CRACKING PERFORMANCE EVALUATION OF MINNESOTA ASPHALT PAVEMENTS

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DEDICATION

I'd like to dedicate this thesis to my sister, Kallie, for her immeasurable support and encouragement for me to pursue my goals.

ABSTRACT

Thermal cracking is the most prevalent distress for asphalt roadways in Minnesota. The cracks form pathways for water to permeate into the pavement structure degrading its integrity and shortening the life span. This thesis investigates asphalt mixture design parameters and laboratory tests measures of 25 pavement sections on 18 highways in Minnesota to draw conclusions on how these parameters relate to transverse cracking performance. The results showed that the coarse gradation of asphalt mixes currently being used by MnDOT typically have higher permeability rates than the typical range for dense graded asphalt mixtures, which makes these pavement sections more susceptible to moisture-induced damage.

Next, this study analyzed the transverse and longitudinal field cracking performance of 295 pavement sections on 28 highways with respect to their asphalt binder type and polymer modification. The effect of asphalt binder type and modification was compared to field cracking performance in relation to construction type, asphalt binder supplier, and dynamic shear rheometer parameters: phase angle and dynamic shear modulus. The polymer-modified PG58-34 binder performed better than the non-polymer modified version.

The last part of this thesis evaluated the sensitivity of flexible pavement thermal cracking performance to variations in disk-shaped compact tension (DCT) fracture energy. This study included nearly 200 simulations representing combinations of 3 climates, 3 asphalt thicknesses, 3 asphalt mixtures and 6 fracture energy levels. The motivation of this work was to investigate the sensitivity to the 400 J/m^2 threshold that is being used in the implementation of the DCT performance test specification. It is concluded from this study that variation of 25 J/m^2 is enough to show a difference in cracking performance..

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CHAPTER 1: INTRODUCTION, BACKGROUND AND LITERATURE REVIEW

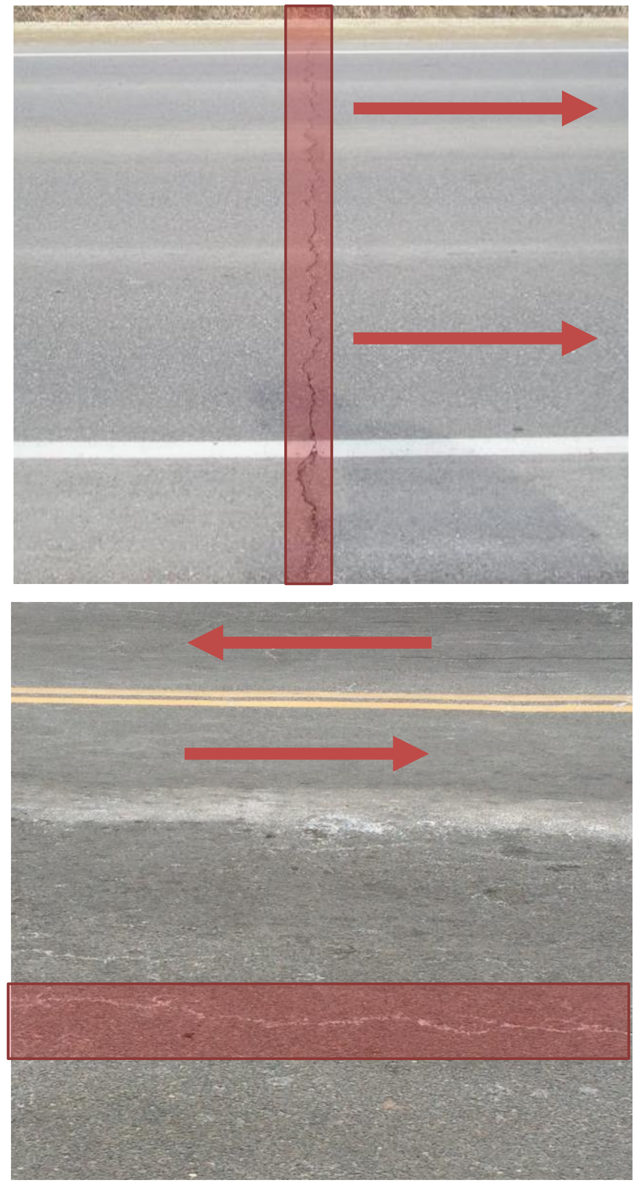
1.1 Introduction

The predominant failure mode of asphalt pavements in Minnesota, and other northern climates, is thermal cracking [1]. Thermal cracking in asphalt pavements has been a recognized issued and heavily researched over the last 10 years. This chapter discusses the mechanisms behind thermal cracking and also the current and future of specifications to negate thermal cracking. In order to effectually evaluate cracking performance and the state of the highway infrastructure, pavement performance data from MnDOT pavement management system database was utilized in this study. The pavement management system (PMS) data is discussed in this chapter. Lastly, the scope and organization of this thesis are presented.

1.2 Literature Review and Background

1.2.1 Cracking Types and Mechanisms

Three types of cracking will be discussed: longitudinal cracking, and thermal and reflective cracking which occur in the transverse direction (perpendicular to the centerline of the roadway). Thermal cracking is top-down cracking of the asphalt layer caused by extreme low temperatures and/or rapid temperature drop. Thermal tensile stresses build up in the continuous asphalt concrete layer as the top of the asphalt layer contracts. Once the tensile stresses exceed the stress threshold for damage initiation the thermally induced stresses are relieved by crack formation. These transverse cracks enable water to flow past the asphalt layer and into the pavement structure leading to degradation of the pavement system. Often times, thermal cracks substantially contribute to the roughness of the pavement due to degradation of asphalt mix near the crack. This results in downward and upward heaves at the transverse crack locations. Reflective cracking also occurs in the transverse direction and is often confused with thermal cracking. Reflective cracks are those that occur in the asphalt overlay directly over the existing cracks and joints due to differential movement between the existing asphalt or concrete pavement and the overlay at the crack locations. The last cracking type discussed here is the longitudinal crack which occurs in the direction of traffic or parallel to the centerline of the roadway. Longitudinal cracking can result from several circumstances including construction joints, reflective cracking and fatigue. Typical transverse and longitudinal cracking on an asphalt pavement in Minnesota is provided in Figure 1, where the arrows represent the direction of traffic.



(a) Transverse (Thermal) Crack (b) Longitudinal Crack

Figure 1: Typical Cracking Types of Asphalt Concrete Pavement

The current national standard used to control low-temperature cracking of asphalt pavements is the Superpave specification which was developed as a part of the Strategic Highway Research Program (SHRP). The Superpave performance grade (PG) binder specifications attempt to control thermal cracking by specifying the low temperature asphalt binder grade. Most commonly used low temperature asphalt binder grades for Minnesota pavements are typically -28°C or -34°C (-18°F to -29°F); these have not shown to effectively lower the amount off thermal cracking. Additionally, throughout the evolution of asphalt pavements, asphalt binders and mixtures have changed to the point where they are no longer adequately characterized by these specifications [2]. Simply specifying a low-temperature binder grade does not account for the recent polymer-modification of binders and the various complex properties of an asphalt mixture (aggregate type, gradation, warm-mix technologies, recycled asphalt materials, etc.). Research has showed that low temperature cracking cannot be characterized by asphalt binder alone [3].

1.2.2 Factors Affecting Pavement Cracking Performance

Previous research by Dave and Hanson (2013) compiled thousands of mix design records and data from separate databases for roadways in Minnesota. With this data, a statistical analysis was conducted to make conclusions regarding what asphalt mixture design parameters most greatly affect transverse cracking performance on Minnesota highways. The two parameters showing potential correlation to cracking performance were asphalt content and PG spread. PG spread is defined as the difference between the high and low temperature for a PG binder grade. For example, the PG spread of a PG58-34 binder is 92°C. Additionally, it was also found that relying on volumetric properties such as asphalt content and PG spread, alone are inadequate for achieving good thermal cracking performance [4].

1.2.3 Summary of Performance Test Implementation

A low temperature cracking asphalt mixture performance specification was developed through the two phases of the pooled fund study on low temperature cracking [2], [3] and have been further refined through other research projects [5], [6]. In Minnesota, there has been an ongoing effort to incorporate performance testing into the asphalt roadway design process. Several performance tests have been analyzed to characterize thermal cracking performance and the use of fracture tests was recommended [5]. The pooled fund study, as well as subsequent research studies have shown that fracture energy of asphalt mixture correlates well with the field cracking performance. This study also provided recommendations for use as a performance specification for new asphalt roadway construction in the state of Minnesota beginning in 2016 [5].

These performance-based specifications utilize the fracture energy of the asphalt mixes, measured using the disk-shaped compact tension (DCT) test, as performance parameter. The DCT test for determination of asphalt mixture fracture energy is standardized by the ASTM D7313 test specification [7]. In previous research efforts, the mixes with fracture energies above 400 J/m^2 presented minimal thermal cracking as opposed to mixes below this threshold [3]. MnDOT conducted a pilot implementation of the aforementioned performance-based specifications beginning in the 2013 construction season that required asphalt mixtures to have a minimum of 400 J/m^2 fracture energy [8]. During the mixture design process for these pilot studies, mixtures with inadequate fracture performance were re-designed with the recommendation of using a binder with a lower low-temperature binder grade and/or use of less recycled asphalt pavement (RAP) [9]. Continued implementation of the fracture energy requirement is underway and it is targeted to become a standard practice for Minnesota highways in 2016. Other agencies have also undertaken similar efforts including a number of Wisconsin Department of Transportation (WisDOT) highway construction projects during 2014 have introduced a minimum DCT fracture energy requirement.

As a part of developing this specification, the question regarding sensitivity of thermal cracking performance to variations in fracture energy arose. It is important to determine the extent of sensitivity associated with the 400 J/m^2 threshold value. In other words, at present the implications in terms of low temperature cracking performance of asphalt mixtures for deviations from the 400 J/m^2 are not known and quantified. One of the objectives of this thesis is to quantify the sensitivity of an asphalt mix's thermal cracking performance to variation in its DCT fracture energy (Or to answer a very commonly posed question: Are asphalt mixtures with a fracture energy of 375 J/m^2 expected to have significantly different thermal cracking performance as compared to one with 400 J/m^2?) [10].

1.2.4 Impact of Lower Asphalt Binder for Coarse Hot Mix Asphalt Mixes

This thesis also investigates the performance of flexible pavements constructed using asphalt mixes with lower binder content. Another property of lower asphalt binder mixes is that they tend to have coarser gradations as compared to traditional asphalt mixtures. The coarse gradation is relative to the MnDOT Standard Specification 3139 [11]. Recently, MnDOT has seen an increase in coarse gradation hot mix asphalt mixtures (HMA) with lower asphalt binder content. It is known that coarse gradation mixtures commonly have larger interconnected void spaces, compared to more fine-graded mixtures [12]. A study by Cooley, et al. (2002), investigated the role of excess void space in the durability of the pavement. This study found that coarse-graded asphalt mixes are susceptible to higher field permeability. It is believed that the increased permeability makes the pavement more susceptible to moisture damage. This study showed that permeability, over a mixture's air content, is more indicative of durability [13].

Several factors have been shown to influence the permeability of pavement. A study by Ford and McWilliams (1998) on asphalt mix permeability showed aggregate particle size distribution, aggregate particle shape, and pavement density effect the permeability of a mix [14]. Another study found the size of the air voids in the pavement are more indicative than the total percentage of air in a mixture [15].

The use of performance measures as part of a material acceptance procedure is continually rising in the field of pavement materials [5]. The use of performance measures as part of a material acceptance procedure is continually rising in the field of pavement materials [16]. This is partly driven by increased use of atypical materials. Good examples for atypical materials in asphalt mixtures include: highly recycled asphalt materials, warm-mix asphalt and alternative asphalt binder sources, such as bio-binders. Uses of performance based specifications require a reliable laboratory measured parameter that is capable of predicting in-service pavement performance. A number of laboratory tests have been developed to provide insight into in-service thermal cracking performance of asphalt mixtures. In order to evaluate thermal cracking performance on a vast scale (statewide), pavement management systems are utilized.

1.2.5 Overview of Laboratory Tests

1.2.5.1 Laboratory Permeability Test

Permeability testing using the falling head method was conducted on the field cores of wear courses with the concern that the coarser gradation of the asphalt mixtures could allow for more water to permeate the pavement surface and lead to degradation and pavement longevity issues. The permeability of asphalt mixtures has been hypothesized to have significant effect on the durability and performance. The cause of high permeability is primarily presence of interconnected voids. The use of permeability over air void level has been recommended by researchers in past as a better measure of asphalt mixture durability [13]. The typical permeability of asphalt permeability has been presented by Cooley et al. (2002); this information is presented in . In the present study, the permeability was measured using the Karol-Warner Permeameter, also commonly referred to as the Florida DOT (FLDOT) lab permeability measurement device. An image of the permeameter as well as the schematic is provided in . The procedure described in the Florida DOT test specification FM 5-565 [17] was followed in the current study. These procedures utilize Darcy’s law for measurement of the asphalt mixture’s hydraulic conductivity or permeability.

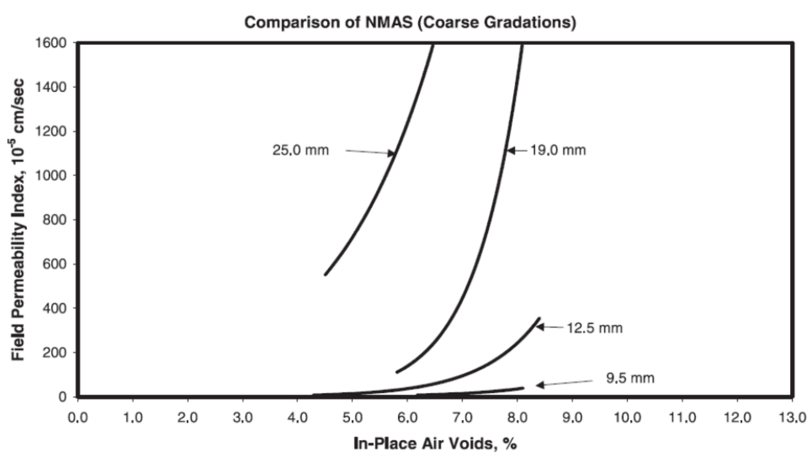


Figure 2: Comparison of In-place Air Voids and Permeability of Asphalt Mixtures (from Cooley et al., 2002)

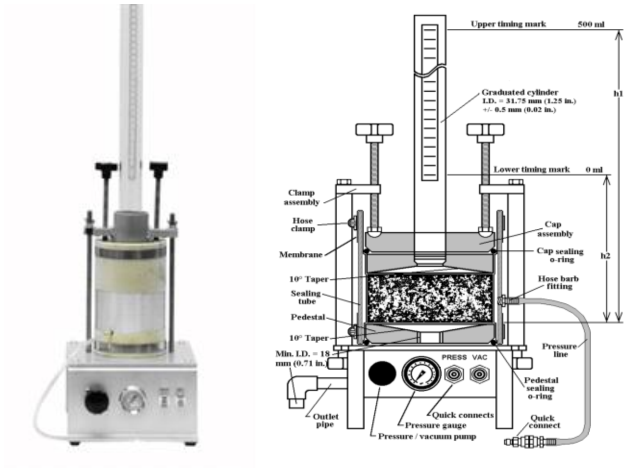


Figure 3: Karol-Warner Permeameter (from Gilson Global [18])

1.2.5.2 Disk-shaped Compact Tension Test

The disk-shaped compact tension test is a method to measure the fracture energy of an asphalt mixture. It is currently being used as a thermal cracking performance test by quantifying the resistance a mixture has to fracture while conditioned to a representative atmospheric temperature. It measures the amount of work required to fracture an asphalt core along a fabricated notch in the specimen. The testing procedure used is specified by ASTM D7313-13.

The specimens used in this study came from field cores, however can also be formed using a gyratory compactor. The test specimen geometry is shown in Figure 4. Once the specimens are prepared, they are temperature conditioned to the temperature 10°C warmer than the binder PG low-temperature by the Superpave PG system at 98% reliability. For example, when testing a specimen with a PG58-34 binder, the specimen was tested at -24°C. The testing temperature was determined using LTPPBind software. Before testing, the specimen is conditioned in a temperature controlled chamber for a minimum of 2 hours and a maximum of 8 hours. Once the specimen is at the specified temperature, it is placed into the environmentally controlled chamber with the load cell (), and is tested by maintaining a constant crack mouth opening displacement (CMOD) of 0.0017 mm/s throughout the applied tensile loading of the specimen.

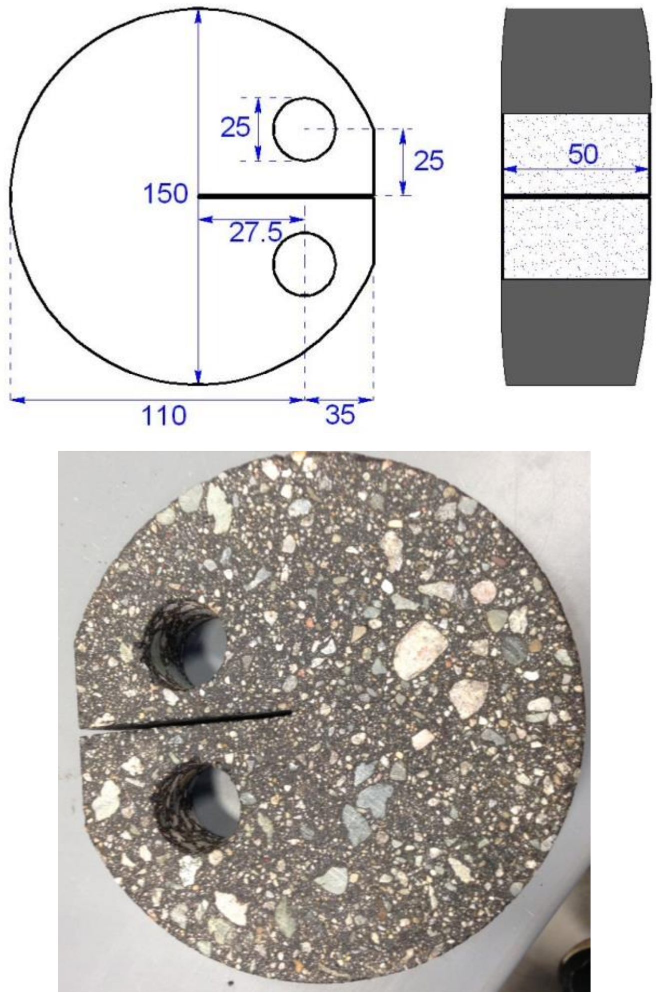


Figure 4: (a) Disk-shaped Compact Tension Specimen Geometry (Dimensions in mm);
(b) Prepared DCT Specimen

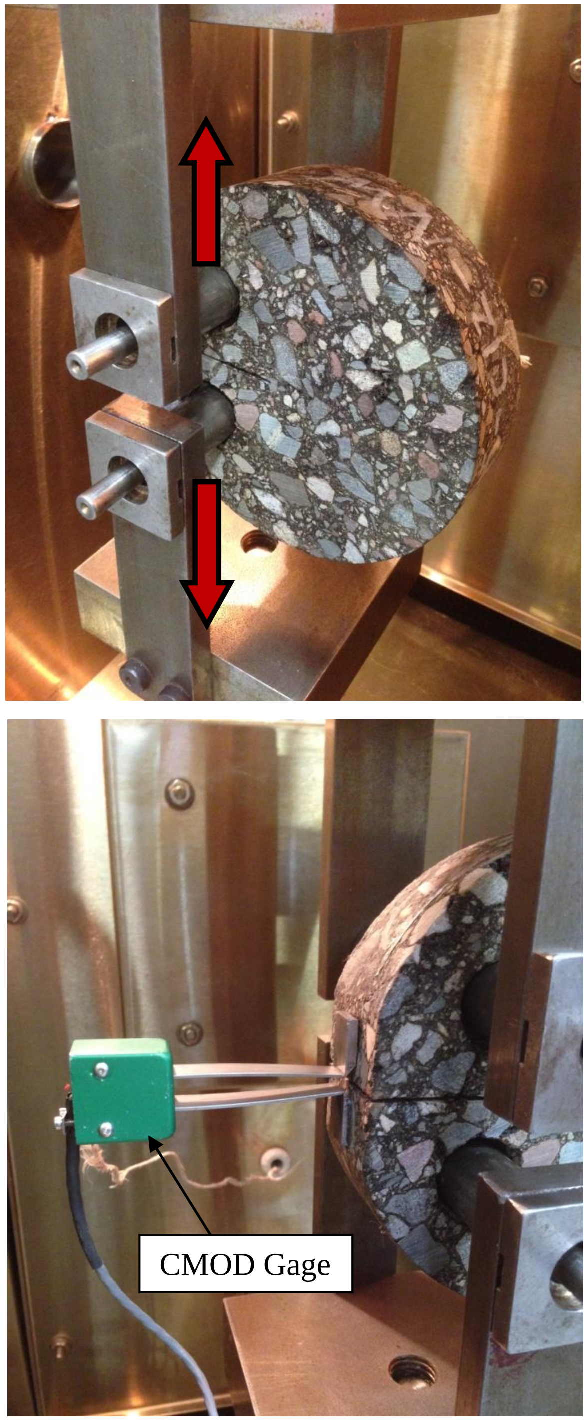


Figure 5: (a) DCT Specimen Mounted onto Apparatus; (b) CMOD Gage Clipped to DCT Specimen

The amount of work required to fracture the sample from the prefabricated notch onward represents the fracture energy. The data acquisition system records the CMOD, as well as the load being applied. The area under the load versus CMOD curve is used to calculate the fracture energy. This value is then normalized by the fractured area which is the ligament length, or length of fracture, multiplied by the thickness of the specimen.

1.2.5.3 Asphalt Content and Gradation

The amount of asphalt binder is often associated with cracking performance of asphalt pavements. The asphalt mixture specimens that were used for fracture energy with the DCT test, were further tested using the ignition oven following the AASHTO T308 test procedure [19]. The test resulted in measurement of the approximate asphalt content in the mixture. The residue from this testing was used to conduct a washed aggregate gradation following the AASHTO T27 test procedure [20]. Approximately half of the DCT specimens post-testing were tested to obtain the asphalt content and aggregate gradation. It should be noted that the measured asphalt content using the ignition oven test requires calibration of the ignition oven through use of chemical extraction process. This was not within the scope of current study hence the ignition oven measured asphalt contents should be treated as approximate asphalt contents.

1.2.5.4 Dynamic Shear Rheometer

The dynamic shear rheometer (DSR) is an asphalt binder test that is used to characterize the resistance to an applied load under the binder’s high temperature. For example, the PG58-34 binders were tested at 58°C and PG64-28 binders were tested at 64°C. The test has two parallel metal plates oriented so a thin asphalt binder specimen is placed between the plates. The test is conducted by applying a sinusoidal oscillating load to one plate at certain frequencies and rotational deformation amplitudes. The test produces two measured parameters that are calculated automatically with the data acquisition software: phase angle (δ) and dynamic shear modulus (G*). The phase angle and dynamic shear modulus measure the resistance to shear deformation of the binder. These parameters are used to grade both aged and un-aged asphalt binders according to the standard specification for performance-graded asphalt binder (AASHTO M 320) [21]. It is typical for polymer modified asphalt binder to have a higher complex modulus and lower phase angle as compared to neat binders [22].

1.2.6 Pavement Management Systems for Cracking Data Collection

Pavement management systems (PMS) take several years to develop and implement. As these systems are continuously developing, they are becoming a new way to indicate pavement performance. The Minnesota Department of Transportation (MnDOT) uses a van-mounted automated collection system for pavement condition surveys [23]. PMS data is a source of both pavement section characteristics and distress data. MnDOT collects data annually, however only gets data for any given pavement section about every other year due to amount of highways in Minnesota. The data contained within the PMS database varies based upon by the developmental agency.

The PMS data is organized first by state project number (SP), next by highway, and then each highway is further broken down into distinct "sections" defined by a start and end reference post. The purpose of having a highway broken into sections is to separate areas with different roadway characteristics, such as lane geometry, drainage characteristics, pavement structure, intersections, traffic level, etc. Although the distress information in the PMS data includes quantified amounts of transverse, longitudinal, and fatigue cracking; rutting; patching; and longitudinal joint deterioration, due to the scope of this study, only transverse and longitudinal cracking counts were utilized. The transverse cracking counts in the PMS data is collected based on the severity of the cracks; low, medium and high. For each severity level, the data is reported in terms of percent cracking (% cracking) which is calculated as 2 times the number of cracks per 150 m (500 ft) length of the survey section. In other words, 75 m (250 ft) of cracking per 150 m (500 ft) of section length equates to 100 percent cracking. The total cracking amounts for a given PMS section for each year of distress survey can be used to calculate additional cracking measures that are representative of field cracking performance. The downfall of the automated collection system is that especially for transverse cracking, it does not discriminate between types of transverse cracking such as thermal and reflective cracking.

A new state project number is assigned to each section within a project each time a major construction or maintenance and rehabilitation (M&R) activity occurs. These activities in this study include thin, medium, and thick overlays (OL) or mill and overlays (M&OL); full-depth reclamation (Reclaim or FDR); and bituminous on aggregate base construction in rural areas (BAB Rural), as shown in the table. However, it is worth noting a new SP number is not assigned when there are pavement preservation activities such as chip seals, crack sealing, or microsurfacing.

Good preventative maintenance of roadways often call for these activities to occur multiple times throughout the pavement life in order to get the best pavement performance for the overall pavement performance life investment. Due to the scope of this project, considering the impact of each pavement preservation activity on the cracking performance throughout the life of each pavement was not directly analyzed. However this is reflected in our study in the sense that often times the automated data distress survey collection sees a decrease in cracking counts after these activities are performed.

1.3 Thesis Scope and Organization

This thesis is divided into three main parts. The purpose for conducting part one of this study was twin fold. The first reason was to investigate the relationship between asphalt mixture volumetric and design properties with field transverse cracking performance and the second was to investigate the impact of coarse gradation low asphalt binder mixtures that are currently being used by the MnDOT, on field performance. The first step in the study was to conduct a laboratory characterization of 25 pavement sections in Minnesota (Chapter 2), and second was to evaluate the transverse cracking performance of those sections to ultimately compare the laboratory results to the transverse field cracking performance (Chapter 3). This study was needed in order to evaluate and quantify how a mixture’s volumetric and mechanical properties affects pavement service life.

The second part investigates 295 pavement sections for the effect of polymer modified asphalt binders on both transverse and longitudinal cracking performance (Chapter 4). The general approach taken to investigate these questions included first identifying a number of pavement study sections. These locations were chosen to capture a variety of variables: asphalt mixtures, asphalt binder types, aggregate type, pavement structure and climate. Next, PMS data was obtained from MnDOT to have historical pavement distress data to utilize as a performance indicator. The crack counts provided by MnDOT's PMS data, were then converted into various cracking measures to quantify pavement performance in multiple perspectives.

The last portion was contribution towards the disk-shaped compact tension specification implementation (Chapter 5). As mentioned previously, the threshold of 400 J/m^2 for fracture energy tends to be the difference between good and poor performing pavement sections. To implement the specification it is necessary to answer the following question: Is an asphalt mixture with a fracture energy of 375 J/m^2 expected to have a significantly different thermal cracking performance as compared to a mixture with 400 J/m^2. This was investigated utilizing IlliTC, a thermal cracking simulation software, to predict thermal cracking performance of various different scenarios. The simulations included testing all combinations of 3 Minnesota climates (warm, intermediate and cold), 3 asphalt thicknesses, and 3 asphalt mixtures typical in Minnesota; at 6 different fracture energy values to gain insight to the sensitivity of thermal cracking performance to fracture energy variation.

CHAPTER 2: LABORATORY CHARACTERIZATION OF COARSE ASPHALT MIXTURES FROM FIELD SECTIONS

2.1 Introduction

Asphalt pavements in colder climates encounter significantly shortened service lives due to excessive transverse cracking. In this study, asphalt pavement sections from a number of different locations were evaluated to encompass various types of asphalt mixtures and asphalt construction types that are commonly used in Minnesota. As part of the investigation into the various factors that affect transverse cracking performance in Minnesota, laboratory characterization of the coarse hot-mix asphalt (HMA) mixtures was conducted. This chapter provides an overview of the laboratory tests that were conducted along with the results of the laboratory tests. This study involved laboratory testing on field procured samples in order to evaluate the impacts of lower asphalt content coarse HMA mixes. Multiple field samples were taken from each section and subjected to a battery of laboratory tests: (1) volumetric, (2) lab permeability, (3) disk-shaped compact tension (DCT), and (4) asphalt content and gradation. The volumetric testing of the specimens included: adjusted asphalt film thickness (AFT) and voids in mineral aggregates (VMA). The laboratory characterization was carried out on 25 pavement sections across 18 Minnesota highways, however, due to the scope of the study, the lab permeability, asphalt content and gradation was only conducted on 12 of the study sections (9 highways).

2.1.1 Field Sections

The field sites were selected in a strategic manner to encompass a variety of variables that are being studied herein. These included mix types (from perspective of traffic level), aggregate and asphalt binder sources, climatic conditions, age and pavement cross-sections. A brief description of each section is presented in Table 1. The specific information regarding the location of pavement section on the highways is presented geographically in Figure 6. It can be seen from the table and figure that the sections discussed herein capture a broad range of locations, pavement ages and construction types. The table describes the highway location, section number, state project (SP) number, as well as the milepost (RP)/landmark and construction year.

