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Evaluating cracking performance of polymer enhanced and fiber reinforced microsurface mixtures using asphalt laboratory testing

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EVALUATING CRACKING PERFORMANCE OF POLYMER ENHANCED AND FIBER REINFORCED MICROSURFACE MIXTURES USING ASPHALT LABORATORY TESTING

by

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Abstract

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This study presents a method to improve and evaluate the cracking resistance of microsurfacing mixtures using common asphalt laboratory testing. A preliminary optimal timing study and a study to evaluate improvements to cracking performance were conducted. The control mixture was based on NJDOT standard mix design specifications. Three mixtures were tested in this study: a fiber reinforced mixture using ¼" glass fibers, an emulsion with increased SBR (polymer) contents, and a mixture using the ¼" glass fibers combined with the increased polymer contents. Three laboratory tests were used to evaluate three different cracking resistance parameters: crack initiation (Semi-Circular Bend Test at intermediate temperatures), reflective cracking (Texas Overlay Tester), and low temperature cracking (Semi-Circular Bend Test at low temperatures). The test results suggest the tests were able to differentiate between mixtures. The results of the SCB testing and the Texas Overlay Tester suggest that mixtures with higher polymer content and higher polymer content with fibers enhanced crack initiation and propagation characteristics when compared to a control. SCB testing at low temperatures show that the presence of higher polymer content and fiber reinforcement increase resistance to crack initiation. The results suggest high polymer contents played a significant role in the improvements to crack resistance.

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Chapter 1

Introduction

1.1 Background

The use of pavement preservation is widely employed by state agencies across the United States and around the world. The benefits of the many methods vary depending on the treatment type, existing roadway conditions, and the competence of engineers and contractors to make the correct decisions on when and how to use respective treatments. However, when used properly, these treatments can help extend pavement life and reduce the overall cost during the roadway's life [1], [2], [3].

There are many different pavement preservation treatments including crack sealing, chip seal, slurry seal, microsurfacing, and thin overlays. Each treatment varies in cost, materials, effectiveness, and application. While these treatments are not meant to offer any structural capacity to roadways, they are meant to provide and improve driving surfaces and protect the integrity of the pavement by sealing the roadway. For example, crack sealing is the addition of hot bituminous material to open pavement cracks to prevent moisture infiltration. Chip seal is the addition of a layer of either hot bituminous material or cold emulsion to existing pavement surface into which uniform sized aggregates are rolled into the binder. This is used to both seal the roadway and provide a new driving surface. Slurry seal and microsurfacing or mixtures of fine crushed aggregates, emulsified binder, cement, and water that are laid onto existing asphalt surfaces to provide a new uniform driving surface and seal the roadway among other added benefits. Thin overlay is the addition of a layer of HMA up to 1.5" thick to existing

pavement. In some instances, thin overlay can offer some added structural capacity, but in general is used to address minor cracking and to provide a new driving surface. This study focuses on the cracking performance of pavement preservation treatments, in particular the use of microsurfacing, which is widely used throughout the United States [1], [3], [4].

Microsurfacing is a pavement preservation treatment using a mixture of fine crushed aggregates, polymer modified emulsified binder, mineral filler (cement), and water, among other potential additives which is applied to a roadway to provide a new driving surface, address cracking, seal the roadway, and slow down the aging process of the base asphalt. As a pavement preservation treatment, microsurfacing is used to increase the effective life of pavement by providing a new driving surface and address distresses, therefore preventing the need for costly reconstruction until a later time.

The microsurfacing components are mixed on site in specially designed equipment at pre-determined rates and poured onto existing asphalt and smoothed through use of a screed on the back of the applicator vehicle. Minor rolling and compaction may or may not be used, traffic is the main densification process for microsurfacing. Driving on a treated roadway can take place within two hours which allows enough time for the emulsion to cure. Microsurfacing can be used for two primary purposes:

- Surface Treatment As a surface treatment, microsurface fulfills the main role of providing a new driving surface while helping to slow aging of the underlying surface [5]. In addition, minor transverse and longitudinal cracking can be addressed [2]. This

type of treatment uses Type II microsurfacing aggregates and lower application rates than the microsurface rutting treatment [6].

- Rutting Treatment As a rutting treatment, the application of microsurface can be used to fill non-active rutting present in roadways [2]. In this case, the rutting of the original roadway should not be structural in nature nor be very severe [5]. In both these cases, the use of microsurface may only temporarily return the driving profile to desired levels. This type of treatment uses Type III microsurfacing aggregates and higher application rates [6]. In addition, this treatment may require several days to finalize the application process [5].

Microsurfacing is a versatile and diverse treatment. It's capabilities as a surface treatment address many issues that could be desired for use on existing roadways.

1.2 Problem Statement

While the use of microsurfacing provides many benefits, the use and acceptance of such a treatment is dependent on its performance. Performance is dependent on two main factors: optimal timing of application, and mixture characteristics. One of the primary issues facing microsurfacing is cracking in the form of reflective and thermal cracking. Cracking early in microsurfacing life could reduce the likelihood of its use in the future as it contributes to increased roughness and causes aesthetic issues. Cracking in microsurfacing could be caused by traditional traffic loaded stresses, thermal cracking, and reflective cracking from existing distresses in the underlying asphalt. In addition, moisture infiltration increases due to the existence of cracking and puts the overall structure of the roadway at risk. Therefore, the ability for microsurface to resist both

reflective and low temperature cracking should be considered important factors in any given microsurface mixture's performance.

The current state of microsurface research focuses on microsurface's long term performance as it relates to pavement and surface conditions primarily using LTPP SPS-3 data. Many of these studies focus on the optimal timing of pavement preservation treatment application. In addition, current research has been conducted to determine tests for microsurface binder grading [7]. Furthermore, state agencies and contractors provide a standard mix design for microsurface which generally includes specified and controlled quantities of cement, emulsion, water, and application rates [8], [6]. However, research into improvements to microsurfacing mixture cracking resistance, particularly from a laboratory performance perspective, is lacking. The effects of the use of additives such as increased quantities of latex polymer or fiber reinforcement on the cracking performance using common asphalt laboratory testing of microsurface mixtures have not been widely evaluated despite its use in the field. As cracking is one of the primary concerns of microsurfacing, the use of certain additives offers potential performance improvements when compared to standard microsurface mixtures. The use of laboratory-based asphalt testing could be used to recommend improvements to microsurface specifications and warrant further evaluation in the field. Therefore, additional research into various microsurface mixtures that can be used to improve cracking performance of microsurfacing is warranted.

