejuvenator A. The test was conducted for 20,000 cycles at 50℃. Plots of rutting versus cycle number for all four mixes is shown in Figure 8-2a. The figure clearly indicates the adverse effect of increased rejuvenator content on rut depth. The mixes with no rejuvenator and 2 percent rejuvenator demonstrated excellent performance and rutting resistant. The poorest performance belongs to the mix with 8 percent rejuvenator, which failed at 9,000 cycles. For comparison, rut depth at 8,000 cycles of all four mixes were interpolated for further analysis. This cycle level was selected only because data points could be established for all four mixes.



(a)



(b)

(c)

Figure 8-2. (a) Hamburg wheel tracking test results, (b) Effect of rejuvenator dosage on flexibility index and rut depth at 8,000 cycles, and (c) Effect of rejuvenator dosage on peak load and rut depth at 8,000 cycles.

Figure 8-2b and 8-2c depict flexibility index and peak load versus rut depth at 8,000 cycles, respectively. Selecting this level of cycles here is not intended for mix design, rather it is selected to present the results as that is roughly the highest number of cycles for which rut depth is available for all rejuvenator contents. Note should be also taken that both FI and rut depth are reported for mixes which have been short term aged. In a more realistic scenario, one should compare FI of LTOA mixes with rut depth of STOA mixes. However, it is easier to prepare STOA mixes if a correlation could be established between FI of short term aged and long-term aged specimens (Chen and Solaimanian 2018). Figure 8-2 guides the user in deciding the dosage rate to gain adequate flexibility without sacrificing the rutting resistance.

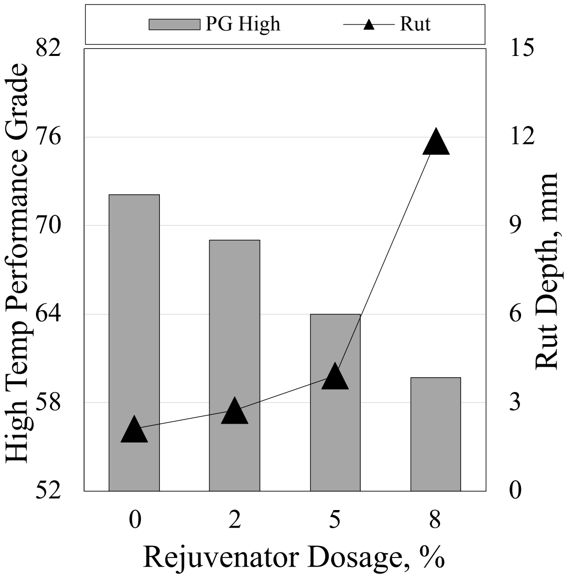
An interesting observation from Figure 8-2c is that the peak load follows linear relationship with the rejuvenator dosage, while rut depth exhibits an exponential relationship. To avoid excessive permanent deformation and to maximize benefits in improving fracture properties of mixes, a minimum threshold value for peak load and for flexibility index should be used. Further investigation is required to establish reliable threshold values. It is worth noting that the above analysis was based on mixes with 35 percent RAP. Clearly, at lower RAP content, the demand for rejuvenator is reduced.

8.4 Comparing SCB Test Parameters to Parameters from Other Performance Tests

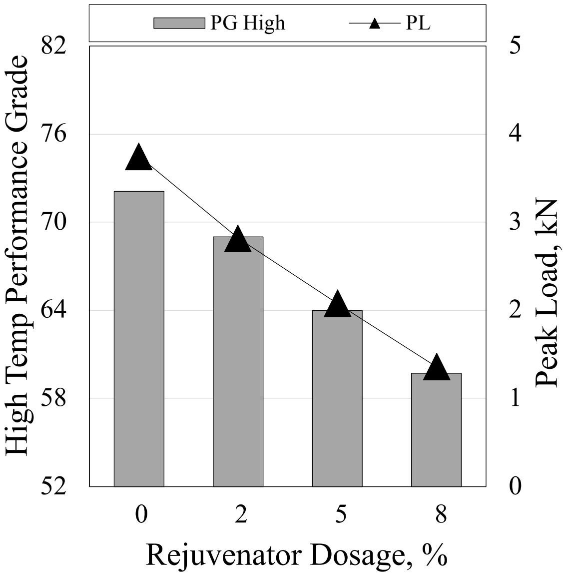
8.4.1 High Temperature Indices

One approach in optimization of the rejuvenator content is through determination of the binder high, intermediate, and low temperature grades. Once the amount of RAP is established (for example, 35 percent), and the target grade is selected (for example, PG 64-22), then work will be done to finalize performance grade of the virgin binder and the rejuvenator content (if any). Two indices were selected to study the effect of rejuvenator dosage on high temperature performance of binders: high temperature performance grade and non-recoverable creep compliance (J_{nr}). Tests were carried out on rolling thin-film oven (RTFO) aged binders, to correspond with the mixes that were consequently all short-term oven aged (STOA).

High temperature continuous grade of asphalt binders versus rut depth at 8,000 cycles from the Hamburg rutting test and peak load values from SCB test are presented in Figure 8-3. Using 45 percent RAP binder replacement (based on using 35 percent RAP materials as percent of total mix by mass) changes the high temperature grade of PG58-28 virgin binder from 58 to 70, i.e. a two-grade jump. However, adding 5 and 8 percent of rejuvenator (by the total binder mass) brings down performance grade by one and two grades, respectively.



(a)



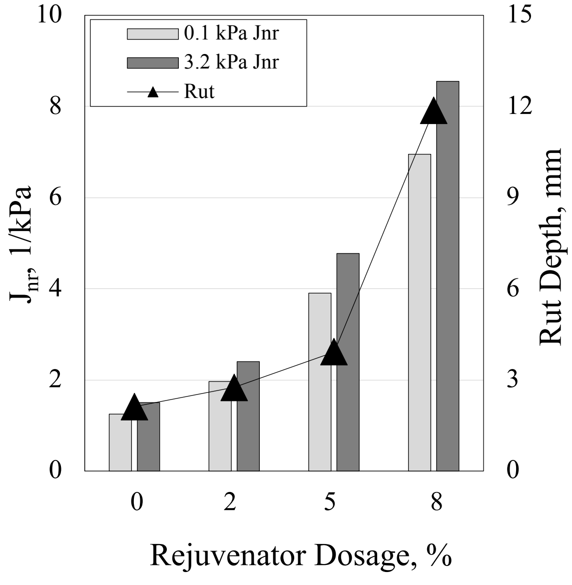
(b)

Figure 8-3. Effect of rejuvenator dosage on (a) high temperature PG and rut depth, and (b) high temperature PG and SCB peak load.

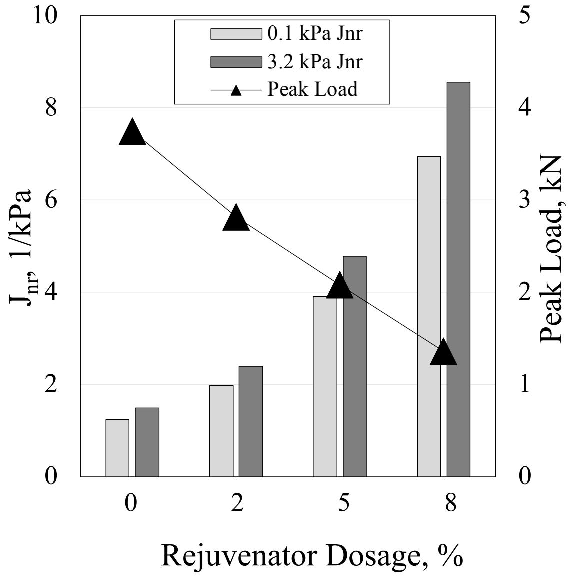
As expected, Figure 8-3 indicates higher rut resistance and higher peak load as a higher PG binder is used in the mix. The correlation for the peak load (strength) is very strong and almost linear.

At 8 percent rejuvenator level, the 35 percent RAP mix showed lower strength than the one with only virgin binder (1.36 kN vs. 1.68 kN). The binder of this mix (PG 58-28 virgin binder, RAP binder, and rejuvenator) had almost a similar continuous performance grade to the virgin binder (59.7 vs. 60.8). However, the neat virgin binder had twice the shear modulus of the modified binder at 20°C. Considering the test results at both high and intermediate temperatures indicates the challenge in optimizing the dosage rate of the rejuvenator to balance the mix performance from both cracking and rutting points of view.

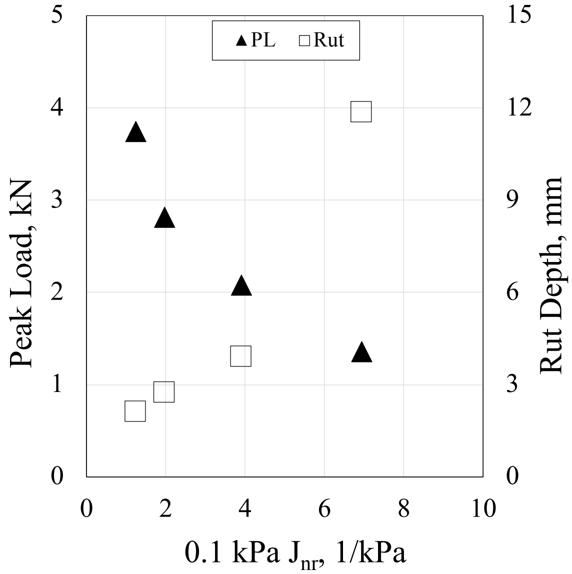
In addition to the binder continuous performance grade, the binder creep compliance J_{nr} was also used to evaluate the effect of rejuvenators on the binder behavior. The creep compliance from Multiple Stress Creep Recovery (MSCR) tests on binders, as well as the wheel tracking rut depth at 8,000 cycles are plotted as a function of rejuvenator dosage rate in Figure8-4a. Similarly, SCB peak load, along with J_{nr} is demonstrated in Figure 8-4b. J_{nr} values of both load levels are presented side by side. Higher J_{nr} values are associated with more non-recoverable deformation, implying higher rutting potential.



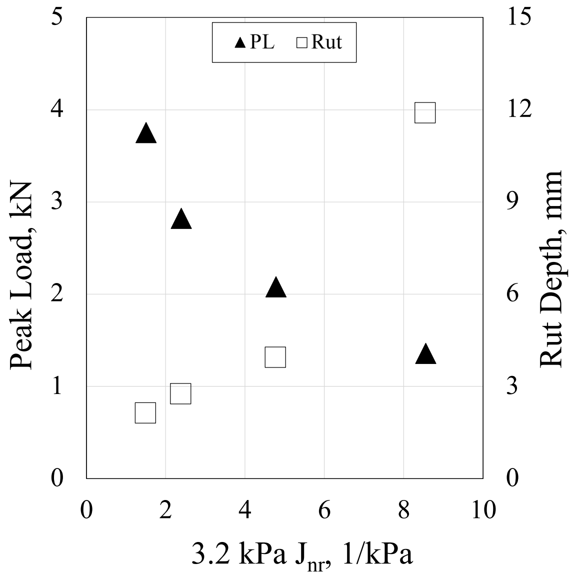
(a)


10
8
6
4
2
0
5
4
3
2
1
0
0.1 kPa Jnr
3.2 kPa Jnr
Peak Load
J_{nr}, 1/kPa
Peak Load, kN
0
2
5
8
Rejuvenator Dosage, %

(b)


5
4
3
2
1
0
15
12
9
6
3
0
PL
Rut
Peak Load, kN
Rut Depth, mm
0
2
4
6
8
10
0.1 kPa J_{nr}, 1/kPa

(c)



(d)

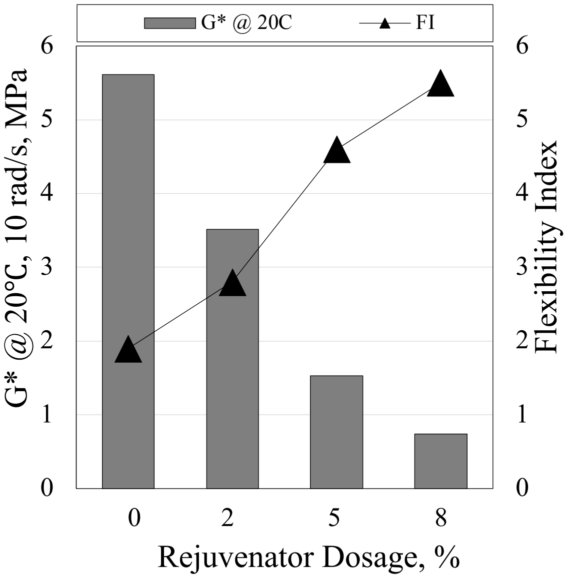
Figure 8-4. Effect of rejuvenator dosage on (a) non-recoverable creep compliance and rut depth, (b) non-recoverable creep compliance and SCB peak load, (c) non-recoverable creep compliance at 0.1 kPa versus peak load and rut depth, and (d) non-recoverable creep compliance at 3.2 kPa versus peak load and rut depth.

Strong correlation is observed between Hamburg rut depth and J_{nr} (Figure 8-4a and 8-4b). It is also interesting to note that the abrupt increase in J_{nr} strongly matches the abrupt increase in rutting from the HWT test when rejuvenator dosage increases from 5 to 8 percent (Figure 8-4a), regardless of stress level. The figure also shows that peak load and Jnr have a strong negative correlation.

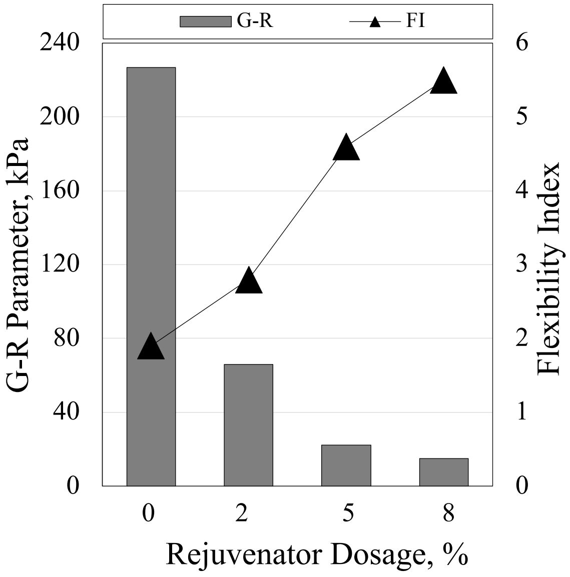
The preceding results indicate the strong correlation between the binder parameters (i.e. continuous grade and J_{nr}) with mix performance (i.e. SCB peak load and HWT rut depth). The SCB peak load (strength) is also a strong indicator of the mix rut resistance from HWT. These results are very encouraging and provide the base for developing a balanced mix design approach using mixture and binder test data used in this research.

8.4.2 Intermediate Temperature Cracking Indices

The binder parameters discussed in the previous section were related to the mix rutting at high temperature. Analysis of binder data presented in this section is associated with the mix cracking at intermediate temperature. Binder testing for this purpose was conducted at 20°C to match the SCB temperature used with mixture testing. The Glower-Rower (G-R) parameter and binder shear modulus (G*) at 20℃ and 10 rad/s are plotted against flexibility index (Figure 8-5). Shear modulus presented in Figure 8-5a was obtained from testing RTFO aged binders, while G-R parameter presented in Figure 8-5b was achieved from testing PAV aged binders. In both figures, flexibility index is from tests on short term aged mix.



(a)



(b)

Figure 8-5. Effect of rejuvenator dosage on (a) binder modulus at 20°C and flexibility index, and (b) Glover-Rowe parameter and flexibility index.

G* at 20°C shows a linear decreasing trend when rejuvenator dosage increases from 0 to 8 percent. Similarly, G-R parameter also decreases with the increase in the rejuvenator content. The effectiveness of rejuvenator on G-R parameter is most significant with the first introduction of rejuvenator into the binder (from zero percent to 2 percent as shown in Figure 8-5b). The effect fades away when the dosage rate exceeds 5 percent, as the decrease in G-R parameter beyond this level is marginal. Assuming a G-R value of 180 kPa, as the point of cracking onset, the corresponding FI value should be between 2 to 3. Although performance threshold for flexibility index is not available yet, a value of 2 to 3 is relatively low compared with virgin mixes with similar gradation, volumetric properties, and aging history. The results imply that discrepancies exist when comparing intermediate temperature cracking indices of binder and those of mixtures.

The black space diagram of the above four binders together with a virgin binder (PG 58-28) are shown in Figure 8-6. The diagram indicates that adding RAP binder into virgin binder (45 percent binder replacement) makes the blended binder stiffer and more brittle, as the data point moves towards the upper left zone of the diagram and crosses cracking onset line. However, using rejuvenator mitigates this stiffening effect of the RAP binder.