Table 1: Summary of Field Sections

Highway	Section Letter	SP #	RP / Landmark	Construction Year	Asphalt Thickness and Construction Type
TH 1	A-1	8821-103	RP 230	2008	100 mm O/L on reclaimed HMA
TH 1	A-2	8821-103	RP 235	2008	37.5 mm O/L on old HMA
TH 2	B	1102-59	RP 157	2003	100 mm O/L on old HMA
TH 6	C	1103-25	RP 53	2010	37.5 mm M/O
TH 6	D-1	3107-42	RP 118	2004	37.5 mm on old HMA
TH 6	D-2	3107-42	RP 123	2004	112.5 mm O/L on reclaimed HMA
TH 9	E-1	6010-26	RP 208	2011	75 mm O/L on reclaimed HMA
TH 9	E-2	6010-26	RP 214	2011	75 mm O/L on reclaimed HMA
CR10	F-1	031-610-016	Jct 445B	2012	37.5 mm O/L on old HMA
CR10	F-2	031-610-016	Jct 446	2012	37.5 mm M/O
TH 10	G-1	0502-95	RP 159	2005	100 mm M/O (sealed cracks)
TH 10	G-2	0502-95	RP 161	2005	100 mm M/O (cracks not sealed)
TH 10	H	5606-42	RP 75	2013	87.5 mm M/O
TH 27	J-1	4803-19	RP 171	2010	75 mm M/O
TH 27	J-2	4803-19	RP 174	2010	75 mm M/O
TH 28	K-1	6104-11	RP 81	2012	75 mm M/O
TH 28	K-2	6104-11	RP 88	2012	112.5 mm M/O
CSAH30	L	1306-44	CSAH 30 at TH 95	2012	150 mm M/O
I-35	M	0283-26	RP 128	2009	100 mm M/O on existing concrete
TH 53	N	8821-177	169 to Ely sign	2008	37.5 mm M/O
TH 113	O-1	4407-12	RP 10	2006	37.5 mm O/L on old HMA
TH 113	O-2	5413-10	RP 5	2006	125 mm O/L on reclaimed HMA
TH 210	P	1805-72	RP 118	2010	50 mm O/L on existing concrete
TH 212	Q	1017-12	RP 147	2008	100 mm SMA new construction
TH 220	R	6016-37	RP 12	2012	75 mm M/O

M/O = Mill and Overlay; O/L = Overlay; BAB = Bituminous on Aggregate Base; RP = mile post

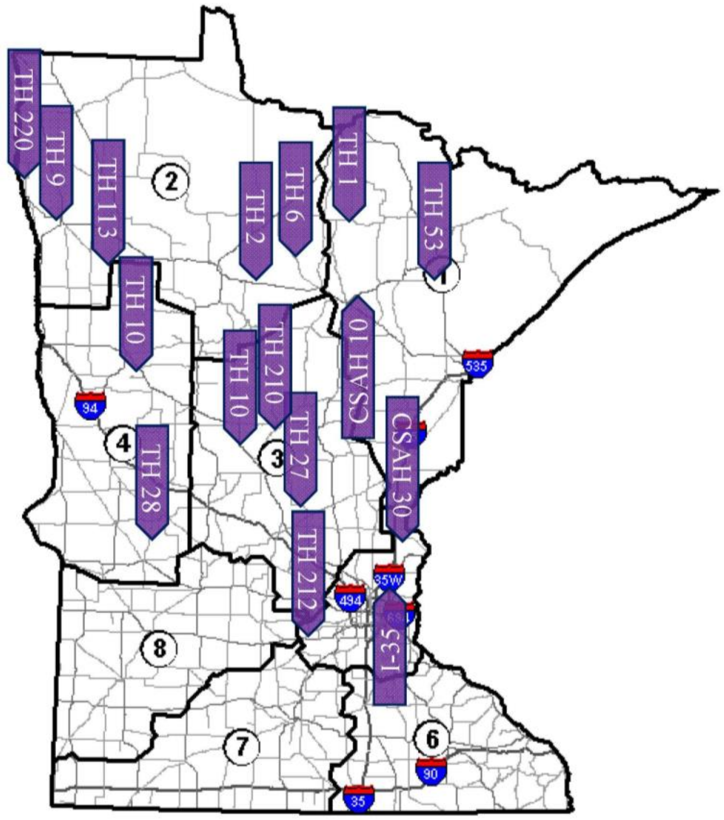


Figure 6: Locations of Pavement Sections in Minnesota

It should be noted that in several instances multiple pavement sections were studied on one highway. This was done for two main reasons, when a pavement construction project consists of multiple types of pavement sections (such as, TH 1 where section A-1 is 37.5 mm thick overlay and section A-2 is 100 mm thick overlay on reclaimed pavement), than two sections were established to study the effects of different construction types while being able to keep climatic conditions as a constant. Secondly, if pavement cracking performance changed drastically within a single construction project (such as, TH 9 where section E-1 showed good cracking performance and section E-2 showed poor performance) than two sections were established. These sections are described as companion sections.

Please note that the focus of the study is on the wear courses and the properties listed here as well as the discussions throughout the paper are focused on wear courses or surface courses. Of the 25 pavement sections studied here, 10 consist of a non-wear course material (also commonly known as binder course or base course), the remainder are comprised only of wear courses. The 10 sections with non-wear course have asphalt thicknesses of 100 mm or higher.

An effort was made to establish all study sections to begin at a reference post (RP) or mile post so that pavement performance data can be readily obtained from the pavement management system (PMS). The study sections were established for a centerline length of 305 m (1000 ft). Each of the pavement sections were visited by researchers to conduct verification crack counts (to verify information from PMS) and to establish the locations for sample procurement through coring. The cracking information for each of the sections was obtained from the MnDOT PMS from the year of construction henceforth. The sampling plan for each section was developed to have cored specimens be procured at an interval of 61 m (200 ft.). It should be noted that except for Section Q (TH212) all other sections were designed and constructed using dense-graded asphalt mixtures as per MnDOT 2360 specifications [11]. Section Q was designed and constructed using stone-matrix asphalt (SMA) mixture.

2.2 Laboratory Test Results

2.2.1 Volumetric Properties

As previously mentioned, the current MnDOT specification for plant mixed asphalt mixes heavily relies on volumetric property specifications, therefore volumetric testing was done to compare the field volumetrics with those outline in MnDOT Specification 2360. The asphalt mix properties of the wear course mixtures of the various pavement sections under study are presented in Table 2. The table shows the pertinent parameters that are typically used for purposes of characterizing asphalt mixtures. The asphalt binder grade used for the virgin binder component of the mixture is shown along with the amount of binder contribution to the mixes form recycled sources. This data was obtained from the mix design record (MDR) provided for each study section by MnDOT.

The three most commonly used volumetric parameters for characterization and specification of asphalt mixtures in practice at present, are adjusted asphalt film thickness (Adj. AFT), voids in mineral aggregates (VMA) and voids filled with asphalt (VFA). These parameters were obtained through the laboratory testing conducted from the field-procured specimens. At present, the MnDOT 2360 specification for plant produced asphalt mixtures utilizes Adj. AFT as a volumetric control parameter, with a required minimum value of 8.50 micron for all dense-graded asphalt mixtures. Notably, TH 6 (Section Letter D) and TH 10 (Section Letter G) were constructed with a pervious specification which allowed the Adj. AFT to be lower than 8.5 microns. This parameter was determined referencing the MnDOT Laboratory Manual 1854 [24]. The Adj. AFT is an indicator of the amount of effective asphalt volume in the mix by discounting any asphalt absorbed by aggregate particles. Adj. AFT is an important property due to the coarse-gradation mixes being studied because it is also dependent on the surface area of the aggregate particle.

The asphalt mix properties of the wear course mixtures of the various pavement sections under study are presented in Table 2. The table shows the pertinent parameters that are typically used for purposes of characterizing asphalt mixtures. The asphalt binder grade used for the virgin binder component of the mixture is shown along with the amount of binder contribution to the mixes form recycled sources. The field core samples were tested as per the AASHTO T166 specifications to measure the bulk specific gravities of the asphalt mixtures [25]. The gradation is also discussed in terms of coarse (C) and fine (F) gradations. These were distinguished on the basis of VMA which is comparable to looking at the void space between aggregate particles which is an indication of coarseness. Mixtures with a VMA of 14% or greater is classified as a fine mix and those less than that are considered coarse mix. In conjunction with the design asphalt content, it is apparent that coarser gradation mixes generally have lower design asphalt contents. These are also reported in Table 2.

Table 2: Section Mix Design Properties

Highway	RP/ Landmark	Section Letter	PG Grade	PG Spread	Design Asphalt Content (%)	RAP (ABR %)	VMA (%)	VFA (%)	Adj. AFT (micron)	Gradation
TH 1	RP 230	A-1	58-28	86	4.7	17.0	14.9	73.1	8.7	F
TH 1	RP 235	A-2	58-34	92	4.7	17.0	14.9	73.1	8.7	F
TH 2	RP 157	B	58-34	92	4.6	26.1	14.0	71.4	8.5	F
TH 6	RP 53	C	58-28	86	4.4	36.4	13.9	71.2	9.2	C
TH 6	RP 118	D-1	58-34	92	5.3	17.0	14.8	73.0	7.5	F
TH 6	RP 123	D-2	58-34	92	5.3	17.0	14.8	73.0	7.5	F
TH 9	RP 208	E-1	58-34	92	4.2	26.2	13.1	69.6	8.9	C
TH 9	RP 214	E-2	58-34	92	4.2	26.2	13.1	69.6	8.9	C
CSAH 10	Jct 445B	F-1	58-28	86	4.3	23.3	13.5	70.4	9.1	C
CSAH 10	Jct 446	F-2	58-28	86	4.3	23.3	13.5	70.4	9.1	C
TH 10	RP 159	G-1	64-28	92	5.3	45.3	14.4	72.3	7.8	F
TH 10	RP 161	G-2	64-28	92	5.3	45.3	14.4	72.3	7.8	F
TH 10	RP 75	H	58-28	86	4.3	23.3	13.7	70.8	8.9	C
TH 27	RP 171	J-1	58-28	86	4.3	37.2	13.6	70.6	8.8	C
TH 27	RP 174	J-2	58-28	86	4.3	37.2	13.6	70.6	8.8	C
TH 28	RP 81	K-1	58-34	92	4.2	23.8	12.5	68.1	9.4	C
TH 28	RP 88	K-2	58-34	92	4.2	23.8	12.5	68.1	9.4	C
CSAH 30	Jct TH 95	L	64-34	98	4.4	11.4	13.4	70.2	9.0	C
I-35	N/A	M	64-28	92	5	34.0	15.1	73.5	10	F
TH 53	Jct 169	N	58-28	86	4.7	29.8	17.6	77.2	9.7	F
TH 113	RP 10	O-1	58-28	86	4.5	20.0	12.6	68.3	9.1	C
TH 113	RP 5	O-2	58-34	92	4.5	20.0	12.6	68.3	9.1	C
TH 210	RP 118	P	58-28	86	4.4	38.6	13.5	70.4	10.5	C
TH 212	N/A	Q	70-34	104	6.4	0.0	19.2	79.2	N/A	F
TH 220	RP 12	R	58-28	86	4.2	23.8	13.5	70.3	9.5	C

Note: All mixtures have a 12.5 mm (1/2-inch) nominal maximum aggregate size.

2.2.2 Lab Permeability

The lab measured permeability for the cored specimens is presented in Table 3. Due to the scope of this study, only 12 of the 25 sections had lab measured permeability conducted. Please note that prior to permeability measurement, the cored specimens were processed by cutting the wear course lifts from the rest of the core to be tested using the Karol-Warner permeameter. As it can be seen from the results, the permeability varied quite significantly for the asphalt mixtures. The typical permeability range for these mixtures (all of them are 12.5 mm sized mixtures as per the MnDOT 3139 designation) would be between 10^{-5} to 10^{-6} cm/s. The mixtures that have permeability greater than this typical range are indicated in red. It can be seen that more than half of the mixtures have permeability that is significantly higher than the typical range. These mixtures are thus prone to inferior durability.

Table 3: Permeability of Various Asphalt Mixtures

Highway	RP / Landmark	Section Letter	Permeability (cm/s)	Comparison to Typical Range (10^{-5} - 10^{-6} cm/s)
TH 6	RP 53	C	1.26E-05	Borderline high
TH 9	RP 208	E-1	8.18E-06	Within typical range
TH 9	RP 214	E-2	9.69E-05	High
CSAH 10	Jct 445B	F	4.81E-05	High
TH 10	RP 159	G-1	5.23E-05	High
TH 10	RP 161	G-2	5.53E-05	High
TH 10	RP 75	H	5.39E-05	High
TH 27	RP 171	J-1	1.48E-05	Borderline high
TH 27	RP 174	J-2	2.33E-07	Within typical range
TH 28	RP 81	K-1	7.86E-06	Within typical range
CSAH 30	Jct TH 95	L	5.65E-07	Within typical range
TH 220	RP 12	R	6.28E-04	Very high

2.2.3 Disk-shaped Compact Tension (DCT) Test

The results from each highway project and the individual study sections that were established can be found Figure 7. As mentioned previously, previous studies have shown that asphalt mixtures with a fracture energy of 400 J/m^2 or more performs superior to the mixtures with a fracture energy less than that threshold. The 400 J/m^2 threshold is indicated on the figure. As shown in the figure, seven samples have a fracture energy at or above the threshold. TH 212 has a fracture energy significantly higher than the other sections and is shown in red in the figure. This is assumed to be due to the stone matrix asphalt (SMA) mix type. All other mixes in this study are traditional dense graded asphalt mixes. Furthermore, the TH 212 mix did not have any recycled asphalt in it and was made with a highly polymer modified asphalt binder.

Additionally, Table 4 shows the sample size, or number of replicates tested, coefficient of variation (COV) and average fracture energy corresponding to each section. Some sections, for example section letter A-1 and D-1 have relatively high COV values indicating significant variablity between replicates. This is presuably due to thin wear course lifts which made it difficult to conduct the testing.

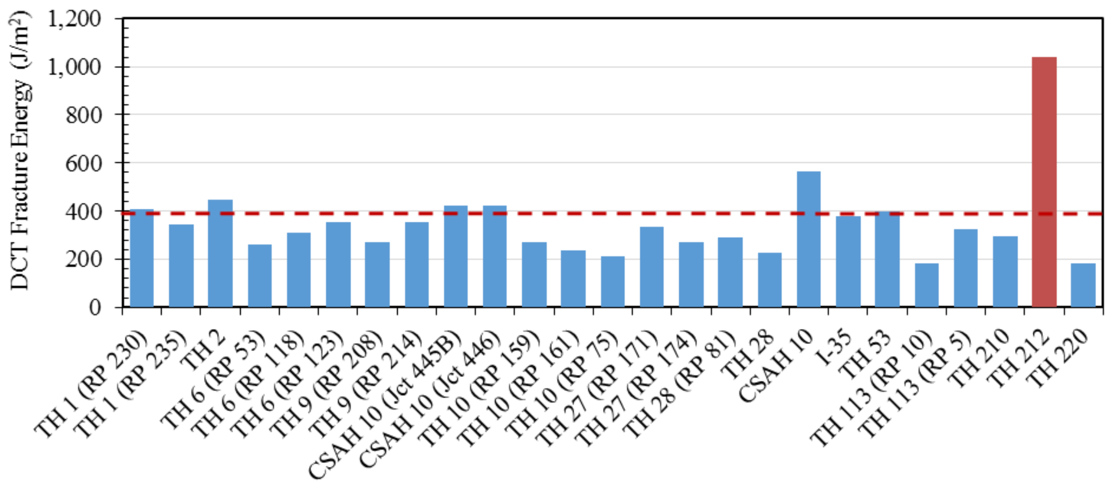


Figure 7: DCT Fracture Energy Results of All Study Sections

Table 4: DCT Fracture Energy Results

Highway	RP/ Landmark	Section Letter	Fracture Energy (J/m^2)	COV	Sample Size
TH 1	RP 230	A-1	408	38%[1]	4
TH 1	RP 235	A-2	342	11%	4
TH 2	RP 157	B	449	23%	4
TH 6	RP 53	C	260	41%	4
TH 6	RP 118	D-1	311	35%[1]	4
TH 6	RP 123	D-2	352	27%	4
TH 9	RP 208	E-1	271	10%	4
TH 9	RP 214	E-2	352	4%	4
CSAH 10	Jct 445B	F-1	423	10%	3
CSAH 10	Jct 446	F-2	423	17%	3
TH 10	RP 159	G-1	270	4%	4
TH 10	RP 161	G-2	238	17%	3
TH 10	RP 75	H	212	14%	4
TH 27	RP 171	J-1	335	23%	4
TH 27	RP 174	J-2	272	3%	3
TH 28	RP 81	K-1	291	9%	3
TH 28	RP 88	K-2	227	12%	2
CSAH 10	Jct TH 95	L	567	17%	3
I-35	N/A	M	379	13%	4
TH 53	Jct 169	N	397	38%	4
TH 113	RP 10	O-1	182	9%	4
TH 113	RP 5	O-2	326	17%	4
TH 210	RP 118	P	293	26%	4
TH 212	N/A	Q	1040	14%	4
TH 220	RP 12	R	183	11%	4

[1]The specimen thicknesses were relatively low due to thin lifts, this is anticipated to be primary reason for high COV in fracture energy results.

2.2.4 Asphalt Content and Gradation

The results from ignition oven testing are shown in Table 5 and the comparison between design asphalt content and measured asphalt content are shown in Figure 8. Most of the sections being looked at here have relatively low design asphalt content, except TH 10 Section G, which is a result of the mixture being designed under earlier specifications. Noticeably, the measured asphalt content is generally greater than the design asphalt content except in the case of TH 10 Section G. There are a couple reasons for this. The first being that some of the mixtures were tested with surface treatments such as slurry and chip seals giving a false high asphalt content for the mixture. The second is that the testing procedure requires oven calibration and this step was not done as it was outside the scope of the project. For those reasons, the measured asphalt content is considered to be unreliable and comparisons to performance were made using design asphalt content instead of the measured asphalt content.

Table 5: Asphalt Content Results

Highway	RP / Landmark	Section Letter	Design Asphalt Content (%)	Measured Asphalt Content (%)
TH 6	RP 53	C	4.4	4.87
TH 9	RP 208, RP 214	E	4.2	4.76
CSAH 10	Jct 445B	F	4.3	5.22
TH 10	RP 159, RP 161	G	5.3	5.03
TH 10	RP 75	H	4.3	5.64
TH 27	RP 171, RP 174	J	4.3	5.55
TH 28	RP 81, RP 88	K	4.2	4.85
CSAH 30	Jct TH 95	L	4.4	5.28
TH 220	RP 12	R	4.2	4.52

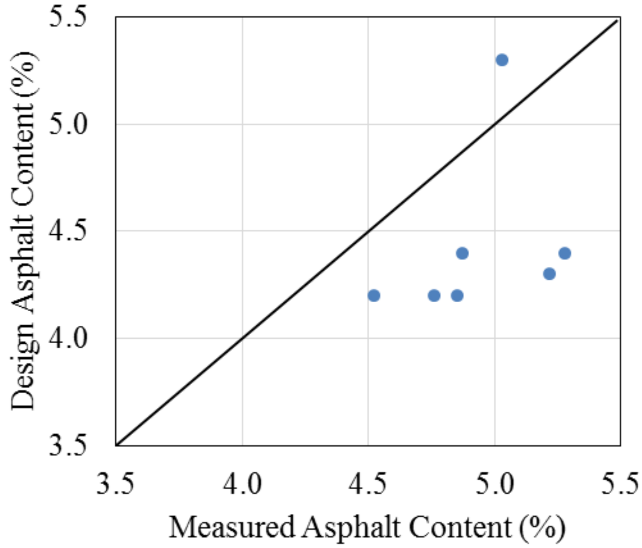


Figure 8: Comparison of Design and Measured Asphalt Content

The results from the gradation analysis of the ignition oven residue is presented in Table 6 and shown graphically in Figure 9. The aggregate gradation requirements put forth by MnDOT are specified in the MnDOT 3139 specifications are also shown in Table 6 and shown as the dashed lines in the figure. Looking at the aggregate gradations, the coarseness of the gradation is apparent as the figure shows on average, 60 percent is retained by the #8 sieve and larger.

Table 6: Ignition Oven Residue Gradation Results

Highway	RP / Landmark	Section Letter	Sieve Size (Percent Passing)					
			3/4 in	1/2 in	3/8 in	#4	#8	#200
MnDOT Requirements (MnDOT 3139)			100	85 - 100	35 - 90	30 - 80	25 - 65	2.0 – 7.0
TH 6	RP 53	C	100	94.2	80.9	58.6	46	4.0
TH 9	RP 208, RP 214	E	100	95.8	85.2	56.6	42.9	3.5
CSAH 10	Jct 445B	F	100	96.4	84.6	53.1	38.4	3.3
TH 6	RP 53	G	100	94.2	80.9	58.6	46	4.0
TH 28	RP 81	H	100	94.1	83.4	63.8	47.1	4.0
TH 27	RP 171, RP 174	J	100	90.4	75.1	50.3	39.4	4.8
TH 28	RP 81, RP 88	K	100	94.3	82.7	56.0	41.0	3.6
TH 28	RP 88	L	100	94.4	82	48.2	34.9	3.1
TH 220	RP 12	R	100	93.9	77.5	49.8	34.4	3.6

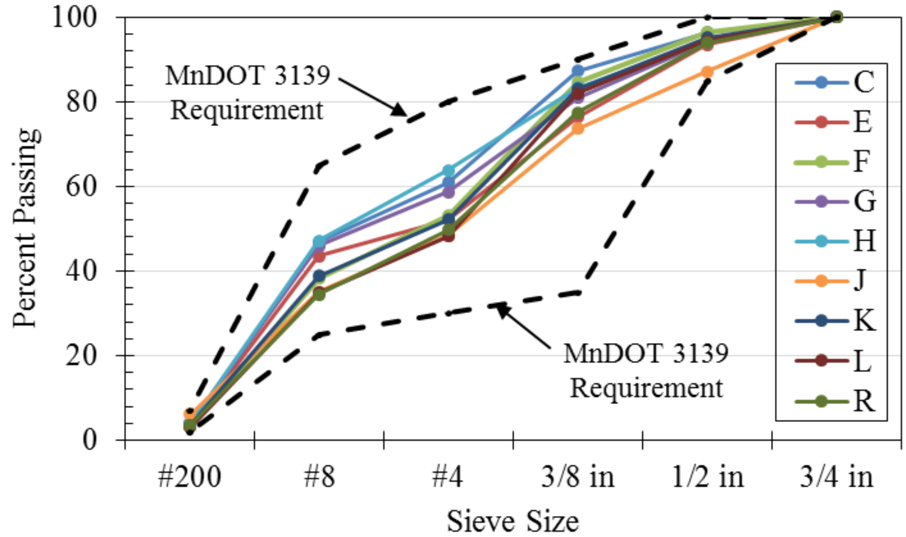
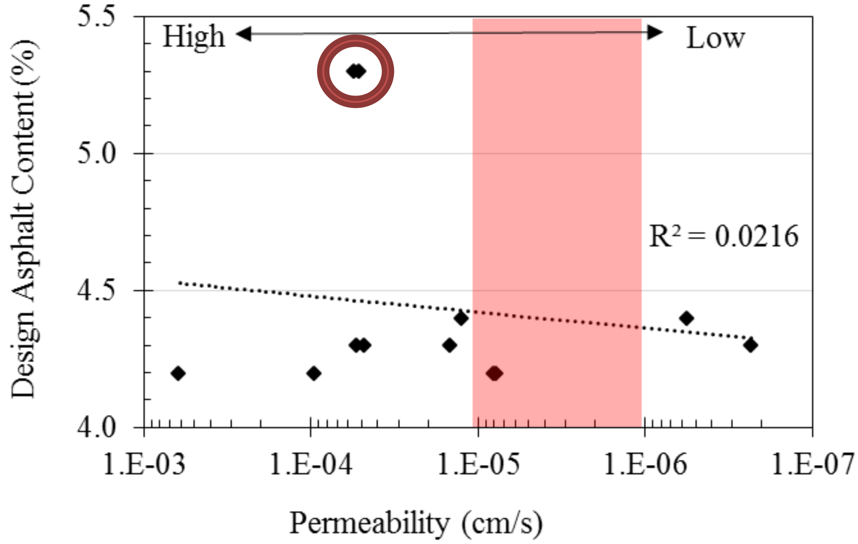
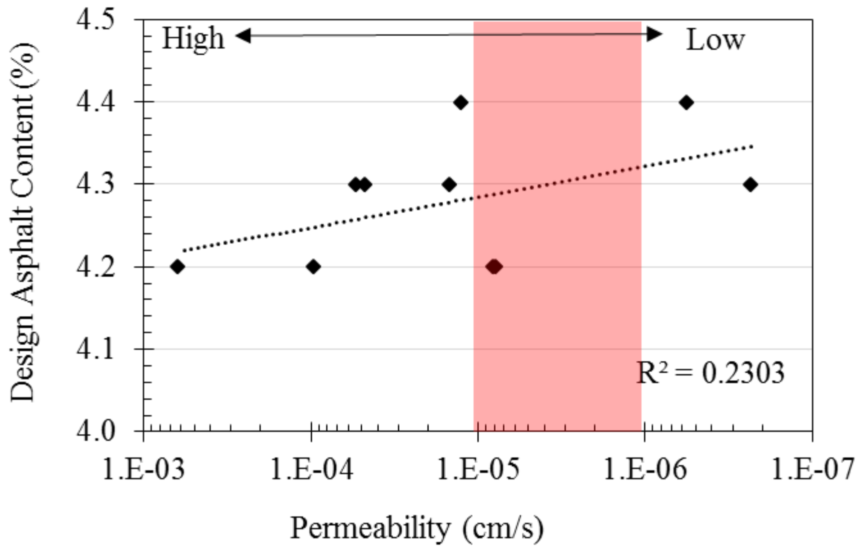


Figure 9: Ignition Oven Residue Gradation by Section

The relationship between laboratory permeability and both asphalt content and percent of gradation coarser than the #8 (2.36 mm) sieve has been provided in and Figure 11. In (a) there is no apparent trend between asphalt content and permeabilty and the line is pulled heavily by TH 10 Section G which is circled on the figure. (b) removes the outlier TH 10 Section G and the expected trend is displayed as the plot shows the general trend that lower asphalt binder content correlates with higher mixture permeability. The reason TH 10 is believed to behave differently than the other mixtures is due to it being designed using early specifications.



(a) All Data Points



(b) Without TH10 Section G-1 and G-2

Figure 10 (a-b): Permeability versus Design Asphalt Content

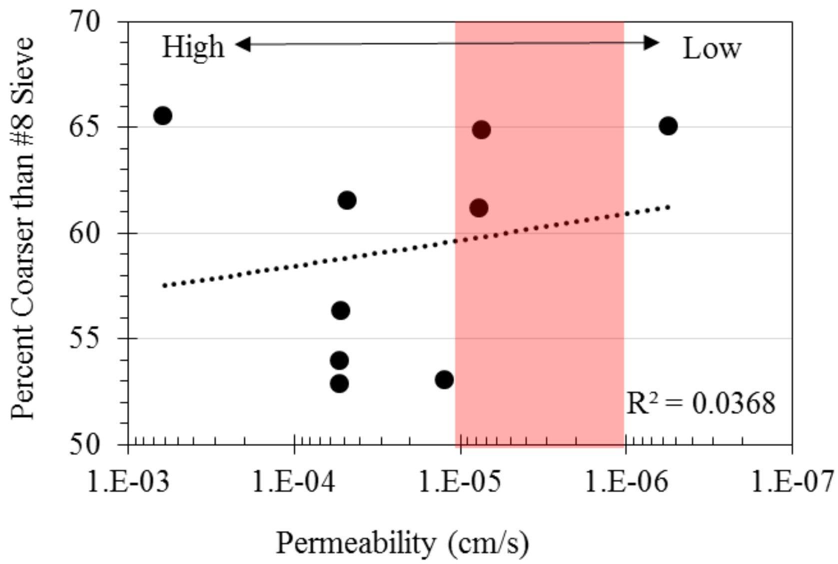


Figure 11: Permeability versus Percent Coarser than #8 Sieve

Due to the lack of trend between the gradation and permeability in Figure 11, it cannot be concluded that gradation is solely responsible for mixture permeability but also relies on other factors such as asphalt binder content.

2.3 Summary and Conclusion

This portion of the investigation of lower asphalt binder on coarse HMA project focused on laboratory testing of field cored samples of coarse asphalt mixtures from 25 pavement sections from Minnesota. The testing spanned across variety of tests to determine asphalt mixtures' permeability, fracture energy, volumetric properties, asphalt content and gradation. On basis of the test results following points can be summarized:

- The asphalt content measured using ignition oven tests on the post-test DCT specimens showed considerably higher asphalt binder amounts as opposed to designed values. It is anticipated that this is due to lack of calibration using chemical extraction method.
- The results from permeability testing indicated that eight of the twelve mixtures have higher permeability than typical ranges for dense graded asphalt mixtures. Specifically six of the mixture have significantly higher permeability. These mixtures are anticipated to have inferior durability and

might be more prone to moisture induced damage and distresses like raveling.