1.3 Research Hypothesis

Laboratory based asphalt testing can be used to evaluate the cracking performance of pavement preservation treatments, in particular microsurfacing. The addition of fibers and increased polymer contents can be used to improve microsurface cracking resistance.

1.4 Goals and Objectives

The goal of this study is to evaluate the laboratory cracking performance of various microsurfacing mixtures using asphalt tests. These mixtures will follow standard state specifications for mix design proportion requirements set by NJDOT and ISSA specifications. Fibers and polymer will be added to evaluate if these materials can help improve cracking resistance of microsurfacing mixtures. To do this, existing asphalt tests commonly used in materials and research facilities will be used. A sample production method to provide microsurfacing specimens for use in these tests was developed that are compatible with these tests. The objectives to achieve the above goal are:

-Conduct a preliminary laboratory optimal timing study on microsurfacing and chip seal to reinforce aspects of pavement preservation treatments witnessed in the field and to verify that laboratory tests can be used to evaluate pavement preservation treatment performance (i.e. are sensitive to treatments).

-Developing a fabrication method for creating microsurface samples that will meet standard specification sizes for the tests conducted in this study.

-Evaluate the sensitivity in volumetrics of microsurface based on the different additives and polymer proportions used in this study.

-Compare and analyze the crack initiation and crack propagation resistance of each microsurface mixture based on the selected tests.

1.5 Research Approach

The first action for this study was to conduct a literature review to gain an understanding of current practice for pavement preservation and microsurfacing in general. This included knowledge based on materials, adequate laboratory tests, and potential sample production methods based on field application of microsurfacing. In order to develop procedures and evaluate cracking performance of microsurfacing considering current practice and experience, two main phases in this study were executed. Chapter 3 (Phase I) describes a laboratory based optimal timing study evaluating the potential for using pavement preservation treatments applied to asphalt samples. This phase focused on the fact that optimal timing is a commonly studied pavement preservation concept based on asphalt and treatment interactions. Chapter 4, Chapter 5, and Chapter 6 (Phase II) describes a laboratory-based study to evaluate cracking performance improvements to microsurfacing mixtures. This was based on experience from Phase I and information from the literature review.

The following tasks were completed in order to achieve the goals and objectives of this study for each phase:

1.5.1 Task 1. Determine the proper materials and mix proportions to use for testing of the chosen mixtures in the laboratory.

This task will be largely determined by state highway agency guidelines and recommendations from contractors. Materials for this study will be obtained locally to

ensure the mixtures include ingredients that are equivalent to those used in the field. This will aid in lowering discrepancies in the mixtures created in the laboratory when compared to common practice.

1.5.2 Task 2. Choose the proper laboratory tests to use to evaluate the materials.

This task will be largely determined by current practice of asphalt testing and past research studies evaluating microsurfacing and pavement preservation treatments. The tests chosen should properly evaluate mechanics intended to represent distresses experienced by microsurfacing in the field.

1.5.3 Task 3. Develop methods for producing samples of pavement preservation treatments and microsurfacing.

The objective of this task is to develop test methods for sampling microsurfacing mixtures and chip seal in Phase I, and microsurfacing mixtures for phase II. There are no common procedures or equipment for producing microsurfacing samples for use in the selected tests. Molds and housing must first be produced that will allow for the molding, curing, extraction, and cutting down to specification sizes. This task is vital to ensure a proper comparison of the different mixtures can be conducted.

1.5.4 Task 4. Conduct performance testing of treatments and analyze data.

The goal of this task is to evaluate reflective cracking using the Texas Overlay Tester, and crack initiation resistance using the Semi-Circular Bend Test. The results of these tests can be used to evaluate which mixtures perform better in reflective cracking and resistance to crack initiation.

1.6 Significance of Study

The past studies for microsurfacing have been mainly linked to optimal timing and performance life based on field data, these studies focused on microsurfacing as a general mixture [9], [10], [11]. In addition, standard mix design of microsurface requirements focused on surface properties such as bleeding, raveling, and aggregate loss. However, this study begins to evaluate the differences in cracking performance based of standard microsurfacing mixtures using varying degrees of additives and fibers and laboratory tests common in asphalt testing facilities. This study will offer the following benefits to broad range of stakeholders, such a local and to state highway agencies:

- Broader understanding of how to improve reflective and thermal cracking performance for microsurface mixtures,
- Provide an understanding for the use of additional and specific materials for microsurface mixtures without the need to change current mix design specifications,
- Methods for fabricating and testing cracking performance of microsurface mixtures using commonly used asphalt laboratory tests.

Chapter 2

Literature Review

2.1 Background

Pavement preservation can be defined as treatments, which are applied at specific times to roadways under certain conditions in order to preserve them and extend their service life while keeping costs at a minimum [2]. These treatments do not offer any structural capacity to roadways, but are used to restore surface condition, seal asphalt pavement, and retard the degradation of roadways [2], [12]. The use of pavement preservation treatments, therefore, ensures the protection of infrastructure assets while, simultaneously, allows access to federal funding [13]. However, the effective use of pavement preservation rests heavily on timing of application, existing roadway conditions, and specific expected benefits of the pavement preservation techniques used [2], [13]. State highway agencies sometimes provide pavement preservation treatment manuals that help engineers and contractors determine the proper treatments based on roadway conditions. In addition, long-term studies such as the Long-Term Pavement Performance Special Pavement Study 3 (LTPP SPS-3) provide researchers with a basis of knowledge to evaluate field performance for these treatments. While experience in the field is crucial to the enhancement of pavement preservation, failure of these treatments to perform adequately may deter many agencies from adopting these treatments in situations where rapid failure of the new treatment occurs [13]. Therefore, it is imperative that research and evaluation of collected data be used to improve the effectiveness and benefits of pavement preservation. While LTPP SPS-3 field data has been used extensively to evaluate pavement preservation treatments, there is a clear lack of

comprehensive laboratory research regarding the performance of pavement preservation treatments and materials.