When rejuvenator was introduced into blended binder, even at the small dosage at 2 percent, the resulting binder escaped from the potential crack zone back to crack free zone. Such mitigation effect escalated when higher rejuvenator dosage was used. Specifically, the virgin binder is between the ones with 2 and 5 percent rejuvenator in this respect. It seems from this data that using close to 3 percent rejuvenator in the 55/45 blend of virgin binder/RAP binder could bring back the crack resistance performance of the blended binder to the level of virgin binder based on G-R parameter.

However, this observation is not extendable to the mix performance which was presented previously. Even at 8 percent rejuvenator content, the flexibility index of the RAP mix is significantly different from that of the virgin mix (flexibility index of 5.5 versus 23.4), given that two corresponding binders have similar continuous high temperature performance grade and mixes have similar volumetric properties. This discrepancy between optimum rejuvenator content from binder test data versus that from mix test data needs special attention. Adding lower percentage of rejuvenator could satisfy existing binder performance criteria but most probably will be inadequate to provide adequate flexibility to the mix to resist cracking.

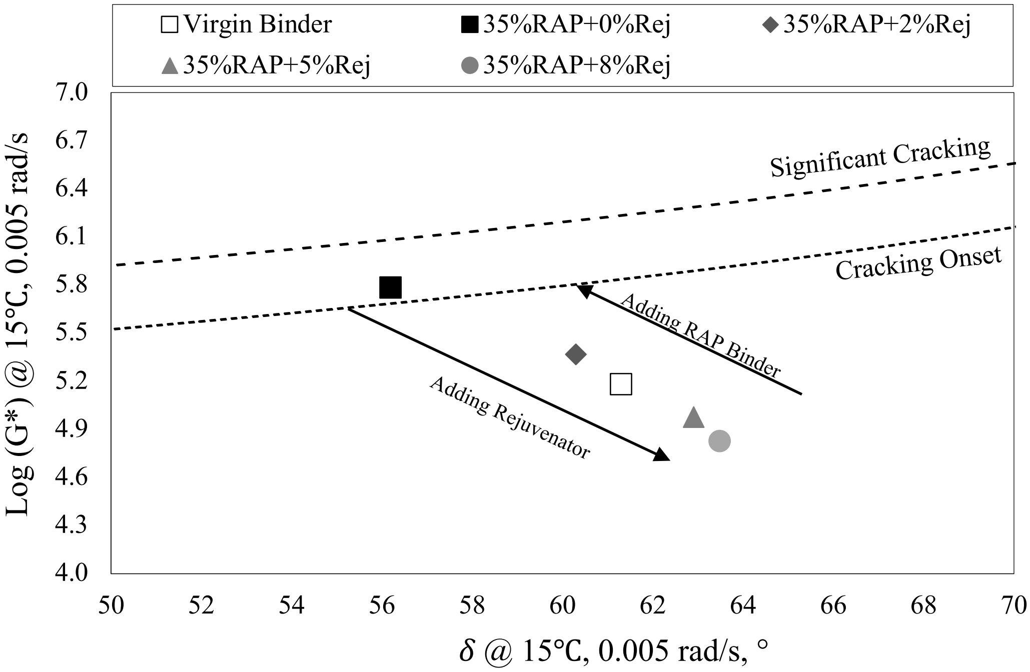


Figure 8-6. Black space diagram of binders with and without rejuvenators.

8.4.3 Discrepancy Verification on Intermediate Temperature Cracking Indices

The results of this study indicate that high temperature performance of binder (performance grade and J_{nr}) agrees with that of the mix (peak load and rut depth); but intermediate temperature properties of binder as indicator of cracking potential do not match the performance indices from mix testing. This conclusion is reached based on the fact that currently proposed level of G-R parameter to indicate crack initiation (i.e., 180 KPa) corresponds to a very low level of flexibility index. This discrepancy may be the result of incomplete blending of the RAP binder and virgin binder, an effect that cannot be evaluated through purely a binder test.

The proceeding speculations were investigated further with expanded material sources. Because of the strong correlation between high temperature performance indices between binder and mix, i.e., peak load and rut depth versus performance grade and Jnr value, only intermediate temperature cracking indices: flexibility index of asphalt mixes, G* at 20℃, and G-R parameter of asphalt binders were employed for further analysis. Aside from mixes with 35 percent RAP and multiple rejuvenator contents, the following mixes were added to enrich the database:

1. benchmark mixes introduced in section 4.1.2;
2. mixes with 35 percent RAP and other rejuvenator contents shown in section 4.1.4;
3. virgin mix (PG 64-22); and
4. mixes with 35 percent RAP and rejuvenator B and C (both at 8 percent).

All mixes were prepared using their design binder content and had 5.5 ± 0.5 percent air voids, consistent with previous presented mixtures. Binders were also prepared following procedures described before.

G* values at 20℃ versus flexibility index are presented in Figure 8-7. Results from STOA mixes with corresponding RTFO aged binders are shown is hollow labels, while data from

LTOA mixes and corresponding PAV aged binders are plotted in solid labels. For each aging group (LTOA and STOA), three categories of mixes are presented in Figure 8-7. The mixes with purely neat binder are referred to as "Virgin Binder". The mixes containing various contents of RAP and RAS are referred to "RAP/RAS Binder". Finally, the mixes with 35 percent RAP that modified with various dosage rates and sources of rejuvenator are referred to as "Rejuvenator".

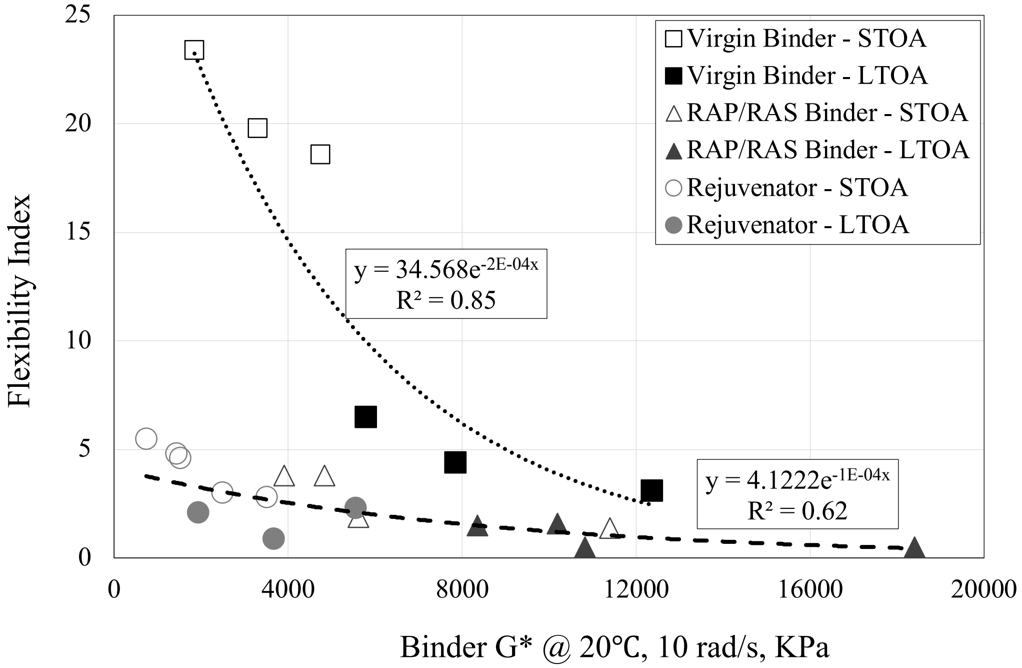


Figure 8-7. Binder G* at 20°C versus flexibility index.

The first observation is that LTOA notably reduces flexibility index. Meanwhile PAV aging raises binder modulus at intermediate temperature. As a result, aging migrates data points toward the lower right corner of the spectrum. The second observation is that adding recycled materials into asphalt mixes significantly reduces flexibility index. For example, LTOA virgin mixes have similar flexibility index values as the STOA ones with recycled materials, even at the highest rejuvenator dosage at 8 percent. In addition, recycled materials also increase binder moduli. Hence, incorporating recycled materials also migrates data points toward the lower right corner. Adding rejuvenator recovers binder shear modulus, bringing that to the level of virgin binder.

Mixes with and without recycled materials seem to follow two different patterns (two regression lines) in Figure 8-7. There are two speculations for this observation. The first is that aside from stiff RAP/RAS binder, incomplete blending of virgin binder and RAP binder may also have an adverse effect on fracture performance of the final mix. The second is that all mixes were tested at their design binder content. Mix design results presented previously prove that asphalt mixes with RAP/RAS materials have lower design binder content, both in terms of virgin and total binder content. There is strong evidence from past research that lower binder content leads to lower flexibility index under similar aggregate gradations (Chen and Solaimanian 2018). As a result, RAP/RAS mixes tend to have lower flexibility indices because of low binder content. However, even at the same binder content, the improvement on flexibility index of RAP/RAS mixes would be minor, and still significantly lower than that of virgin mixes at the same aging condition.

To complement the research with binder results, the G-R parameter was plotted versus flexibility index (Figure 8-8). G-R parameters were obtained on PAV aged binders, hence, mix results came from LTOA mixes.

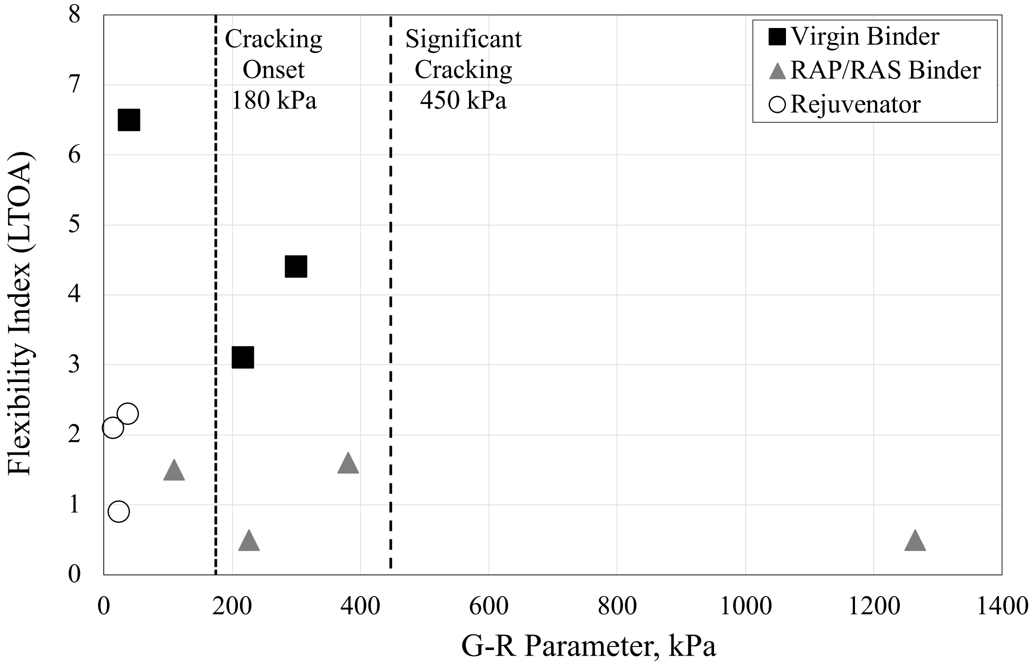


Figure 8-8. Glover-Rowe parameter versus flexibility index.

Binders with rejuvenator deliver the value of G-R parameter below cracking onset, in the meantime their corresponding mixes have extremely low flexibility index values. These results indicate that based on FI, the mixes with rejuvenators are heavily susceptible to cracking, but based on G-R, they are acceptable. Such discrepancy can be the result of several factors. For example, the blending of the virgin binder and RAP binder does not produce one fully blended phase, hence reducing flexibility. The observed difference could also be an indication that current binder aging (RTFO + 20 hours PAV) protocol may not be severe enough to age binders with rejuvenators, and not matching the long-term mix aging as used in this research.

Black space diagram of all binders (20 hours PAV aged) is shown in Figure 8-9. The results on extracted RAP binder (no laboratory aging) is also included for comparison. It can be seen that adding rejuvenator significantly improves binder fracture performance as it moves data points away from cracking onset line. It is true for all rejuvenator sources. The graph also indicates that G-R parameter for PG 64-22 and PG 76-22 crosses the cracking onset line in spite of the fact that their corresponding mix FI is higher than that of the mixes with rejuvenator.

This is another indication of discrepancy between binder and mix fracture performance indices at intermediate temperature.

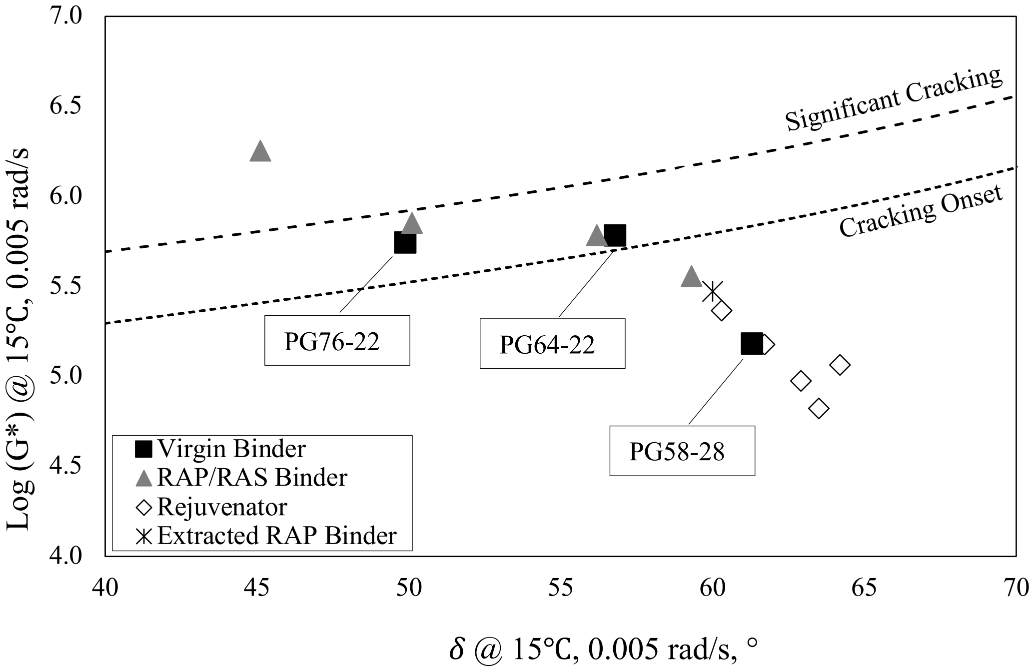


Figure 8-9. Black space diagram of all binders.

8.5 CONCLUSIONS AND RECOMMENDATIONS

An experimental study was undertaken to optimize the rejuvenator contents for high RAP asphalt mixes, and explore the possibility of using the SCB test to satisfy requirements of the balanced mixture design of asphalt mixes containing RAS and high percent of RAP. Both binder characterization tests and mixture mechanical tests were performed, and results were cross compared and analyzed collectively. Based on the presented test results and discussion, following findings can be drawn:

1. Adding rejuvenator into RAP mixes linearly increases flexibility index. It also linearly decreases peak load (mix strength). In addition, it exponentially increases rut depth in HWT test. The agreement between peak load of SCB test and rut depth in HWT test implies the possibility of using a standalone monotonic fracture test for balanced mix design. Such test can be used to evaluate intermediate temperature fracture performance and high temperature rutting performance of asphalt mixes through a single test-setup.

2. Adding RAP binder into virgin binder increases high temperature performance grade of the blended binder; and incorporating rejuvenator into such binder decreases high temperature performance grade. Adding rejuvenator also significantly raises non-recoverable creep compliance of the final binder, which translates into less resistance to permanent deformation. High temperature performance indices of binder and mixes agree with each other well.
3. Incorporating rejuvenator into binder that contains residual RAP/RAS binder significantly decreases shear modulus and G-R parameter value at intermediate temperature, which implies better crack resistance of the binder. Although adding rejuvenator also enhances flexibility index of stiff RAP/RAS containing asphalt mixes, the impact is not as dramatic as that observed in the binder. There exists some discrepancy between intermediate temperature fracture indices of binder and mixes.

Further work is needed to establish performance threshold for mix fracture test. Threshold values should not be a single number. Rather, traffic, climatic, and most importantly, the structure of pavement should be accounted for when proposing such thresholds. Additionally, existing performance thresholds from binder and mixture tests at intermediate temperature need re-evaluation to reach agreement.

Chapter 9 EFFECT OF LONG-TERM AGING ON FRACTURE RESISTANCE OF ASPHALT MIXTURES

In previous chapters, fracture resistance of asphalt mixture with different material variables, crumb rubber modifiers, and recycled materials were evaluated using the proposed SCB fracture test protocol. In this chapter, instead of focusing on one particular mixture, the effect of long term aging, i.e., the oxidation applied to asphalt paving materials during years of service, is investigated using all the data collected before, with expanded data collected from mixtures prepared in multiple laboratories and plants.