- Only seven out of twenty-five mixtures have fracture energies that are above the recommended threshold of 400 J/m^2. Twelve sections have substantially lower fracture energies (less than 300 J/m^2), even after consideration of lowering fracture energies due to pavement being in service for several years. These sections are expected to have significantly inferior transverse cracking performance and shortened service lives.
- Gradation analysis of residue show that the mixtures meet the MnDOT specified gradation bands. Overall, all gradation results show relatively coarser trend.

CHAPTER 3: COMPARISON OF LABORATORY CHARACTERIZATION TO TRANSVERSE CRACKING PERFORMANCE OF MINNESOTA PAVEMENTS

3.1 Introduction

As part of the investigation into the various factors that affect transverse cracking performance in Minnesota, the next step was to quantify each sections field performance and compare the laboratory test results of the coarse HMA mixes to the field performance. The transverse cracking amount for each pavement section was obtained through MnDOT's PMS data. The transverse cracking performance over the pavement service life is presented for each study section. The transverse cracking counts from MnDOT were converted into previously developed cracking performance measures that account for the amount, rate and timing of cracking. This study presents the current cracking performance from 25 pavement sections across 18 highways in Minnesota that have been studied to evaluate the effects of asphalt mix designs, fracture properties and laboratory permeability on pavement transverse cracking performance.

Next, this chapter discusses the comparison between the field cracking performance and the laboratory tested parameters. The field cracking performance is also compared with the asphalt mix design parameters. The field performance is presented using various cracking measures and is compared with mix design aspects such as amount of asphalt binder, binder grade and amount of recycling. The disk-shaped compact tension (DCT) fracture energies and laboratory permeability measured on the field cored samples are also compared with the cracking performance.

3.2 Cracking Performance Measures

For purposes of quantifying pavement performance over time and conducting analysis between the amount of cracking and laboratory tests, as well as asphalt mix parameters, a number of measures of field cracking performances can be calculated. In this study, the researchers looked at transverse cracking amounts in terms of total cracking. This is the sum total of low, medium and high severity cracks. Please note that all data presented in this report includes the crack counts that researchers collected during the site visits. Thus, the field visit information was incorporated with the PMS data providing the cracking performance information for the pavements from their construction until 2013/2014.

The total cracking amounts for a given PMS section for each year of distress survey can be used to calculate additional cracking measures that are representative of field cracking performance. In a previous MnDOT research study, a number of different cracking measures were evaluated and assessed, such as, maximum and average transverse cracking amount, maximum transverse cracking rates and average transverse cracking rates. These are described in Table 7. The reasoning for use of these measure as opposed to others is that these measures captures the cracking amounts of the pavement in context of its performance. For example, a roadway experiencing 0% cracking for the first four years of the service life then cracking to a current amount of 50% is a superior performer to a roadway cracking at 50% in year one and staying at 50% until the current time period, if only current cracking amounts are used this performance difference is neglected. The calculation of these measures are described next, this will help clarify why these measure might be better suited as opposed to use of current cracking amount. Also, a study of the Minnesota state highway network showed that on average, asphalt pavements crack at the rate of 6% per year.

The first three measures, MTCTotal, MTCRTotal, and ATCTotal from the table have previously been presented for the sections in this study by Helmer (2015) and will not be presented here [26]. However, the measures are still discussed here because they will utilized in Chapter 4. The cracking measure TCTotal was also used in the previous study, however was calculated without normalizing the area under the curve by the service life, therefore the corrected definition and result for the parameter are discussed here. Lastly, another performance measure, average total transverse cracking rate (ATCRTotal) was not used in the previous study and also used to characterize pavement performance.

Table 7: Description of Transverse Cracking Measures (Reproduced from Dave et al., 2015 [5])

Measure	Description	Unit
Maximum Total Transverse Cracking Amount (MTCTotal)	Maximum transverse cracking amount (low + medium + high) of all survey years for a pavement section normalized against number of years for which pavement section has been in service.	% cracking/year
Maximum Total Transverse Cracking Rate (MTCRTotal)	Maximum increase in total transverse cracking amounts (low + medium + high) between any two consecutive years of service.	% cracking/year
Average Total Transverse Cracking (ATCTotal)	Sum of total transverse cracking (low + medium + high) for every survey year of a pavement section normalized against number of years for which pavement section has been in service.	% cracking/year
Average Total Transverse Cracking Rate (ATCRTotal)*	Average increase in total transverse cracking amounts (low + medium + high) between consecutive years of service of a pavement section normalized against number of years for which pavement section has been in service.	% cracking/year
Total Transverse Cracking (TCTotal)**	Sum of the total transverse cracking (low + medium + high) work over the service life. Total area is then normalized against the number of years for which pavement section has been in service.	% cracking/year

* ATCRTotal is a new cracking measure that has not been used prior to this study
**TCTotal was used previously however has a revised definition and calculated differently

The primary function behind all five cracking measures is to determine a measure that fairly depicts the cracking performance for a section. For example, Figure 12 shows the performance of two pavement sections over 6 years of service. By comparing the sections in year 6, they are experiencing a similar amount of cracking. However, performance relative to the entire life of the pavements, Section A-1 performs much better than Section A-2 by not cracking for the first 5 years.

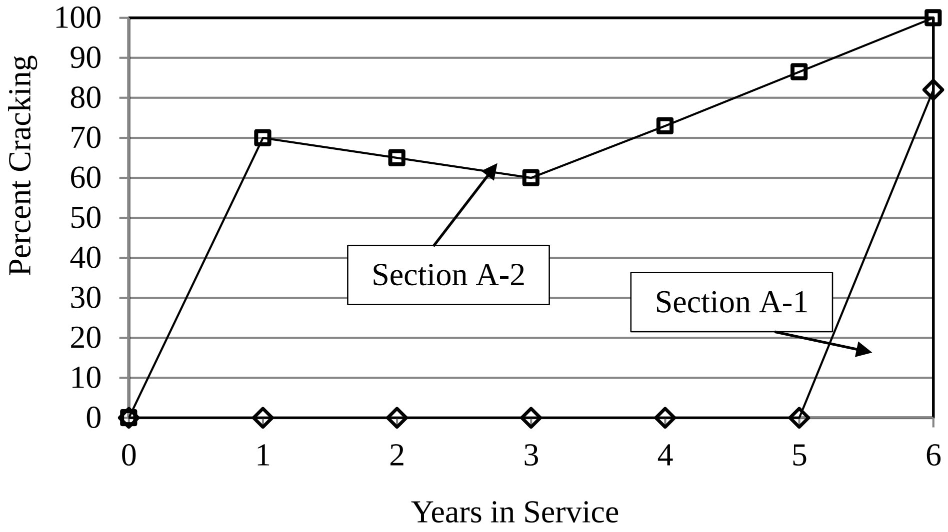


Figure 12: Transverse Cracking Performance of Section A-1 and A-2 (TH 1)

The five cracking measures each evaluate cracking performance slightly different, so scrutinizing the sections by all five measures fives merit to each performance. An explanation and graphical representation of the cracking measures are to follow. Although only the transverse cracking measures are used in this chapter, the longitudinal cracking measures are calculated the same way and will be implemented in Chapter 4.

A. <u>Maximum Total Transverse/Longitudinal Cracking Amount (MTCTotal/MLCTotal):</u>

This measure is computed using the maximum cracking value measured from any one year of the pavement's performance life from Figure 13. This intuitively occurs at the end of service life for both pavements. From Figure 13, this cracking measure is calculated with the maximum cracking amount of 59 percent. After normalizing this value for the 11 year service life, the maximum total transverse cracking amount is 5.36 percent per year. The goal of this measure is to be able to rank the pavements in terms of current performance since it utilizes the current cracking amount. To estimate pavement performance, pavement cracking about 5 percent per year would be expected to perform for nearly 20 years until reaching 100 percent cracking.

B. Maximum Total Transverse/Longitudinal Cracking Rate (MTCRTotal/MLCRTotal):

The maximum total transverse cracking rate is the greatest increase in cracking between any two consecutive years in service. From Figure 13, this cracking measure is calculated considering the cracking between construction and year 1 where it reached 12 percent cracking, therefore the maximum total transverse cracking rate. This measure is important because a recent study showed that on average Minnesota highways crack 6 percent each year. In terms of service life, a pavement could last quite a while if it truly performed to that average. However the same study also presented that on average each roadway also undergoes a year with cracking as high as 31 percent in one year [27].

C. Average Total Transverse/Longitudinal Cracking (ATCTotal/ALCTotal):

This measure is not as intuitively defined Figure 13, however it represents the summation of the total transverse cracking in percent cracking for each survey year represented by each point and then simply normalized by the years of service. Using the performance in Figure 13, the calculation for average total transverse cracking is performed as follows:

$$ATCTotal=\frac{12+19+26+27+28+28+28+33+38+49+59}{11}=31.5\ \%\ cracking/yr.$$

D. Average Total Transverse Cracking Rate (ATCRTotal):

This measure is the summation of the difference in total transverse cracking in percent cracking for each consecutive year, normalized by the years in service. Using the performance in Figure 13, the calculation for average total transverse cracking is performed as follows:

$$ATCRTotal=\frac{12+7+7+1+1+0+0+0+5+5+11+10}{11}=5.4\ \%\ cracking/yr.$$

E. Total Transverse/Longitudinal Cracking (TCTotal/LCTotal):

This measure is described in Figure 13 as the area beneath the percent cracking versus years in service curve. By using this measure, it discriminates between sections that perform worse for a longer period of time. For the values in Figure 13, the total transverse cracking amount is 2.6%/yr.

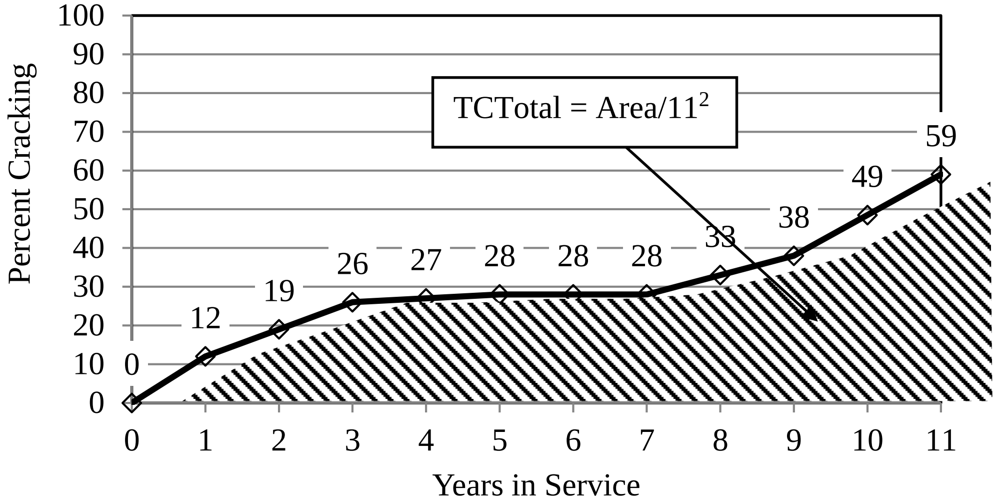


Figure 13: Transverse Cracking Performances of Section B (TH 2)

3.2.1 Transverse Cracking Performance of All Study Sections

The transverse cracking performance of all pavement sections studied in this project is presented here. The current amount of cracking on all pavement sections using MnDOT's definition of percent cracking is provided in Figure 14. As previously mentioned, 100 percent cracking indicates there are 75 m (250 ft) of crack length in the transverse direction for a 150 m (500 ft) pavement section length. The horizontal axis presents the pavement sections in the order they were constructed. Therefore, TH 1 (RP 230) was constructed in 2003 (been in service the longest) and is on the left, whereas CSAH 30 was constructed in 2013 and is on the right side of the figure. This figure does shows a general trend that older pavements have cracked more than younger pavements, however there is still significant variation supporting that there are several other factors such as mixture type, pavement structure, and construction type that can be altered to prevent cracking. On average, these sections are currently at about 40.4 percent cracking.

The amounts of transverse cracking with respect to the pavement service life for each of the 25 individual pavement sections can be found by referencing Helmer, 2015 [26]. The details on the field notes and the select pictures of the sections are also presented in the Appendix of that report. Additionally, performance of each section using the MTCTotal, ATCTotal as well as others not discussed here, are presented by Helmer.

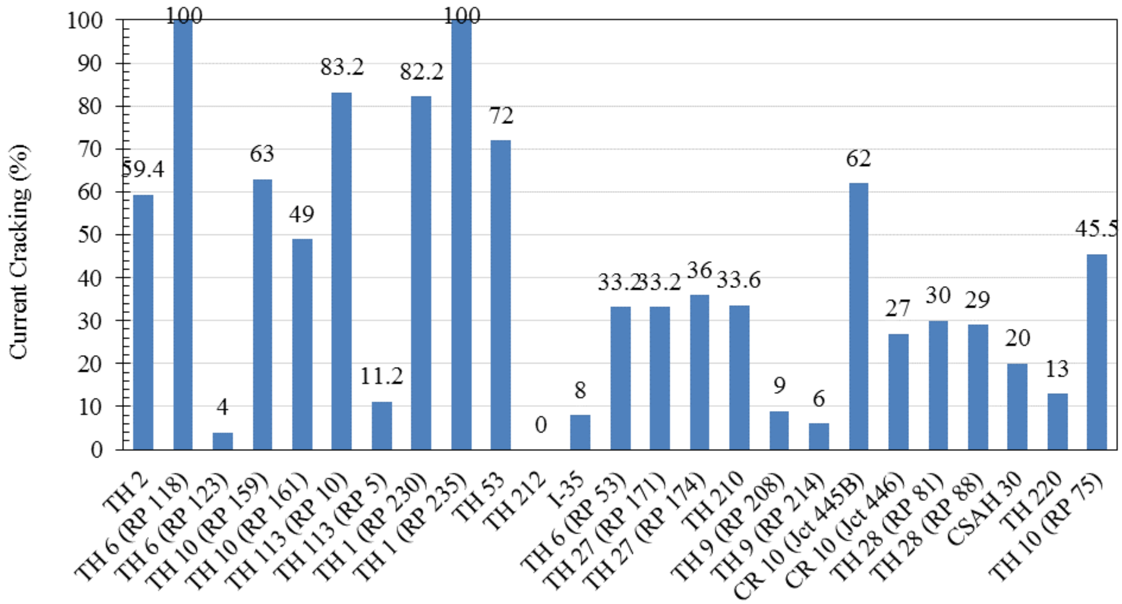


Figure 14: Current Cracking Performance for All Study Sections

The average transverse cracking rates (ATCRTotal) are shown in Figure 15. It can be seen that 11 out of 25 sections have average transverse cracking rates at or above 10%/yr., indicating that these pavements will reach 100% transverse cracking conditions in span of 10 years or less from construction. The average of all sections for average transverse cracking rate is 10.4 %/yr. Noticeably TH 10 RP 75 has the poorest performance of the study sections since it has an average transverse cracking rate of 46 %/yr., which may be explained by the mixture being among the lowest fracture energy values.

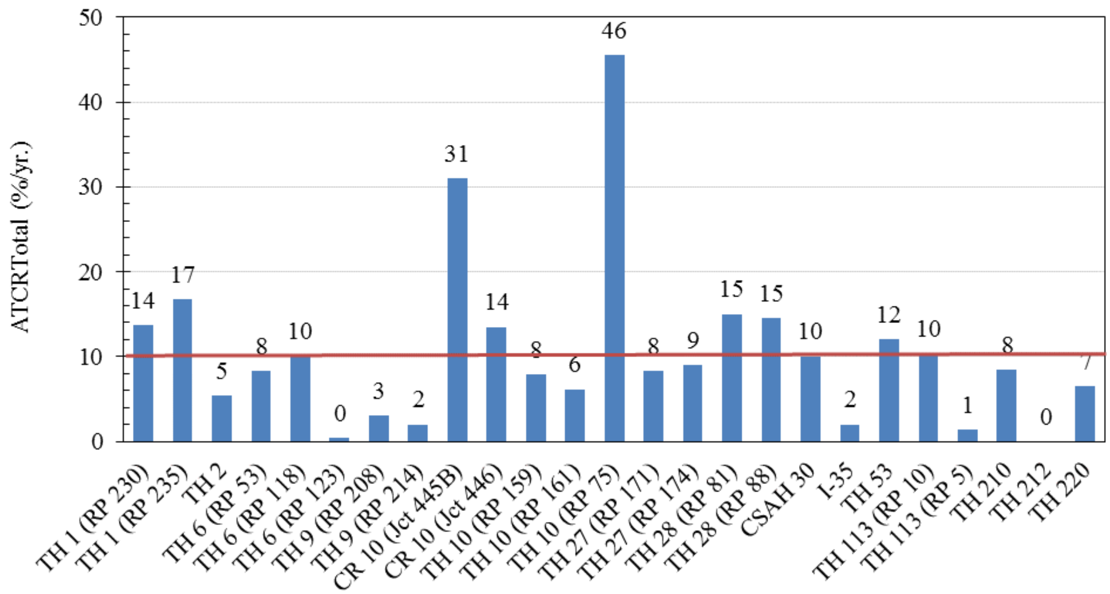


Figure 15: Average Total Transverse Cracking Rate (ATCRTotal) for All Study Sections

The TCTotal parameter for all pavement sections is shown in Figure 16 and TCTotal normalized for asphalt concrete (AC) thickness in Figure 17. As previously described, a pavement with TCTotal of 5%/yr. will reach 100% cracking in approximately 20 years. It can be seen that two of the pavements have substantially poor cracking performance as compared to others. There are several pavements with TCTotal between 3 and 7% mark with average of all sections to be approximately 5.2%/yr. It should be noted that large number of sections in this study have only been in service for 2 years at the time of data collection and analysis, circumstantial evidence has shown that it is usually 5-8 years before clear distinction is seen between the transverse cracking performances of good and poor performing sections.

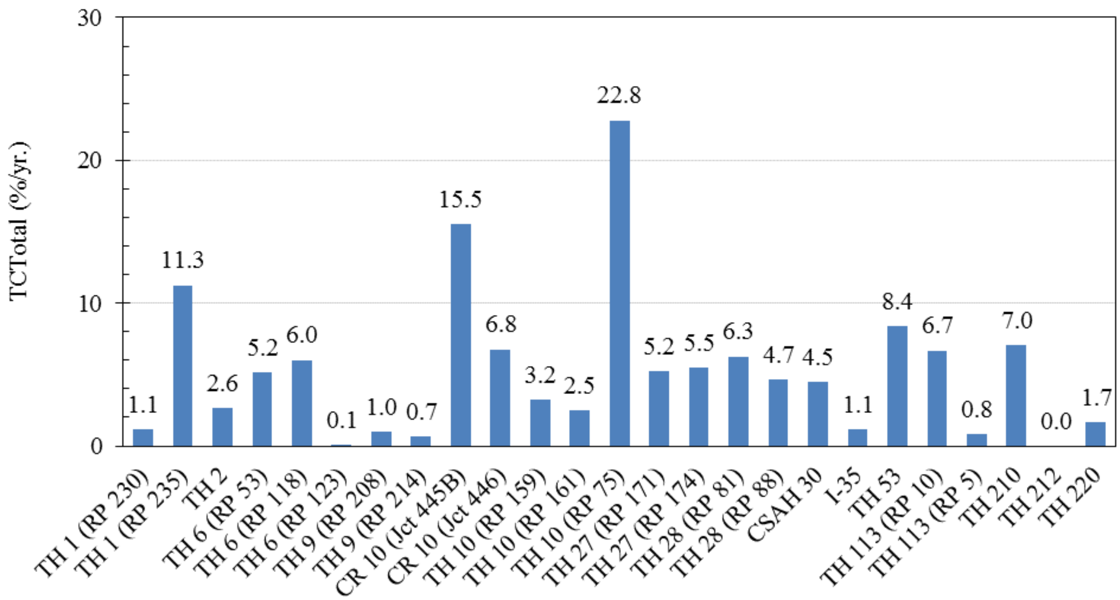


Figure 16: Total Transverse Cracking (TCTotal) for All Study Sections

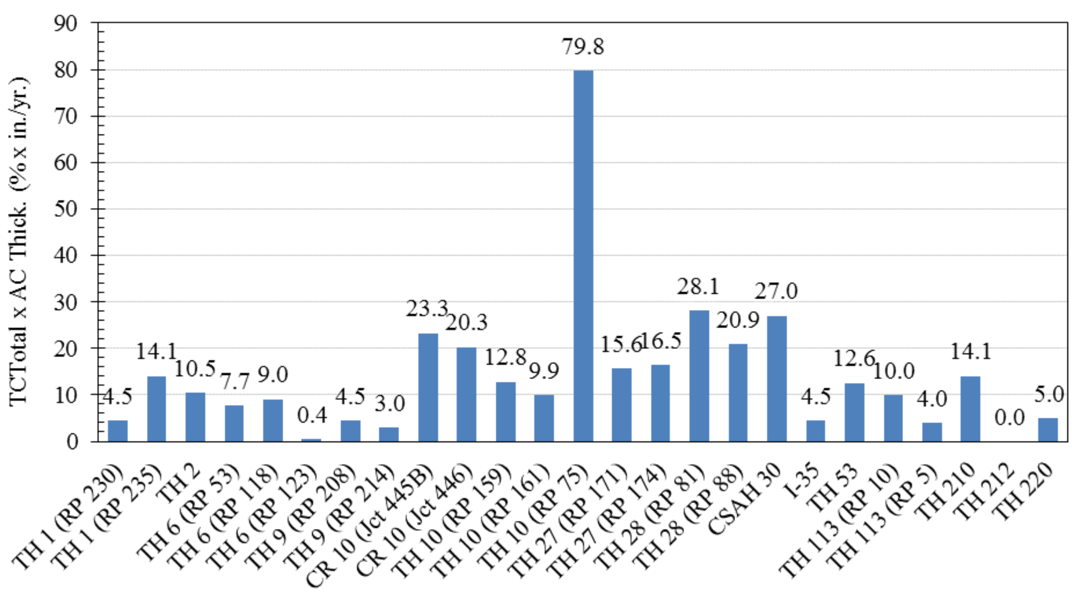


Figure 17: TCTotal Adjusted for AC Thickness for All Study Sections

3.3 Effects of Mixture Design and Laboratory Parameters on Field Performance

The comparison of design mixture properties and laboratory results with the aforementioned cracking measures are presented here. For brevity, only key figures have been provided here, however supplemental figures can be found in Appendix A. All these parameters can be observed when compared to additional cracking measures by Helmer, 2015 [26].

3.3.1 Comparison of Design Mixture Properties with Field Performance

The amount of asphalt binder is often associated with cracking performance of asphalt pavements. Since a major focus of this study is to evaluate the impact of low asphalt binder content of the mixtures on its cracking performance, comparison plots are generated between cracking performance measures and asphalt contents. The results showing comparisons between the design binder content and various cracking performance measures are shown in Figure 18 and Figure 19 and results comparing the ignition oven asphalt binder content to cracking performance are shown in Figure 20 and Figure 21. In general, Figure 18 and Figure 19 is the expected result, however the ignition oven results contradict this. As previously mentioned, the difference between design and ignition oven asphalt content is being investigated and the ignition oven asphalt content should still be taken as approximate since the test procedure requires oven calibration which was beyond the scope of this project. Regardless, it can be seen that the design asphalt content by itself may not be a good indicator of the pavement's cracking performance as there is a weak correlation.

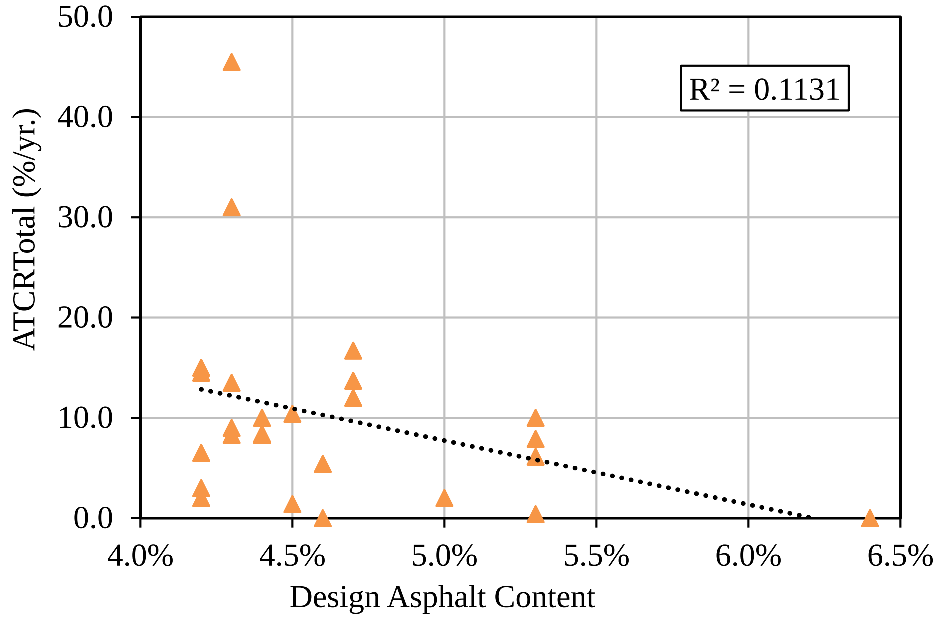


Figure 18: Average Total Transverse Cracking Rate (ATCRTotal) versus Design Asphalt Content

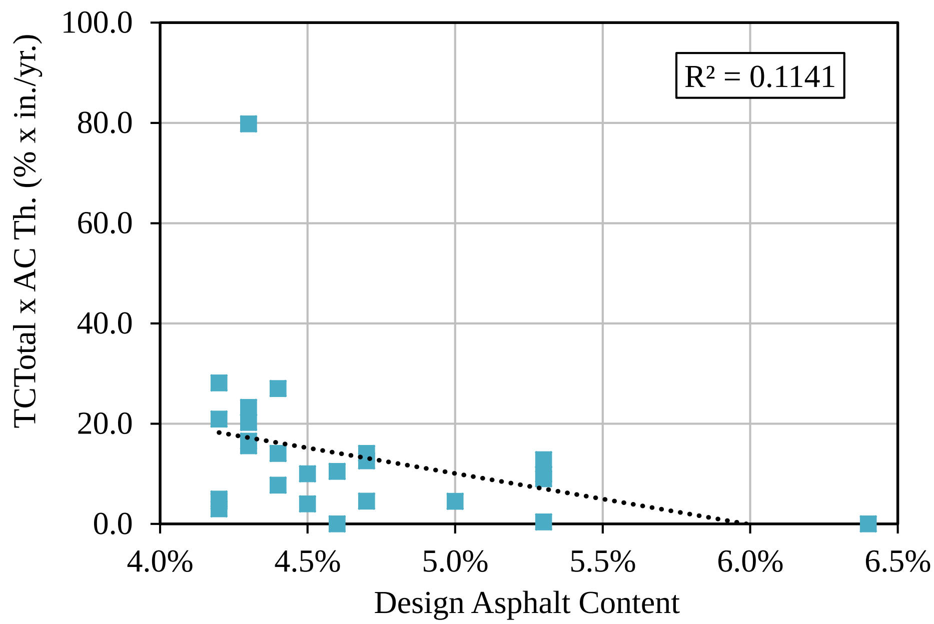


Figure 19: TCTotal Adjusted for AC Thickness versus Design Asphalt Content

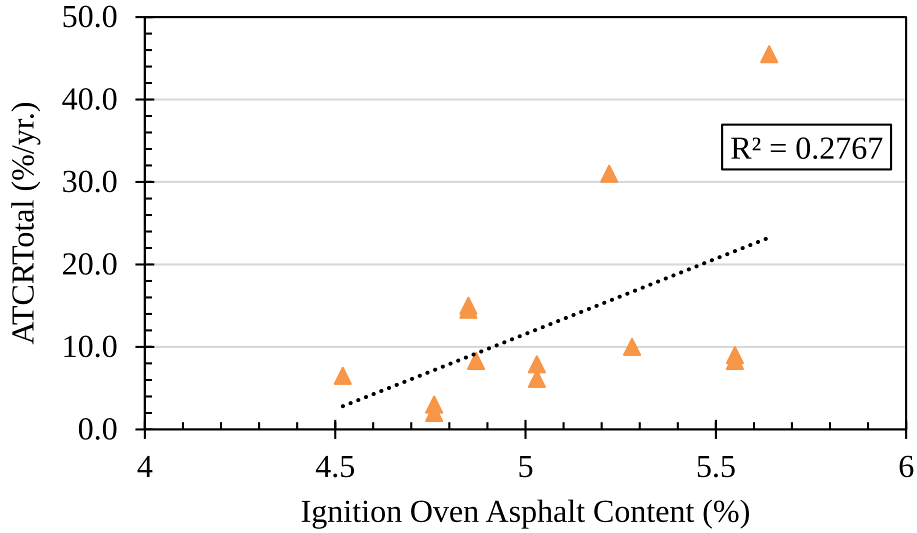


Figure 20: Average Total Transverse Cracking Rate (ATCRTotal) versus Ignition Oven Asphalt Content