2.2 Definition and Benefits of Pavement Preservation

Pavement preservation is a strategy used to maintain and/or improve the condition of roadways that are still in good condition through the use of treatments such as thin overlay, chip seal, microsurfacing, slurry seal, and crack sealing [2], [14], [3], [4]. These strategies do not improve structure or capacity of a roadway but improve roadway conditions by restoring driving surfaces and help to retard roadway condition deterioration by sealing the roadway and filling cracks [14]. Pavement preservation treatments also help extend the life of pavement systems, which also helps reduce the costs incurred from pavement reconstruction [14].

The costs of maintaining transportation and roadway infrastructure have put a spotlight on pavement preservation treatments. The Moving Ahead for Progress in the 21st Century Act (MAP-21) and Fixing America's Surface Transportation Act (FAST) are examples of federal acts that focus on the importance of pavement preservation [14]. Federal-aid funds are available to roadwork projects falling under pavement preservation and preventative maintenance performed on highways [14]. Under 23 USC 119, the National Highway Performance Program offers support and funding to specific construction projects and maintenance of facilities located on the National Highway System [13]. This includes preservation projects with intentions to maintain and achieve "performance targets" and "improve infrastructure condition" [15]. The combined benefits and available funding of pavement preservation inevitably contribute to the growing popularity of pavement preservation treatments. However, the use of pavement

preservation should be cost efficient by extending the service life of the pavement and should function as intended. The pavement preservation treatments should offer desirable benefits when compared to more costly remedies such as traditional pavement rehabilitation and pavement reconstruction. Additionally, using the correct treatment applications at the correct time is important in order to be sure the treatments are used to optimal effect.

Early failure of pavement preservation treatments can delay full implementation of treatments into State Highway Agency (SHA) guidelines and programs [13]. It is therefore important to understand the different types and variations of pavement preservation treatments, the efficiency of these techniques in addressing distresses and increasing roadway conditions, the process of determining the optimal timing to apply them on roadways, and the different strategies of their implementation. By compiling information from available sources and conducting further research [2], it is possible to improve pavement preservation design, performance, and implementation, which should increase the frequency at which these treatments are used.

2.3 Pavement Preservation Treatments

A compilation of various pavement preservation methods, the variations, and the alternatives of these methods are presented in this section. Background information regarding several pavement preservation treatments is necessary to choose versatile treatments that can be used and studied in a variety of circumstances. This information also allows engineers to determine what type of testing can be used to improve pavement preservation performance.

2.3.1 Crack sealing. Crack sealing is a pavement preservation treatment in which a bituminous material is used to fill in cracks and prevent moisture infiltration [2]. The treatment is generally expected to last 2 to 6 years [2], [12]. Both crack sealing and crack filling are highly versatile pavement preservation treatments, spanning a wide range of cracking types and application types. It is one of the most commonly used and low-cost pavement preservation treatments, amounting to $0.30 to $1.50 per linear foot [2], [16].

Like other pavement preservation treatments, crack sealing adds no structural benefit and its application should be applied to uniform and well cleaned longitudinal cracks, minor block cracks, or transverse cracks [2], [17]. Generally, crack sealing is applied to cracks less than ¾", while *crack filling* is used for cracks larger than ¾" [17]. Crack sealing is generally carried out during cooler months due to their use on working cracks, or cracks that expand rapidly, which ensures the cracks are at their widest [17].

The variation in different methods of crack sealing and crack filling are situation dependent. The various types of crack sealing and filling can generally be broken down into strategies that are placed directly in the crack, placed into and overtop of the crack, or creating a reservoir where the crack is in order to place material inside. Figure 1 illustrates these various methods. Various sealants and fillers are used based on application method including low modulus rubberized asphalt, rubberized asphalt, crumb rubber, asphalt emulsion, asphalt cement, and cutback asphalt [17]. Crack sealing and filling methods include clean and seal (to improve adhesion), saw and seal (to create a reservoir and fill underlying cracks in new pavement), rout and seal, crack filling (create a reservoir in existing longitudinal and transverse cracks) , full-depth crack repair

(milling asphalt overtop of cracks and filling the new reservoir with HMA), and crack sealing followed by overlays (to reduce cracking in new overlays) [17].

These different crack sealing and filling approaches are widely used and should be applied using proper judgement of conditions including climate, temperature, road conditions, crack conditions, crack preparation, and time of year [12], [17]. As mentioned, crack sealing and filling benefits roadways by preventing moisture from infiltrating cracks.