9.1 INTRODUCTION

Oxidative aging is a major driving force causing distress in asphalt mixes and an important contributor to the loss of serviceability of asphalt pavement. Aging results in significant changes in rheological properties of asphalt binder during construction and service life of the pavement.

Short-term aging occurs during production and construction as the temperature is high and asphalt coating on the aggregate is thin. It is normally simulated in the laboratory by conditioning loose mixes in an oven for two to four hours at elevated temperatures right after mixing, and is referred to as short-term oven aging (STOA). Long-term aging, on the other hand, describes the slower process of change in asphalt properties due to oxidation and radiation during service period of the pavement. Aging, as a result of years of service in the field, could be simulated in the laboratory by placing compacted asphalt specimens or un-compacted loose mixes in an oven for an extended period of time, normally at a lower temperature than STOA. Such process is often designated as long-term oven aging (LTOA). Aging causes asphalt mixes to stiffen and become brittle, leading to a high potential for cracking (Elwardany et al. 2017, Kim et al. 2018).

Numerous studies have shown the effect of LTOA or equivalent aging protocols on fracture and fatigue properties of asphalt mixes. Using conventional asphalt mixes and crumb rubber modified (CRM) asphalt mixes prepared with both wet and dry process, Liang and Lee reported increased indirect tensile strength of asphalt mixes after LTOA (1996). Harvey and Tsai reported increased initial stiffness of asphalt mixes because of LTOA (1997). The authors claimed that initial stiffness rises with the increase of aging duration. However, the authors also stated that increase in initial stiffness due to LTOA was not always detrimental as indicated through simulation. The reason for such observation was attributed to other parameters affecting performance of long-term aged mixes, such as the type of asphalt and aggregate, pavement structure, and air void. Raad et al. performed controlled-strain beam fatigue tests on specimens obtained from a 10-year-old pavement section (2001). Comparing to results of original (un-aged) mixes, it was observed that field aging reduced fatigue properties of both asphalt mixes used in the study, in the meantime raised initial stiffness at intermediate temperature. Using disk-shaped compact tension (DCT) test, Brahams et al. reported fracture energy changes of asphalt mixes with different aging durations (2009). They demonstrated that fracture energy rises to a peak value at 6 to 8 hours of aging, then decreases with the increase of oven aging time at 135℃. Not only did peak load rise with the increase of aging time, the post peak-load softening curve shifted at the same time, both of which indicated a more brittle and less ductile mix. Based on their test results, however, the difference of fracture energy between mixes right after compaction and mixes after six years of field aging was not significant. Islam and Tarefder employed four-point bending beam fatigue test to study the effect of different aging protocols on fatigue property and stiffness behavior of asphalt mixes (2015). Similar to previous studies, the authors reported increased stiffness of asphalt mixes under different LTOA protocols. Mogawer et al. investigated the effect of aging and rejuvenator on fatigue and cracking resistance of asphalt mixes. The dynamic modulus ratio of LTOA and STOA samples revealed significant stiffening of mixes, especially at high temperature. Results of cyclic fatigue tests were strain level dependent; while results of fracture based semi-circular bend (SCB) test showed decreased critical strain energy release rate for all mixes except one after LTOA (Mogawer et al. 2017). Bonaquist et al. 2017 reported reduced flexibility index (FI) after LTOA using the SCB test (2017). Overall, most studies reported increased stiffness and reduced fracture resistance or fatigue life after LTOA or field aging.

To accurately predict long term pavement performance, laboratory performance tests need to be performed on asphalt mixtures which have been exposed to long term aging. Elwardany et al. (Elwardany et al. 2017) proposed that laboratory aging should be performed on loose mixes instead of compacted specimens as required in AASHTO R30 to reduce oxidation gradient. They also suggested the aging temperature should not exceed 100℃ to reduce the potential of altering oxidation mechanisms. Braham et al. (Braham et al. 2009) investigated low temperature fracture properties of asphalt mixtures using the disk-shaped compact tension (DCT) test. The authors noticed that the AASHTO R30 protocol did not age the material as severely as field exposure does. With the continuous increase of aging time at 135℃, the fracture energy increased till it reached a peak value after almost 6 hours of aging, then started to decrease. At 48 hours of aging at 135℃, laboratory aging matched the field aging in terms of dynamic modulus.

In summary, most reported results from mechanical tests on LTOA mixes have shown reduced fracture resistance and fatigue properties due to increase in mix stiffness and reduction in mix ductility compared with STOA mixes. However, existing data were limited to finite material types, and comparisons using newly developed test protocols and performance indices are lacking. Such comparison is important as decision needs to be made by mix designers as to what aging level to apply when performing mechanical test, and what countermeasures can be applied to minimize detrimental effect of LTOA on fracture resistance and fatigue properties of asphalt mixes.

9.2 OBJECTIVE

The overall objective of the chapter was to determine how the fracture properties of LTOA mixes compare with those from STOA mixes using the SCB test. The following tasks were accomplished to achieve the objective of the study: 1) Evaluate impact of LTOA on performance indices from SCB test; 2) investigate relationship between fracture performance indices of STOA mixes with those of LTOA mixes; 3) investigate sensitivity of material variables to LTOA; and 4) investigate sensitivity of fracture properties of asphalt mixes with recycled materials to LTOA.

9.3 MATERIALS AND TEST PROGRAM

9.3.1 Materials

Several material types and sources were included in this study to minimize the bias caused by utilizing a single source of material. Among all mixes, one was selected as the core material, and it was used for parametric study and prepared in the central laboratory, simply referred to as the single source mix in this chapter. It consists of all materials studies and analyzed in previous chapters. The remaining mixes were prepared in more than 15 different laboratories. The purpose of including such a large number of material sources was to develop a reasonable data range for the results covering a wide range of typical mixes that are used in actual construction. These mixes are simply referred to as multiple source mixes in this paper.

For the single source mixes prepared in the central laboratory, different sets of specimens were prepared to address specific goals. Specifically, virgin mixes included three difference binder stiffness (PG58-28, PG64-22, and PG76-22), four different air voids (2, 4, 7, and 10 percent), and four binder contents (design, design±0.5 percent, and design+1.0 percent). Crumb rubber modified (CRM) mixes consisted of one virgin binder, one CRM content, and four different gradations. In addition, mixes with 25 and 35 percent RAP, 5 percent recycled asphalt shingles (RAS), and 25 percent RAP with 5 percent RAS (all percentage by total mass) were included. Finally, two sets of specimens were prepared to include the effect of rejuvenators on RAP mixes when long-term aged.

Specimens from multiple source laboratories also covered a wide range of variables. These specimens included two different binder grades (PG64-22 and PG76-22), binder contents ranging from 4.7 to 6.6 percent, four RAP contents ranging from 0 to 20 percent, and multiple aggregate types, sources, and gradations.

9.3.2 Material Processing, Specimen Preparation, and Test Program

Specimens manufactured using single source mixes were batched, mixed, aged, compacted, cut, prepared, and tested all in the central lab. As for specimens manufactured using multiple source mixes, they were first mixed, aged, and compacted in various labs and plants, then carefully sealed and shipped to the central lab. Finally, they were cut, prepared, and tested at the central lab following the same process used for the single source mixes. The single source specimens were prepared in pairs, one set going through STOA and the other set through LTOA. They only differed in aging protocols. The same applies to multiple source mixes as well.

For STOA specimens, immediately after mixing at 150℃, they were conditioned at 150℃ for two hours before compaction. This temperature was selected for all mixes to provide a consistent conditioning temperature regardless of the binder grade. For LTOA specimens, the loose mixtures were first conditioned at 150℃ for two hours after mixing, then followed by 120 hours of long-term aging at 85℃. Finally, the loose mix was conditioned at 150℃ for two hours before compaction. The long-term aging was conducted on loose mixtures rather than compacted specimens to eliminate the effect of aging gradient on test results. The recent work in National Cooperative Highway Research Program (Kim et al. 2018) promotes long-term aging of loose mixtures instead of compacted specimens. Temperature of 85℃ was selected based on AASHTO R 30 conditioning protocol. During the 120 hours conditioning process, loose mixes were stirred twice to ensure a more uniform aging. A Superpave® Gyratory Compactor was utilized to compact all specimen at 150℃ to a fixed target height of 150 mm.

The following specimen preparation process such as cutting, drying, etc., were followed by protocols used in chapter three.

9.4 RESULTS AND ANALYSIS

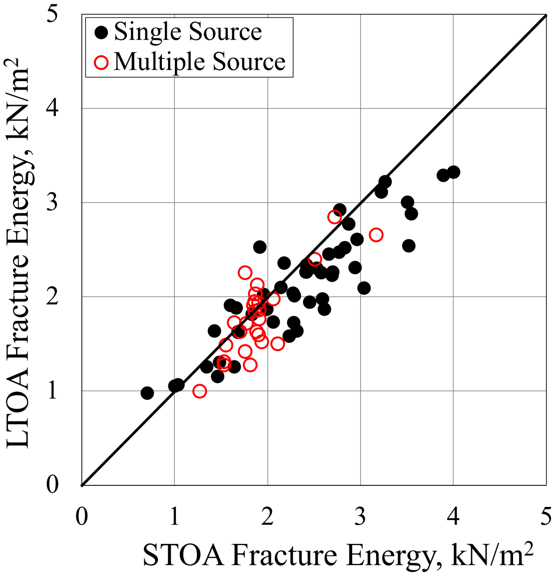
As introduced in the previous section, there are two sources of materials: single source mixes, which were mixed and prepared in the central lab, consisting of 49 different mixtures; and multiple source mixes, which were mixed and prepared in 15 difference laboratories and plants, consisting of 26 different mixtures.

The combined results from these two sources will be presented first to: 1) demonstrate the relationship of performance indicators between STOA and LTOA mixes, and 2) showcase and compare the data quality of each performance indicator from both sources. The data quality here refers to the variation of the overall data distribution, or bias and skewness, if there are any. Results presented in the following sections, namely, effect of LTOA on material variables and recycled materials, were solely from single source mixes.

9.4.1 Comparison of Performance Indices as Affected by Aging Level

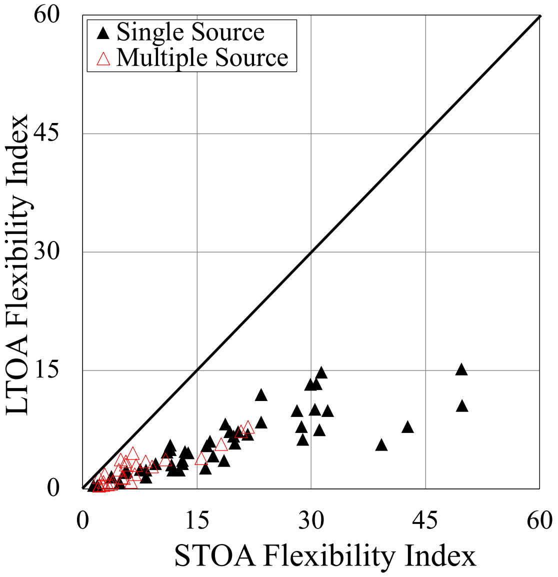
Information presented in this section demonstrates the general relationship between performance indices of STOA and LTOA mixes from both mixture sources. Such information is useful when conducting simple performance prediction using properties of STOA mixes.

Because very soft and compliant mixes, as well as very stiff and brittle mixes were covered in the data pool, the data range presented here is considered to be representative of a wide range of mixes. Figure 9-1 shows the correlation of fracture energy, flexibility index, peak load, and stiffness index between STOA and LTOA specimens from both source of specimens, to better showcase the distribution of the data, error bars are not presented. The data variation, however, will be discussed next.



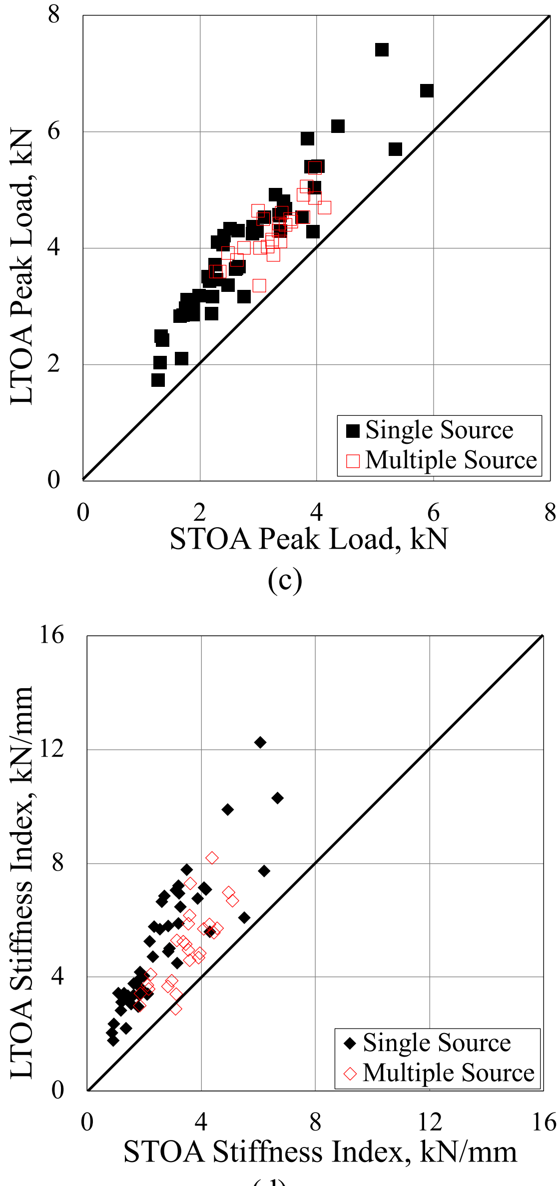
Single Source
Multiple Source
LTOA Fracture Energy, kN/m^2
STOA Fracture Energy, kN/m^2
0
1
2
3
4
5
0
1
2
3
4
5

(a)



Single Source
Multiple Source
LTOA Flexibility Index
STOA Flexibility Index
0
15
30
45
60
0
15
30
45
60

(b)



(c)

(d)

Figure 9-1. Distribution and correlation of SCB test parameters under STOA and LTOA status. (a) Fracture energy, (b) flexibility index, (c) peak load, and (d) stiffness index.

In general, STOA mixes exhibit slightly higher fracture energy (Figure 9-1a) but significantly higher flexibility index (Figure 9-1b) compared with LTOA mixes. On the other hand, LTOA mixes constantly present higher peak load (Figure 9-1c) and notably higher stiffness index (Figure 9-1d). The trend is expected since higher fracture energy and flexibility index imply better resistance to fracture, and it is well established that LTOA mixes have lower resistance to fracture due to oxidation and aging compared with STOA mixes. Higher peak load and stiffness index of LTOA mixes further support this statement and match results reported from previous studies.

There is a significant difference between STOA and LTOA specimens in terms of peak load, initial stiffness, and flexibility index, but there is not much difference in terms of fracture energy. The reasons for such statement are twofold. For one, fracture energy has a considerably narrower range of values compared with the other three parameters. Specifically, the highest value of fracture energy is only four times larger than the lowest value, yet the comparable numbers for flexibility index and stiffness index reach approximately 50 and 12, respectively. Furthermore, LTOA does not alter the range of values for fracture energy. Moving from STOA to LTOA mixes, fracture energy values spread between 1 to 4 kJ/m^2, remaining almost constant within this range. Unlike fracture energy, however, the range of flexibility index and stiffness index change significantly after LTOA. In addition. data points representing flexibility index, peak load, and stiffness were deviated from the line of equality, further supporting the conclusion that there is a significant difference between STOA and LTOA specimens regarding these parameters.

The fairly linear relationship and reasonable coefficient of determination (R^2 value) of all four regression expressions imply the possibility of predicting flexibility of asphalt mixtures after long-term aging using performance data obtained from STOA mixes. Such correlation establishes foundation for fracture performance prediction that could be implemented in mix design and quality control.

One should note that results presented in Figure 9-1 combine those from single source material (black solid labels in the figure) and those from multiple source materials (shown as red hollow labels in the figure). The multiple source specimens fall in the range set by single source specimens, although they were fabricated at different laboratories, and using different material types and sources.

Another important item worth noting is that, in general, multiple source specimens have much smaller range of performance indices. Such a difference is expected when considering how the mixes were prepared in the central lab (single source) versus multiple labs. Some of the mixes in the central lab were intentionally prepared at extreme values of parameters in mix composition, for example high air void paired with high binder content, or low air void paired with low binder content. Multiple source specimens, on the other hand, were targeted in an air void range of 5.5±0.5 percent, and were manufactured with corresponding design binder content, or at just 0.5 percent above the design binder content. Changes in multiple source specimens leant more towards binder stiffness, recycled material content, aggregate types, and gradation.