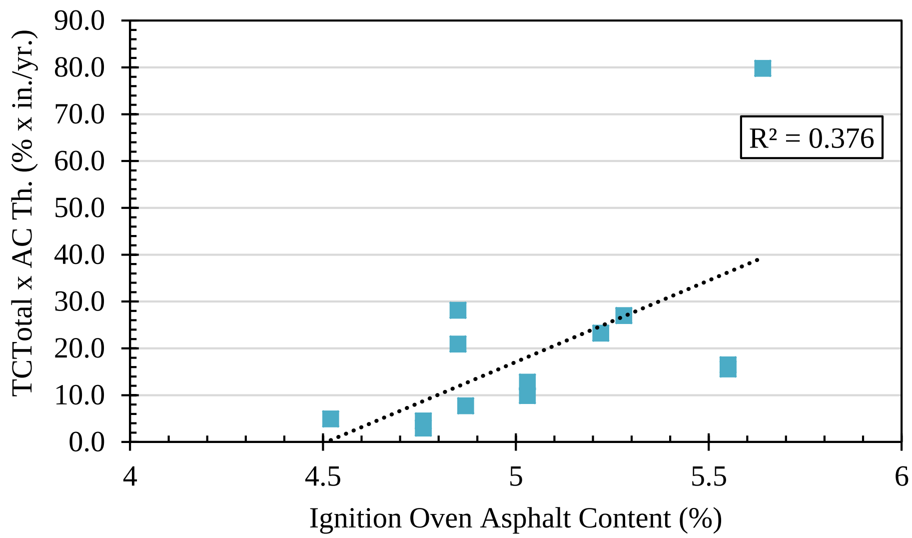
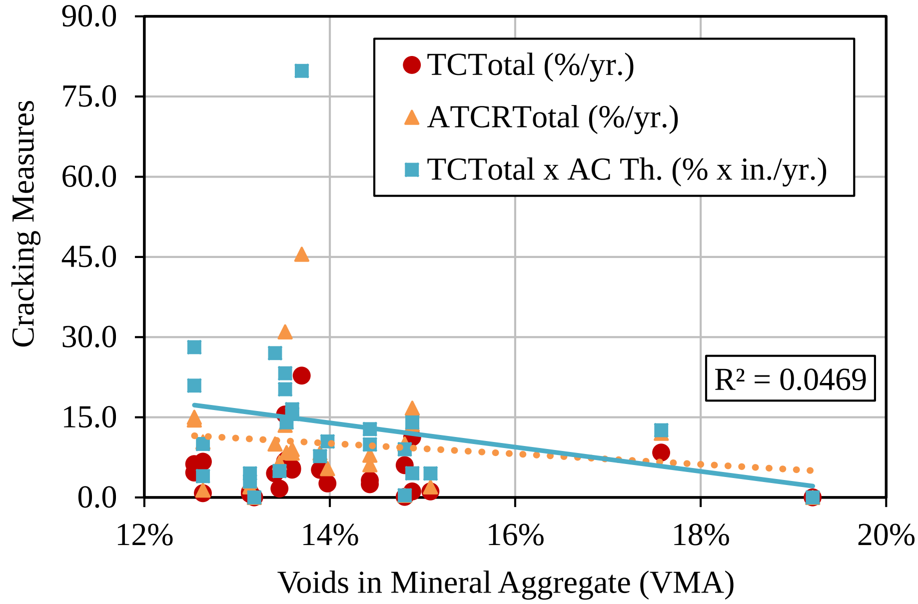
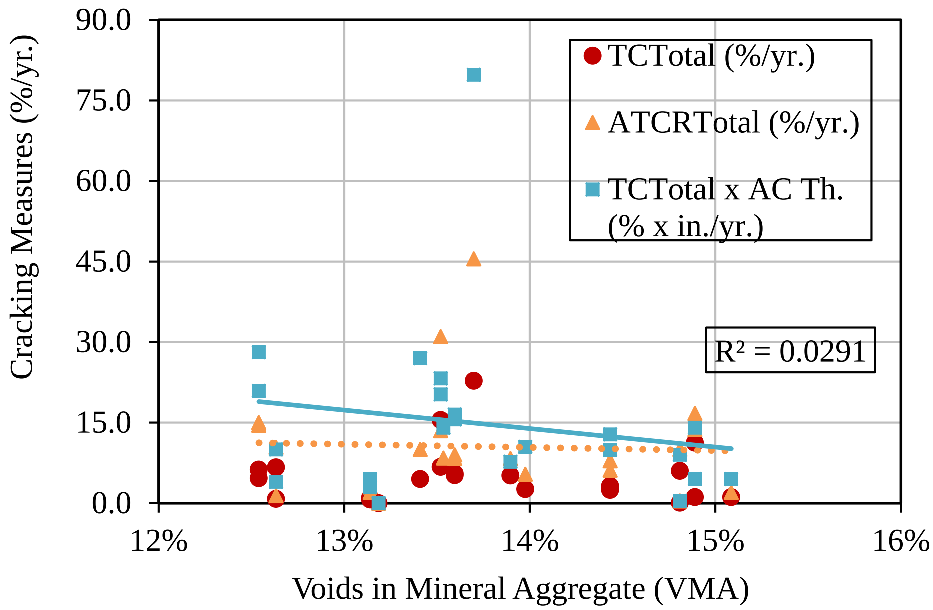


Figure 21: TCTotal Adjusted for AC Thickness versus Ignition Oven Asphalt Content

The cracking performance measures are plotted against the volumetric properties VMA, adjusted AFT, and VFA in Figure 22, Figure 23, and Figure 24, respectively. In both VMA (Figure 22) and adjusted AFT (Figure 23), trend-lines are fitted between TCTotal (dotted line), ATCRTotal (solid line) cracking measures. Please note that the intent of these trend-lines is simply to show the weakness of the relationship and they are only for purposes of graphical display. Trends are relatively weak for both VMA and AFT. Also there are two figures (a) and (b) for both parameters, noting that (a) represents all the data whereas (b) removes the statistical outliers from the data. In case of VMA, the loose trends for ATCRTotal and TCTotal normalized for AC thickness are in agreement with the general consensus of improved cracking performance with increased VMA. The adjusted AFT trend with the cracking performance is in agreement with general consensus but still it is very weak relationship. Lastly, AFT is shown with respect to TCTotal normalized for AC thickness and even though it is a weak correlation, as VFA increases, the amount of cracking decreases. This further confirms that use of volumetric measures as a predictor of asphalt mixture's field cracking performance may not be adequate by itself.

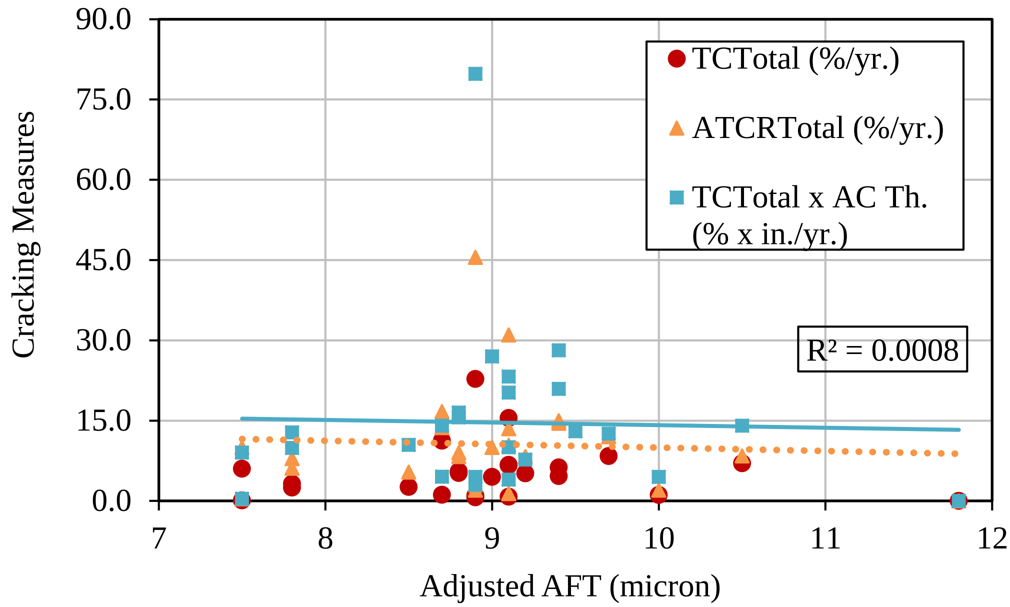


(a) All Data Points

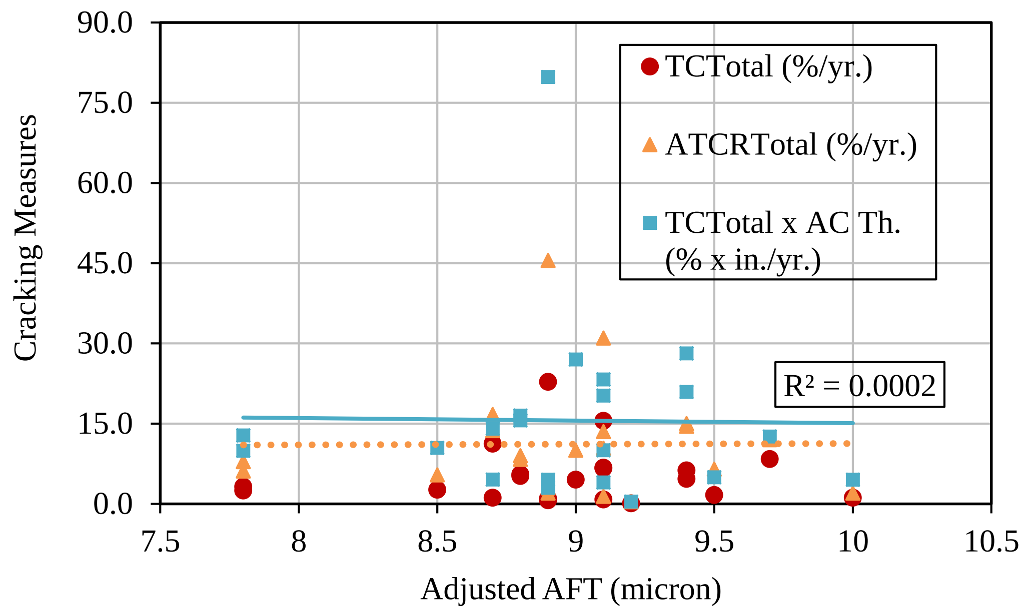


(b) Outliers Removed

Figure 22 (a-b): Cracking Performance versus Voids in Mineral Aggregates (VMA) (solid trend-line fitted to TCTotal; dotted trend-line fitted to ATCRTotal)



(a) All Data Points



(b) Outliers Removed

Figure 23 (a-b): Cracking Performance versus Adjusted Asphalt Film Thickness (AFT) (solid trend-line fitted to TCTotal; dotted trend-line fitted to ATCRTotal)

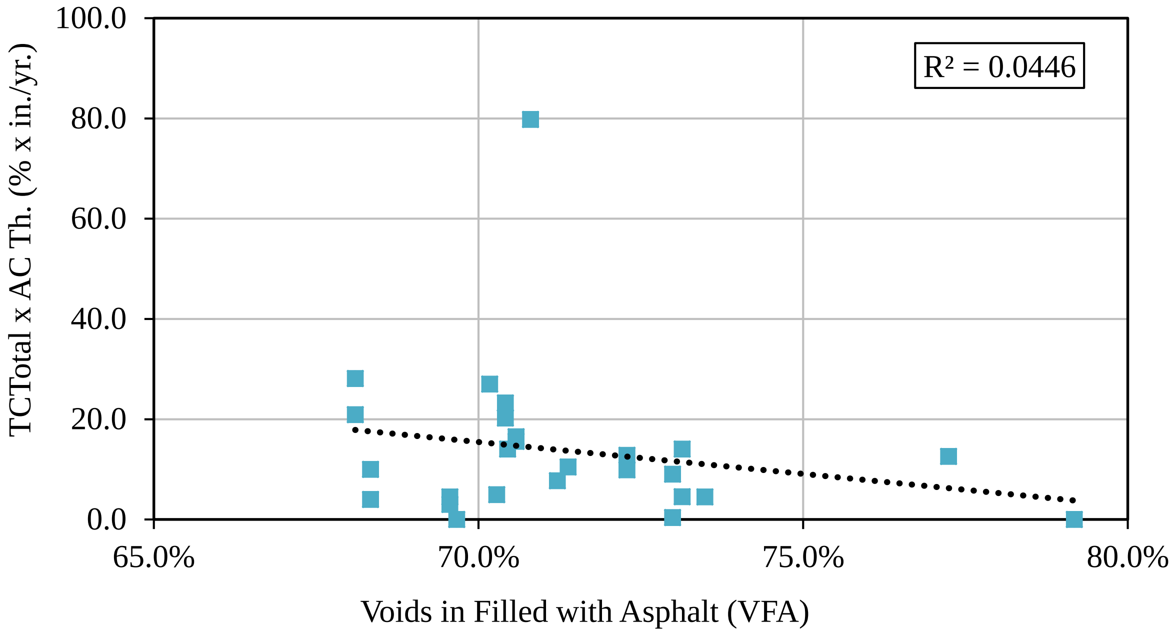


Figure 24: TCTotal Adjusted for AC Thickness versus Voids Filled with Asphalt (VFA)

The performance grade of the asphalt binder is compared next with the various field performance measures. The binder grade used in this comparison represents the specified grade for the mixture and typically represents the virgin binder component of the mixture. Figure 25 compares the spread of asphalt binder grade (difference between high and low grade temperatures) versus the TCTotal. From the data, it is apparent that on average, as the spread of the binder grade increase, the transverse cracking performance improves. The coefficient of determination (R^2) was similar for the TCTotal adjusted for AC thickness parameter, however much lower for ATCRTotal.

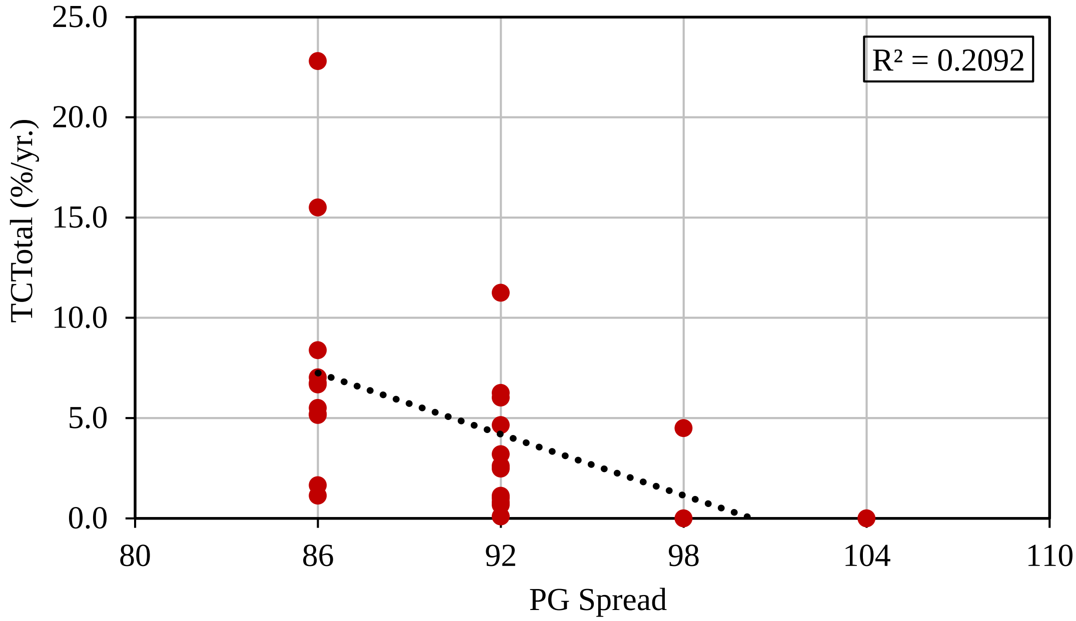


Figure 25: Total Transverse Cracking (TCTotal) versus PG Spread

The PG low temperature grade (referred to as PGLT) of the binders are compared with TCTotal and is presented in Figure 26. The relationship of PGLT to TCTotal and ATCRTotal were similar, however the trend with TCTotal adjusted for AC thickness was poor. It can be seen from the fitted trend-line that the PGLT has some effect on the cracking performance with -34 graded binders showing superior cracking performance compared to the -28 binders. The observation of the TCTotal data indicates that the average cracking rate for all mixtures with PGLT of -28 ºC is approximately 6.6 %/yr. as opposed to 3.4%/yr. for mixes with PGLT of -34 ºC. This would translate in pavement life to 100% cracking for -28 ºC binders in under 8 years and approximately 14 years for -34 ºC binders. This observation is consistent with other recent studies of MnDOT pavements.

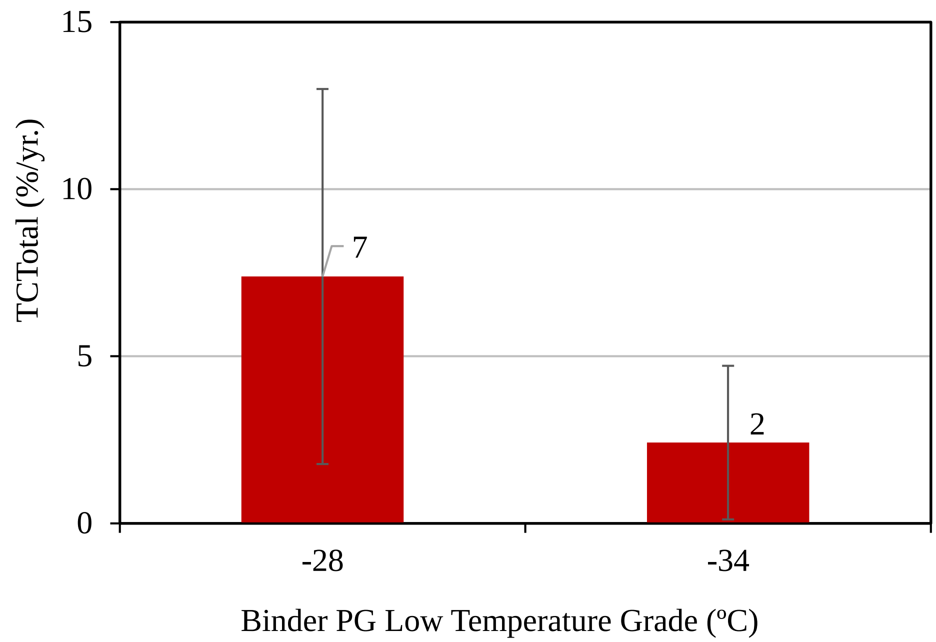


Figure 26: Total Transverse Cracking (TCTotal) versus PGLT

The amount of recycled binder as percent of total binder amount is compared with field cracking performance next. The comparison in terms of TCTotal is presented in Figure 27 respectively. The very loose trend shown by this figure does conform to expected result being that higher amounts of RAP generally have higher cracking rates. Note that the data has a very poor correlation for all cracking measures.

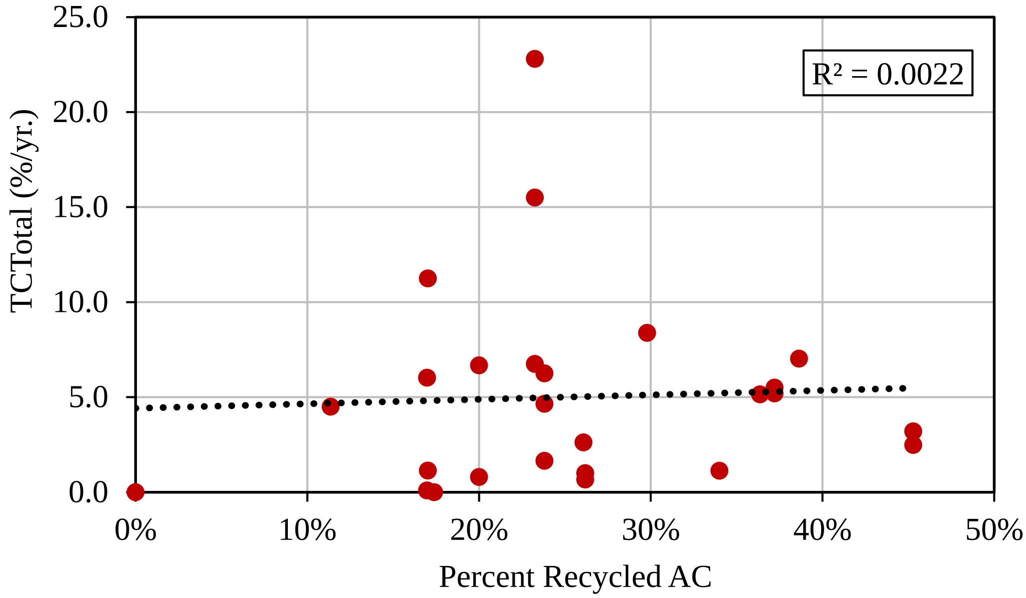


Figure 27: Total Transverse Cracking (TCTotal) versus Percent Recycled Binder

Finally, the type of pavement construction (thin mill and overlay versus thick mill and overlay versus reclaim and overlay) was compared with the transverse cracking performance. The construction types in this study include: thin overlays (up to 75 mm or 3 inch); thick overlays (over 75 mm or 3 inch); reclaim pavement (typically old asphalt layer reclaimed and an overlay of 75 – 100 mm on top) and new construction or reconstruction. Most of the study sections fall in the first 3 categories with only 2 sections represented by new construction. The comparison between cracking performance and the construction type is shown in Figure 28 through Figure 30. The bars represent the average of each cracking measure while the error bars represent the standard deviation of each cracking measure for each construction type. As seen in previous studies, the type of construction has a very significant effect on the cracking performance. In this study, the average cracking rate for thin overlay construction is realized to 15 %/yr. as opposed to 8%/yr. for thick overlays and 4%/yr. for reclaim sections. Note that reflective cracking is also included in the transverse cracking count, which is one reason why thin overlays see higher cracking amounts. This data shows that the reclaim construction type performs better than overlays.

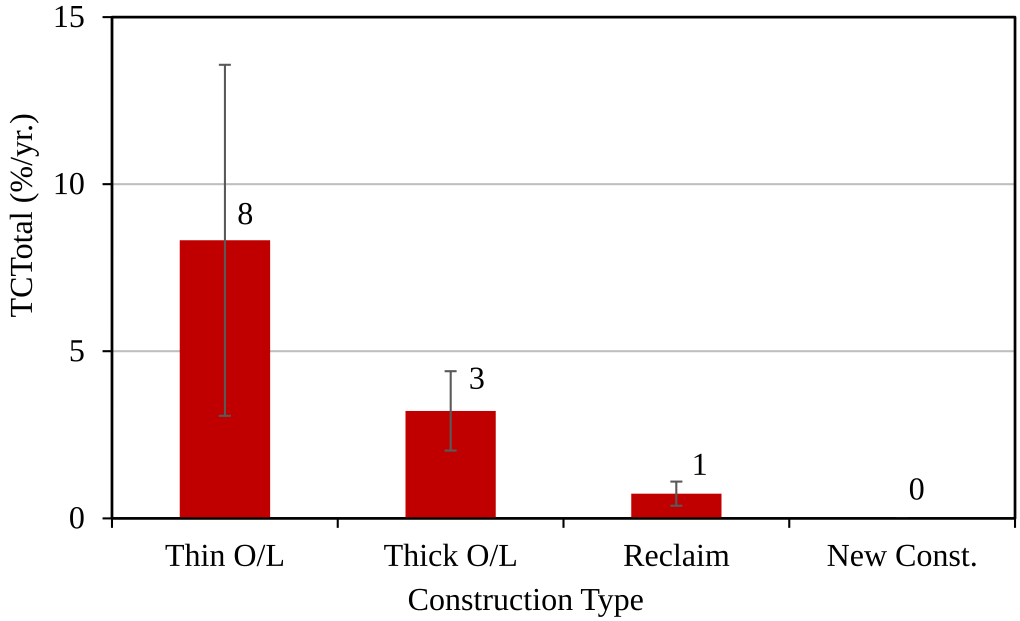


Figure 28: Total Transverse Cracking (TCTotal) versus Construction Type

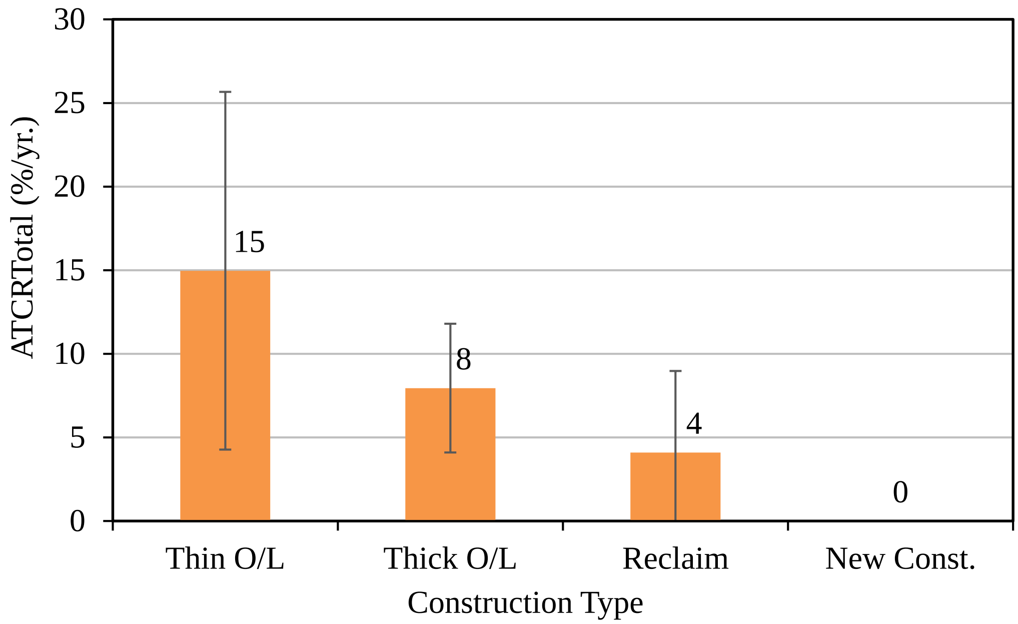


Figure 29: Average Total Transverse Cracking Rate (ATCRTotal) versus Construction Type

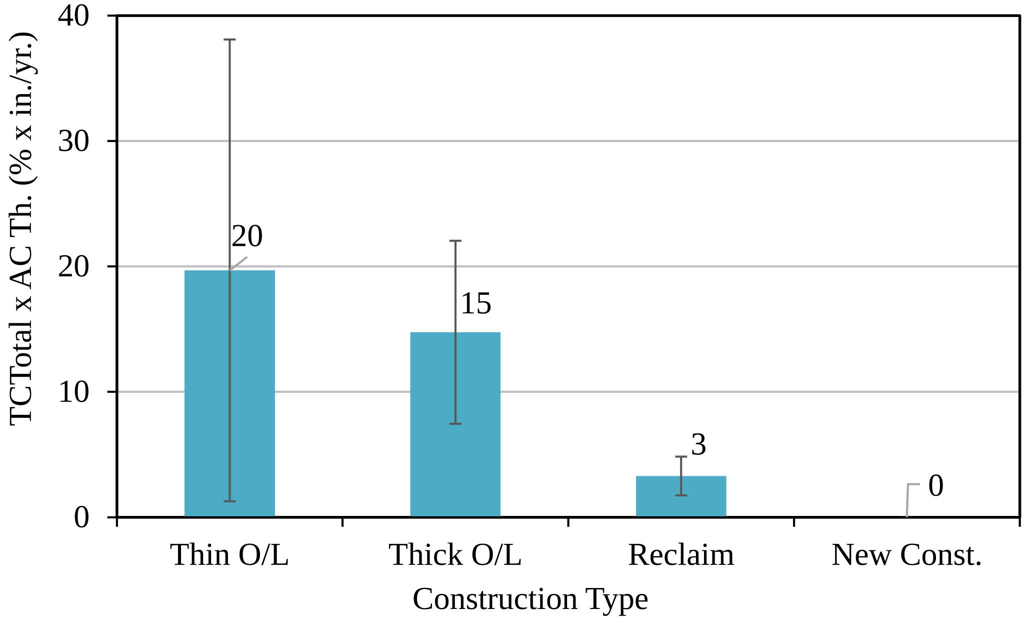


Figure 30: TCTotal Adjusted for AC Thickness versus Construction Type

3.3.2 Comparison of Laboratory Measured Mixture Properties with Field Performance

3.3.2.1 Lab Permeability

The permeability of asphalt mixtures has been hypothesized to have significant effect on the durability and performance. The cause of high permeability is primarily presence of interconnected voids. The use of permeability over air void level has been recommended by researchers in past as a better measure of asphalt mixture's durability. The comparisons between lab measured permeability (using Karol-Warner permeameter and Florida DOT test procedure) and cracking performance are plotted in Figure 31 and Figure 32. In general it can be seen that as the permeability increases the cracking performance deteriorates. The comparison between ATCRTotal and permeability show that of eight mixtures with permeability greater than typical range for dense graded asphalt mixtures, six have very high average cracking rates.