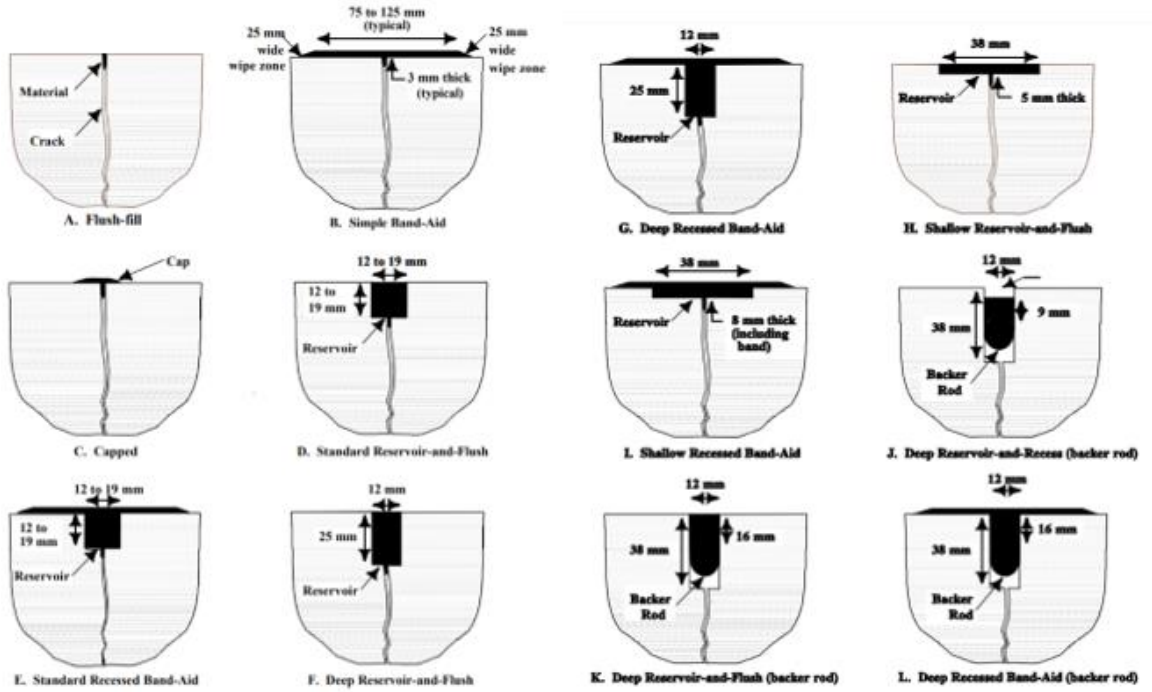

Figure 1. Crack sealing and filling application approaches. [18]

2.3.2 Chip seal. There are varieties of overlay preservation treatments that can be used to seal roadways, fix minor cracking, fill rutting, and restore the driving surface to better conditions. Chip sealing is a pavement preservation treatment in which a

bituminous binder is applied to a prepared surface. Aggregates are then rolled into the binder [12]. Figure 2 illustrates a general single chip seal application. There are various types of chip seal practices available based on traffic, environment, preservation objectives, cost, and pavement conditions. Emulsion, performance graded asphalt, asphalt rubber binder (hot applied), and rejuvenating emulsion binders are the main forms of binders used and should be selected based on project specifications [12], [19], [20], [21], [22].

Chip sealing can provide from up to 4-7 year life extension to roadways [21]. The standard application and use of emulsion chip sealing is generally to address minor cracking and provide surface friction to roadways that are structurally sound. However, emulsion chip sealing is not often used to address rutting [12], [20]. Various agency guidelines recommend to avoid using chip sealing to address rutting, cracking and distresses larger than ¼", alligator cracking, potholes, flushing, or base failure [12], [20], [23]. If the use of chip seals is chosen for the purpose of providing a waterproof layer to a distressed roadway or a roadway with large cracks, then pretreatment of the cracks may be necessary using crack sealing [20].

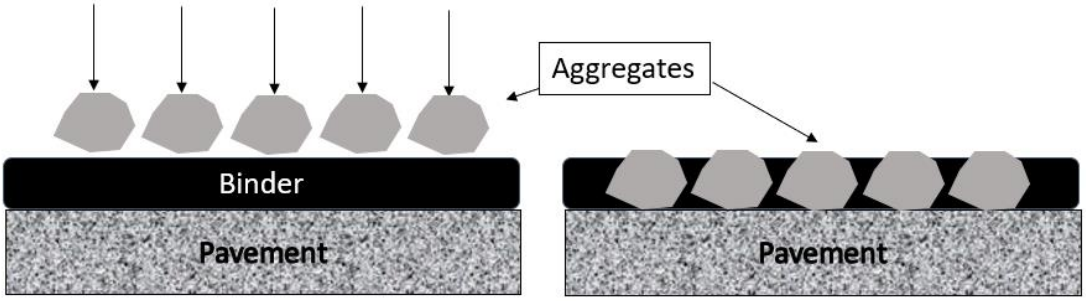

Figure 2. Application of a single layer chip seal.

While using chip seal provides many benefits, issues concerning the use of chip seals do exist. NHCRP Report 680, "Manual for Emulsion Based Chip Seals for Pavement Preservation", provides guidelines and practices for using emulsion-based chip seals to address these issues. The report highlights that possible traffic volume issues arising from the use of emulsion-based chip sealing include embedding. In addition, using less binder may be necessary to avoid this issue on high volume roadways. In this case, modified emulsion binder may be necessary to prevent the aggregates from dislodging. Rapid setting emulsions are used in most cases to ensure that the least time necessary for traffic control is needed [20]. Humidity and weather conditions can affect the setting time of anionic emulsion binders and must be considered due to traffic control requirements necessary to ensure proper setting of the seal [20].

In addition to proper binder selection specific to chip sealing projects, aggregates and layering are additional parameters considered in effectively using chip seals as a pavement preservation method. The various layer and aggregate choices include single chip, double chip seal, single chip seal with choke stone, fog seal coating of the chip seal,

stress absorbing membrane seal, stress absorbing membrane interlayer, scrub seals, and other interlayer applications [12], [20]. Chip seal variations include:

2.3.2.1 Single chip seal. This type of chip seal is a single layer of aggregates rolled into a layer of either hot or emulsified asphalt binder. This type of chip seal is the most commonly used method and is carried out on roadways that do not require more advanced methods of chip seal [20], [24].

2.3.2.2 Double chip seal. This type of chip seal is carried out by applying an initial chip seal layer followed by an additional chip seal overtop of the original. The second chip seal layer is generally conducted using smaller aggregates than the layer below. This method can be used for roadways experiencing higher loads when compared to the roadways where single chip seals are appropriate [20], [24].

2.3.2.3 Cape seal. This type of chip seal is a single chip seal layer followed by the application of a slurry seal [24].

2.3.2.4 SAMI (Stress Absorbing Membrane-Interlayer). This type of a chip seal is a single chip seal layer followed by a thin overlay [20].

According to the NHCRP Report 680, “Manual for Emulsion-Based Chip Seals for Preventative Maintenance”, the aggregate size, shape, gradation, cleanliness, moisture content, toughness durability, and porosity are all important aggregate characteristics to consider when selecting chip seals as a pavement preservation method. Interlocking and required binder quantities are affected by aggregate size, shape, and gradation [20]. Large aggregates will require more binder, which offers better sealing to the roadway [20]. Interlocking of aggregates, gradation, and the use of lighter weight aggregates are important factors in decreasing the risk of windshield cracking due to loose chips [12],

[20], [25]. Issues of traffic volume and chip dislodgement are primary concerns when using chip seals. While chip sealing is an excellent choice for low and medium volume roadways, there are other pavement preservation treatments that can be used in a wider variety of traffic conditions.