The aforementioned observation that fracture energy is less sensitive to LTOA compared with other parameters is further supported by aging index data presented in Table 9-1. Aging index is defined as the ratio of a specific performance index of LTOA mixes to the corresponding performance index of STOA mixes, the purpose of which is to normalize the changes in the specific parameter.

Table 9-1. Aging Index of All Parameters.

Mix Source	**Statistical Parameter**	**Material Parameter**			
		Fracture Energy	**Flexibility Index**	**Peak Load**	**Stiffness Index**
Single Source Mixes	Average	0.92	0.32	1.47	2.05
	St. Dev.	0.15	0.10	0.20	0.42
Multiple Source Mixes	Average	0.94	0.38	1.33	1.48
	St. Dev.	0.13	0.18	0.13	0.27

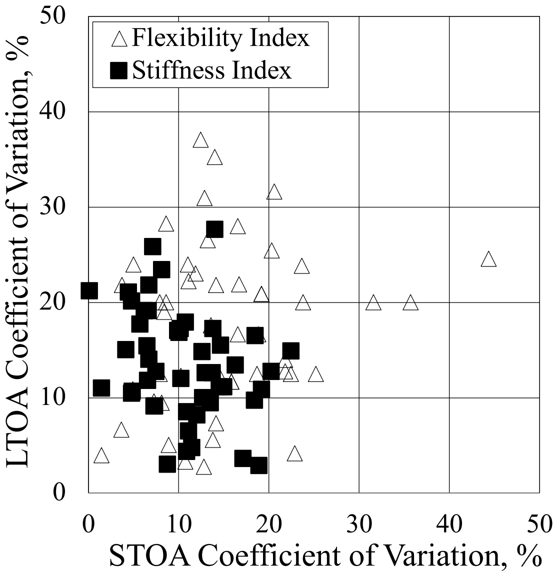
Using student t-test (which is not shown for brevity), it can be shown that, the average fracture energy for short term aged specimens is not statistically different from that of long-term aged specimens. In other words, the average aging index for fracture energy is statistically equal to one. On the contrary, all other parameters have aging indices statistically different than one, meaning there are notable differences between STOA and LTOA mixes. Furthermore, average aging indices from multiple source specimens are statistically equivalent to that of single source specimens except stiffness index, for which the single source specimens yield a higher value than multiple source specimens.

9.4.2 Data Quality

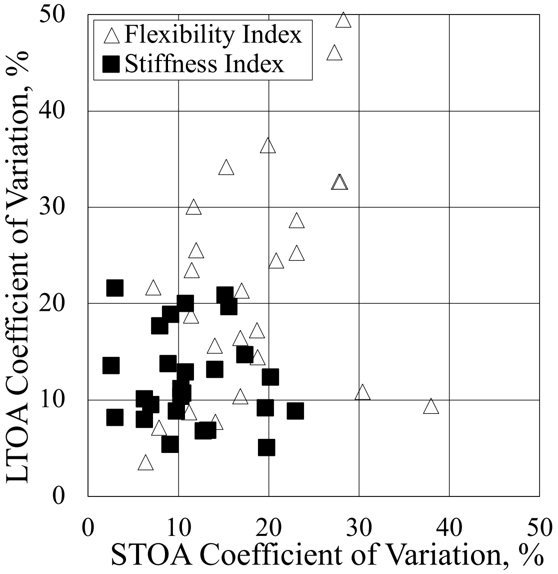
Quality of testing and generated test data can never be emphasized enough because conclusions and findings from the research work can only be reliable if the generated data is reliable. One measure of data quality is coefficient of variation (COV), as used in this work.

COV measures relative dispersion or variation in a data set; the lower the value, the less variation a data set has. For cyclic fatigue tests, COV sometimes exceeds 30 percent, making statistical interpretation of test results a daunting task. Monotonic based test poses its advantages in terms of test variability as most often COV is well below 30 percent.

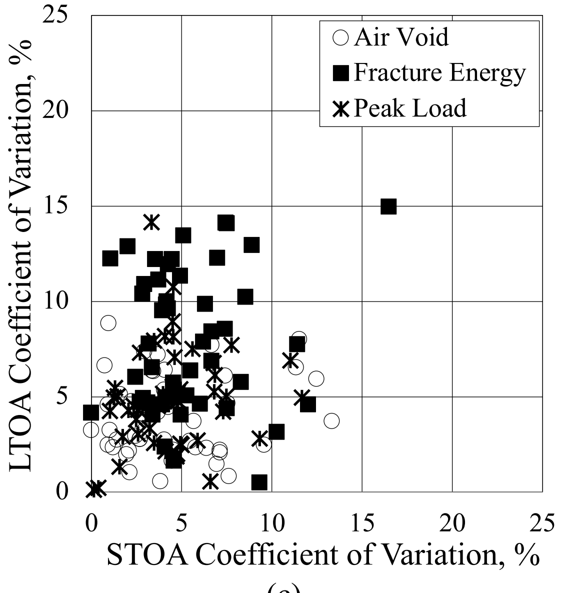
The quality of data is not only determined by quality of test equipment, test procedure operator, and interpretation methodology, but also deeply affected by specimen preparation. The COV distribution and comparison between STOA and LTOA specimens for all four parameters as well as air void, from both sourced specimens, are presented in Figure 9-2.


Flexibility Index
Stiffness Index
LTOA Coefficient of Variation, %
STOA Coefficient of Variation, %
0
10
20
30
40
50

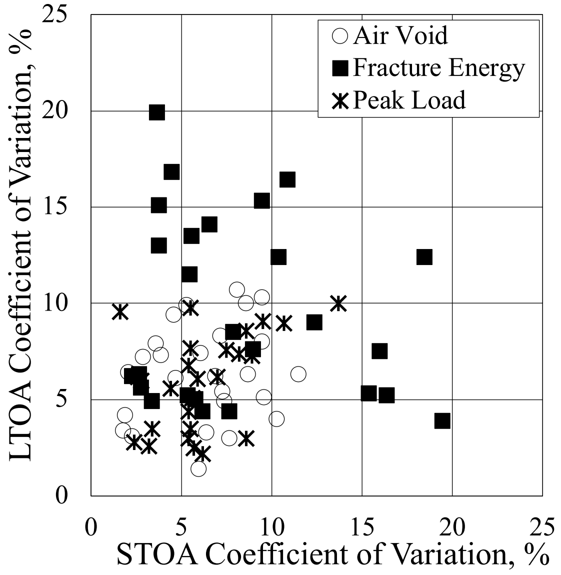
(a)


Flexibility Index
Stiffness Index
LTOA Coefficient of Variation, %
STOA Coefficient of Variation, %
0
10
20
30
40
50

(b)



(c)



(d)

Figure 9-2. STOA and LTOA COV comparison of (a) fracture energy and flexibility index of single source specimens, (b) fracture energy and flexibility index of multiple source specimens, (c) air void, peak load, and stiffness index of single source specimens, and (d) air void, peak load, and stiffness index of multiple source specimens.

The majority of COV values of air void, fracture energy, and peak load are less than 20 percent (Figure 9-2c and 9-2d), while COV values of flexibility index and stiffness are higher and more scattered (Figure 9-2a and 9-2b). However, there is no discernable skewness from any indices of any source of materials. It indicates that LTOA does not affect variation of performance test data.

Another general observation from Figure 9-2 is that COVs of multiple source specimens are higher compared with that of single source specimens, although distribution pattern of the corresponding parameter is surprisingly similar. The observation is further supported by average values presented in Table 9-2, since multiple source specimens always have higher COV values than single source specimens for the corresponding parameter, the only exception being stiffness index from LTOA mixes.

Table 9-2. Average Coefficient of Variation of All Parameters.

Source	**Aging Condition**	**Material Parameter**				
		Air Void	**Fracture Energy**	**Flexibility Index**	**Peak Load**	**Stiffness Index**
Single Source Mixes	STOA	4.5	5.5	15.2	4.4	10.6
	LTOA	4.0	8.0	17.5	4.9	13.7
Multiple Source Mixes	STOA	6.3	8.3	18.4	6.1	11.4
	LTOA	6.4	9.6	22.1	6.0	12.3

Based on average values of COVs presented in Table 9-2, the COV of peak load is almost equivalent to that of air void, followed closely by fracture energy. For these three parameters, COV is lower than 10 percent for both material sources and aging conditions. This low COV is an indication of low variation and good data quality. On the other hand, the highest COV, regardless of specimen source and aging condition, belongs to flexibility index. High COV from flexibility index is associated with the way it is being calculated, since determining the inflection point on the post-peak slope is complicated, if not impossible. Slight change in curve shape could result in notable difference at inflection point, which deeply affects the calculation of flexibility index.

From authors' experience of testing more than 1200 SCB specimens, flexibility index always yields higher COV compared with other parameters. However, notes should be taken that compared with COV values reported from conventional cyclic fatigue tests, flexibility index still has lower variation. This is true in spite of the fact that in rare cases COV for FI could reach values as high as 30 to 50 percent. The highest average COV value of flexibility index (long term aged multiple source mixes) of 22.1 percent (Table 9-

2) is still significantly lower than 30 percent, which is commonly reported in cyclic fatigue tests.

One last observation is that within each material source, the COV of LTOA and STOA mixes are statistically equivalent, as proven by student t-test (not shown for brevity). Thus, it is safe to say that LTOA process does not have adverse effect on the quality of SCB test data, as long as specimens are prepared in good quality (for example, low COV of air void).

9.4.3 Effect of Long-Term Aging on Performance Indices in the light of Changes in Mix Parameters

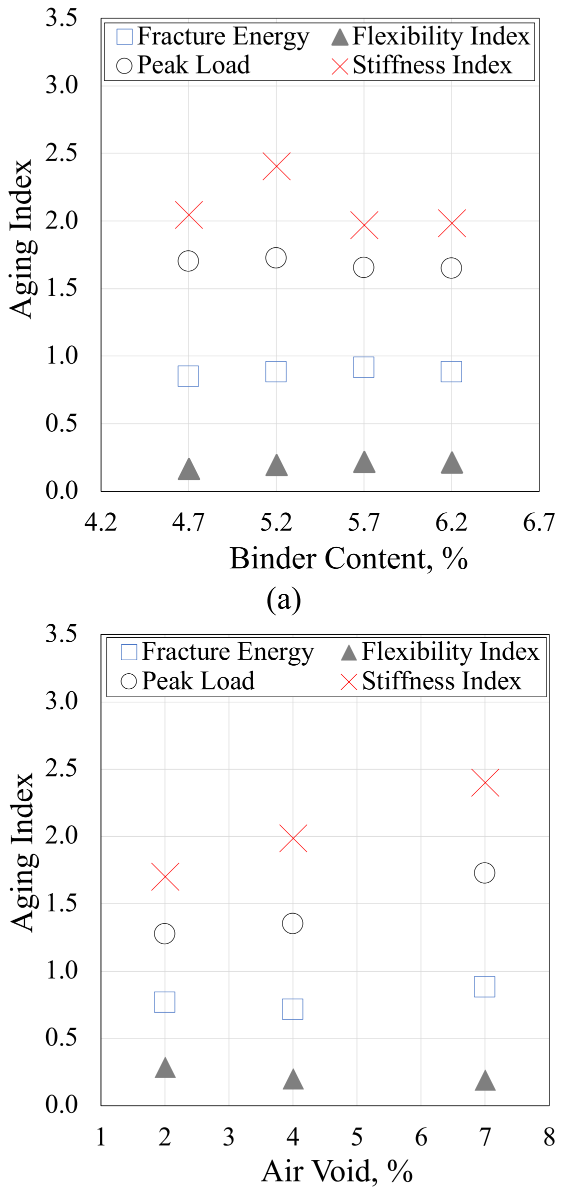
Changes in the mixture composition can significantly affect fracture properties of asphalt mixes. The most important mix parameters include asphalt content, asphalt stiffness, asphalt volume, aggregate type, aggregate gradation, and air void.

The effect of binder content, air void, and binder stiffness at intermediate temperature on SCB test parameters have been investigated in a previous study (Chen and Solaimanian 2018). Results in that study showed that fracture energy increases with the increase of binder content and binder stiffness, but beyond a point, increasing stiffness of binder results in reduction of fracture energy. Fracture energy was also observed to decrease with the increase of air void. On the other hand, flexibility index increases with the increase of binder content, and decreases with the increase of binder stiffness. To differentiate the effect of binder content and binder stiffness, flexibility index is more sensitive than fracture energy. In addition, flexibility index increases with the increase of air void level. As for peak load and stiffness index, they both reach the maximum value at the design binder content, then decrease with the increase of binder content. Furthermore, they both decrease with the increase of air void, and increase with the increase of binder stiffness, regardless of aging status.

The focus here is to investigate the effect of these material variables on aging index, i.e., the ratio of a specific performance index of LTOA mixes (such as FI) to the corresponding performance index of STOA mixes. Apparently, the closer an aging index is to one, the less is the impact of LTOA. On the other hand, the further away the index is from one, the wider the gap is between performance parameter from STOA mix and LTOA mix. In other words, the farther the aging index is from unity for a performance parameter, the more that parameter is affected by aging. In the case of flexibility index and initial mix stiffness, further change of aging index from unity is also an indicator of poorer performance in terms of crack resistance. However, the same could not be stated for peak load and fracture energy.

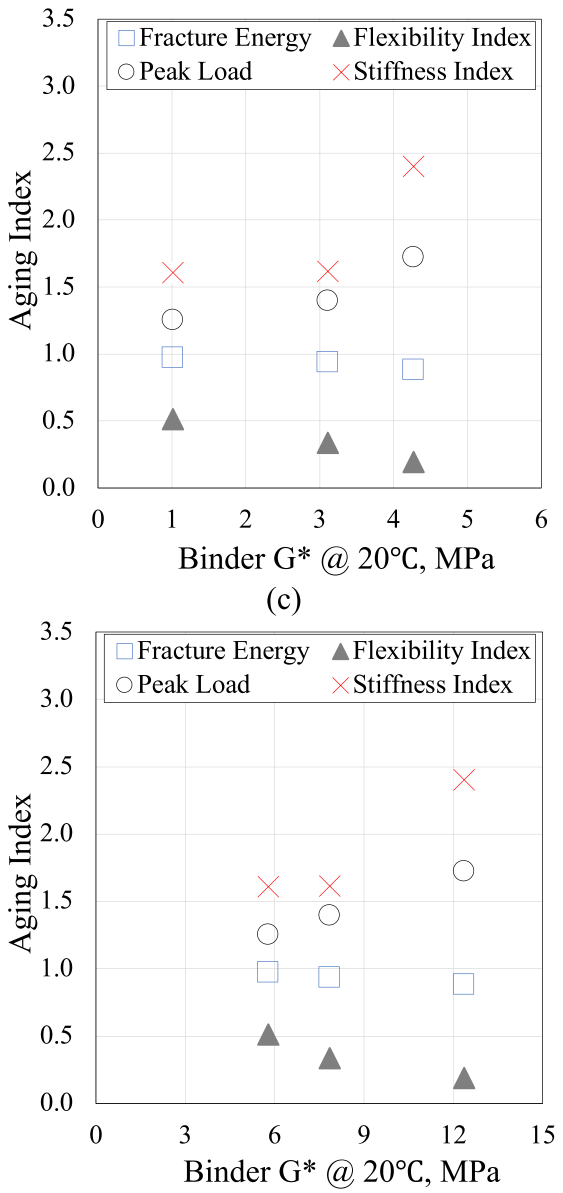
It is highly possible that a change in material composition could alter mix's susceptibility to aging. For example, increase in air void in mixes results in more exposure of binder to oxygen, consequently it should lead to more aging. Theoretically, the change in aging susceptibility should be reflected in the aging index. For some performance parameters, the aging index is not sensitive to the changes in the material variable as discussed below.

The effect of binder content, air void, and binder stiffness at intermediate temperature (20°C) on aging index are presented in Figure 9-3. It is worth mentioning that although binder content and air void can be controlled carefully so that STOA and LTOA mixes have equivalent material composition, binder stiffness does change as a result of aging. Thus, in Figure 9-3, the aging index versus modulus for the rolling thin film oven (RTFO) aged binder and pressure aging vessel (PAV) aged binder are presented separately. Each plot represents results from mixes with one changing material variable, while the other two are kept fixed. Specifically, mixes in Figure 9-3a are the ones with PG 64-22 binder, 7 percent air void, and binder content increase from 4.7 to 6.2 percent with a 0.5 interval; mixes in Figure 9-3b are the ones with PG 64-22 binder, 5.2 percent binder content (design), and air void change from 2 to 7 percent; and mixes in Figure 9-3c and 9-3d have air void of 7 percent, binder content of 5.2 percent, and binder modulus of three grades as listed before. Similar trends can be found in other material composition combinations.