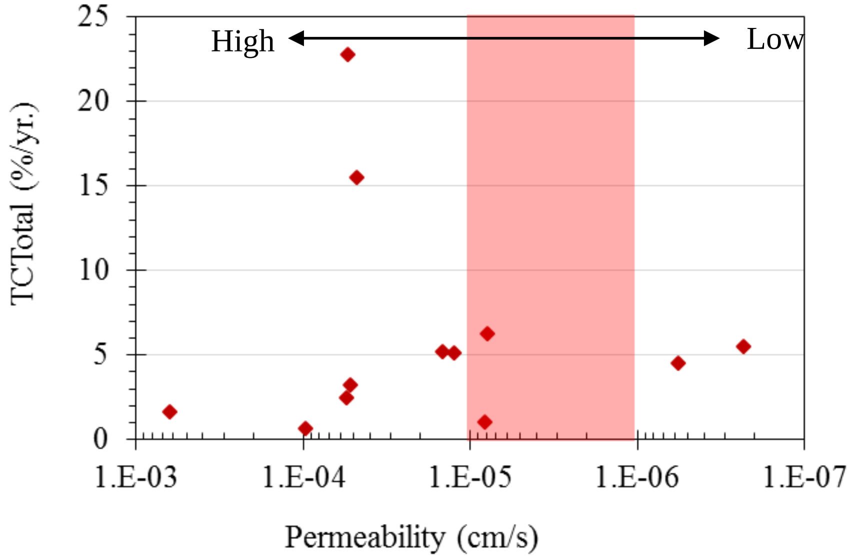


Figure 31: Total Transverse Cracking (TCTotal) versus Permeability
(shaded box indicates typical permeability range for dense graded asphalt mixtures)

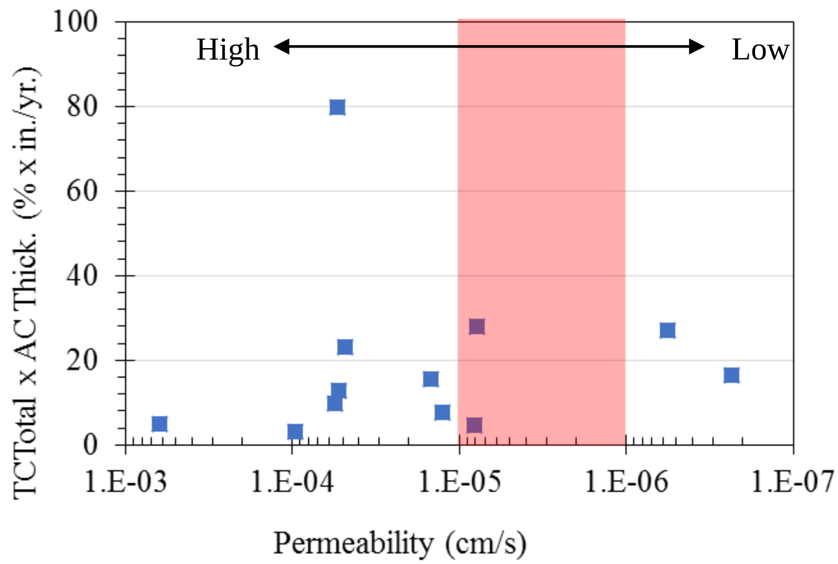


Figure 32: TCTotal Adjusted for AC Thickness versus Permeability
(shaded box indicates typical permeability range for dense graded asphalt mixtures)

3.3.2.2 Disk-shaped Compact Tension Test

The disk-shaped compact tension (DCT) fracture energy tests were conducted on the field procured samples from each pavement section. The DCT fracture energy is being closely evaluated by MnDOT and several other transportation agencies as a cracking performance prediction parameter for asphalt mixtures. Several agencies including MnDOT have conducted pilot implementations of minimum fracture energy requirements in the asphalt mixture specifications.

The comparison between the DCT fracture energies and cracking performance measure of the pavement sections are presented in Figure 33 through Figure 37. The recommended minimum threshold value of 400 J/m^2 is also indicated on the plots. In Figure 33, while a trend between DCT fracture energy and current cracking amount is not evident, it can be seen that out of the 19 mixtures that are below the recommended threshold, 14 are above or approaching substantial transverse cracking amount of 30%. The comparison between DCT fracture energy total transverse cracking (TCTotal), average transverse cracking rate (ATCRTotal), and TCTotal normalized for AC thickness are plotted in Figure 34 & Figure 35, Figure 36 and Figure 37 respectively. Once again it can be seen that of the 19 mixtures below the recommended fracture energy threshold of 400 J/m^2, nine have very high average cracking rates, greater than 10%/yr. This indicates these roads are cracking at a rate to reach 100 percent cracking in 10 years or less. It should be noted that only one mixture meets the recommended threshold and thus from this dataset it cannot be concluded that once fracture energy increases above 400 J/m^2 the pavement cracking performance improves dramatically.

There is no strong relationship between fracture energy and performance until the data is separated by construction type, like in Figure 35. Thin overlays are more likely to include reflective cracking in the cracking measures. Therefore by removing thin overlays to focus on thermal cracking of thick overlays and full depth relacamation (FDR) constrution types, a correlation is present. This correlation shows as fracture energy increases, performance improves which is consistent with previous research.

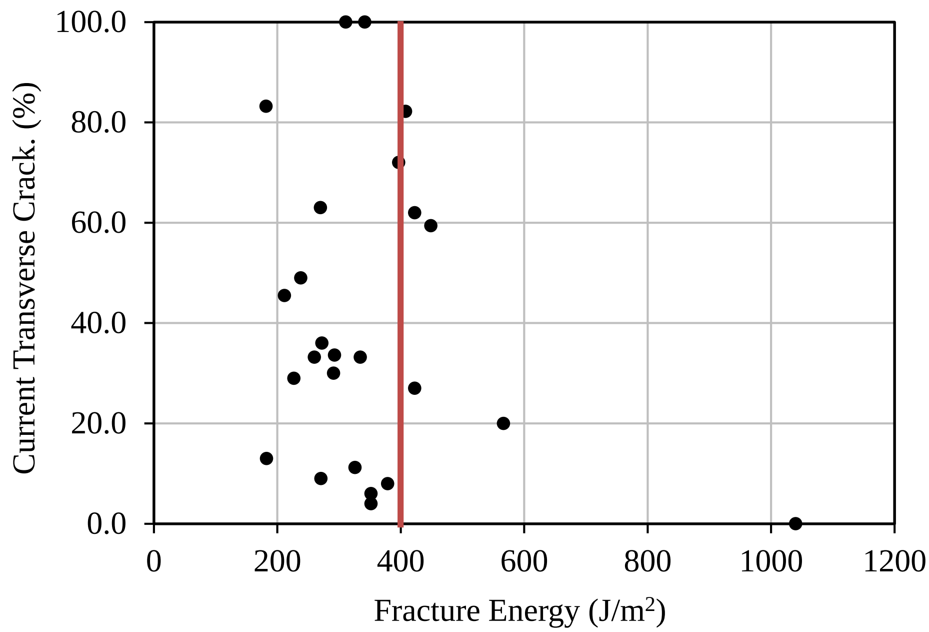


Figure 33: Current Transverse Cracking Amount versus DCT Fracture Energy of All Study Sections

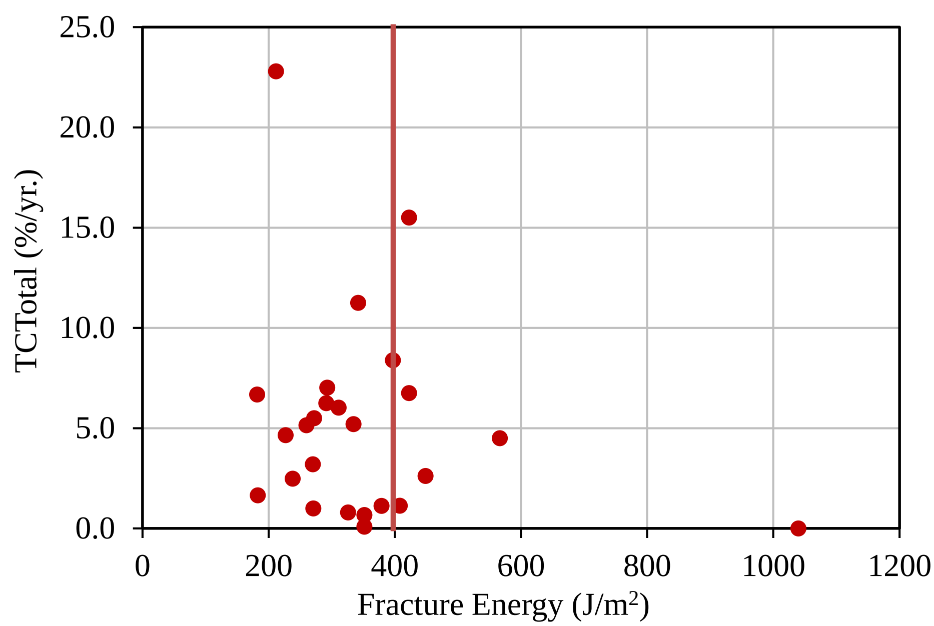


Figure 34: Total Transverse Cracking (TCTotal) versus DCT Fracture Energy of All Study Sections

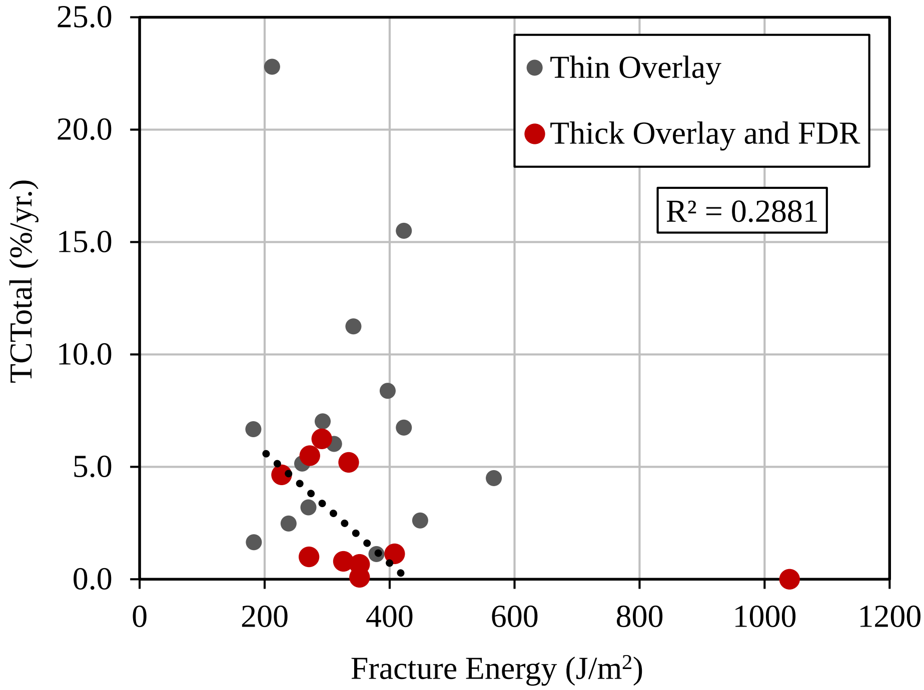


Figure 35: Total Transverse Cracking (TCTotal) versus DCT Fracture Energy of All Study Sections Separated by Construction Type (trend-line fitted to Thick Overlay and FDR)

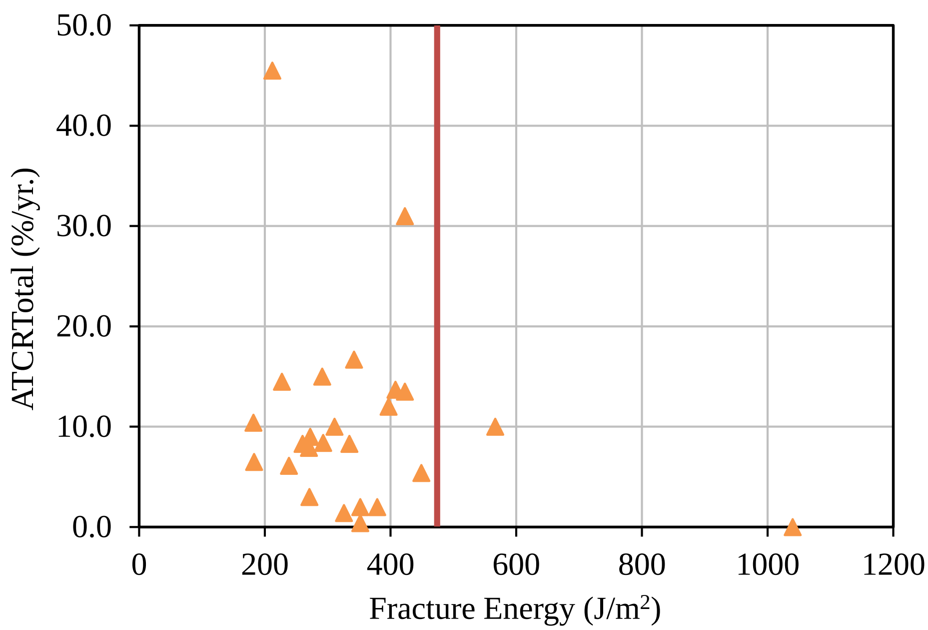


Figure 36: Average Total Transverse Cracking Rate (ATCRTotal) versus DCT Fracture Energy of All Study Sections

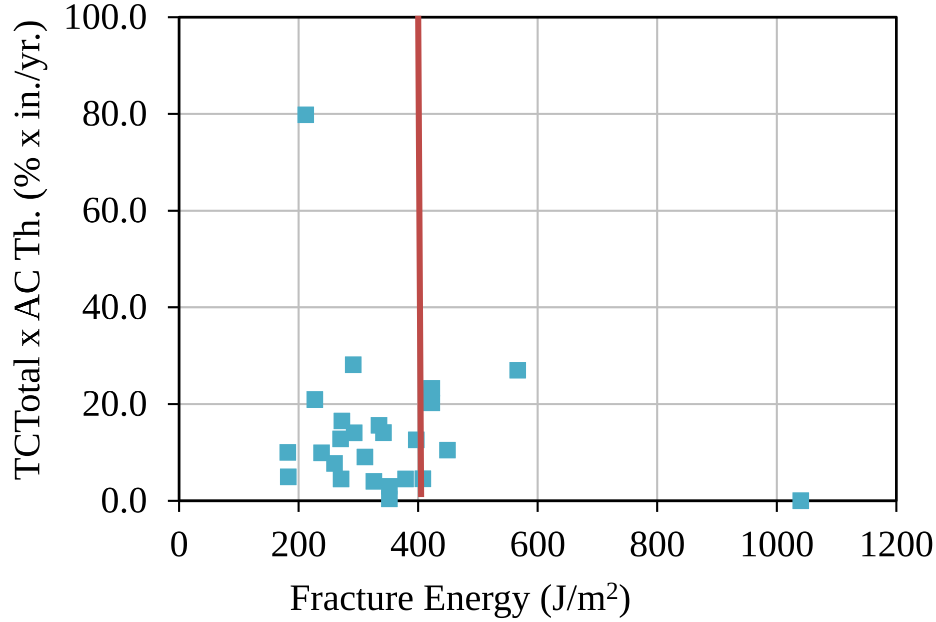


Figure 37: TCTotal Adjusted for AC Thickness versus Fracture Energy

The comparison between current cracking performance and DCT fracture energy of the companion sections (highways with two nearby study sections) are shown in Figure 38. Noticeably for the 10 sections across the 5 sites, each section that has a higher fracture energy has a lower current transverse cracking amount. This further supports the use of DCT fracture energy as a transverse cracking performance measure.

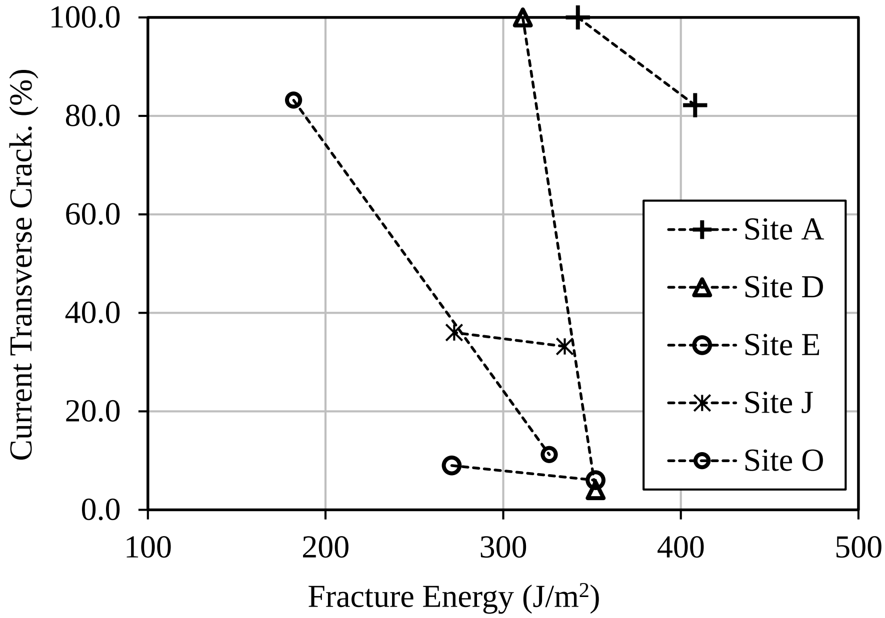


Figure 38: Current Transverse Cracking Amount versus DCT Fracture Energy of Companion Sections

3.3.2.3 Aggregate Gradation

The comparison between cracking performance and the gradation of recovered aggregates from ignition oven residue of field samples is presented in this sub-section. The gradation measures in terms of amount of aggregate passing on various MnDOT control sieves was conducted. After a thorough analysis two set of comparisons showed the highest correlations. Figure 39 shows the average transverse cracking rates plotted against the fraction of aggregate passing ½ inch sieve and retained on #8 sieve. It can be seen that a relatively strong correlation exists between this parameters and average cracking rate, with cracking rate decreasing as this intermediate portion of aggregate gradation increases. Similarly, the same comparison is plotted between total transverse cracking and aggregate fraction passing ½ inch sieve and retained on #8 sieve in Figure 40. Nonetheless, the a strong trend is once again seen whereby as the fraction of aggregate between ½ in and #8 sieve increases the field cracking rate also increases.

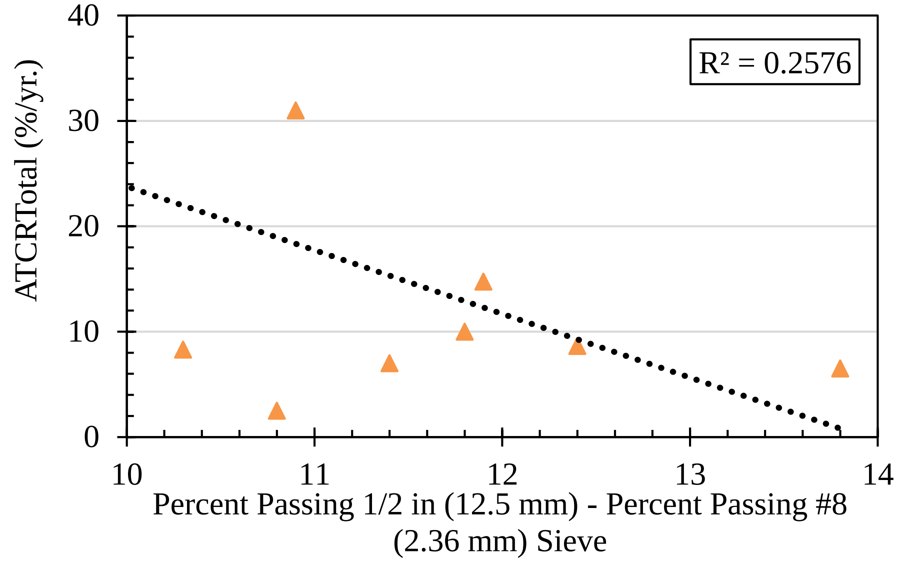


Figure 39: Average Transverse Cracking Rate (ATCRTotal) versus Percent Aggregate Between 1/2 inch and #8 Sieve Sizes

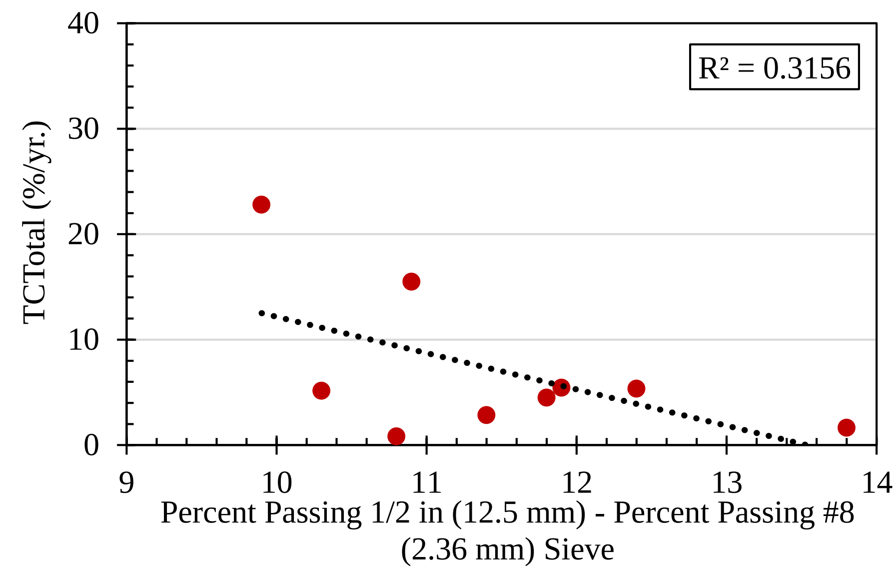


Figure 40: Total Transverse Cracking (TCTotal) versus Percent Aggregate Between 1/2 inch and #8 Sieve Sizes

3.4 Summary and Conclusion

This study evaluated 25 pavement sections at 18 sites within Minnesota. The sections encompass a variety of asphalt mixtures and asphalt construction types that are typically used in Minnesota. The transverse cracking performance of these pavements was obtained from pavement management system and through crack surveys. The cracking amounts were converted to a set of cracking performance measures that allow for comparisons between various sections. The cracking performance is compared with various asphalt mixture attributes and construction types.

The comparisons between asphalt mixture attributes and cracking performance measures showed that total asphalt binder amount and recycled asphalt binder amount may not be sufficient controls to control thermal cracking. Performance testing, in addition to currently used controls (mix volumetrics and constituent properties), is recommended to ensure good cracking performance. The DCT fracture energy results for companion sections show that mixtures with higher fracture energies exhibit lower amounts of transverse cracking.

On basis of the results and the discussion presented in this report following observations can be made:

- The pavement sections studied in this project generally show poor transverse cracking performance with anticipated pavement age to reach 100% cracking average for these mixtures to be approximately 9.5 years and the average transverse cracking rate of 10.4% per year.
- The construction type continues to show a very strong correlation with the transverse cracking performance. A recently completed MnDOT research on asphalt pavement performance made very similar conclusion [5]. In the present study of 25 pavement sections, the milling and thin overlays exhibit average transverse cracking rate of 15% as compared to 8% for milling and thick overlays and 4% for reclaim sections. Thin overlays are designated as overlays with less than 75 mm (3 inch) thickness.
- Of the asphalt mix designs parameters, the only two showed a strong trend: the low temperature grade of the asphalt binder and the gradation.

- The binders with -34 grade show approximately 12% average transverse cracking rate as opposed to approximately 26% for mixtures with -28 low temperature grade.
- All mixtures in this study are ¾ inch sized mixtures as per MnDOT 2360 specifications. For these mixtures, as the amount of aggregate fraction between ½ inch and #4 sieve increases the average cracking rate decreases and as the fraction between #4 and #200 sieve increases the cracking rate increases. In other words, for these coarse mixtures as the intermediate size material on coarse side increases the cracking performance improves and the trend is reversed on the finer sieves. Thus, it is recommended that the mixtures be designed with more uniform gradations to improve the cracking resistance. It is recommended that the gradation bands be reevaluated to accomplish this goal.
- The typically used volumetric measures for ensuring the performance of asphalt mixtures, i.e. asphalt film thickness and voids in mineral aggregates did not show a consistent trend with cracking performance. This is in agreement with previous research results of MnDOT studies.

- Majority of section with high cracking rates have DCT fracture energy that is under the recommended threshold of 400 J/m^2. However there is limited data for mixtures with fracture energy that meets the threshold, thus it cannot be conclusively reported that a trend between DCT fracture energy and cracking performance is seen in this study. It should be noted that the samples tested in this study are all from field cores and procured at different pavement ages, thus the lack of trend is not entirely unexpected.
- The DCT fracture energy and the permeability show a reasonable trend with mixtures having higher permeability have lower fracture energies.
- The results presented herein will be used in conducting pavement performance evaluation using tools such as, IlliTC which will allow for making fair comparisons between the sections in terms of their anticipated cracking performances.

CHAPTER 4: EFFECTS OF BINDER GRADE AND MODIFICATIONS ON FIELD CRACKING PERFORMANCE

4.1 Introduction

The purpose of the research presented in this chapter was to determine the effects of polymer-modified asphalt binders on asphalt pavement field performance in terms of longitudinal and transverse cracking. MnDOT's pavement management system (PMS) was utilized as a performance indicator and means of quantifying cracking performance using various transverse and longitudinal cracking measures. These quantities were derived from survey pavement distress data within the PMS database. The PMS data provided by MnDOT includes historical records of all construction activities as well as field measured performance for a variety of pavement sections throughout the state.

The pavement projects and sections in this research include pavements with various attributes. In order to capture the generalized effects of binder type on cracking performance, 37 projects consisting of Minnesota state highways were reviewed from year 2001 to 2013. A goal of this study was to look at the effect of asphalt binder on cracking performance by analyzing pavements with a breadth of variables which include but are not limited to:

- Asphalt binder type (performance grade and polymer modification)
- Pavement type: bituminous on bituminous (BOB), bituminous on aggregate base (BAB), or bituminous on concrete (BOC)
- Pavement structure (AC, base and/or subbase thickness)
- Pavement age
- Traffic (annual average daily traffic (AADT) and percent trucks)
- Original SP construction, maintenance or repair activity
- Frequency and extent of pavement preservation and maintenance activities such as crack seals or chip seals (these activities reside under the original SP number)
- Performance in driving lane(s) as compared to passing lane
- Location and corresponding climate variations within Minnesota

4.2 Research Method & Data Sources

This section will discuss the research method and two data sources used to gather pavement distress and binder characteristics: pavement management systems (PMS) and asphalt binder data, in addition to the cracking performance measures used to quantify field performance. Due to the large amount of information, the process of sorting through the each entry by hand and repeatedly calculating crack performance measures would be a long and cumbersome process. Therefore, algorithms in the form of "Macros" were developed in Microsoft Excel using Visual Basic to automate the preliminary data analysis procedures which included reducing and combining the PMS and asphalt binder data.

4.2.1 PMS Data of Study Sections

PMS data is a source of both pavement section characteristics and distress data. For the most part, the data used in this study had survey data for each section every 2-3 years. MnDOT supplied the PMS data for the aforementioned pavement sections studied herein. As previously discussed, for each cracking type and each severity level, the surveyed data is normalized over the length of the section and reported in units of percent cracking.

In order to consolidate the overwhelming amount of PMS data provided, the data is classified into study groups. "Study groups" are defined in this thesis as instances where there was PMS data for multiple consecutive pavement sections on a highway, corresponding to the same construction project (defined by the SP number). The study groups used in this research are sorted by the binder types studied and provided in Table 8. Noticeably there are instances where there are several SP numbers for one highway as well as several highways that fall under one SP number. This occurs when there is pavement construction of a roadway that includes construction of the roadway intersections. In instances where a highway and SP combination appear more than once, it is due to the fact that there was a gap in the highway length where pavement management data was not provided. However all unique study groups can be distinguished by the beginning and end section number. For example, SP1502-26 on highway US2 had 2 study groups. One group had 17 consecutive sections (section numbers 2060-2076) and the other had 2 consecutive sections (2251-2252). Since the location of these sections are not the same, they were kept as separate study groups. To understand the vast amount of data, considering the US2 study group with 17 sections, each section had 7 years of pavement distress data analyze. This means there was 119 rows of data corresponding to one study group. In total, this study evaluated the cracking performance of 295 pavement sections and each of the sections had corresponding distress data for every year that a pavement survey was conducted. Most of the study groups include multiple consecutive pavement sections which allows for more relevant distress data to be incorporated into the cracking measures for those groups. These 37 study groups encompass 28 Minnesota highways and 30 different SP's. Another thing to note from the table, is that of all the study groups provided, only 3 were constructed with polymer modified PG58-34 (PG58-34 PMAB) asphalt binder and only 5 were constructed with neat PG64-28 (PG64-28 Non-PMAB) asphalt binder. When considering the number of section studied, 15% of the 295 study sections are PG58-34 PMAB mixtures and 19% are PG64-28 Non-PMAB.