2.3.3 Thin overlay. Thin overlay is the application of a thin layer of hot mixed asphalt (HMA) overtop of existing pavement. Variations of thin overlay exist based on layer thickness, types of binder, gradation, and aggregate types. The thickness of thin overlays is generally less than 1 ½", however the exact thickness that constitutes a thin overlay varies from state to state [12], [25], [26]. According to the NCHRP Report 523, the thickness of a thin HMA overlay is between 0.75" and 1.5" [2]. Aggregates used in thin overlaying are generally less than 12.5 mm NMAS [27]. Thin overlays, as is the case with most preservation treatments, are applied to pavement that is structurally sound and within a certain roadway condition criterion [16], [26]. Thin overlays are not usually used to address structural failures, high levels of thermal cracking, or end of pavements' service life. However, thin overlays can add some functional integrity [2]. The life expectancy of thin overlays is 7 to 10 years [2]. Figure 3 shows an example of a cross section of thin overlay applied to a base of asphalt.

Figure 3. Thin-overlay applied to HMA.

The proper choice of thin overlays is dependent on traffic type, pre-treatment pavement conditions, and environmental conditions [12] while the selection criteria of thin overlays vary based on state agency policies. In fact, there are many visual and distress cues that can provide information on when to apply a thin overlay. Thin overlays could be used to address raveling, minor longitudinal cracking not in the wheel path, minor transverse cracking, friction loss, roughness, low bleeding levels, and minor block cracking [20], [27]. Milling can be used to provide a suitable surface for the thin overlay, remove any deficiencies at the pavement surface, and supply recyclable material [2], [26], [27].

The three main types of thin overlay based on gradation of the aggregates are dense graded, open graded, and gap graded [12], [16]. Asphalt binders, particularly pavement graded and modified binders, are chosen based on expected weather and traffic conditions [16]. Each combination and mixture offer various benefits as pavement preservation treatments. Dense graded thin overlays have a continuous aggregate gradation across all aggregate sizes [12]. They can be used to mitigate raveling,

oxidation, minor cracking, minor surface irregularities, skid problems, and waterproof pavements [12], [16]. Open graded thin overlays offer better water draining capabilities than densely graded thin overlays and can help mitigate wet weather accidents, wet-night visibility, skid resistance, cross slope, noise, oxidation, flushing, bleeding, and mitigation of minor cracking [12], [16]. Gap graded overlays make use of both coarse and fine aggregates and help to relieve raveling, oxidation, reflection cracking, minor surface irregularities, flushing, skid problems, and have been known to reduce hydroplaning issues [12]. Typical costs based on gradation are \$1.75 to \$2.00 per yd^2 for dense graded mixes and \$1.25 to \$1.42 per yd^2 for open graded mixes [2].

In addition to aggregate and binder options, there have been many material innovations, new technologies, and strategies that have been used to improve thin overlay performance [27]. This has led to a wide variety of thin overlay options which include:

2.3.3.1 UTBWC (Ultra-thin bonded wearing course, aka Novachip^{TM}). This is a thin overlay used by many state agencies as a pavement preservation method [26], [28]. This method offers longer lasting life to the pavement, adds only a very thin lift, and reduces clearance adjustments [29]. It is an open graded HMA which makes use of a thick polymer modified emulsion tack prior to the application of the HMA overlay [26], [28]. A study in Minnesota showed that after seven years of service, roadway conditions and ride quality remain high using UTBWC, while no weathering or raveling was witnessed [29]. The cost of this method in 2007 was estimated at \$4 per yd^2 [29]. One major drawback to this method is that it requires unique equipment for application, which is more expensive than typical thin overlay costs.

2.3.3.2 Dense graded 4.75mm NMAS. These mixtures can be used to decrease costs by reducing overlay thickness and provide quieter riding conditions [26], [30]. Cooley and Brown (2003) [31] found that 4.75mm NMAS mixtures are rut resistant and tend to be less permeable than larger NMAS. In addition, Son et al. (2016) [32] found that by using stone matrix asphalts for 4.75mm NMAS, issues with decreased friction related to low NMAS mixes can be mitigated by using stone matrix asphalt mixes.

***2.3.3.3 Open Graded Friction Course*.** This is a thin overlay that increases water drainage on roads, increasing safety for drivers in regard to hydroplaning [33]. OGFC overlays using normal asphalt mixes tend to have low durability and strength [33]. Faghri et al., (2002) [33] used an addition of styrene-butadiene-styrene (SBS) polymer that doubled the strength of OGFC mixes and increased permeability [33]. Islam et al. (2018) found that OGFC is more flexible and less susceptible to low temperature transverse cracking than regular asphalt concrete mixes [34]. A polymer modified OGFC overlay could make a good candidate for roadways often exposed to poor weather conditions.

2.3.3.4 Paver Placed Elastomeric Surface Treatment (PPEST). This is a form of thin overlay using a chemically bonded blend of asphalt and crumb rubber compacted to a thickness of no less than 0.75” and up to 1.25” [35]. Prior to application a tack coat is applied to ensure proper binding of the PPEST to the surface [35]. PPEST can be applied to roadways experiencing moderate cracking and adds about 4 to 6 years of life to the applied pavement [22].

Thin overlays can also be placed overtop of stress absorbing membranes (SAM) or stress absorbing membrane interlayers (SAMI) [12]. Ogundipe et al., (2013) [36] studied the effects of stress absorbing membrane interlayers on overlays. The authors

found that SAMI helped mitigate reflective cracking in asphalt overlays under certain conditions. SAMI and overlays of lower thickness tended to have better results than thicker layers and tended to work best at higher temperatures [36]. Addressing cracking prior to the use of thin overlays or SAMI and SAM is important for its performance [12]. For roads with minimum cracking, SAM and SAMI can be placed underneath to strengthen the thin overlay [12].