□ Fracture Energy
▲ Flexibility Index
○ Peak Load
× Stiffness Index
Aging Index
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
4.2
4.7
5.2
5.7
6.2
6.7
Binder Content, %
□ Fracture Energy
▲ Flexibility Index
○ Peak Load
× Stiffness Index
Aging Index
1
2
3
4
5
6
7
8
Air Void, %

(a)

(b)



(c)

(d)

Figure 9-3. Effect of material variables on aging indices of all parameters. (a) Binder content, (b) air void, (c) RTFO binder stiffness, and (d) PAV binder stiffness.

There are several observations from Figure 9-3. First, aging indices of fracture energy and flexibility index does not change with binder content (Figure 9-3a), although both parameters increase with the increase of binder content. Aging index of stiffness index, on the other hand, reaches its maximum value at design binder content (5.2 percent), but then quickly decreases. The maximum aging index of the peak load is also observed at design binder content, although its overall trend is flat.

From Figure 9-3b, it is also clear that aging index for stiffness index and peak load rises with the increase of air void, although both parameters actually decreased. It seems that air void has deeper impact on STOA mixes than LTOA mixes in terms of stiffness index and peak load, because both peak load and stiffness dropped notably faster for STOA mixes than LTOA mixes when air void increased. This effect is expected as higher air void leads to increased aging index. Meanwhile, an opposite trend can be found for flexibility index, in which its aging index dropped slightly, while a significant jump occurred in flexibility index for both STOA and LTOA mixes when air void increases. Similar to binder content, aging index of fracture energy remains insensitive to air void changes. The impact of air void is expected since higher air void results in more exposure for oxidation, leading to higher aging. A sensitive performance parameter should respond accordingly.

Finally, it is clear from Figure 9-3c and 9-3d, that aging index of flexibility index decreases with the increase of binder stiffness, which matches the actual values of flexibility index for both aging conditions. On the contrary, stiffness index and peak load increased with the increase of binder stiffness, so did their aging indices. Fracture energy showed a slight decrease in aging index when stiffer binder was used, but the response was far from noticeable.

Granted, fracture energy is one of the most widely used and accepted performance indices. However, as revealed in this paper, its sensitivity to material variables and aging is not as significant as other parameters such as speak load, and flexibility index. Hence, fracture energy should be used with extreme cautious. Although stiffness index and peak load deliver similar sensitivity to material variable and aging, the latter is preferred due to lower COV for better distinguishability. In addition, flexibility index remains a robust performance indicator for fracture property evaluation, as it has shown sensitivity to not only material variables, but also to aging level. As a results, peak load and flexibility index is pursued further for the following studies.

9.4.4 Effect of LTOA on Mixes with Recycled Materials

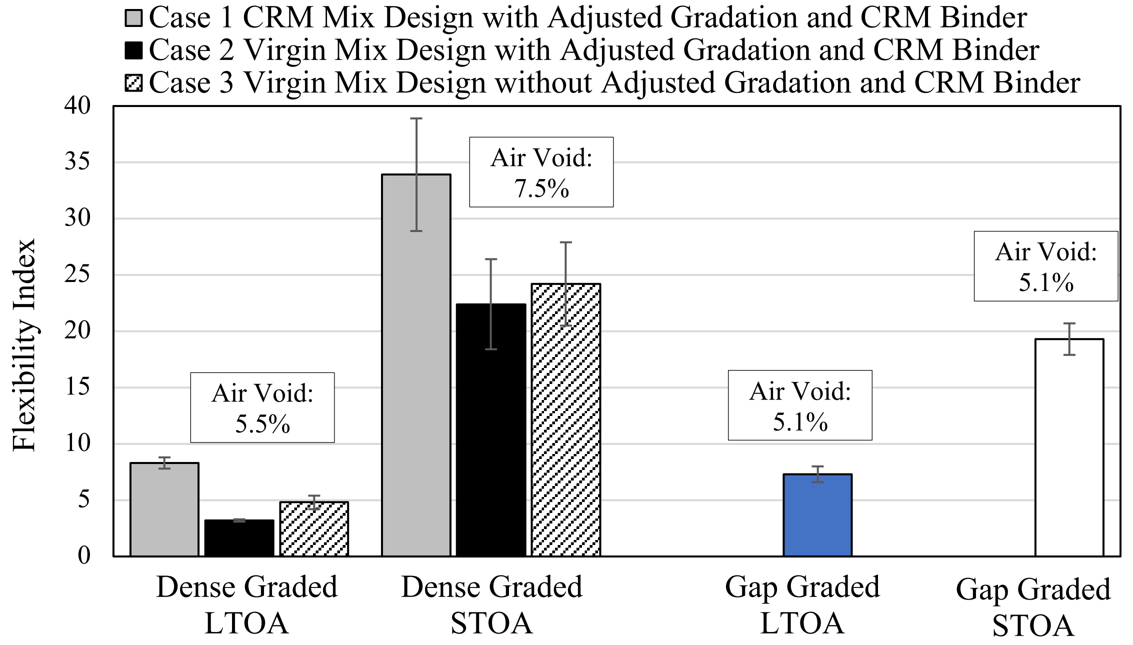
9.4.4.1 Effect of Aging on Crumb Rubber Asphalt Mixes

Data demonstrated in this section show the impact of gradation and binder content, combined with LTOA on fracture properties of asphalt mixes with crumb rubber modifiers (CRM). The effect of gradation includes dense vs. gap gradation, and gradation adjustment for CRM. Such information is helpful when designing CRM mixes if fracture resistance is of concern.

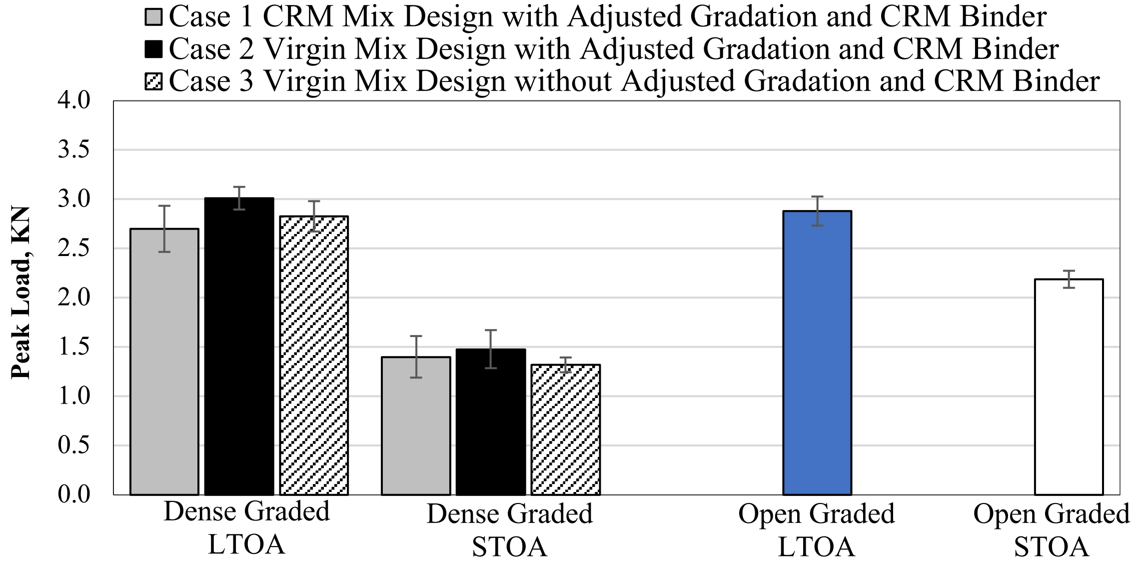
Results presented in Figure 9-4 came from CRM mixes with PG 58-28 binder and 15 percent crumb rubber. Aside from dense gradation and gap gradation comparison, different cases represent various gradation combinations with the goal of evaluating the impact of gradation adjustment on densely graded CRM mixes.

The three cases shown in Figure 9-4 covered various what-if scenarios. For example, case 1 and case 2 mixes adjusted gradation to make room for CRM particles although both of them are densely graded the difference between cases 1 and 2 was that the binder content for the former was optimized based on CRM mix design (5.7%) whereas for case 2, the binder content was the same as virgin mix with similar gradation (5.2%). Case 3 was used to address the question of what happens to a mix when a virgin binder is replaced with crumb rubber modified binder without adjusting gradation or binder content of the original virgin mix. Therefore, one can see that for cases 2 and 3, no mix design is conducted, and the binder content designed for virgin mixes with similar gradation (5.2 %) is simply used in cases 2 and 3. Case 1, 2, and 3 all belong to dense graded mixes. One gap graded CRM mix was also included for comparison, with a mix design binder content of 6.2%.

In summary, comparing case 1 and 2 answers the question of what difference does it make when performing mix design for CRM mixes; comparing case 2 and 3 answers the question of whether gradation adjustment should be performed for densely graded CRM mixes. Apparently, case 1 demands the most efforts as it requires both mix design and gradation adjustment; case 3 require neither; while case 2 only asks for adjustments on the gradation. The gap graded mixes can be compared with either case to show the effect of dense vs. gap gradation. However, one should remember the focus is still on what kind of impact does LTOA pose on CRM mixes.



(a)



(b)

Figure 9-4. (a) Flexibility index and (b) peak load comparison between CRM mixes.

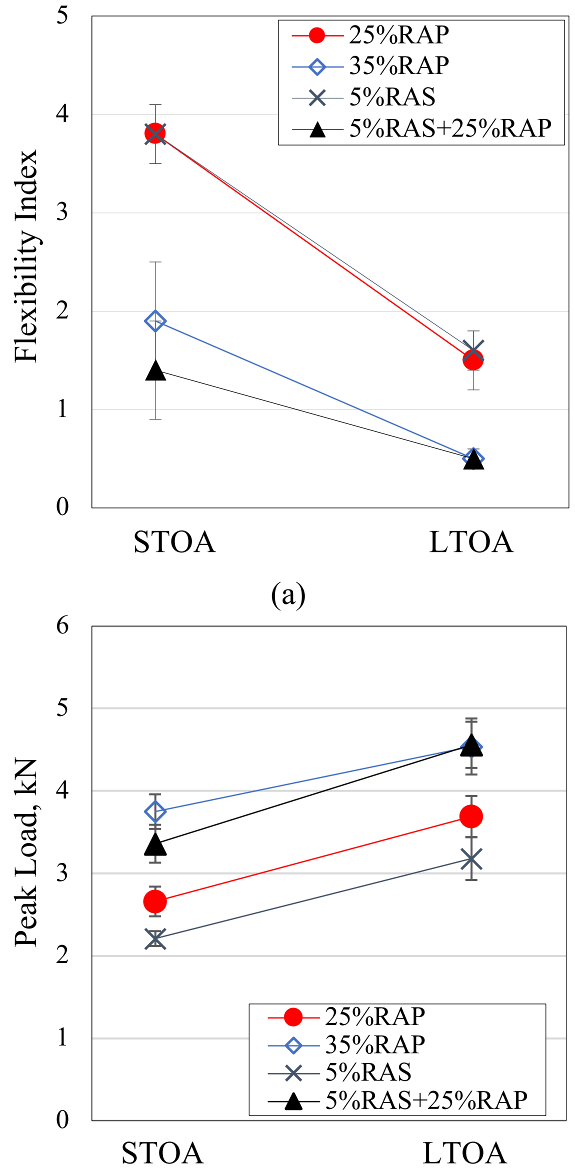
It is clear that similar to virgin mixes, STOA specimens have notably higher flexibility index values for all cases (Figure 9-4a), indicating higher fracture resistance before mixes are exposed to LTOA. In the case of dense graded CRM mixes, higher FI of STOA mixes is not only the result of lower aging level but also caused by higher air void compared with LTOA mixes. The reason STOA dense graded CRM mixes have higher air void is that compacted specimens swelled and rebounded after compaction. The authors discovered that such swell and rebound cannot be reduced in dense graded CRM mixes even with higher compaction energy. The details of specimen swell can be found elsewhere (Solaimanian and Chen 2018). One cannot compare aging index of dense graded CRM mixes, however, because of unequal air void levels. On the other hand, the aging index of gap graded CRM mix (0.38) is in the range of that from virgin mixes (ranges from 0.2 to 0.5 in Figure 9-3), indicating similar aging resistance in terms of flexibility index for such mix.

Also similar to virgin mixes is that STOA CRM mixes have lower peak load than LTOA CRM mixes, further showing the stiffening effect of long-term aging. The reason dense graded CRM mixes have lower peak load under STOA status compared with Gap graded one is high initial air void. After long-term aging, the peak load values among cases are comparable and close to that of gap graded CRM mix, as they all share similar air void level.

9.4.4.2 Effect of Aging in the presence of RAP, RAS, and Rejuvenator

It is well known that incorporating recycled materials into asphalt mixes stiffens the final mix thus making it prone to cracking. Two common approaches to mitigate such stiffening effect is adding more virgin binder or adding recycling agent, i.e., rejuvenator. Results presented here compare the impact of LTOA on these two methods, together with the impact of LTOA on the contents of recycled materials.

Four RAP/RAS mixes were prepared first to investigate the impact of LTOA on their fracture properties. All specimens were prepared using their design binder content and PG58-28 binder, then compacted to a level to ensure the final air void of tested SCB specimens were 6.5±0.5 percent.



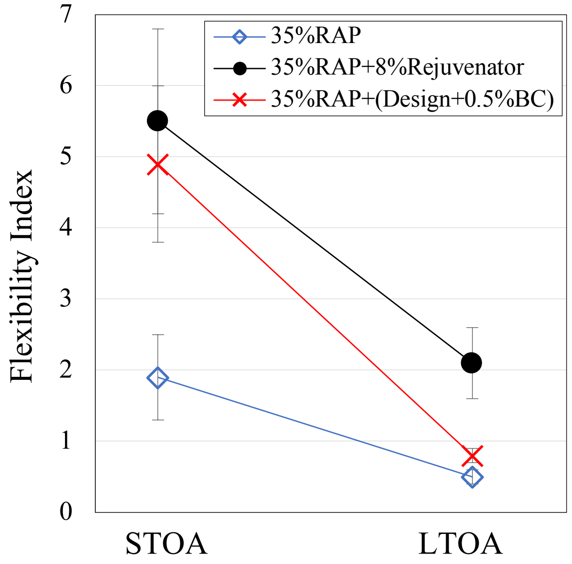
(a)

(b)

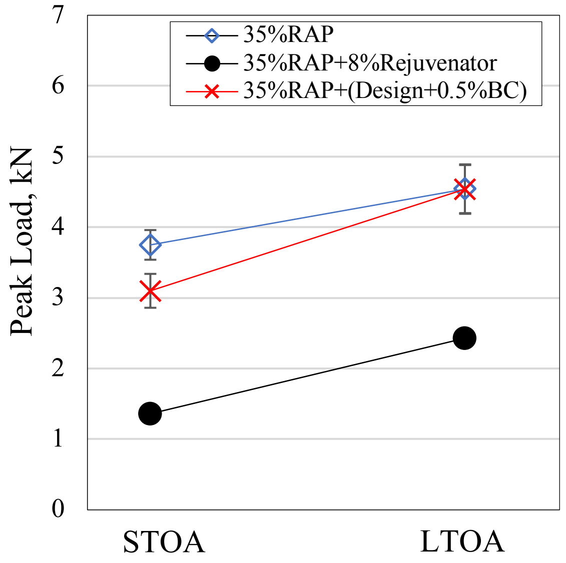
Figure 9-5. Flexibility index of (a) RAP and RAS mixes. And peak load of (b) RAP mixes with rejuvenator and extra virgin binder.

From Figure 9-5a, it is clear that: 1) all mixes with recycled materials have significantly lower flexibility index compared with virgin mixes prepared using the same PG58-28 binder, which averaged 23.5 and 11 for STOA and LTOA mixes, respectively; 2) relatively softer mixes with recycled materials have higher flexibility index for both STOA and LTOA levels. Specifically, mixes with 25 percent RAP and mixes with 5 percent RAS have twice the flexibility index as the other two, indicating that the test condition used in the study and flexibility index are sensitive and capable in differentiating impact of recycled material content and stiffness; 3) all four mixes have lower aging indices than virgin mix using the same aggregate skeleton and virgin binder, implies that adding recycling material compromises not only fracture properties of asphalt mixes, but also aging resistance.

The general trends of peak load align with that found in previous data (Figure 9-5b). Mixes with relatively higher flexibility indices returned lower peak load, and vice versa. Unlike flexibility index, however, aging indices around 1.45 for peak load is comparable to virgin mixes,



(a)



(b)

Figure 9-6. Flexibility index of (a) RAP mixes with rejuvenator and extra virgin binder. And peak load of (b) RAP mixes with rejuvenator and extra virgin binder.