Table 8: Summary of Study Sections

Highway	SP	Beginning Section No.	End Section No.	No. of Sections	Construction Type	Construction Year	Last date of PMS data
PG58-34 Non-PMAB							
US14	0804-73	3286	3291	6	BAB Rural	2005	2013
MN7	1004-24	7821	7829	9	Thin OL	2002	2013
US8	1301-94	2474	2477	4	Med M&OL	2004	2013
US61	1302-18	4809	4813	5	Med M&OL	2004	2012
US2	1502-26	2060	2076	17	Med M&OL	2005	2012
US2	1502-26	2251	2252	2	Med OL	2005	2015
US169	2776-02	6155	6160	6	Thin M&OL	2005	2013
I90	3280-107	711	722	12	Med M&OL	2004	2013
US71	3408-14	5085	5087	3	BAB Rural	2003	2010
US14	5202-44	3491	3504	14	Thick M&OL	2004	2012
US2	6001-52	2154	2166	13	Thick OL	2006	2012
US53	6915-122	3907	3908	2	Thin M&OL	2004	2012
US14	7408-29	3345	3346	2	Thick M&OL	2002	2013
US14	7408-29	3516	3518	3	Med M&OL	2001	2013
US218	7408-29	6733	6733	1	BAB Rural	2002	2013
PG58-34 PMAB							
MN23	3408-14	9600	9624	25	BAB Rural	2004	2012
MN13	7001-93	8429	8439	11	Thin M&OL	2003	2012
MN15	8304-28	8544	8549	6	Med M&OL	2004	2013
PG64-28 Non-PMAB							
MN47	0206-49	11449	11462	14	BAB Rural	2004	2013
MN47	3002-09	11467	11485	19	BAB Rural	2005	2012
MN38	3108-56	11089	11094	6	BAB Rural	2004	2013
MN32	5703-42	10806	10812	7	Thick M&OL	2007	2012
MN51	6215-85	11602	11606	5	Thin M&OL	2003	2012
PG64-28 PMAB							
MN316	1926-17	15832	15843	12	Med M&OL	2004	2012
MN55	2723-109	11677	11683	7	Thick M&OL	2003	2013
MN100	2735-183	14306	14308	3	Med M&OL	2004	2012
MN100	2735-183	14329	14331	3	Thin M&OL	2004	2012
MN100	2785-301	14295	14295	1	Med M&OL	2005	2012
MN100	2785-301	14318	14318	1	Med M&OL	2005	2012
I494	2785-301	1875	1876	2	Med M&OL	2005	2013
MN65	3307-38	12843	12846	4	BAB Rural	2007	2013
MN171	3507-12	14830	14831	2	Med M&OL	2006	2012
MN112	4011-16	14589	14590	2	BAB Rural	2004	2012
MN238	4913-19	15529	15531	3	Med M&OL	2004	2013
MN56	5004-17	11944	11948	5	BAB Rural	2006	2013
MN210	5603-10	15161	15182	22	Reclaim	2006	2012
MN95	8208-31	14208	14213	6	Thin M&OL	2004	2013

4.2.2 Asphalt Binder Data

The next step was to match all the projects and distress information with the asphalt binder data associated with each project. The asphalt binder data includes the SP number, binder supplier, binder performance grade, polymer modification and laboratory test measures for rheological parameters.

The asphalt binder data consisted of two performance grades (PG) commonly used throughout Minnesota: PG58-34 and PG64-28, which have the same PG spread. Of these performance grades, both polymer modified asphalt binders (PMAB) and non-polymer modified asphalt binders (Non-PMAB) were analyzed. This dataset was organized by MnDOT's reference system linking the specific SP number to the binder type in terms of performance grade and polymer-modification; binder supplier; and rheological properties of both aged and un-aged binder samples.

For each SP number, the binder was tested at the time of construction using the dynamic shear rheometer (DSR), as described by AASHTO T 315 [25], on both un-aged and rolling thin film oven (RTFO) aged binder samples to characterize the viscous and elastic behavior of the binder. The DSR is an asphalt binder test intended to determine the linear viscoelastic properties of the binder. As a result, the two DSR parameters: phase angle and complex modulus, were provided for both aging conditions.

This data encompasses a wide range of polymer-modified binders with various chemical makeups from seven different suppliers. The result of analysis on this dataset will provide preliminary conclusions to whether there are an apparent differences cracking performance of polymer-modified and non-polymer modified binders for the two binder low-temperature performance grades (PGXX-28 and PGXX-34) commonly used in Minnesota.

4.3 Results

The results of this study are provided herein. All the transverse and longitudinal calculated cracking measures are provided in Appendix B. The following sub-sections include comparisons of cracking performance with construction type, binder type, binder supplier, and DSR rheological parameters.

4.3.1 Construction Type versus Cracking Performance

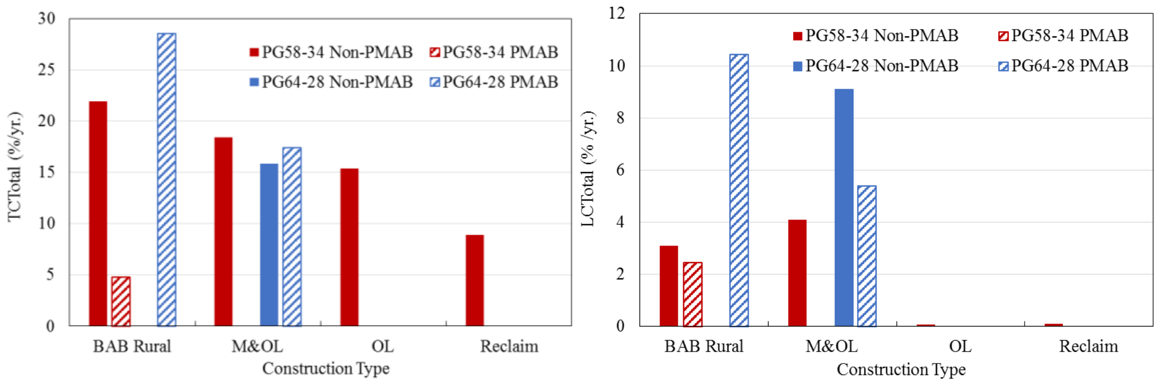
Table 9 illustrates the number of projects that fall under each construction type. From this data, PG64-28 binder tends to be more common for BAB Rural and M&OL projects. By looking at Figure 41, it is apparent that there is significantly more transverse cracking than longitudinal cracking on these pavement sections, which re-iterates that transverse/thermal cracking is the predominant distress on Minnesota roadways.

Figure 41 shows how the different construction types relate to the TCTotal and LCTotal cracking measures. Figure 41 (a) shows in the mill and overlay construction (M&OL), the PG58-34 Non-PMAB performs similar to PG64-28 PMAB. Even though the PG64-28 binder is polymer-modified, the PG58-34 has a superior low-temperature PG binder grade. However in bituminous-aggregate base rural (BAB Rural) construction, PG58-34 shows significantly better transverse cracking performance. As expected, the polymer modified PG58-34 shows better TCTotal performance than the neat PG58-34 binder.

Polymer-modified binders generally perform slightly better than the corresponding performance graded non-polymer modified binders as indicated in Figure 41 (b). Although the PG58-34 PMAB had a low number of occurrences in this project, the data suggest that the binder performed better than the other 3 types. Figure 41 (a) and (b) suggest the PG64-28 non-polymer modified binder performed better than the polymer-modified version, however when the construction types are broken up, it shows the opposite. Overall for both transverse and longitudinal cracking measures, the bituminous on aggregate base (BAB Rural) construction type sees superior performance to the overlay (OL) and mill and overlay (M&OL) construction types.

Table 9: Construction Type Frequency of Study Groups by Binder Type

Binder Type		Construction Type				Total
		BAB Rural	M&OL	OL	Reclaim	
PG58-34	Non-PMAB	4	7	3	1	15
	PMAB	3	0	0	0	3
PG64-28	Non-PMAB	0	5	0	0	5
	PMAB	3	11	0	0	14



(a) TCTotal (b) LCTotal

Figure 41: Construction Type versus Cracking Performance

4.3.2 Binder Type versus Cracking Performance

The number of study groups characterized by each binder type were presented previously in Table 9. The binder types are shown according to their calculated transverse and longitudinal cracking performance measures; this is illustrated in Figure 42 (a-h). The binder types are distinguished by bars; the solid bars represent Non-PMAB and patterned bars represent PMAB. These bars indicate the average cracking measure of all the projects with that binder type. The error bars on these figures are indicative of the maximum and minimum cracking measure occurrence among the binder type sample groups.

Consistently throughout the transverse and longitudinal cracking measures, the polymer modified PG58-34 binder performed better than the non-polymer modified version, as expected. Conversely, for the longitudinal cracking measures, the polymer modified PG64-28 seemed to perform worse than the non-polymer modified binder. Additionally for the longitudinal cracking measures, the PG58-34 binders (both PMAB and Non-PMAB) performed better than the PG64-28 PMAB. Since the PG58-34 binder has a superior low-temperature PG grade, the polymer-modified PG58-34 was expected to have superior cracking performance. By comparing the figures, all cracking measures confirm that projects with the PG58-34 PMAB out-performed the other 3 binder types in this study. However, as previously mentioned, it should be noted that this data is limited by the sample size of the PG58-34 PMAB binder type, shown in Table 9.

By comparing all the transverse cracking measures of the PG58-34 binders, the Non-PMAB case consistently saw approximately 3 times or more cracking than the PG58-34 PMAB case. Therefore this suggests that polymer modified binders may have better transverse cracking performance than non-polymer modified PG58-34 binders. The same comparison for all the longitudinal measures generally showed similar cracking performance of PMAB and Non-PMAB PG58-34 binders. Each longitudinal cracking measure for the PG58-34 PMAB and Non-PMAB were within 0.5% cracking/yr. of each other.

Separately looking at the PG64-28 binders, the longitudinal cracking measures imply that PMAB perform better than Non-PMAB in all measures except for maximum cracking rate (MLCRTotal) in which case sees similar performance. However, strangely the transverse cracking measures for Non-PMAB seem to consistently perform better than PMAB. As a result no conclusions can be made regarding superior performance of either the PMAB or Non-PMAB of the PG64-28 binder types. The variable results in the PG4-28 binders are believed to be a consequence of the binder's low temperature not being suitable for Minnesota's cold climate. Regardless of whether the binder is polymer-modified or not, any -28 binder is generally expected to crack under the subjected climatic conditions of Minnesota.

Overall, this data suggest the polymer modification may help provided more cracking resistance in the transverse direction than the longitudinal direction, however this concept should be investigated further.

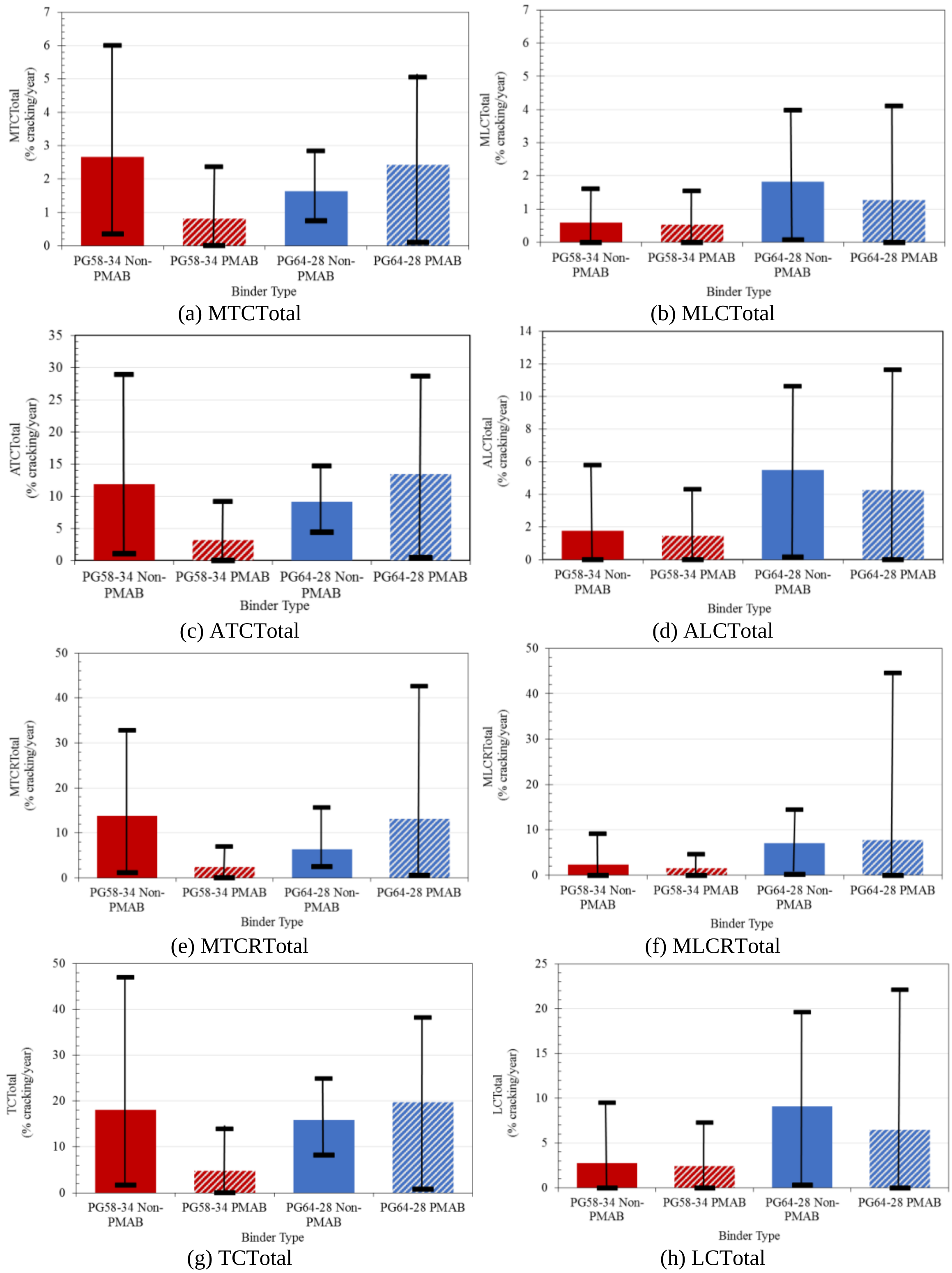


Figure 42: Binder Type versus Various Cracking Measures

4.3.3 Binder Supplier versus Cracking Performance

Instead of simply comparing cracking performance to binder type, it was also compared to the asphalt binder supplier. All of the asphalt binder of the 37 study groups came from one of seven suppliers listed in Table 10. The researchers decided to keep the supplier names confidential and they are identified by letters A-G in the table. The PG58-34 PMAB and PG64-28 Non-PMAB seemed to be limited to one asphalt binder supplier. This is likely due to the low number of instances of those binder types in the study groups provided. As a result, the performance based on supplier were only compared for the PG58-34 Non-PMAB (Figure 43) and PG64-28 PMAB (Figure 44).

For the PG58-34 Non-PMAB, the binders from Supplier B generally performed slightly superior to those of Supplier A. One thing to note is that Supplier B had twice as many study groups. The PG64-28 PMAB showed the Supplier F and Supplier G to have the most cracking.

Table 10: Frequency of Suppliers for Asphalt Binders Types of Study Groups

Supplier	A	B	C	D	E	F	G
PG58-34 Non-PMAB	5	10	-	-	-	-	-
PG58-34 PMAB	-	-	3	-	-	-	-
PG64-28 Non-PMAB	5	-	-	-	-	-	-
PG64-28 PMAB	-	-	-	5	5	3	1

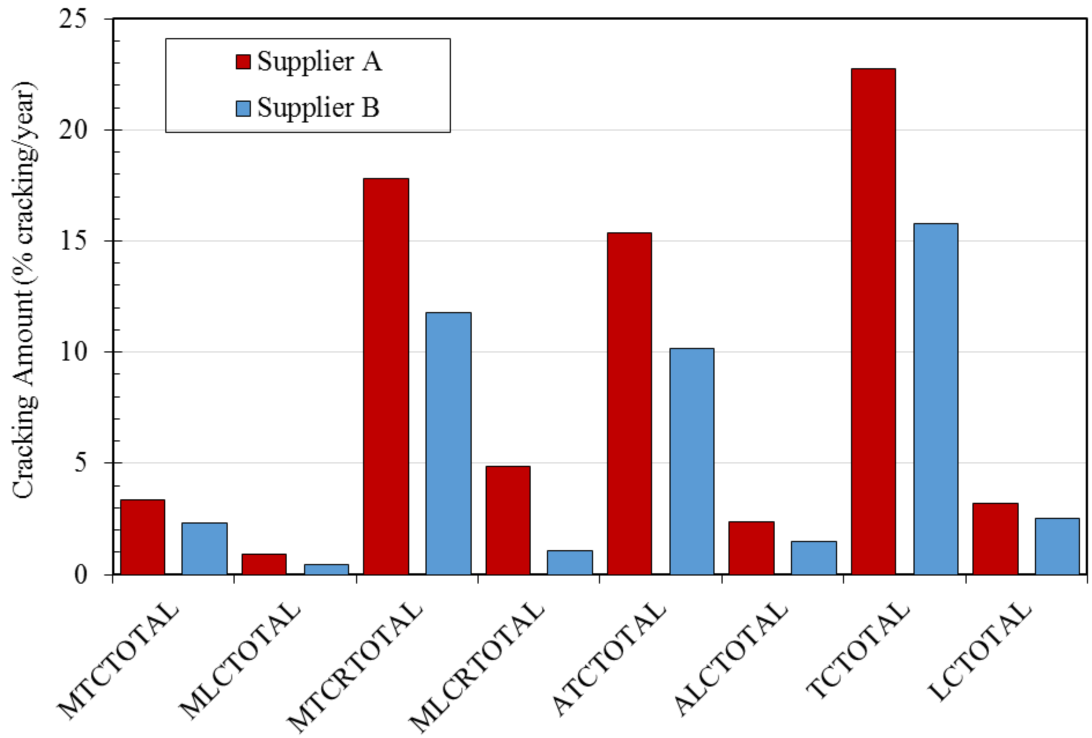


Figure 43: Cracking Performance versus Supplier of PG58-34 Non-PMAB

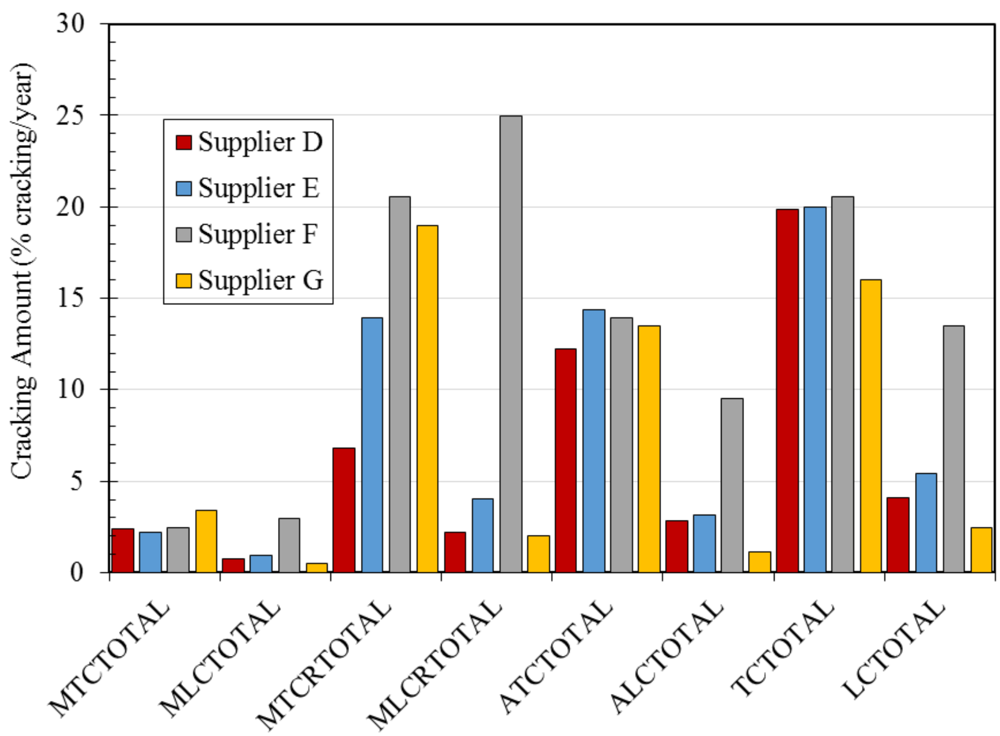
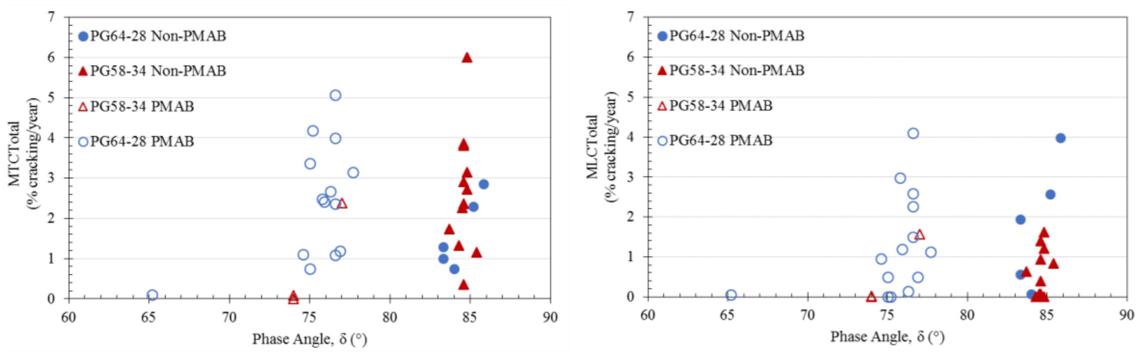


Figure 44: Cracking Performance versus Supplier of PG64-28 PMAB

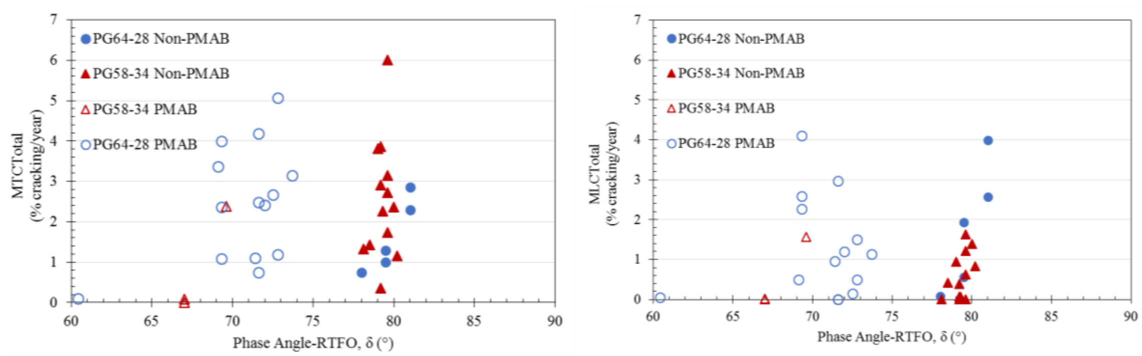
4.3.4 DSR Parameters versus Cracking Performance

When comparing the cracking measures MTCTotal and MLCTotal in Figure 45, it is apparent that the binders without polymer modifiers have a higher phase angle which means they are behaving in more viscous manner. This trend is the same for both transverse and longitudinal cracks as well as the DSR results on aged (RTFO) and unaged binders shown in Figure 46.



(a) MTCTotal (b) MLCTotal

Figure 45: DSR Phase Angle of Un-aged Binder versus Cracking Performance

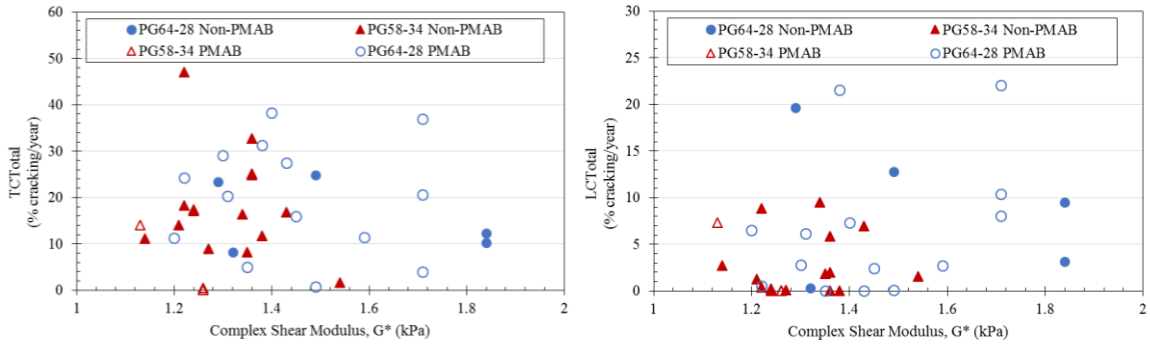


(a) MTCTotal (b) MLCTotal

Figure 46: DSR Phase Angle of Aged Binder versus Cracking Performance

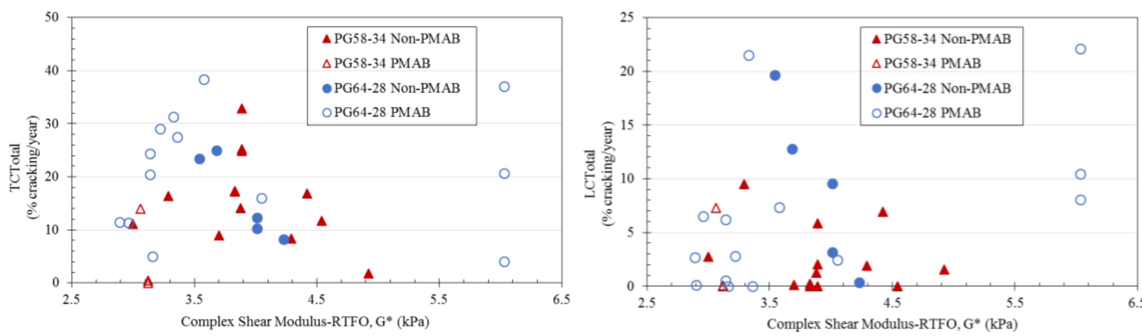
The following results present the cracking performance versus the DSR complex shear modulus parameter, G*. Figure 47 provides the cracking measure TCTotal (a) and LCTotal (b) versus the complex modulus of un-aged asphalt binder. Figure 48 provides the cracking measure TCTotal (a) and LCTotal (b) versus the complex modulus of aged

(RTFO) asphalt binder. Figure 47 (a) shows a downward trend suggesting that the increased binder stiffness leads to less transverse cracking. Figure 47 (b) does not show any discernable trends.



(a) TCTotal (b) LCTotal

Figure 47: Complex Shear Modulus of Un-aged Binder versus Cracking Performance



(a) TCTotal (b) LCTotal

Figure 48: Complex Shear Modulus of Aged Binder versus Cracking Performance

4.4 Summary and Conclusion

In summary, the effects of polymer-modified asphalt binders were investigated in relation to the "neat" binders of the same performance grade on various cracking measures. The cracking performance was presented on the basis of 4 different transverse and longitudinal cracking measures. The initial results considering the average cracking performance suggest:

- Transverse cracking is more prevalent on Minnesota roadways than longitudinal cracking;
- The asphalt mixtures used in bituminous on aggregate base (BAB Rural) construction type (also commonly referred to as conventional asphalt pavement) generally performs superior to overlays and mill and overlays;
- The phase angle measurements on both aged and un-aged asphalt binders showed polymer modified binders to have lower phase angles than neat binders, which is consistent with past research. However, there were no evident trends between binder modification and neat binders, likely due to the lack of data for PG58-34 PMAB and PG64-28 Non-PMAB;
- The dynamic shear rheometer measured complex modulus did not show any discernable trends between binder type and performance or polymer modified versus neat binders;
- Polymer-modified PG58-34 binders perform better than non-polymer modified PG58-34 binders although should be studied with a larger sample size;
- PG64-28 binders did not provide a conclusive relationship to cracking performance. This is likely due to the fact that the PG low temperature grade of -28°C is not suitable for most climates in Minnesota. Therefore pavements with that low temperature binder grade would likely crack regardless of if the binder is neat or polymer-modified.

Although this study made strong preliminary findings, these results could be improved with further research including:

- A larger sample size to include more study groups;
    - Obtain more study sections with the PG58-34 PMAB and PG64-28 Non-PMAB binder types;
    - Incorporation of more binder grades. PG64-34 is another binder type that is used in Minnesota and would likely provide more conclusive results (due to the lower low-temperature binder grade) than the PG64-28 binders.

- More closely consider the effect of pavement preservation activities (chip seals, crack sealing, and microsurfacing) on the cracking performance measures.

CHAPTER 5: SENSITIVITY OF THERMAL CRACKING PERFORMANCE TO VARIATIONS IN FRACTURE ENERGY

5.1 Introduction

The Minnesota Department of Transportation is in process of pilot implementation of the low temperature cracking performance specifications with anticipation of full implementation occurring in year 2016. These specifications utilize the fracture energy of the asphalt mixes, measured using the disk-shaped compact tension (DCT) test, as performance parameter. The specifications were developed through the two phases of the Pooled Fund Study of Low Temperature Cracking [2], [3] and through continuous modifications conducted under the present project [6]. In the 2013 construction season, MnDOT conducted a pilot implementation of the aforementioned performance based specification that required asphalt mixtures to have a minimum of 400 J/m^2 fracture energy [8]. During the development of these specifications, it became crucial to gain insight into the sensitivity of DCT fracture energy in affecting the thermal cracking performance of asphalt pavements. The IlliTC thermal cracking simulation system [3], [29] was employed in the present research to evaluate the effects of fracture energy on the low temperature cracking of asphalt pavements. The abridged version of this study is provided herein, however the published referred journal paper presenting this study in its entirety is attached for reference in Appendix C [10].

5.2 Simulation Variables

Thermal cracking performance of asphalt pavements most significantly depend on climate, asphalt mixture properties and the pavement structure. The scope of the present research is limited to the three climatic conditions defined by south, central and northern Minnesota, three types of asphalt mixtures, and three pavement structures (or traffic levels). For the various combinations of these variables six fracture energy levels were evaluated. The IlliTC thermal cracking simulation system accounts for these three variables.