2.3.4 Microsurfacing, slurry seal, and fog seal. There are variations of very thin applications asphalt based mixtures that can be used mainly to seal roadways, address oxidation and raveling, and restore surface conditions. These treatments include:

2.3.4.1 Slurry seals. are mixtures of well graded aggregates, asphalt emulsion and water that is spread over the pavement surface at a thickness of 10 mm to 20 mm using a squeegee or spreader box [2], [4], [17]. Slurry seals provide added surface friction, which protects against moisture penetration, addresses raveling, minor cracking, and oxidation [2], [17].

2.3.4.2 Microsurfacing. is a pavement preservation method using a polymer modified asphalt emulsion, water, dense graded aggregates, cement, and additives applied to a pavement surface at a thickness of between 10 mm and 20 mm [2], [12], [4], [17], [27]. Application of microsurface is carried out by pouring the mixture onto the roadway using specially designed machinery. Microsurfacing provides added surface friction, protects against moisture penetration, addresses raveling, minor cracking, and oxidation [2], [17]. Microsurfacing can also be used for filling of ruts based on aggregate type and the way in which it is applied to the roadway [2], [17].

2.3.4.3 Fog sealing. is a treatment in which an emulsion binder is sprayed onto existing roadway surfaces. Fog seals can be used to seal roadways, address raveling and oxidation, and to fill very small cracks [2]. However, fog seals may lower skid resistance on roadways and may not be good candidates when skid resistance is an issue [2].

While the components of slurry seal and microsurfacing are similar, the main difference between these treatments is the breaking conditions during which water leaves the mixture and hardens. Microsurfacing uses chemical breaking as the main mechanism for hardening, where slurry seals use thermal breaking [2], [17]. This makes microsurfacing suitable for a wider array of environmental conditions as it does not rely on heat from its surroundings to cure. While fog seals can offer the benefits of restoring flexibility to the existing asphalt, this technique lacks the surface friction benefits of microsurfacing and slurry seals. Generally, these pavement preservation methods are initially used on roadways showing oxidation and/or minor cracking [2], [17]. Microsurfacing appears to be a more robust preservation method as it can handle more advanced stages of oxidation, be applied to roadways showing rutting, and has an expected life of 4 to 7 years [2], [17]. Fog and slurry seals have expected life of 1 to 2 years and 3 to 5 years, respectively [2]. Costs for slurry seal and microsurfacing are roughly between \$0.70 and \$1.00 per yd^2 and between \$0.90 and \$1.70 per yd^2, respectively [2].

Ji et al., (2012) [37] evaluated microsurfacing based on various roadway conditions such as PCR and International Roughness Index (IRI). The authors found that microsurfacing is a cost-effective preservation method when applied to structurally sound roadways and help in addressing rutting and slowing down the appearance of reflective

cracking. However, microsurfacing's ability to positively address PCR and IRI are limited [37]. This may be in part due to the roadway conditions during which pavement preservation treatments were performed. Hajj et al., (2011) [38] used performance data to evaluate the effects of slurry seal. The authors found that the use of slurry seal greatly increases PCI when added between 3 and 9 years of pavement age and can extend the service life of the pavement when applied at 3 years of age. Hajj et al., (2011) [38] surmised that the use of the slurry seal reduced aging effects on the roadway, and further protected it from thermal and fatigue cracking that could propagate due to aging. The use of microsurfacing and slurry seals are therefore effective measures when used to address, in particular, aging and are able to extend life by preventing premature distresses due to aging.

2.4 Treatment Application: Selection and Timing

In order to select the best pavement preservation methods, it is necessary to understand the nature of when and under what conditions these methods are used. The addition of pavement preservation at a specific time in a pavement life can extend the effective life of the pavement as seen in Figure 4. There have been several studies conducted that focused on the optimization of using pavement preservation methods based on life cycle cost analysis, cost-benefits, roadway life extension, current pavement conditions, and increase to roadway conditions [11], [9], [10], [39]. Developed models and studies can be used for correlating data collected in the laboratory to full scale testing results to determine cost effectiveness and benefits obtained from the use of specific pavement preservation treatments. The various methods of measuring pavement

conditions make it necessary to establish criteria that can be expressed and compared across treatments and conditions.

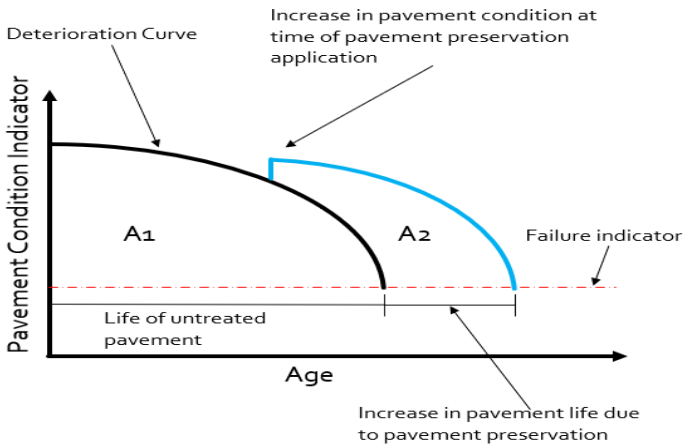

Figure 4. Pavement condition deterioration with and without pavement preservation treatment.

Pavement condition indices can be gathered throughout the pavement life and will deteriorate with time. These pavement condition indices can be composite indices or represent a targeted distress such as cracking or rutting. When a pavement preservation treatment is applied to the roadway, the pavement condition should be improved. The deterioration of the pavement and resurfaced pavement will eventually reach a specific limit that is dependent on factors such as agency budgets and serviceability of the pavement. Figure 4 represents a general case of how a pavement preservation treatment can extend the service life of the pavement [2], [11].

The effectiveness of a treatment can be measured using various methods including the added life to the pavement, or by computing the area of benefit beneath the

deterioration curves. Variations in the way agencies account for distresses and costs associated with a treatment can determine the effectiveness or benefit-cost ratio of a pavement preservation treatment [2].