Adding rejuvenator is among the common approaches used to improve fracture properties of stiff mixes with recycled materials. From previous experience (Chen and Solaimanian 2018), adding extra virgin binder also improves fracture property in terms of flexibility index. As shown in Figure 9-6a, adding high dosage of rejuvenator and adding 0.5 percent virgin binder enhances flexibility indexes of mixes with 35 percent RAP significantly right after STOA, and the difference between two methods are statistically insignificant. However, the advantage of using rejuvenator in lieu of simply adding more virgin binder is dominant when analyzing the results after LTOA. The mix with rejuvenator holds its flexibility index value at a significantly higher level compared to the one without rejuvenator and the one with more virgin binder. Peak load values further support such observation as the one with no extra virgin binder returned equal peak load after LTOA when compared with the one with extra virgin binder. While the one with rejuvenator had much lower peak load value even after LTOA. The aging index of the mix with rejuvenator is also comparable to virgin mixes.

When comparing flexibility indexes after LTOA, the one with 35 percent RAP and rejuvenator performed better than the mix with 25 percent RAP or the mix with 5 percent RAS. It indicates a strong softening effect of such recycling agent. Although LTOA has believed to always diminish softening effect of rejuvenator, the material used in this study showed notable softening effect even after LTOA. Furthermore, aging index has the potential to serve as a useful parameter when comparing effectiveness of rejuvenators or other approaches for mixes with recycled materials.

9.5 SUMMARY AND CONCLUSIONS

With a goal of determining how the fracture properties of long-term aged mixes (LTOA) compared with those from short-term aged mixes (STOA), a large number of asphalt mixes were tested using the semi-circular bend (SCB) test. Based on this testing and analysis of data, the following conclusions can be drawn:

1. Flexibility index, peak load, and stiffness index expressed prominent sensitivity to LTOA, while fracture energy showed very little to none. LTOA alters data range significantly for all performance indices but fracture energy.
2. Relatively good correlation could be developed between response parameters after STOA with those after LTOA, indicating the potential of testing specimens under STOA conditions and reliably predicting the results under LTOA. LTOA does not have detrimental effect on data quality of SCB test. Similar data variation can be obtained in LTOA mixes compared with STOA mixes, as long as specimens are consistently manufactured. Air void, peak load, and fracture energy have similar and small data variation. Flexibility index exhibited the highest variation, yet it was lower than variation observed in conventional cyclic fatigue tests.
3. Multiple source specimens from different sources do not demonstrate significantly higher variability in data compared with single source specimens. Aging index of performance parameters do not change with the increase of binder content, indicating the insensitivity of binder content to LTOA. However, aging indices from all parameters except fracture energy showed notable increasing or decreasing trend when air void and binder stiffness changes.
4. Fracture energy demonstrated the least sensitivity to aging condition and material composition. Peak load and stiffness index share similar behavior, but the former has

much lower data variation. Flexibility index showed sensitivity to both material composition and aging.

5. The gap graded CRM mixes used in this study performed similarly to virgin mixes in terms of aging resistance (giving similar aging index for flexibility).
6. Mixes with RAP and RAS expressed lower aging resistance and lower flexibility index compared with virgin mixes. The difference among mixes with different recycling material content and effect of rejuvenating methods are noticeable after LTOA. Mixes with lower recycling material content and mixes with rejuvenator showed superior fracture performance compared with mixes with high recycled material content and mixes with no rejuvenator at all. Proposed aging index has the potential to evaluate aging resistance among rejuvenating materials.

Chapter 10 CONCLUSIONS AND RECOMMENDATIONS

Cracking in asphalt pavement is a challenging problem and has been the subject of numerous research studies for decades. There is not a commonly accepted test protocol for testing asphalt mixtures for cracking resistance characterization for the purpose of mixture design or quality control/quality assurance. A simple but popular fracture test, the semi-circular bend (SCB) fracture test, was selected based on criteria proposed in previous studies. A comprehensive research was undertaken to evaluate the influence of important test conditions, and the overall capability of the test to discriminate changing material variables at the most appropriate test condition. A large quantity of asphalt paving materials that are commonly used in the commonwealth of Pennsylvania were characterized via such a test. In addition, the possibility of implementing such test as the sole mechanical test to perform the performance-based balanced mix design was also explored. Conclusions from each study are summarized below.

10.1 CONCLUSIONS

10.1.1 The Effect of Test Temperature and Displacement Rate on the Semi-Circular Bend Test

The effect of displacement rate and test temperature on the SCB test results was investigated, because it is essential to establish the most appropriate SCB test protocol for routine mix design and material quality control. The experiment included investigating the sensitivity of multiple characterization parameters to material variables under different test conditions.

The SCB test proved to be simple to run and practical for routine mix design. No complicated specimen-preparation processes such as coring or gluing were required, and both SGC specimens and field cores could be used for test specimen manufacturing. Four specimen replicates could be tested within a short period of time, and four replicates could be cut from one SGC specimen. The test could be conducted at effective fatigue temperature of the region of interest.

Fracture energy (FE) and flexibility index (FI) exhibited sufficient sensitivity to material variables under most testing conditions. Peak load (PL) showed the highest sensitivity to mix variables in every test condition and carried the smallest coefficient of variation among all response parameters. Specifically, at the test temperature of 25℃, FI peaked at 5 mm/min, then decreased with the increase of displacement rate, but the overall trend remained flat compared with other parameters. However, other characterization parameters increased as the displacement rate increased. At the proposed effective temperature of 18℃ for some areas of the northeast region, all response parameters except FI increased with the increase of displacement rate. FI decreased with the increase of displacement rate at this temperature. For other parameters, similar trends were observed at both 25℃ and 18℃.

FE, PL, and stiffness index (SI) increased with the decrease of air void, while FI increased with the increase of air void. The observed increase of FI with air void in the SCB test requires close evaluation and must be considered in combination with other properties, such as strength, for proper assessment of the mix ability in regard to cracking resistance. As expected, FI increases with the increase of binder content and decrease of binder stiffness.

Considering these results and the range of values obtained for FI, it is proposed that testing be conducted at the site effective temperature and a displacement rate of 5 mm/min.

10.1.2 The Effect of Material Variable on SCB Test Performance Indicators

A series of SCB tests was performed to investigate the effect of asphalt mix composition on the SCB test result using the proposed SCB test procedure. Material variables included binder content, air void level, binder stiffness, and aging condition.

Based on the laboratory test results and statistical analysis, it was observed that the proposed SCB test procedure, with a displacement rate of 5 mm/min and a test temperature of 20℃, is adequately sensitive to capture the effect of all investigated material variables.

In addition, once specimens were prepared and ready to be tested, a suite of tests with 4 replicates could be finished within a short period of time (for example, in less than 10 minutes).

There was no significant difference between SCB specimens cut from the top and bottom layers of the specimen in terms of their air void distribution and mechanical properties, as long as the material was uniformly compacted with no segregation. Four specimens cut from a single SGC could be used as independent replicates.

Fracture energy increased with the increase of binder content and binder stiffness, but beyond a point, increasing stiffness of binder resulted in reduction of fracture energy. Fracture energy was also observed to decrease with the increase of air void. These trends match the ones observed in stress-controlled cyclic fatigue tests. On the other hand, flexibility index increases with the increase of binder content, and decreases with the increase of binder stiffness. These trends match the ones observed in strain-controlled cyclic fatigue tests. To differentiate the effect of binder content, FI is more sensitive than FE. The relationship between binder stiffness and SCB test parameters reported here is limited to materials used in this study. Further work is needed to verify the potential correlation between binder stiffness/modulus and SCB test parameters using a broader selection of materials. On the other hand, FI increases with the increase of air void level. Analysis shows that the value of the flexibility index is largely determined by the slope, overshadowing the influence of fracture energy. The authors believe ne conclusion that can be drawn is that FI must be coupled with either a strength index or a stiffness index to ensure adequate strength of the mix.

10.1.3 Fracture Properties of Asphalt Mixtures with Crumb Rubber Modifiers (CRM)

The effect of several material parameters such as CRM content, virgin binder stiffness, binder content, and aggregate gradation on fracture performance of CRM mixes was investigated via an SCB fracture test. Corresponding binders were subjected to LAS and DSR tests. The following conclusions can be drawn from the laboratory investigation:

The optimum binder content to reach 4 percent air voids is higher for CRM asphalt mixes compared with mixes made with virgin binder. In addition, higher CRM content results in higher optimum binder content. Using the same CRM binder, the gap-graded mix required higher binder content to reach 4 percent air voids at the specified number of gyrations, compared with dense-graded CRM mixes.

CRM mixes showed reduced initial stiffness and post-peak stiffness compared with mixes manufactured with the same base virgin binder or virgin binder at the same performance grade. This observation indicates that rubber particles in CRM binder increase elasticity and ductility of asphalt mixes.

At design binder content, CRM mixes had a higher flexibility index compared with mixes produced with the same base virgin binder or virgin binder at the same performance grade. This higher flexibility results from both the increase in binder content and increase in ductility due to the use of crumb rubber. However, in dense-graded CRM mixes, a higher percentage of crumb rubber does not necessarily result in higher flexibility. Some CRM mixes in this study delivered low flexibility, possibly a result of a significant increase in binder stiffness. On the other hand, CRM mixes showed lower fracture energy and peak load compared with mixes with the same base virgin binder or virgin binder with the same performance grade. This observation is expected, as, in general, CRM mixes have lower pre-peak and post-peak stiffness. This lower stiffness yields in a stretched low-peak displacement-load curve, resulting in reduced fracture energy and peak load. Similar to the flexibility index, the difference of fracture energy and peak load among CRM mixes with the same binder, but slightly adjusted gradation, is negligible. Additionally, for the same CRM binder, using gap-graded mixes showed a significantly improved flexibility index and fracture energy, as well as similar peak load values, compared with the one with dense-graded mix. Thus, it is recommended that CRM binder be used with gap-graded mixes rather than dense-graded mixes.

CRM binders outperformed virgin binders at the low strain level in the LAS test; they also outperformed their base virgin binder at high strain levels in LAS tests. The predicted fatigue life increased with the increase of CRM contents when using the same virgin binder as the base binder. CRM binder with PG58-28 as base binder showed strong cracking resistance based on the G-R parameter value. CRM binder with PG64-22 as base binder and PG76-22 virgin binder presents less cracking resistance due to higher stiffness. Currently there is no agreement between the rankings of SCB tests and binder tests. However, soft base virgin binder modified with 10 to 15 percent rubber has a high possibility of outperforming the modified virgin binder, in terms of both binder fatigue performance and mix fracture properties.

10.1.4 Fracture Properties of Asphalt Mixtures with Recycled Materials

An experimental study was undertaken to evaluate the fracture behavior of asphalt mixes containing RAS and a high percentage of RAP. It was observed through volumetric design that adding RAP/RAS into asphalt mixes reduces design binder content. Specifically, incorporating recycled materials into asphalt mixes not only reduces virgin binder demand, because of residual binder contribution, but also lowers total binder content compared with similarly structured virgin mixes. SCB test results show that incorporating RAP/RAS materials significantly lowers flexibility index and raises peak load values of the final mixes. Normally, mixes with higher peak load deliver a lower flexibility index.

Blending methods (such as blending with binder first, or directly adding into the aggregate) do not alter the effectiveness of rejuvenators. No statistical difference was discovered in the study when comparing results obtained using two blending methods. Adding rejuvenator into RAP mixes linearly increased the flexibility index. It also linearly decreased peak load (mix strength).

10.1.5 Optimize rejuvenator contents for Asphalt Mixtures with Recycled Materials and Using SCB Test for Balanced Mixture Design

Both binder characterization tests and mixture mechanical tests were performed to evaluate the balanced design of asphalt mixes containing RAS and a high percentage of RAP, and results were cross compared and analyzed collectively. It was discovered that adding rejuvenator into RAP mixes linearly increases flexibility index, linearly decreases peak load (mix strength), and exponentially increases rut depth in the HWT test. The agreement between peak load in the SCB test and rut depth in the HWT test implies the possibility of using a stand-alone monotonic fracture test for balanced mix design. Such a test can be used to evaluate intermediate-temperature fracture performance and high-temperature rutting performance of asphalt mixes through a single test setup.

Adding RAP binder into virgin binder increases high-temperature performance grade of the blended binder; and incorporating rejuvenator into such binder decreases high-temperature performance grade. Adding rejuvenator also significantly raises the non-recoverable creep compliance of the final binder, which translates into less resistance to permanent deformation. High-temperature performance indices of binder and mixes agree with each other well. Additionally, incorporating rejuvenator into binder that contains residual RAP/RAS binder significantly decreases shear modulus and G-R parameter value at intermediate temperature, which implies better crack resistance of the binder. Although adding rejuvenator also enhances the flexibility index of stiff RAP/RAS containing asphalt mixes, the impact is not as dramatic as that observed in the binder. There exists some discrepancy between intermediate temperature fracture indices of binder and mixes.

10.1.6 Effect of Long-Term Aging on Fracture Resistance of Asphalt Mixtures

A large number of asphalt mixes were tested to determining how the fracture properties of long-term oven-aged mixes (LTOA) compared with those from short-term oven-aged mixes (STOA) using the SCB test. Based on this testing and analysis of data, it was observed that the flexibility index, peak load, and stiffness index expressed prominent sensitivity to LTOA, while fracture energy showed little to none. LTOA alters the data range significantly for all performance indices except fracture energy. Relatively good correlation could be developed between response parameters after STOA with those after LTOA, indicating the potential for testing specimens under STOA conditions and reliably predicting the results under LTOA. LTOA does not have detrimental effects on the data quality of the SCB test. Similar data variation can be obtained in LTOA mixes compared with STOA mixes, as long as specimens are consistently manufactured. Air void, peak load, and fracture energy have similarly small data variation. Flexibility index exhibited the highest variation, yet it was lower than the variation observed in conventional cyclic fatigue tests.

Multiple-source specimens do not demonstrate significantly higher variability in data compared with single-source specimens. The aging index of performance parameters does not change with the increase of binder content, indicating the insensitivity of binder content to LTOA. However, aging indices from all parameters except fracture energy showed notable increases or decreases trend when air void and binder stiffness changes. Fracture energy demonstrated the least sensitivity to aging condition and material composition. Peak load and stiffness index share similar behavior, but the former has much lower data variation. Flexibility index showed sensitivity to both material composition and aging.

The gap-graded CRM mixes used in this study performed similarly to virgin mixes in terms of aging resistance (giving similar aging index for flexibility). On the other hand, mixes with RAP and RAS expressed lower aging resistance and a lower flexibility index compared with virgin mixes. The difference among mixes with different recycling material content and the effect of rejuvenating methods are noticeable after LTOA. Mixes with lower recycling material content and mixes with rejuvenator showed superior fracture performance, compared with mixes with high recycled material content and mixes with no rejuvenator at all. The proposed aging index has the potential to evaluate aging resistance among rejuvenating materials.

10.2 RECOMMENDATIONS

Owing to differences in mixing process and compaction mechanism, there are discernible gaps between fracture properties of laboratory-prepared asphalt mixes to those prepared in the plant and compacted in the field. Further work is needed to establish a reliable relationship between the two mixes to provide mix design guidelines. Prediction models using material composition variables and their interactions yielded reasonable accuracy in this study. However, a broader selection of material variables is needed to enhance the prediction model. Further work is also needed to investigate the influence of interactions among material variables. In addition, work is needed to establish a performance threshold for the mix fracture test. Threshold values should not be a single number; rather, traffic, climatic, and—most importantly—the structure of pavement should be accounted for when proposing such thresholds. All the above efforts build foundations for performance-based mixture design, which is a big step forward toward improving infrastructures.

Another important necessity is to establish a relationship between the SCB fracture test and other mechanical tests such as dynamic modulus or uniaxial push-pull/pull-pull fatigue tests (or direct tension fatigue test). Because such tests have been linked to pavement-performance prediction software such as MEPDG and FlexPAVE. A relationship like this would open a door to predict future pavement performance using simple tests, which in turn would further improve the sophistication of pavement design.

REFERENCES.

AASHTO T 101-12, Standard Method of Test for Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep. AASHTO, 2016. Washington D.C.

AASHTO T 350-14, Standard method of test for multiple stress creep and recovery (MSCR) test of asphalt binder using a dynamic shear rheometer (DSR). AASHTO, 2014. Washington D.C.

Airey, G.D., Rahman, M.M. and Collop, A.C., Absorption of bitumen into crumb rubber using the basket drainage method. *International Journal of Pavement Engineering*, Vol. 4, No. 2, 2003. pp. 105-119.

Al-Khateeb, G., and Shenoy, A. A Distinctive Fatigue Failure Criterion, *Journal of the Association of Asphalt Paving Technologists*, Vol. 73, 2004. pp. 585-622.