The characteristics of the three asphalt mixtures chosen for the simulations are shown in Table 11. The asphalt mix designations “PG28R,” “PG34R,” and “PG34” are indicative of the PG low temperature binder grade and has an “R” when the mixture has recycled asphalt pavement (RAP) in the asphalt mixture.

Table 11: Asphalt Mixes Used for IlliTC Simulations

Asphalt Mix	PG28R	PG34R	PG34
MnROAD Cell	Cell 21	Cell 22	Cell 35
Virgin Binder Grade	PG 58-28	PG 58-34	PG 58-34
Total Percent AC	5.2%	5.2%	5.6%
Recycled Binder as Percent of Total AC	28%	28%	0%
Amount of RAP	30%	30%	0%

The IlliTC system utilizes a "Preanalyzer" module which identifies critical events which are defined by instances when thermally induced stresses approach 85% of the asphalt mixture's tensile capacity. For all scenarios except the PG28R mix in the Cold climate, the asphalt mix and climate combinations do not experience any critical events exceed the as-measured IDT tensile strength provided in Table 12. Therefore, a reduced strength referred to as the "critical tensile strength" was used for the purpose of facilitating simulations for parametric evaluation. The measured disk-shaped compact tension (DCT) fracture energy of each mix is also provided in the table.

Table 12: Tensile Strength Values that Allowed One or More Critical Cooling Events to be Simulated

Asphalt Mix	PG28R	PG34R	PG34
DCT Fracture Energy, G_f (J/m^2)	575.22	594.85	645.41
As-measured IDT Tensile Strength (MPa)	4.72	5.00	4.50
Climate	Critical Tensile Strength (MPa)		
Cold	4.72*, 5.43	3.75	3.13
Intermediate	3.18	2.40	1.71
Warm	2.73	2.00	1.43

5.3 Results

The results from the parametric evaluation are shown in Table 13. Each scenario outlined in the matrix was simulated at 6 fracture energy levels: 300, 350, 375, 400, 425 and 450 J/m^2. Due to IlliTC ending the simulation at various times, the performance of each simulation was evaluated at the temperatures specified in parentheses in the first column. Note that the background color of the table is indicative of the how representative the simulation properties are of typical material properties: green represents use of realistic material properties, whereas red indicates use of artificially low tensile strengths in order to conduct the sensitivity analysis. Without using the artificially low values, these asphalt mix-climate scenarios in red would not crack. The majority of the scenarios showed cracking (C), a few cases showed damage (D), two cases showed no damage (ND) and some showed dependence on fracture energy (G_f).

Table 13: IlliTC Simulation Results

Asphalt Mix	PG28R			PG34R			PG34		
Climate (Temperature)	Pavement Thickness (cm)								
	10	15	20	10	15	20	10	15	20
Cold (-28.0°C)	C	C	C	C	C	C	C	G_f	ND
Intermediate (-25.4°C)	C	C	C	C	C	C (G_f at -22.1°C)	C	C	C
Warm Case-1 (-22.0°C)	C	G_f	D	C	C	ND			
Warm Case-2 (-21.0°C)	G_f	D	D						

C = Cracking; D = Damage; ND = No damage; G_f = Dependent on fracture energy.

The four scenarios that indicate fracture energy dependence in the aforementioned matrix are outlined in Table 14. From the table it is apparent that the variation of 25 J/m^2 is enough for these mixes to go from no damage to damaged or damaged to cracked.

Table 14: Fracture Energy Dependence of Pavement Cracking Performance

Asphalt Mix	PG28R	PG28R	PG34R	PG34
Climate	Warm Case-1	Warm Case-2	Intermediate	Cold
Pavement Thickness (cm)	10	15	20	15
Fracture Energies (J/m^2) Corresponding to Thermal Cracking Performance Levels				
No Damage (ND)	No data	No data	No data	≥425
Damaged (D)	450	425-450	375-450	300-375
Cracked (C)	≤425	≤400	≤350	No data

5.4 Summary and Conclusion

This study evaluated the sensitivity of thermal cracking to variations in DCT fracture energy by using a matrix of scenarios including three asphalt mixture types, three asphalt layer thicknesses and three climatic conditions. The motivation of this work was to investigate the sensitivity to the 400 J/m^2 threshold that is being used in the implementation of the disk-shaped compact tension performance test specification. The results suggest that variations up to 25 J/m^2 are high enough to see a significant difference in thermal cracking performance. As previously mentioned, for more information regarding this study, please reference Appendix C (Dave and Hoplin, 2015 [10]).

CHAPTER 6: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE EXTENSIONS

The first portion of this study investigated the pavement performance of 25 pavement sections on 18 highways in Minnesota. Multiple field core samples were obtained and subjected to a battery of laboratory tests including volumetric, lab permeability, disk-shaped compact tension test and asphalt content and gradation. The results from the laboratory tests were presented and then compared to the field performance calculated from cracking counts obtained from MnDOT's pavement management system. The goal of this study was to investigate the impact of coarse hot-mix asphalt mixes with low asphalt binder content on pavement performance. The findings included:

- The results from permeability testing indicated that eight of the twelve mixtures have higher permeability than typical ranges for dense graded asphalt mixtures. Specifically six of the mixture have significantly higher permeability. These mixtures are anticipated to have inferior durability and might be more prone to moisture induced damage and distresses like raveling.
- Only seven out of twenty-five mixtures have fracture energies that are above the recommended threshold of 400 J/m^2. Twelve sections have substantially lower fracture energies (less than 300 J/m^2), even after consideration of lowering fracture energies due to pavement being in service for several years. These sections are expected to have significantly inferior transverse cracking performance and shortened service lives.
- Gradation analysis of residue show that the mixtures meet the MnDOT specified gradation bands. Overall, all gradation results show relatively coarser gradation.
- The construction type continues to show a very strong correlation with the transverse cracking performance. In the present study of 25 pavement sections, the milling and thin overlays exhibit the highest average cracking rate when compared to reclaims and new construction.

The future of this study would be to utilize the IlliTC thermal cracking prediction software (similar to what was done in the sensitivity study in Chapter 5) to theoretically get more accurate predictions of pavement performance life than what are given by the various cracking measures. The laboratory results from this study can be used as input parameters into the IlliTC system in order to make more supported conclusions on the effect of low asphalt binder on coarse hot mix asphalt mixes.

The second part of this study analyzed the transverse and longitudinal field cracking performance of 295 pavement sections on 28 highways with respect to their asphalt binder type and polymer modification. Similar to the first part of this thesis, several cracking measures were employed to look at the pavement performance from various perspectives. The effect of asphalt binder type and modification was compared to performance by looking at the construction type, asphalt binder supplier, and dynamic shear rheometer parameters: phase angle and dynamic shear modulus. The results looking at average cracking performance suggest:

- Transverse cracking is more prevalent on Minnesota roadways than longitudinal cracking;
- The dynamic shear rheometer phase angle on both aged and un-aged asphalt binders showed polymer modified binders to have lower phase angles than neat binders, which is consistent with past research;
- Polymer-modified PG58-34 binders perform better than non-polymer modified PG58-34 binders although should be studied with a larger sample size;
- PG64-28 binders did not provide a conclusive relationship to cracking performance. This is likely due to the fact that the PG low temperature grade of -28°C is not suitable for most climates in Minnesota. Therefore pavements with that low temperature binder grade would likely crack regardless of if the binder is neat or polymer-modified.

This study could be improved by including a larger sample size. In this case the frequency of PG58-34 neat binder and PG64-28 polymer-modified binder, out-weighed the frequency of PG58-34 polymer-modified and neat PG64-28 binders. Additionally, the impact of pavement preservation activities, such as chip seals, crack sealing and microsurfacing, were outside the scope of this study, however largely impact the crack counts measured by the automated equipment used to conduct crack surveys.

The last part of this thesis evaluated the sensitivity of flexible pavement thermal cracking performance to variations in DCT fracture energy. This study included nearly 200 simulations including every combination of 3 climates, 3 asphalt thicknesses, 3 asphalt mixtures and 6 fracture energy levels. The motivation of this work was to investigate the sensitivity to the 400 J/m^2 threshold that is being used in the implementation of the disk-shaped compact tension performance test specification. The conclusion of this work found that a variation of 25 J/m^2 is enough to show a difference in cracking performance.

Due to the fact that artificial “critical tensile strengths” had to be used, this study could be improved by investigating asphalt mixtures more susceptible to cracking in the Minnesota climate. This would improve results by using more realistic input parameters into the IlliTC thermal cracking simulation software.

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APPENDIX A: TRANSVERSE CRACKING PERFORMANCE OF MINNESTOA ROADWAYS—SUPPLEMENTAL TABLES & FIGURES

Table 15: Transverse Cracking Performance Measures of All Study Sections

Highway	Section	Total Transverse Cracking (%)	ATCR-Total (%/yr.)	TCTotal (%/yr.)	TCTotal x AC Thick. (%/yr.)
TH 1	A-1	82.2	13.7	1.1	4.5
TH 1	A-2	100.0	16.7	11.3	14.1
TH 2	B	59.4	5.4	2.6	10.5
TH 6	C	33.2	8.3	5.2	7.7
TH 6	D-1	100.0	10.0	6.0	9.0
TH 6	D-2	4.0	0.4	0.1	0.4
TH 9	E-1	9.0	3.0	1.0	4.5
TH 9	E-2	6.0	2.0	0.7	3.0
CH 10	F-1	62.0	31.0	15.5	23.3
CH 10	F-2	27.0	13.5	6.8	20.3
TH 10	G-1	63.0	7.9	3.2	12.8
TH 10	G-2	49.0	6.1	2.5	9.9
TH 10	H	45.5	45.5	22.8	79.8
TH 27	J-1	33.2	8.3	5.2	15.6
TH 27	J-2	36.0	9.0	5.5	16.5
TH 28	K-1	30.0	15.0	6.3	28.1
TH 28	K-2	29.0	14.5	4.7	20.9
CH 30	L	20.0	10.0	4.5	27.0
I-35	M	8.0	2.0	1.1	4.5
TH 53	N	72.0	12.0	8.4	12.6
TH 113	O-1	83.2	10.4	6.7	10.0
TH 113	O-2	11.2	1.4	0.8	4.0
TH 210	P	33.6	8.4	7.0	14.1
TH 212	Q	0.0	0.0	0.0	0.0
TH 220	R	13.0	6.5	1.7	5.0

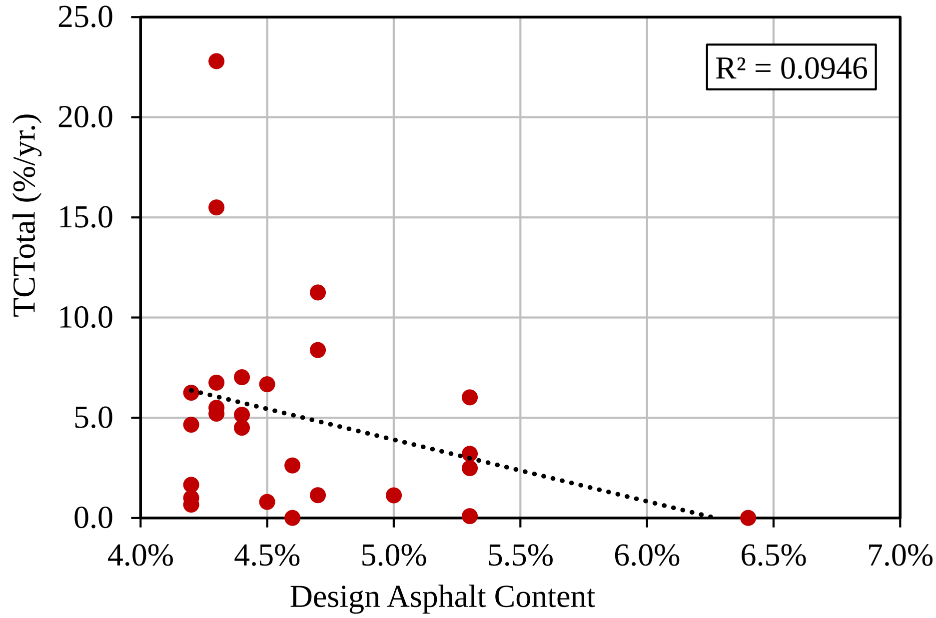

Figure 49: Total Transverse Cracking (TCTotal) versus Design Asphalt Content

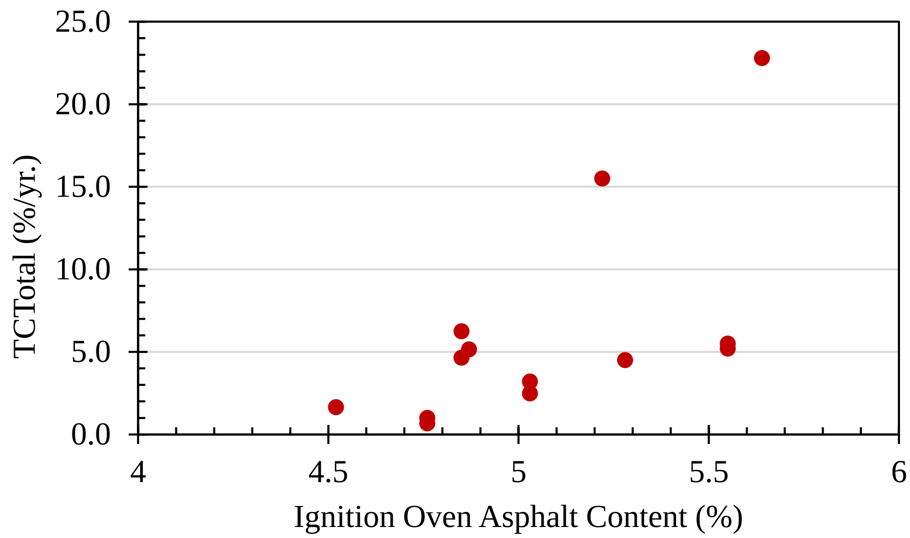

Figure 50: Total Transverse Cracking (TCTotal) versus Ignition Oven Asphalt Content

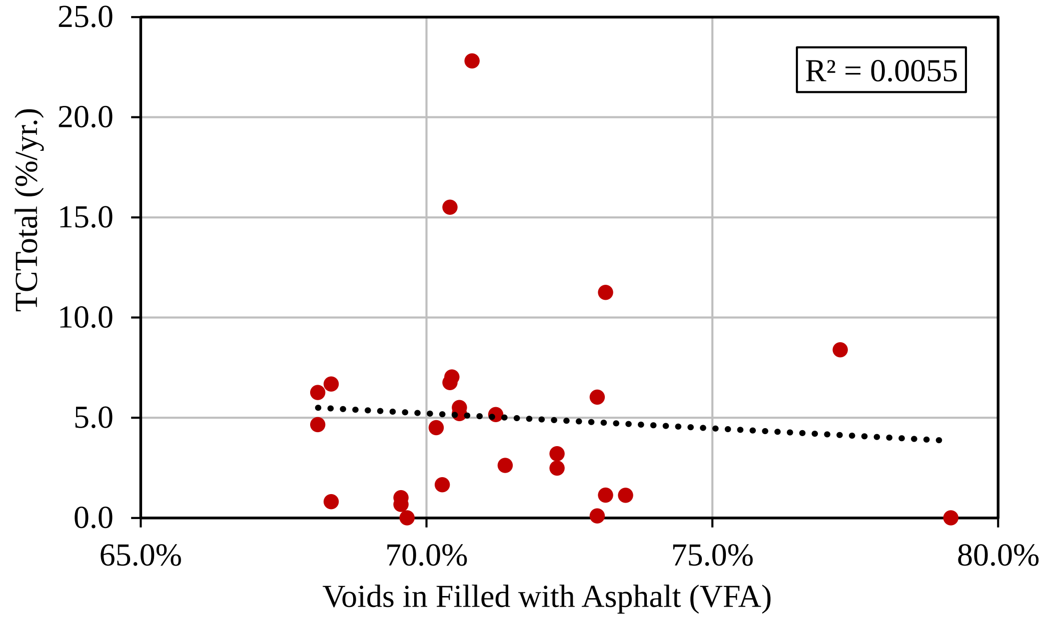

Figure 51: Total Transverse Cracking (TCTotal) versus Voids Filled with Asphalt (VFA)

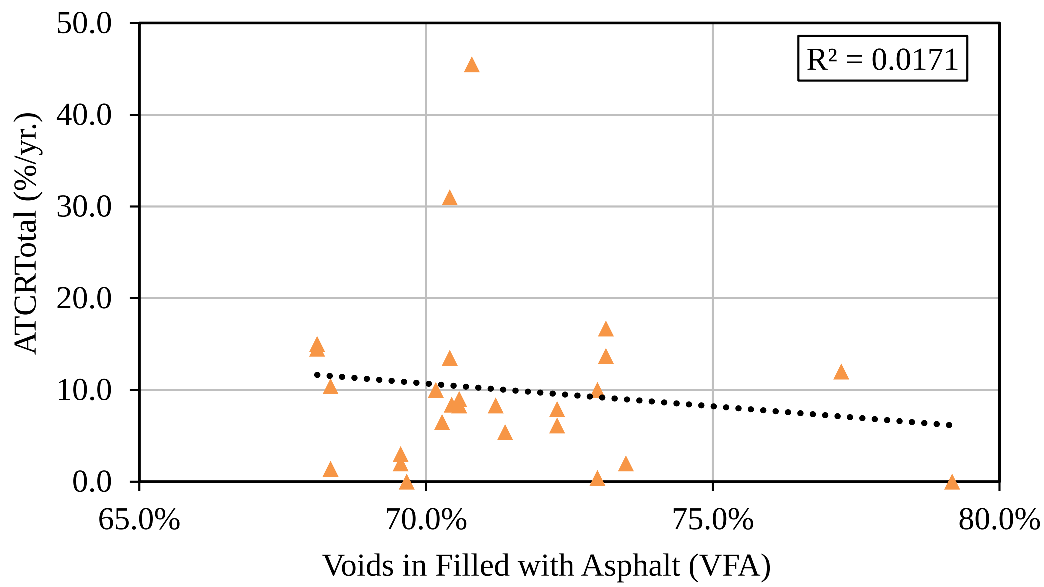

Figure 52: Average Total Transverse Cracking Rate (ATCRTotal) versus Voids Filled with Asphalt (VFA)

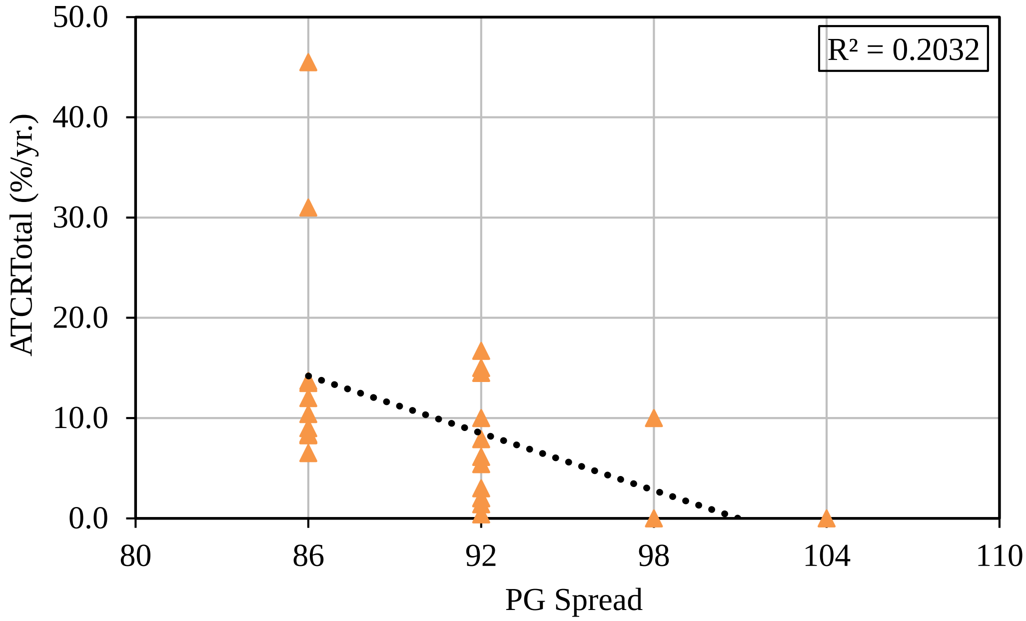

Figure 53: Average Total Transverse Cracking Rate (ATCRTotal) versus PG Spread

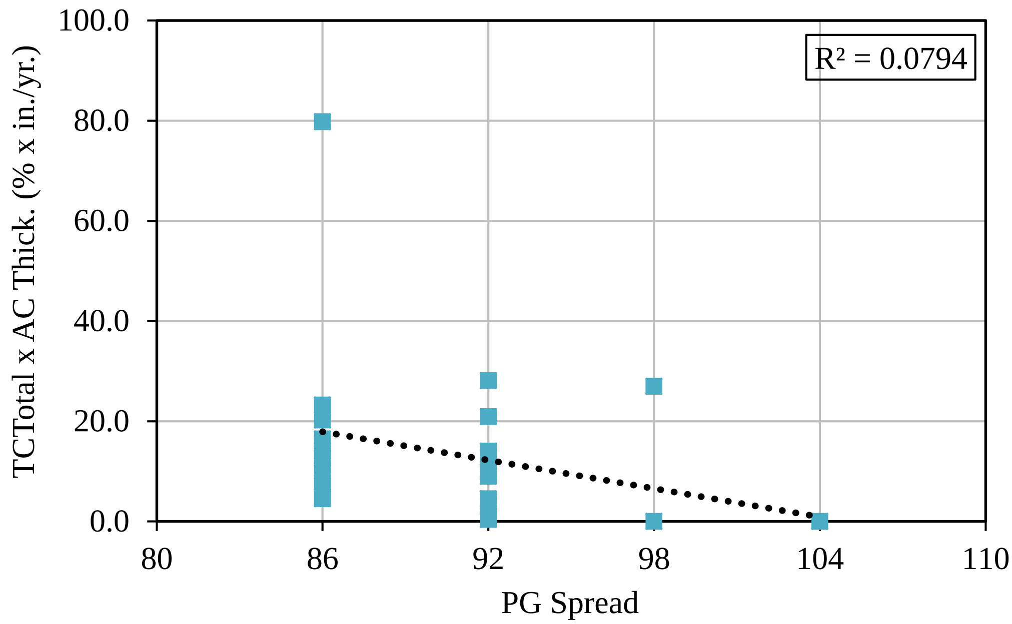

Figure 54: TCTotal Adjusted for AC Thickness versus PG Spread

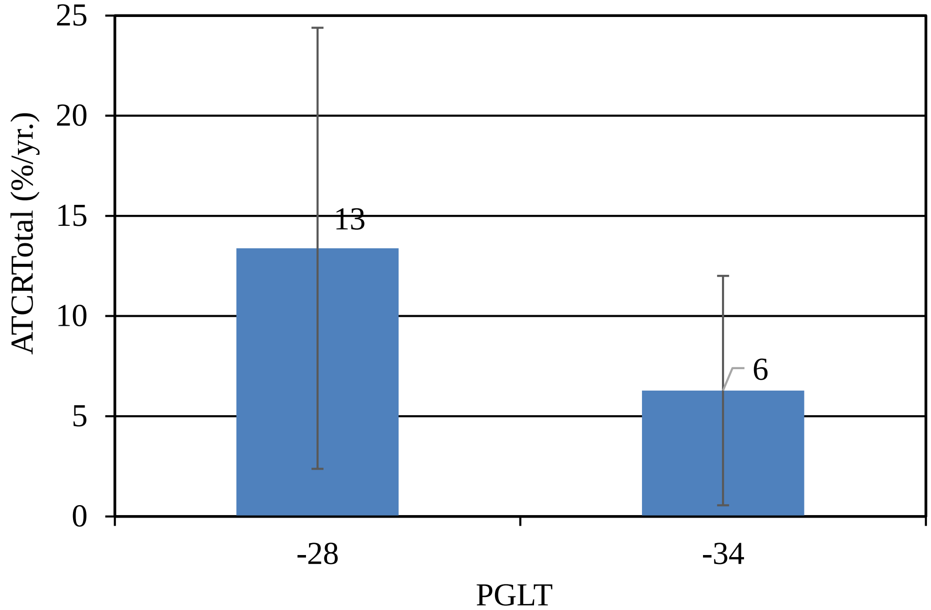

Figure 55: Average Total Transverse Cracking Rate (ATCRTotal) versus PGLT

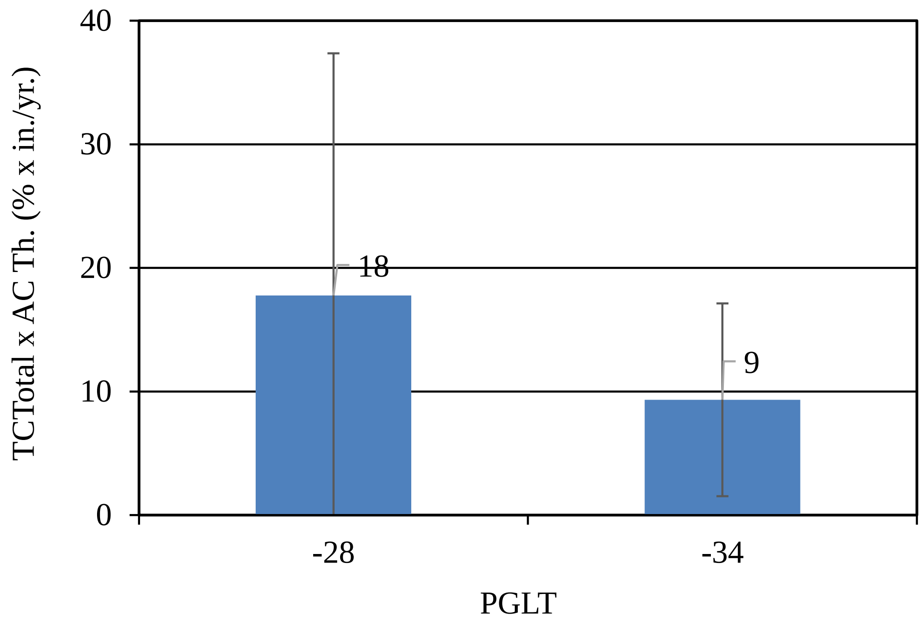

Figure 56: TCTotal Adjusted for AC Thickness versus PGLT

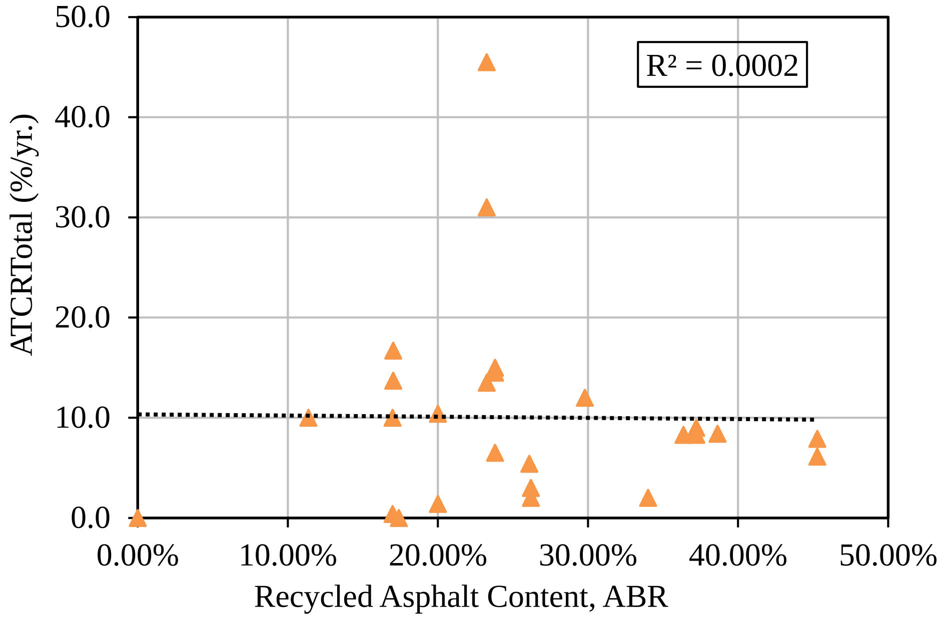

Figure 57: Average Total Transverse Cracking Rate (ATCRTotal) versus Recycled Asphalt Content