The NCHRP report 523 offers a methodology for determining the cost-benefit of pavement preservation treatments. By comparing the areas beneath the deterioration curves of the do-nothing cases (A_1 in Figure 4) and the treatment cases (A_2 in Figure 4), the overall benefits of individual pavement preservation treatments can be compared with other treatments based on individual and/or multiple distresses [2], [11]. Maximizing the area of the post treatments curve (A_2 in Figure 4), is a basis on which optimal timing can be found [2], [11]. When the application of a pavement preservation at a specific time results in the greatest increase of the area under the deterioration curves, this is considered to be the optimal timing for application of that specific treatment [2], [11]. This methodology was used to create a Microsoft Excel based program, called OPTime, to help determine the optimum application time for various treatment options based on collected field data and performance of pavement condition indices. Figure 5 shows the input flowchart that OPTime is based on.

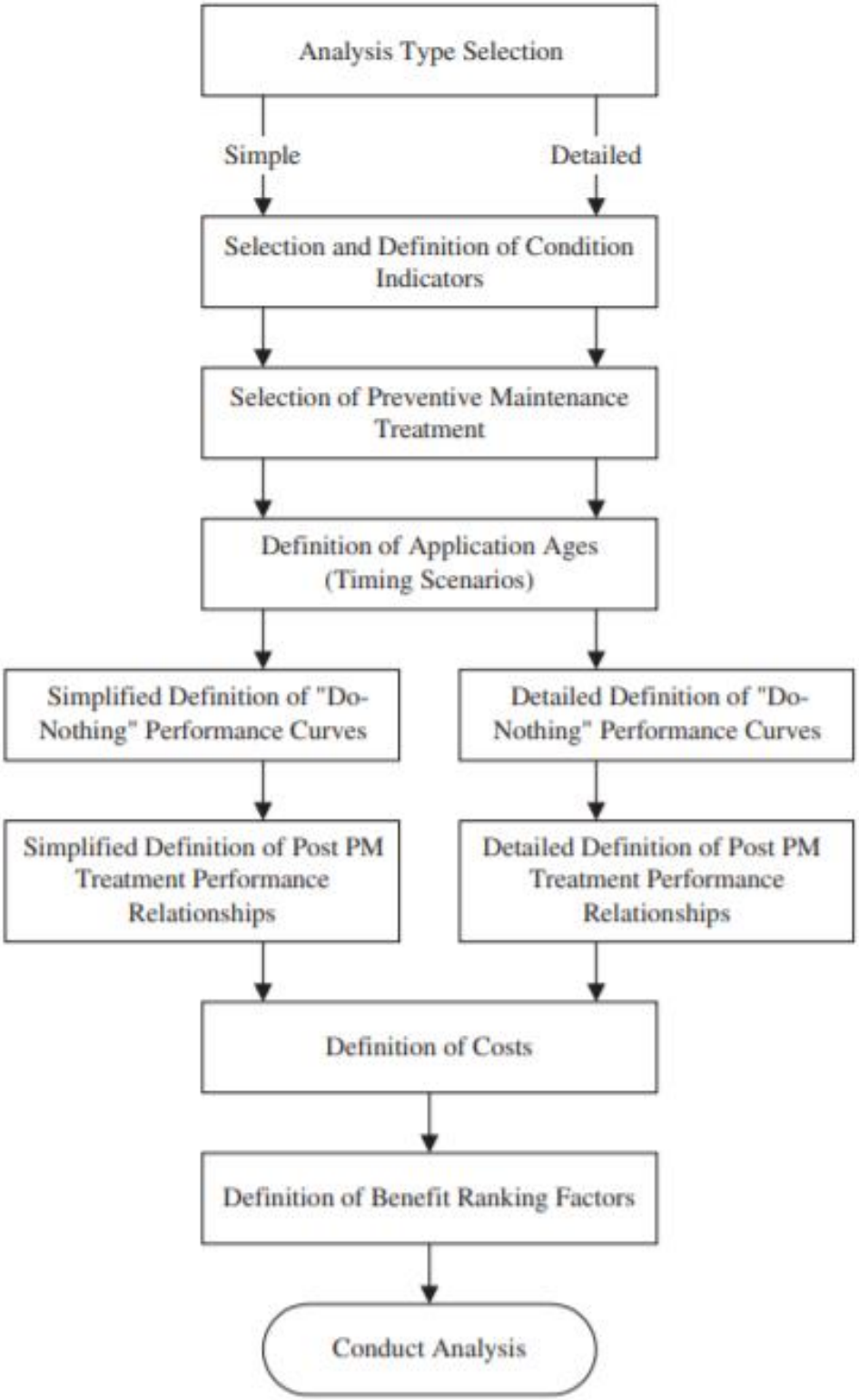

Figure 5. Data input flow chart for OPTime [2]

Haider and Dwaiket (2003) [11] developed mathematical linear regression models based on exponential decay of IRI over the lifetime of a pavement that can be used to determine the best time to apply pavement preservation methods. The data collected in the Long-Term Pavement Performance Program (LTTP) Specific Pavement Studies-3 (SPS3) was used to evaluate the usefulness of the model. The equations were designed to calculate the area between the deterioration curves and the threshold failure criteria in IRI [11]. By using this method, the application year for the pavement preservation treatment and the failure criteria (in IRI) can be tuned for different state highway agency needs. A failure criteria of 2.5m/km was used to evaluate the model's output. The deterioration graph is presented in Figure 6.