Al-Qadi, I.L., Aurangzeb, Q., Carpenter, S.H., Pine, W.J. and Trepanier, J., *Impact of high RAP contents on structural and performance properties of asphalt mixtures*. FHWA-ICT-12-002. 2012.

Al-Qadi, I.L., Ozer, H., Lambros, J., El-Khatib, A., Singhvi, P., Khan, T., Rivera-Perez, J., and Doll, B., *Testing protocols to ensure performance of high asphalt binder replacement mixes using RAP and RAS*, Report No. FHWA-ICT-15-017, Illinois Center for Transportation, Rantoul, IL, 2015.

Anagnos, J.N. and Kennedy, T.W., *Practical method of conducting the indirect tensile test*, Center for Highway Research University of Texas at Austin. 1972.

Anderson, R.M., King, G.N., Hanson, D.I. and Blankenship, P.B., Evaluation of the relationship between asphalt binder properties and non-load related cracking. *Journal of the Association of Asphalt Paving Technologists.* Vol. 80. 2011. pp. 615-664.

Aschenbrener, T., and G. Currier. *Influence of Testing Variables on the Results from the Hamburg Wheel-Tracking Device*. Colorado Department of Transportation, CDOT-DTD-R-93-22. 1993.

Bahia, H.U. and Davies, R., Effect of crumb rubber modifiers (CRM) on performance related properties of asphalt binders. *Journal of the Association of Asphalt Paving Technology*, Vol. 63, 1994. pp. 414-414.

Bahia, H.U. and Davies, R., Factors controlling the effect of crumb rubber on critical properties of asphalt binders. *Journal of the Association of Asphalt Paving Technologists*, Vol. 64. 1995. pp. 130-162.

Barry, M.K., *An analysis of impact factors on the Illinois flexibility index test*, Master thesis, University of Illinois at Urbana–Champaign. 2016.

Bazant, Z.P. and Planas, J. *Fracture and Size Effect in Concrete and Other Quasibrittle Materials.* CRC Press, Boca, 1998.

Bennert, T., Daniel, J., and Mogawer, W., Strategies for incorporating higher RAP percentages: Review of northeast states implementation trials. *Journal of Transportation Research Board*. Vol. 2445, 2014, pp. 83-93.

Bennert, T., Haas, E. and Wass, E., Indirect Tensile Test (IDT) to Determine Asphalt Mixture Performance Indicators during Quality Control Testing in New Jersey. *Journal of the Transportation Research Board*, 2018.

Bonaquist, R., Paye, B., and Johnson C., Application of Intermediate Temperature Semi-Circular Bending (SCB) Test Results to Design Mixtures with Improved Load Associated Cracking Resistance. *Journal of the Association of Asphalt Paving Technologists*, Vol. 86. 2017. pp. 1-35.

Braham, A.F., Buttlar, W.G., Clyne, T.R., Marasteanu, M.O. and Turos, M.I., The effect of long-term laboratory aging on asphalt concrete fracture energy. *Journal of the Association of Asphalt Paving Technologists*, Vol. 78. pp. 2009, 417-454.

Buncher, M.S., *Evaluating the effects of the wet and dry processes for including crumb rubber modifier in hot mix asphalt*. Doctoral dissertation, Auburn University, 1995.

Buttlar, W.G. and Roque, R., Development and evaluation of the strategic highway research program measurement and analysis system for indirect tensile testing at low temperature. *Transportation Research Record*, Vol. 1454. 1994. pp. 163-171.

Carpenter, S.H., and Jansen, M. Fatigue Behavior Under New Aircraft Loading Conditions, *Proceedings of Aircraft Pavement Technology in the Midst of Change*, 1997. pp. 259- 271.

Chen, X., and Solaimanian, M. Simple Indices to Identify Fatigue Performance of Asphalt Concrete. *Journal of Testing and Evaluation.* Volume 48, Issue 5, 2018. ISSN 0090-3973.

Chiangmai, C.N., *Fatigue-fracture relation on asphalt concrete mixtures*, Doctoral dissertation, University of Illinois at Urbana-Champaign. 2010.

Chong, K. and Kuruppu, M.D., New specimen for fracture toughness determination for rock and other materials. *International Journal of Fracture*, Vol. 26, No. 2, 1984. pp. 59-62.

Christensen D. and Anderson D., Interpretation of Dynamic Mechanical Test Data for Paving Grade Asphalt. *Journal of the Association of Asphalt Paving Technologists*, Vol. 61, 1992, pp. 67-116.

Christensen, D.W., Bonaquist, R., and Jack, D. P., *Evaluation of Triaxial Strength as a Simple Test for Asphalt Concrete Rut Resistance*. Final Report No. 359704, Pennsylvania Department of Transportation. 2000.

Christensen Jr, D.W. and Bonaquist, R., Use of strength tests for evaluating the rut resistance of asphalt concrete. *Journal of the Association of Asphalt Paving Technologists*, Vol. 71. 2002. pp. 692-711.

Christensen, D.W. and Bonaquist, R.F., *Evaluation of indirect tensile test (IDT) procedures for low-temperature performance of hot mix asphalt*, Report No. 530. Transportation Research Board. 2004.

Cominsky, R. J., G. A. Huber, T. W. Kennedy, and M. Anderson. *The Superpave Mix Design Manual for New Construction and Overlays*. SHRP Report A-407. SHRP, National Research Council, Washington D.C. 1994.

Copeland, A., *Reclaimed asphalt pavement in asphalt mixtures: state of the practice*, No. FHWA-HRT-11-021. 2011.

D'Angelo, J. and Dongré, R., Practical use of multiple stress creep and recovery test: Characterization of styrene-butadiene-styrene dispersion and other additives in polymer-modified asphalt binders. *Journal of the Transportation Research Board*, Vol. 2126, 2009. pp.73-82.

Daniel, J.S. *Development of a simplified fatigue test and analysis procedure using a viscoelastic, continuum damage model and its implementation to Westrack mixtures*, Doctoral dissertation, North Carolina State University. 2001.

Daniel, J.S. and Kim, Y.R., Development of a simplified fatigue test and analysis procedure using a viscoelastic, continuum damage model. *Journal of the Association of Asphalt Paving Technologists*, Vol. 71, 2002. pp. 619-650.

Deacon, J.A., Coplantz, J.S., Tayebali, A.A. and Monismith, C.L., Temperature considerations in asphalt-aggregate mixture analysis and design. *Transportation Research Record*, Vol. 1454, 1994. pp. 97-112.

Di Benedetto, H., Ashayer Soltani, A. and Chaverot, P., Fatigue damage for bituminous mixtures: a pertinent approach. *Journal of the Association of Asphalt Paving Technologists*, Vol. *65*. 1996. pp 142-158.

El-Basyouny, M. and Jeong, M., Effective temperature for analysis of permanent deformation and fatigue distress on asphalt mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2127, 2009. pp.155-163.

Elwardany, M.D., Yousefi Rad, F., Castorena, C. and Kim, Y.R., Evaluation of asphalt mixture laboratory long-term ageing methods for performance testing and prediction. *Road Materials and Pavement Design*, Vol. 18, No. S1. 2017, pp. 28-61.

Epps, J.A. and Monismith, C.L., Influence of mixture variables on the flexural fatigue properties of asphalt concrete. *Journal of the Association of Asphalt Paving Technologists*. Vol. 38, 1969. pp. 423-464.

Epps, J.A. and Monismith, C.L. Fatigue of asphalt concrete mixtures - summary of existing information. *Fatigue of Compacted Bituminous Aggregate Mixtures*, ASTM STP 508, American Society for Testing and Materials, 1972, pp. 19-45.

Ghuzlan, K.A., *Fatigue damage analysis in asphalt concrete mixtures based upon dissipated energy concepts*. Doctoral dissertation, University of Illinois at Urbana-Champaign. 2001.

Ghuzlan, K.A. and Carpenter, S.H., Energy-derived, damage-based failure criterion for fatigue testing. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1723, 2000. pp. 141-149.

Hadley, W.O., Hudson, W.R. and Kennedy, T.W., *An evaluation of factors affecting the tensile properties of asphalt-treated materials*. Center for Highway Research, University of Texas at Austin. 1969.

Hadley, W.O., Hudson, W.R. and Kennedy, T.W., *A method of estimating tensile properties of materials tested in indirect tension*. University of Texas at Austin, Center for Highway Research. 1970.

Harvey, J. and Tsai, B.W., Long-term oven-aging effects on fatigue and initial stiffness of asphalt concrete. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1590, 1997. pp. 89-98.

Heitzman, M.A., Design and construction of asphalt paving materials with crumb rubber modifier. *Transportation Research Record*, Vol. 1339, 1992. pp. 1-8.

Heitzman, M.A., *State of the practice: Design and construction of asphalt paving materials with crumb-rubber modifier. Final report*. FHWA/SA--92/022. Federal Highway Administration, Washington, DC. 1992.

Hintz, C., Velasquez, R., Johnson, C. and Bahia, H., Modification and validation of linear amplitude sweep test for binder fatigue specification. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2207, 2011. pp. 99-106.

Hofman, R., Oosterbaan, B., Erkens, S.M.J.G. and van der Kooij, J., Semi-circular bending test to assess the resistance against crack growth. *6th RILEM Symposium on Performance Testing and Evaluation of Bituminous Materials*, 2003. pp. 257-263.

Hondros, G., The evaluation of Poisson's ratio and the modulus of materials of a low tensile resistance by the Brazilian (indirect tensile) test with particular reference to concrete. *Australian Journal of Applied Science*, Vol. 10, No. 3, 1959. pp. 243-268.

Hopman, P.C., Kunst, P.A.J.C. and Pronk, A.C. A Renewed Interpretation Method for Fatigue Measurements, Verificatino of Miner's Rule. *Proceedings of 4th Eurobitume Symposium in Madrid*, Vol. 1, 1989. pp. 557-561.

Huang, B., Shu, X. and Tang, Y., Comparison of semi-circular bending and indirect tensile strength tests for HMA mixtures. *Advances in Pavement Engineering*, Vol. 1, 2005. pp. 155-169.

Huang, L. Cao, K., and Zeng, M., Evaluation of semicircular bending test for determining tensile strength and stiffness modulus of asphalt mixtures. *Journal of Testing and Evaluation*, Vol. 37, No.2, 2009. pp. 1-7.

Hudson, W.R. and Kennedy, T.W., *An indirect tensile test for stabilized materials*. Center for Highway Research, University of Texas at Austin. 1968.

Im, S., Karki, P. and Zhou, F., Development of new mix design method for asphalt mixtures containing RAP and rejuvenators. *Construction and Building Materials*, Vol. 115, 2016. pp. 727-734.

Islam, M.R. and Tarefder, R.A., Study of asphalt aging through beam fatigue test. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2505, 2015. pp. 115-120.

JMP® 13 Online User Manual. http://web.archive.org/web/20180330162151/https://www.jmp.com/support/help/Technical_Details.shtml

Johnson, C.M. and H.U. Bahia. Evaluation of an Accelerated Procedure for Fatigue Characterization of Asphalt Binders. Submitted for publication in Road Materials and Pavement Design. 2010.

Johnson, E., Johnson, G., Dai, S., Linell, D., McGraw, J. and Watson, M., *Incorporation of recycled asphalt shingles in hot-mixed asphalt pavement mixtures*, No. MN/RC 2010-08, 2010.

Kaloush, K.E., Witczak, M.W., Sotil, A.C. and Way, G.B., Laboratory evaluation of asphalt rubber mixtures using the dynamic modulus (E*) test. In *82th Transportation Research Board Annual Meeting, Washington DC*. 2003.

Kaseer, F., Cucalon, L.G., Arámbula-Mercado, E., Epps Martin, A., Epps, J., "Practical Tools for Optimizing Recycled Materials Content and Recycling Agent Dosage for Improved Short- and Long-Term Performance of Rejuvenated Binder Blends and Mixtures". *Journal of Association of Asphalt Paving Technology*, Vol. 87, 2018. pp. 516-553.

Kim, Y.R., Castorena, C., Elwarny, M., Rad, F.Y., Underwood, S., Gundla, A., Gudipudi, P., Farrar, M.J., Glaser, R.R. *NCHRP Report 871: Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction*. TRB, National Research Council, Washington, D.C. 2018.

Kim, M., Mohammad, L.N., Challa, H. and Elseifi, M.A., A simplified performance-based specification for asphalt pavements. *Road Materials and Pavement Design*, Volume 16*,* Suppl 2, 2015. pp.168-196.

Kim, Y.R., *Evaluation of healing and constitutive modeling of asphalt concrete by means of the theory of nonlinear viscoelasticity and damage mechanics.* Doctoral dissertation, Texas A&M University. 1988.

Kim, Y.R., Lee, H.J. and Little, D.N., Fatigue characterization of asphalt concrete using visco-elasticity and continuum damage theory. *Journal of the Association of Asphalt Paving Technologists*, Vol. 66. 1997, pp. 520-569.

Kim, Y.R. and Little, D.N., One-dimensional constitutive modeling of asphalt concrete. *Journal of Engineering Mechanics*, Vol. 116, No. 4, 1990. pp. 751-772.

Kim, Y.R. and Wen, H., Fracture energy from indirect tension testing. *Journal of the Association of Asphalt Paving Technologists*, Vol. 71. 2002. pp.779-793.

Kutay, M., Gibson, N., Youtcheff, J. and Dongré, R., Use of small samples to predict fatigue lives of field cores: Newly developed formulation based on viscoelastic continuum damage theory. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2127, Transportation Research Board of the National Academies, Washington, D.C.,2009. pp. 90-97.

Lee, H.J. and Kim, Y.R., Viscoelastic continuum damage model of asphalt concrete with healing. *Journal of Engineering Mechanics*, Vol. 124, No. 1, pp. 1998. 43x-40.

Li, X., Marasteanu, M., Williams, R. and Clyne, T., Effect of reclaimed asphalt pavement (proportion and type) and binder grade on asphalt mixtures. *Journal of the Transportation Research Board*, Vol. 2051, 2008. pp. 90-97.

Liang, R. and Lee, S., Short-term and long-term aging behavior of rubber modified asphalt paving mixture. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1530, 1996. pp.11-17.

Lim, I.L., Johnston, I.W. and Choi, S.K., Stress intensity factors for semi-circular specimens under three-point bending. *Engineering Fracture Mechanics*, Vol. 44, No., 1993, pp.363-382.

Ling, C., Swiertz, D., Mandal, T., Teymourpour, P. and Bahia, H., Sensitivity of the Illinois Flexibility Index Test to Mixture Design Factors. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2631. 2017, pp. 153-159.

Majidzadeh, K., Kauffmann, E.M. and Ramsamooj, D.V., Application of fracture mechanics in the analysis of pavement fatigue. *Journal of the Association of Asphalt Paving Technologists*, Vol. 40. 1971. pp. 227-246.

Masad, E., Jandhyala, V.K., Dasgupta, N., Somadevan, N. and Shashidhar, N., Characterization of air void distribution in asphalt mixes using X-ray computed tomography. *Journal of materials in civil engineering*, Vol. 14, No. 2. 2002, pp. 122-129.

McDaniel, R., and Anderson, R. M., NCHRP Report 452: *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual*. TRB, National Research Council, Washington, D.C., 2001.

McDaniel, R. S., A. Shah, and G. Huber. *Investigation of Low and High Temperature Properties of Plant Produced RAP Mixtures*. Report No. FHWA-HRT-11-058. Purdue University, West Lafayette, IN. 2012.

McDaniel, R. S., H. Soleymani, R. M. Anderson, P. Turner, and R. Peterson, *Recommended Use of Reclaimed Asphalt Pavement in the SuperPave Mixture Design Method*, NCHRP Final Report (9-12), TRB, Washington, D.C., 2000.

Mogawer, W.S., Austerman, A., Roque, R., Underwood, S., Mohammad, L. and Zou, J., Ageing and rejuvenators: evaluating their impact on high RAP mixtures fatigue cracking characteristics using advanced mechanistic models and testing methods. *Road Materials and Pavement Design*, Vol. 16, Suppl. 2, 2015. pp.1-28.

Mogawer, W.S., Booshehrian, A., Vahidi, S. and Austerman, A.J., Evaluating the effect of rejuvenators on the degree of blending and performance of high RAP, RAS, and RAP/RAS mixtures. *Road Materials and Pavement Design*, Vol. 14, Suppl. 2, 2013, pp.193-213.

Mohammad, L.N., Cooper Jr, S.B. and Elseifi, M.A., Characterization of HMA mixtures containing high reclaimed asphalt pavement content with crumb rubber additives. *Journal of Materials in Civil Engineering*, Vol. 23, No. 11, 2011. pp.1560-1568.