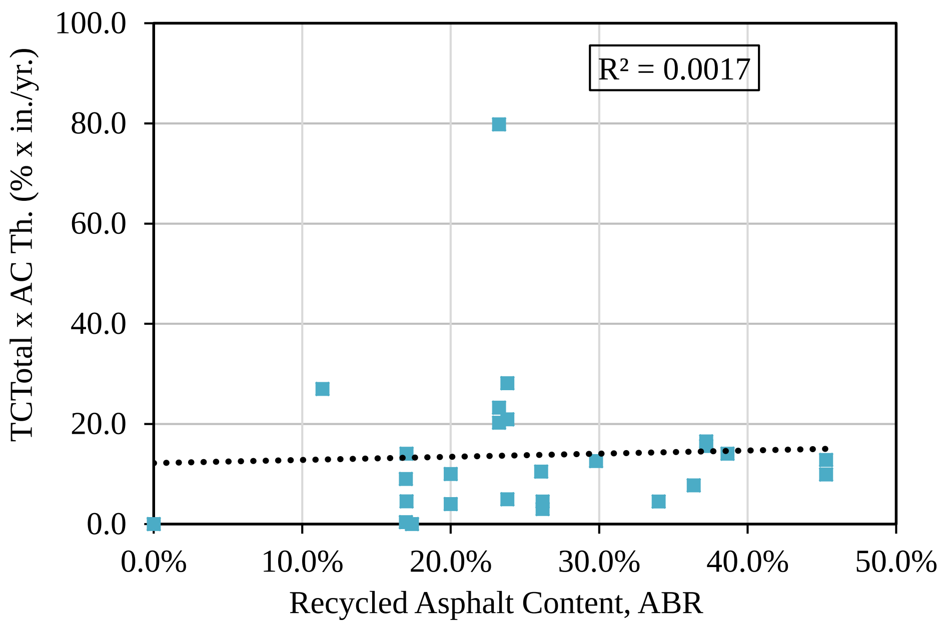

Figure 58: TCTotal Adjusted for AC Thickness versus Recycled Asphalt Content

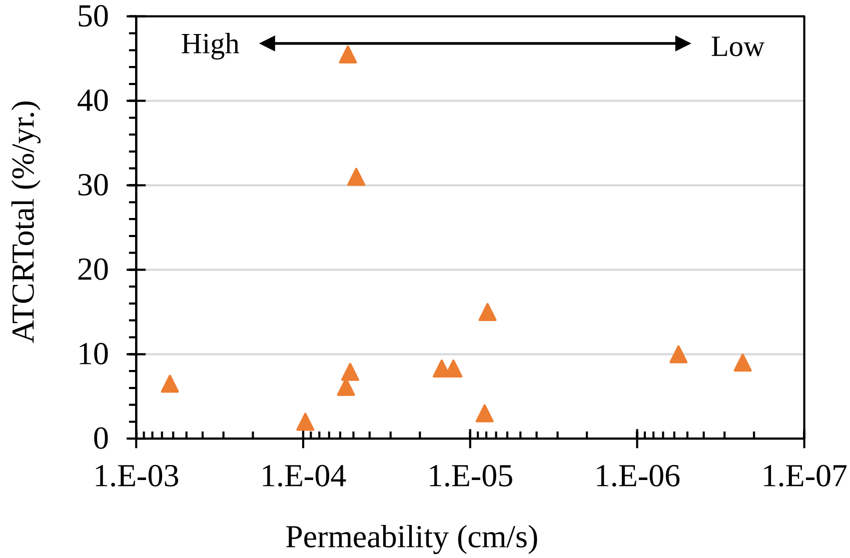

Figure 59: Average Total Transverse Cracking Rate (ATCRTotal) versus Permeability

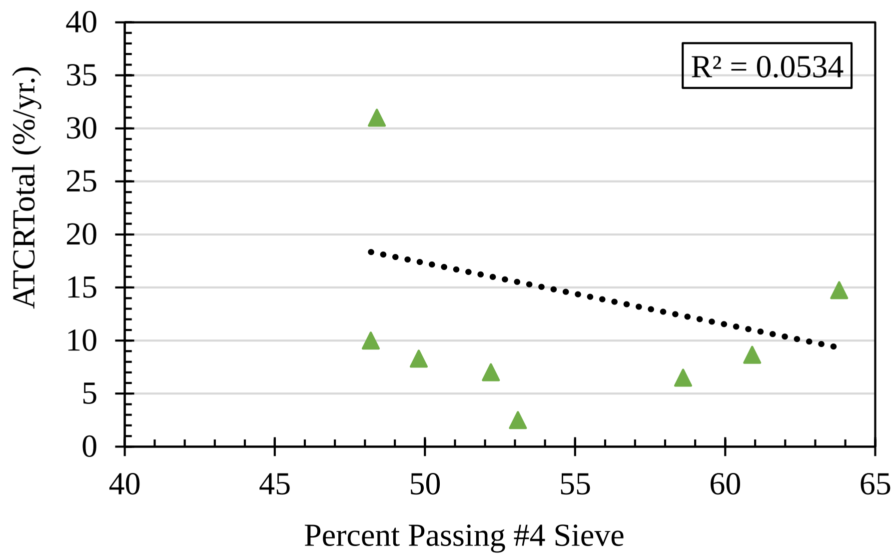

Figure 60: Average Total Transverse Cracking Rate (ATCRTotal) Percent Passing #4 Sieve

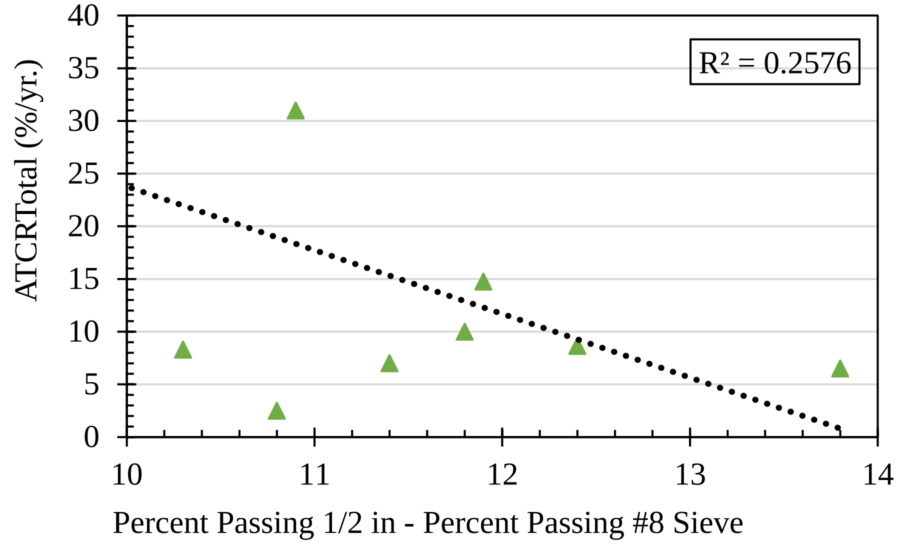

Figure 61: Average Total Transverse Cracking Rate (ATCRTotal) versus Percent Passing ½ in Sieve to Percent Passing #8 Sieve

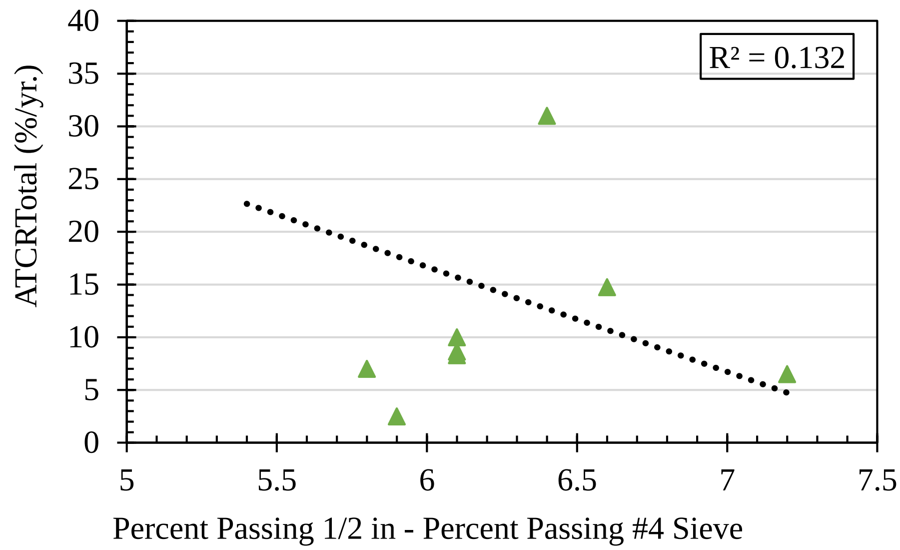

Figure 62: Average Total Transverse Cracking Rate (ATCRTotal) versus Percent Passing ½ in Sieve to Percent Passing #4 Sieve

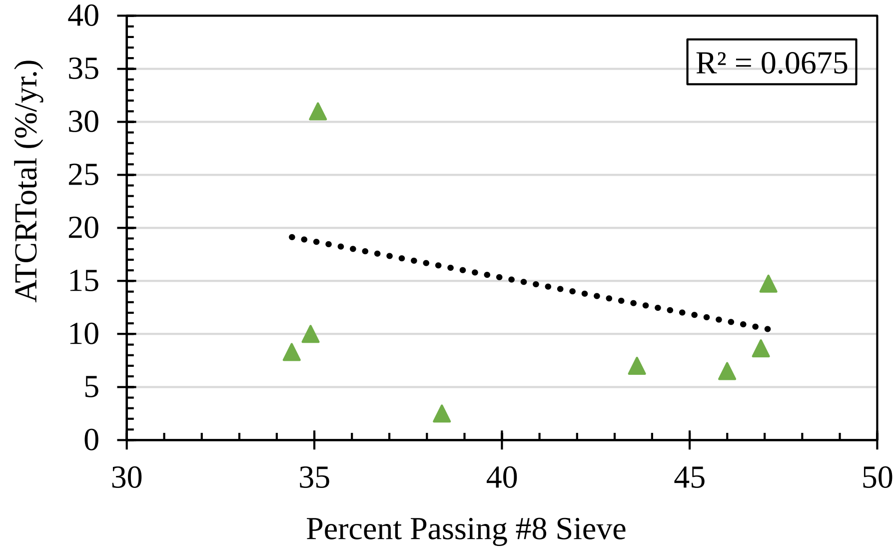

Figure 63: Average Total Transverse Cracking Rate (ATCRTotal) versus Percent Passing #8 Sieve

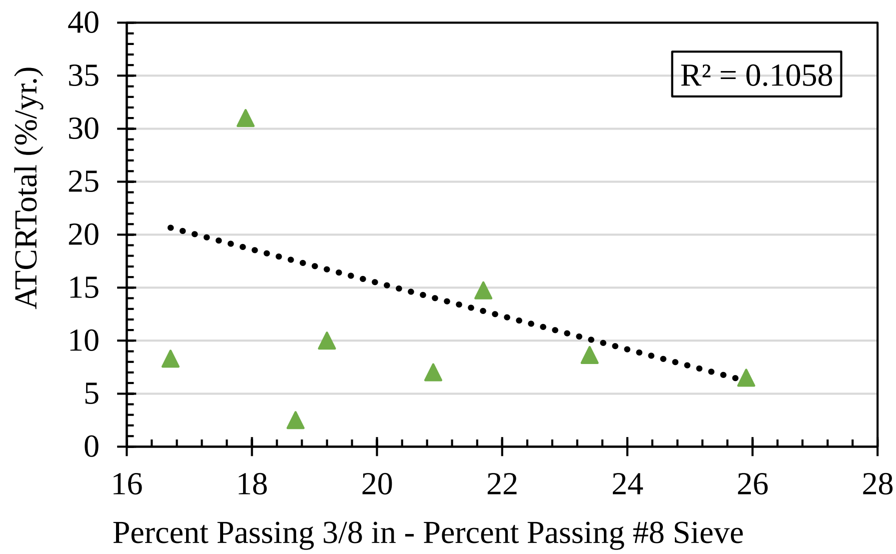

Figure 64: Average Total Transverse Cracking Rate (ATCRTotal) versus Percent Passing 3/8 in Sieve to Percent Passing #8 Sieve

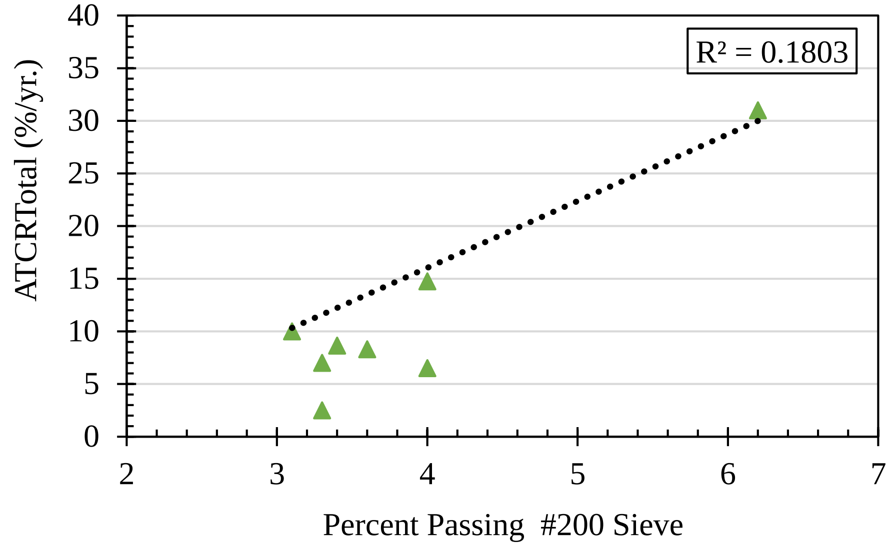

Figure 65: Average Total Transverse Cracking Rate (ATCRTotal) versus Percent Passing #200 Sieve

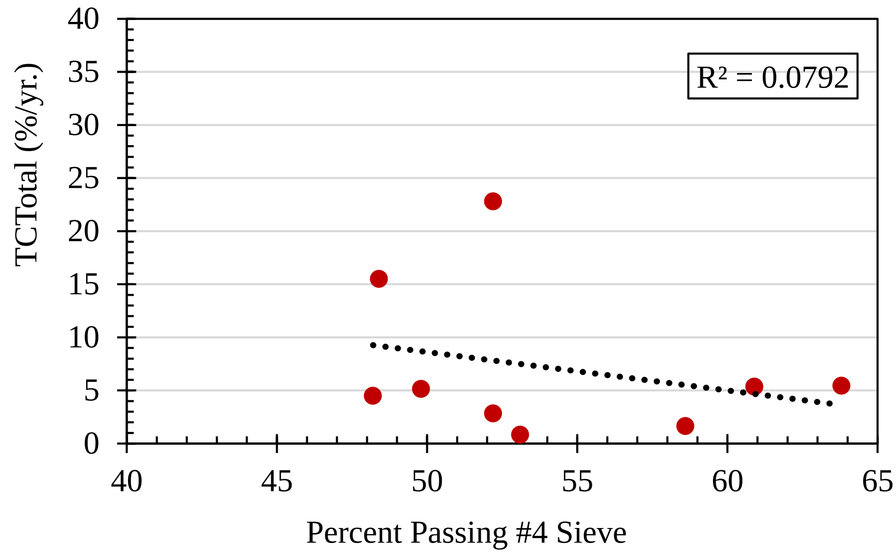

Figure 66: Total Transverse Cracking (TCTotal) versus Percent Passing #4 Sieve

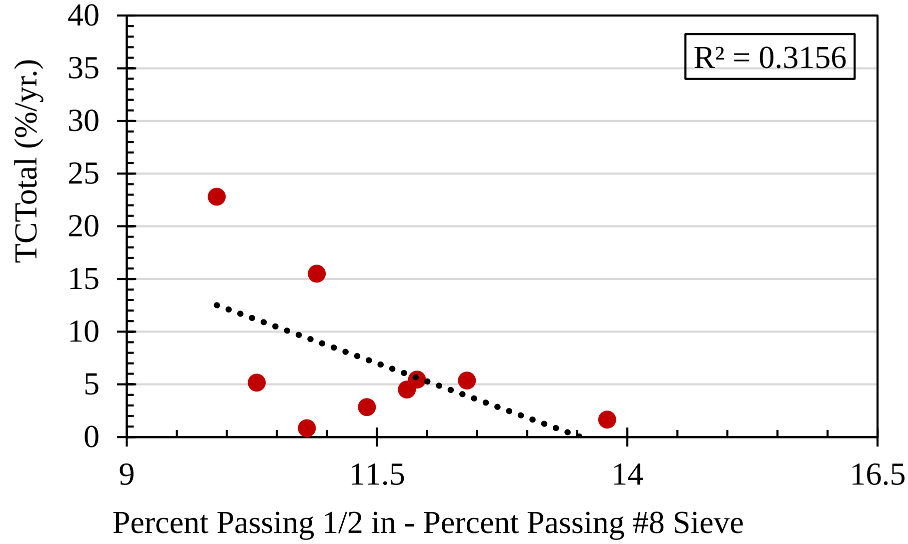

Figure 67: Total Transverse Cracking (TCTotal) versus Percent Passing ½ in Sieve to Percent Passing #8 Sieve

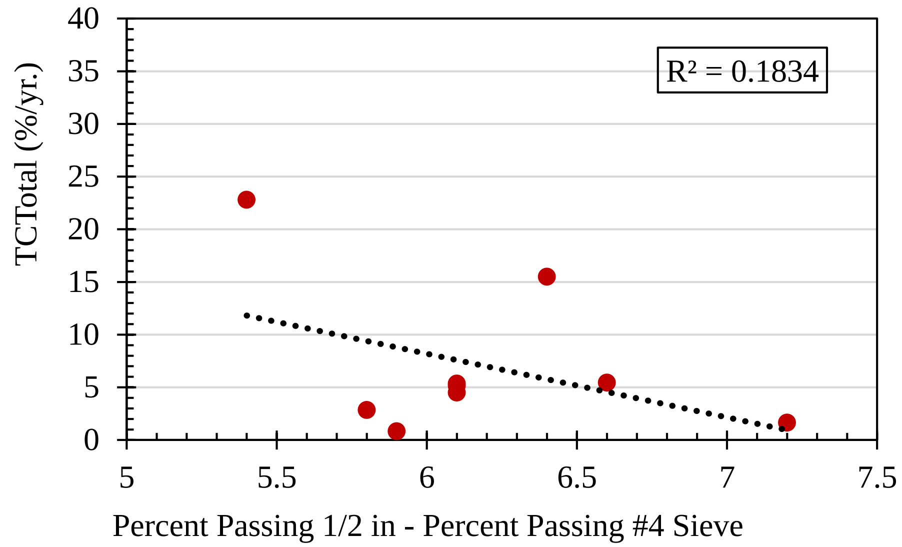

Figure 68: Total Transverse Cracking (TCTotal) versus Percent Passing ½ in Sieve to Percent Passing #4 Sieve

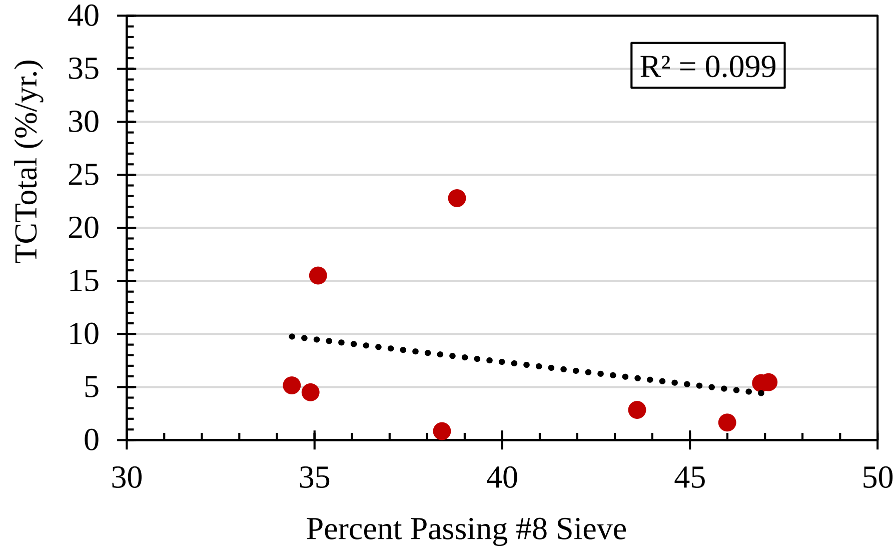

Figure 69: Total Transverse Cracking (TCTotal) versus Percent Passing #8 Sieve

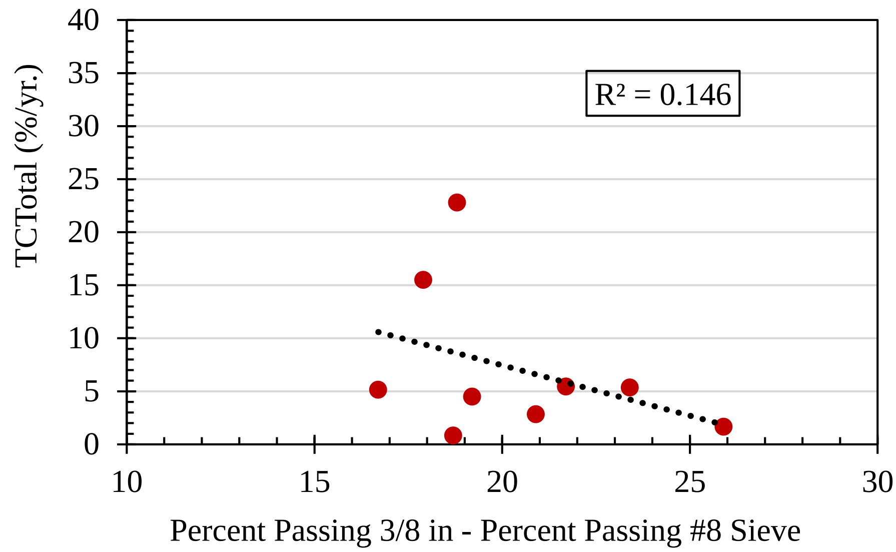

Figure 70: Total Transverse Cracking (TCTotal) versus Percent Passing 3/8 in Sieve to Percent Passing #8 Sieve

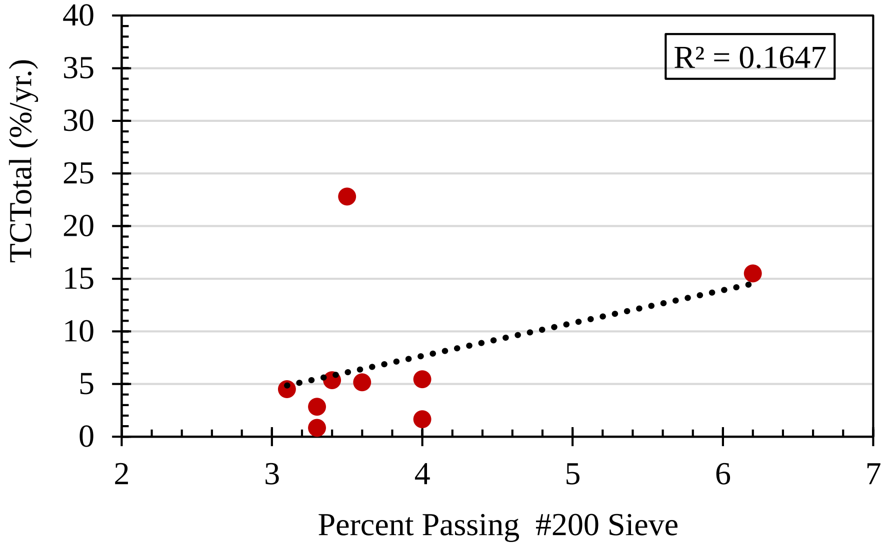

Figure 71: Total Transverse Cracking (TCTotal) versus Percent Passing #200 Sieve

APPENDIX B: EFFECTS OF BINDER GRADE AND MODIFICATIONS ON FIELD CRACKING PERFORMANCE—SUPPLEMENTAL TABLES

Table 16: Transverse Cracking Measures

SP	End Section No.	Construction Type	MTC-TOTAL (%/yr.)	MTCR-TOTAL (%/yr.)	ATC-TOTAL (%/yr.)	TC=-TOTAL (%/yr.)
PG58-34 Non-PMAB						
1004-24	7829	Thin OL	1.2	10.7	8.4	14.1
2785-301	14295	Med M&OL	2.7	7.5	13.3	24.9
2785-301	14318	Med M&OL	3.1	8.5	13.8	25.1
2785-301	1876	Med M&OL	6.0	29.5	28.9	32.8
2725-59	11702	BAB Rural	3.8	32.9	12.6	16.8
1502-26	2076	Med M&OL	2.2	6.6	10.9	18.3
6001-52	2166	Thick OL	1.4	7.4	6.4	8.3
1502-26	2252	Med OL	4.6	30.0	29.0	47.0
5703-42	10812	Thick M&OL	1.7	5.7	7.0	11.1
0206-49	11462	BAB Rural	0.4	1.2	1.1	1.7
3507-12	14831	Med M&OL	1.3	5.0	6.0	11.7
5603-10	15182	Reclaim	2.3	6.6	6.6	8.9
6005-55	2235	Thick M&OL	2.4	6.7	10.8	16.4
1401-150	2766	BAB Rural	3.9	27.0	12.4	17.4
1401-150	10719	BAB Rural	2.9	21.3	11.3	17.2
PG58-34 PMAB						
3408-14	5087	BAB Rural	0.0	0.0	0.0	0.0
3408-14	9624	BAB Rural	0.1	0.3	0.2	0.4
3307-38	12846	BAB Rural	2.4	7.0	9.3	14.0
PG64-28 Non-PMAB						
6215-85	11606	Thin M&OL	2.3	15.7	14.8	24.9
1302-18	4813	Med M&OL	2.9	5.9	13.3	23.5
2776-02	6160	Thin M&OL	0.8	5.1	4.5	8.3
2735-183	14308	Med M&OL	1.3	2.8	7.4	12.3
2735-183	14331	Thin M&OL	1.0	2.5	6.0	10.3
PG64-28 PMAB						
1301-94	2477	Med M&OL	5.1	16.3	24.3	38.3
5202-44	3504	Thick M&OL	2.4	6.0	13.1	20.4
8304-28	8549	Med M&OL	2.7	6.6	13.9	24.3
4011-16	14590	BAB Rural	0.8	2.0	3.3	5.0
1926-17	15843	Med M&OL	1.1	3.3	6.7	11.3
8208-31	14213	Thin M&OL	2.5	16.8	17.9	31.3
3280-107	722	Med M&OL	4.2	17.7	28.8	27.5
7001-93	8439	Thin M&OL	3.2	28.4	18.3	29.1
4913-19	15531	Med M&OL	1.2	6.3	6.3	11.4
0804-73	3291	BAB Rural	0.1	0.6	0.5	0.8
7408-29	3346	Thick M&OL	2.4	14.0	13.8	20.6
7408-29	3518	Med M&OL	4.0	42.7	25.3	37.0
7408-29	6733	BAB Rural	1.1	5.0	2.8	4.0
6915-122	3908	Thin M&OL	3.4	19.0	13.5	16.0

Table 17: Longitudinal Cracking Measures

SP	End Section No.	Construction Type	MLC-TOTAL (%/yr.)	MLCR-TOTAL (%/yr.)	ALC-TOTAL (%/yr.)	LC-TOTAL (%/yr.)
PG58-34 Non-PMAB						
1004-24	7829	Thin OL	0.8	9.2	1.5	1.3
2785-301	14295	Med M&OL	0.0	0.0	0.0	0.0
2785-301	14318	Med M&OL	1.2	4.3	3.0	5.9
2785-301	1876	Med M&OL	1.6	6.5	3.8	2.0
2725-59	11702	BAB Rural	0.9	4.3	3.6	6.9
1502-26	2076	Med M&OL	0.1	0.5	0.2	0.4
6001-52	2166	Thick OL	0.4	1.5	1.3	1.9
1502-26	2252	Med OL	1.1	2.9	4.9	8.9
5703-42	10812	Thick M&OL	0.6	0.8	1.8	2.7
0206-49	11462	BAB Rural	0.4	1.8	0.7	1.6
3507-12	14831	Med M&OL	0.0	0.0	0.0	0.0
5603-10	15182	Reclaim	0.1	0.4	0.1	0.1
6005-55	2235	Thick M&OL	1.4	2.8	5.8	9.5
1401-150	2766	BAB Rural	0.0	0.0	0.0	0.0
1401-150	10719	BAB Rural	0.1	0.3	0.1	0.3
PG58-34 PMAB						
3408-14	5087	BAB Rural	0.0	0.1	0.0	0.0
3408-14	9624	BAB Rural	0.0	0.0	0.0	0.0
3307-38	12846	BAB Rural	1.6	4.7	4.3	7.3
PG64-28 Non-PMAB						
6215-85	11606	Thin M&OL	2.6	12.9	8.5	12.8
1302-18	4813	Med M&OL	4.0	14.6	10.7	19.6
2776-02	6160	Thin M&OL	0.1	0.2	0.2	0.3
2735-183	14308	Med M&OL	1.9	5.8	6.7	9.5
2735-183	14331	Thin M&OL	0.6	1.8	1.6	3.2
PG64-28 PMAB						
1301-94	2477	Med M&OL	1.5	3.3	5.1	7.3
5202-44	3504	Thick M&OL	1.2	4.1	4.5	6.2
8304-28	8549	Med M&OL	0.1	0.6	0.3	0.5
4011-16	14590	BAB Rural	0.0	0.0	0.0	0.0
1926-17	15843	Med M&OL	1.0	3.2	4.2	6.5
8208-31	14213	Thin M&OL	3.0	8.5	11.7	21.5
3280-107	722	Med M&OL	0.0	0.0	0.0	0.0
7001-93	8439	Thin M&OL	1.1	9.2	2.5	2.8
4913-19	15531	Med M&OL	0.5	2.3	1.4	2.7
0804-73	3291	BAB Rural	0.1	0.2	0.1	0.1
7408-29	3346	Thick M&OL	2.3	16.0	7.7	8.0
7408-29	3518	Med M&OL	4.1	44.7	10.6	10.4
7408-29	6733	BAB Rural	2.6	14.3	10.3	22.1
6915-122	3908	Thin M&OL	0.5	2.0	1.2	2.4

APPENDIX C: FLEXIBLE PAVEMENT THERMAL CRACKING SENSITIVITY TO FRACTURE ENERGY VARIATION OF ASPHALT MIXTURES