Mohammad, L., Huang, B. and Roberts, F., Accelerated loading performance and laboratory characterization of crumb rubber asphalt pavements. *Road Materials and Pavement Design*, Vol. 1, No. 4. 2000. pp.467-493.

Mohammad, L.N., Wu, Z. and Aglan, M.A., Characterization of fracture and fatigue resistance on recycled polymer-modified asphalt pavements. *In Proceedings of the RILEM: 5th International Conference on Cracking in Pavements Mitigation, Risk Assessment and Prevention*, France, 2004, May. pp. 375-382.

Molenaar, A.A.A., Scarpas, A., Liu, X. and Erkens, S.M.J.G., Semi-circular bending test; simple but useful? *Journal of the Association of Asphalt Paving Technologists*, Vol. 71. 2002. pp. 794-815.

Monismith, C.L. and Deacon, J.A., Fatigue of asphalt paving mixtures. *Journal of the Transportation Engineering Division*, Vol. *95*, No. 2, 1969. pp. 317-346.

Monismith, C.L., Epps, J.A., and Finn, F.N., Improved asphalt mix design. *Journal of the Association of Asphalt Paving Technologists*, Vol. 54. 1985. pp. 340-406.

Mull, M.A., Stuart, K. and Yehia, A., Fracture resistance characterization of chemically modified crumb rubber asphalt pavement. *Journal of materials science*, Vol. 37, No. 3, 2002. pp. 557-566.

Neto, S.A.D., Farias, M.M., Pais, J.C., Pereira, P.A. and Sousa, J.B., Influence of crumb rubber and digestion time on the asphalt rubber binders. *Road materials and pavement design*, Vol. 7, Issue. 2, 2006. pp. 131-148.

Nsengiyumva, G., *Development of Semi-Circular Bending (SCB) Fracture Test for Bituminous Mixtures*, Master Thesis. University of Nebraska Lincoln, Lincoln, NE, 2015.

Ozer, H., Al-Qadi, I., Kanaan, A. and Lippert, D., Performance characterization of asphalt mixtures at high asphalt binder replacement with recycled asphalt shingles. *Journal of the Transportation Research Board*, Vol. 2371, 2013. pp. 105-112.

Ozer, H., Al-Qadi, I.L., Lambros, J., El-Khatib, A., Singhvi, P. and Doll, B., Development of the fracture-based flexibility index for asphalt concrete cracking potential using modified semi-circle bending test parameters. *Construction and Building Materials*, Vol. 115, 2016. pp.390-401.

Ozer, H., Al-Qadi, I.L., Singhvi, P., Khan, T., Rivera-Perez, J. and El-Khatib, A., Fracture characterization of asphalt mixtures with high recycled content using Illinois semicircular bending test method and flexibility index. *Journal of the Transportation Research Board*, Vol. 2575, 2016. pp.130-137.

Park, S.W., Kim, Y.R. and Schapery, R.A., A viscoelastic continuum damage model and its application to uniaxial behavior of asphalt concrete. *Mechanics of Materials*, Vol. 24, No. 4, 1996. pp. 241-255.

Paris, P.C. and Erdogan, F., A critical analysis of crack propagation laws. *Journal of basic engineering*, Vol. 85, No. 4, 1963. pp. 528-533.

Pell, P.S. and Cooper, K.E., The effect of testing and mix variables on the fatigue performance of bituminous materials. *Journal of the Association of Asphalt Paving Technologists*, Volume. 44, 1975. pp.1-37.

Pronk, A.C., and Hopman, P.C., Energy Dissipation: The Leading Factor of Fatigue. In *Highway Research: Sharing the Benefits: Proceedings of a Conference of the United States Strategic Highway Research Program*, London, 1991, pp. 255-267.

Putman BJ, Amirkhanian SN. Crumb rubber modification of binders: interaction and particle effects, *Proceedings of Asphalt Rubber,* Asphalt Rubber 2006, Palm Springs, CA.

Raad, L. and Saboundjian, S., Fatigue behavior of rubber-modified pavements. *Transportation research record: journal of the transportation research board*, Vol. 1639, 1998. pp. 73-82.

Raad, L., Saboundjian, S. and Minassian, G., Field aging effects on fatigue of asphalt concrete and asphalt-rubber concrete. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1767, 2001. pp. 126-134.

Reese, R. Properties of Aged Asphalt Binder Related to Asphalt Concrete Fatigue Life, *Journal of the Association of Asphalt Paving Technologists*, Vol. 66, 1997. pp. 604-632.

Reinke, G. and Glidden, S., Development of Mixture Creep Performance Tests Using a Dynamic Shear Rheometer. *TRB E-Circular E-C068 New Simple Performance Tests for Asphalt Mixes*, 2004. pp.1-44.

Rice, J.R. A Path Independent Integral and Approximate Analysis of Strain Concentration Notches and Cracks. *Journal of Applied Mechanics*, Vol. 35, 1968.

Roque, R. and Buttlar, W.G., The development of a measurement and analysis system to accurately determine asphalt concrete properties using the indirect tensile model. *Journal of the Association of Asphalt Paving Technologists*, Vol. 61. 1992. pp. 304-332.

Roque, R., Zhang, Z., and Sankar, B., Determination of crack growth rate parameters of asphalt mixtures using the Superpave lDT. *Journal of the Association of Asphalt Paving Technologists,* Vol. 68. 1999. pp. 404-433.

Rowe, G.M., Performance of asphalt mixtures in the trapezoidal fatigue test. *Journal of the Association of Asphalt Paving Technology*, Vol. 62, 1993. pp. 344-344.

Rowe, G.M., Prepared Discussion for the AAPT paper by Anderson et al.: Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking, *Journal of the Association of Asphalt Paving Technologists*, 80, 2011. pp. 649-662.

Rowe, G.M. and Bouldin, M.G. *Improved Techniques to Evaluate the Fatigue Resistance of Asphaltic Mixtures*, Proceedings of 2nd Eurasphalt & Eurobitume Congress, Book 1, Barcelona, Spain, 2000. pp. 754-763.

Sabouri, M., T. Bennert, J.S. Daniel, and Y.R. Kim., A Comprehensive Evaluation of the Fatigue Behavior of Plant-Produced RAP Mixtures. *Road Materials and Pavement Design*, Vol. 16, Suppl. 2, 2015, pp. 29-54.

Sabouri, M. and Kim, Y., Development of a failure criterion for asphalt mixtures under different modes of fatigue loading. *Transportation Research Record: Journal of the Transportation Research Board*, Volume. 2447, 2014. pp. 117-125.

Saha, G. and Biligiri, K.P., Fracture properties of asphalt mixtures using semi-circular bending test: A state-of-the-art review and future research. *Construction and Building Materials*, Vol. 105, 2016. pp. 103-112.

Schapery, R.A., A micromechanical model for non-linear viscoelastic behavior of particle-reinforced rubber with distributed damage. *Engineering Fracture Mechanics*, Vol. 25, No. 5-6, 1986. pp. 845-867.

Schapery, R.A., Correspondence Principles and a Generalized J Integral for Large Deformation and Fracture Analysis of Viscoelastic Media, *International Journal of Fracture*, Vol. 25, 1984. pp. 195-223.

Shen, J., Amirkhanian, S., Lee, S.J. and Putman, B., Recycling of laboratory-prepared reclaimed asphalt pavement mixtures containing crumb rubber-modified binders in hot-mix asphalt. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1962, 2006. pp. 71-78.

Shen, S. *Dissipated Energy Concepts for HMA Performance: Fatigue and Healing*, Ph.D. Dissertation, University of Illinois at Urban-Champaign, IL, 2006.

Shen, S., Airey, G.D., Carpenter, S.H. and Huang, H., A dissipated energy approach to fatigue evaluation. *Road materials and pavement design*, Vol. 7, No. 1, 2006. pp. 47-69.

Shen, S. and Carpenter, S.H., Application of the dissipated energy concept in fatigue endurance limit testing. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1929, 2005. pp. 165-173.

SHRP A-404, *Fatigue Response of Asphalt-Aggregate Mixes*. Asphalt Research Program, Institute of Transportation Studies, University of California, Berkeley. Strategic Highway Research Program, National Research Council. 1994.

Shu, X., Huang, B. and Vukosavljevic, D., Laboratory evaluation of fatigue characteristics of recycled asphalt mixture. *Construction and Building Materials*, Vol.22, No.7, 2008. pp.1323-1330.

SHRP A-404, *Fatigue Response of Asphalt-Aggregate Mixes*. Asphalt Research Program, Institute of Transportation Studies, University of California, Berkeley. Strategic Highway Research Program, National Research Council. 1994.

Smit, A., Van de Ven, M.F.C. and Fletcher, E., Towards the Use of the Semi-Circular Bending Test as a Performance Related Specification Test. *South African Transport Conference, Johannesburg, Republic of South Africa,* Vol. 3. 1997.

Solaimanian, M. and Chen, X. Effect of Aging and Compaction Magnitude on Swelling Characteristics of Rubber Modified Asphalts. *Proceedings of the Canadian Society for Civil Engineering Annual Conference*, 2018. Paper No. MA28.

Soltani, A. and Anderson, D.A., *Uniaxial Fatigue of Asphalt Mixes: A New Approach*. Final Report. FHWA-PA-2003-019-97-04 (20). Pennsylvania Transportation Institute. 2005.

Takallou, H., Hussain Bahia, Dario Perdomo, and Robert Schwartz. Use of Superpave technology for design and construction of rubberized asphalt mixtures. *Transportation Research Record: Journal of the Transportation Research Board,* Vol. 1583, 1997. pp. 71-81.

Tangella, S. C., Craus, J., Deacon, J. A., and Monismith, C. L., *Summary Report on Fatigue Response of Asphalt Mixtures*. SHRP-A/IR-90-011. Institute of Transportation Studies, University of California, Berkeley. 1990.

Tayebali, A.A., Deacon, J.A., Coplantz, J.S. and Monismith, C.L., Modeling fatigue response of asphalt-aggregate mixtures. *Journal of the Association of Asphalt Paving Technologists*, Vol. 62. 1993. pp. 385-421.

Tayebali, A.A., Rowe, G.M., and Sousa, J.B., Fatigue response of asphalt-aggregate mixtures. *Journal of the Association of Asphalt Paving Technologists*, Vol. 61. 1992. pp. 333-360.

Timm, D.H., West, R.C. and Taylor, A.J., Performance and Fatigue Analysis of High Reclaimed Asphalt Pavement Content and Warm-Mix Asphalt Test Sections. *Transportation Research Record: Journal of the Transportation Research Board*, Volume. 2575, 2016. pp. 196-205.

Tseng, K.H. and Lytton, R.L., Fatigue damage properties of asphalt concrete pavements, *Transportation Research Record*, Vol. 1286. 1990. pp. 150-163.

Underwood, B.S., A continuum damage model for asphalt cement and asphalt mastic fatigue. *International Journal of Fatigue*, Vol. 82, 2016. pp. 387-401.

Underwood, B.S., Kim, Y.R. and Guddati, M.N., Improved calculation method of damage parameter in viscoelastic continuum damage model. *International Journal of Pavement Engineering*, Vol. 11, No. 6, 2010. pp. 459-476.

Underwood, B., Baek, C. and Kim, Y., 2012. Simplified viscoelastic continuum damage model as platform for asphalt concrete fatigue analysis. *Transportation Research Record: Journal of the Transportation Research Board*, (2296), pp.36-45.

van de Ven, M., Smit, A.D.F. and Krans, R.L., Possibilities of a semi-circular bending test. *Eighth International Conference on Asphalt Pavements*. Vol. II. 1997. pp. 939-950.

Van Dijk, W., Moreaud, H., Quedeville, A. and Uge, P., September. The fatigue of bitumen and bituminous mixes. In *Presented at the Third International Conference on the Structural Design of Asphalt Pavements, Grosvenor House, Park Lane, London, England, Sept. 11-15, 1972.* (Vol. 1, No. Proceeding).

Van Dijk, W., Practical fatigue characterization of bituminous mixes. *Journal of the Association of Asphalt Paving Technologists*, Vol. 44, 1975. pp. 38-72.

Van Dijk, W. and Visser, W., The Energy Approach to Fatigue for Pavement Design. *Journal of the Association of Asphalt Paving Technologists,* Vol. 46. 1977. pp. 1-40.

Walubita, L.F., Jamison, B.P., Das, G., Scullion, T., Martin, A.E., Rand, D. and Mikhail, M., Search for a laboratory test to evaluate crack resistance of hot-mix asphalt. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2210, No. 1, 2011. pp.73-80.

Venudharan, V., Biligiri, K.P., Sousa, J.B. and Way, G.B., Asphalt-rubber gap-graded mixture design practices: a state-of-the-art research review and future perspective. *Road Materials and Pavement Design*, Vol. 18, Issus 3, 2017. pp. 730-752.

Wen, H., *Fatigue performance evaluation of WesTrack asphalt mixtures based on viscoelastic analysis of indirect tensile test*. Doctoral dissertation, North Carolina State University. 2001.

West, R., Willis, J.R. and Marasteanu, M., *NCHRP Report 752: Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content*. TRB, National Research Council, Washington, D.C. 2013.

Wijk, G., August. Some new theoretical aspects of indirect measurements of the tensile strength of rocks. In *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, Vol. 15, No. 4, 1978. pp. 149-160.

Wu, Z., Mohammad, L.N., Wang, L.B., and Mull, M.A., Fracture resistance characterization of superpave mixtures using the semi-circular bending test. *Journal of ASTM International*, Vol. *2*, No. 3, 2005. pp.1-15.

Xiao, F., Zhao, P.W. and Amirkhanian, S.N., Fatigue behavior of rubberized asphalt concrete mixtures containing warm asphalt additives. *Construction and Building Materials*, Vol. 23, No. 10, 2009. pp. 3144-3151.

Xie, Z., Turner, P., Taylor, A., Tran, N., McCurdy, A., Laboratory Evaluation of Performance Properties of Asphalt Binders and Mixes Containing a New Rejuvenator. *Journal of Association of Asphalt Paving Technology*. Vol. 87, 2018. pp. 614-646.

Yan, Y., Roque, R., Cocconcelli, C., Bekoe M, Lopp, G., Evaluation of cracking performance for polymer-modified asphalt mixtures with high RAP content. *Road Materials and Pavement Design*, Vol. 18 Suppl. 1, 2016, pp. 450-470.

Zeiada, W., *Endurance limit for HMA based on healing phenomenon using viscoelastic continuum damage analysis*, Doctoral dissertation, Arizona State University, 2012.

Zhang, J., Sabouri, M., Guddati, M.N. and Kim, Y.R., Development of a failure criterion for asphalt mixtures under fatigue loading. *Road Materials and Pavement Design*, Volume *14*, 2013. pp. 1-15.

Zhou, F., Hu, S., Das, G., Lee, R., Scullion, T. and Claros, G., Successful high RAP mixes designed with balanced rutting and cracking requirements. *Journal of the Association of Asphalt Paving Technologists*, Vol. 81. 2012. pp. 477-506.

Zhou, F., Im, S., Hu, S., Newcomb, D. and Scullion, T., Selection and preliminary evaluation of laboratory cracking tests for routine asphalt mix designs. *Road Materials and Pavement Design*, Vol. 18, Sup11, 2017. pp.62-86.

Zhou, F., Im, S., Morton, D., Lee, R., Hu, S. and Scullion, T., Rejuvenator characterization, blend characteristics, and proposed mix design method. *Journal of Association of Asphalt Paving Technology*, Vol. 84, 2015. pp.675-704.

Zhou, F., Li, h., Hu, S., Lee, R., Scullion, T., Claros, G., Epps, J., Button, J., Evaluation of use of recycled asphalt shingles in HMA, *Journal of Association of Asphalt Paving Technology*. Vol. 82, 2013. pp. 367-402.

Zhou, F., Hu, S., Scullion, T., Mikhail, M. and Walubita, L.F., A balanced HMA mix design procedure for overlays (with discussion*). Journal of the Association of Asphalt Paving Technologists*, Vol. 76. 2007. pp. 823-850.

VITA

Xuan Chen

Xuan Chen was born and raised in Yueyang, China where he attended Yingshan elementary school and later attended Baling middle school. Xuan started his high school life at Yueyang No. 1 high school in 2006, then transferred to Hainan high school a year later. After graduating from high school in 2009, he continued his education at the Southeast University, one of the best engineering schools in China, where he studied highway and bridge engineering. At Southeast University, Xuan worked for Dr. Jun Yang during his senior year to investigate the mechanical properties of high modulus asphalt mixes. In August 2013, two months after he received his Bachelor of Science degree, he began graduate school at the Pennsylvania State University, then started working under the advisory of Dr. Mansour Solaimanian in April 2014. Xuan received his Master of Science degree in May 2015 and continued his research with Dr. Solaimanian in characterizing fracture properties of asphalt mixes and exploring performance based balanced mixture design.