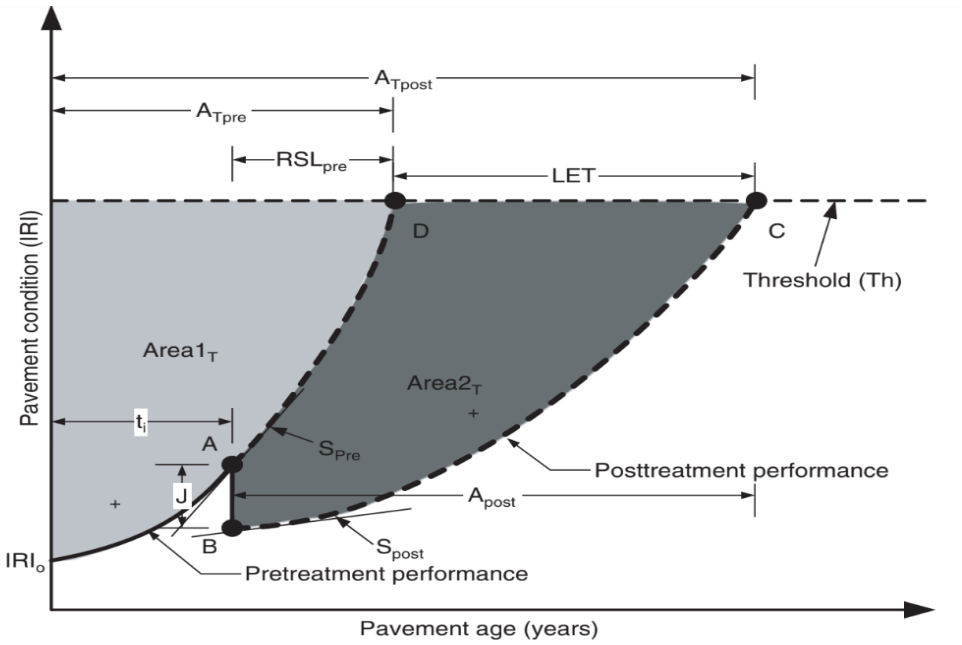

Figure 6. IRI deterioration versus pavement age [11]

To represent the IRI conditional curves, exponential functions were used to represent the pretreatment and posttreatment performance. The basis for this model was developing equations to represent the posttreatment area ($Area2_T$ in Figure 6) through integration of the posttreatment performance curves [11]. By maximizing the areas in Equation 1 and Equation 2 for t_i or setting the derivatives of the equations equal to 0, the equations can be solved for the optimal timing for treatment application Where, *Th* is the IRI failure threshold, a_1 is the starting IRI value, β_1 the deterioration rates of the performance curves, t_i is the treatment application time, F_s is the post treatment slope adjustment factor, and F_j is the performance factor after treatment [11].

$$Area2_T = \frac{Th\ln\left(\frac{Th}{\alpha 1}\right) - Th + \alpha_1}{\beta_1\alpha_1 e^{\beta_1 t_i}F_s} - Th\left(\frac{\ln\left(\frac{Th}{\alpha_1}\right)}{\beta_1} - t_i\right) + \frac{Th}{\beta_1} - \frac{\alpha_1 e^{\beta_1 t_i}}{\beta_1} \quad \text{Equation 1}$$

$$Area2_T = \frac{Th\ln\left(\frac{Th}{e^{\beta_1 t_i \alpha_1 (1-F_j)}}\right)(1-F_j)}{\beta_1 F_s} - \frac{Th(1-F_j)}{B_1 F_s} + \frac{\alpha_1 e^{\beta_1 t_i}(1-F_j)^2}{\beta_1 F_s} - Th\left(\frac{\ln\left(\frac{Th}{\alpha_1}\right)}{\beta_1} - t_i\right) + \frac{Th}{\beta_1} - \frac{\alpha_1 e^{\beta_1 t_i}}{\beta_1} \quad \text{Equation 2}$$

This model focused solely on the IRI as the determining factor in finding the optimal time [11]. The IRI levels pre and post preservation for different preservation methods determine the deterioration rates after application [11]. While limited by the fact

that only the IRI shift from pretreatment to posttreatment determines the optimal timing of application, the model can be extended to other preservation alternatives [11]. This is particularly useful for agencies that record IRI data on their roadways and may be considering implementing pavement preservation treatments.

Wang and Wang (2017) [9] used an IRI deterioration to a failure threshold model that used traffic volumes based on Annual Average Daily Truck Traffic (AADTT) and found optimal timing based on agency and user costs. By relating IRI to costs, this model introduces additional parameters to determine optimal timing to use the pavement preservation methods of thin overlay, crack seal, and chip seals (Wang and Wang 2017). The IRI data was gathered from LTTP SPS-3. The results for this method indicated that there is an optimum timing to apply various preservation alternatives based on IRI deterioration, life expectancy, and agency/user costs [9]. By applying the additional factors of cost, this model provides valuable information beyond the condition and limits of pavement but also a cost basis that would allow agencies to make both economic and sound engineering decisions.

The findings of Wang and Wang's (2017) [9] method agree with Haider and Dwaiket's (2011) [11] model that roadways with lower IRI values benefit from treatments later in the pavement's life, while pavements with higher IRI values benefit from treatments earlier in their service life. That is to say that the application of these treatments to roadways when they are in good condition see the greatest benefits in life extension based on pavement condition indicators. These findings were further reinforced by the fact that roadways experiencing higher AADTT have longer service life extensions if the pavement preservation methods are applied earlier in their life cycle [9]. By

comparing benefits for agency and user costs using two different traffic conditions, the study found that there is an optimal timing for agency costs, generally later in the pavement life, whereas user cost benefits are higher when pavement preservation is used earlier in the pavement's life. In general, the study found that thin overlay has the highest cost benefits, while crack seals have the lowest (with the exception of user cost benefits) [9].

Wang et al. (2012) [10] also used life cycle cost analysis to determine net benefits and cost benefits using fixed application years using Equivalent Uniform Annual Costs (EUAC). In this case, the net benefits using EUAC was the difference between the annual costs of do-nothing scenarios and the annual cost of roadway treated with pavement preservation. A benefit factor was computed by dividing the net benefits by the uniform annual cost for the pavement preservation treatment. The pavement condition data was collected from the Pennsylvania Department of Transportation overall pavement index (OPI) [10]. Using these factors, crack seal, chip seal, microsurfacing, thin overlay, and NovaChip were compared to find the varying degrees of benefits based on the application years [10]. While this method limits the ability to find optimal times based on application year, it presents an economic focused basis for choosing pavement preservation methods. The model presented the ability to choose economically beneficial preservation methods that increase lifespan of roadways while simultaneously comparing cost benefit [10]. This study concluded that NovaChip and thin overlay offer the greatest net benefits, while crack sealing presented the greatest cost benefits due to its low costs [10]. The addition of cost benefits in this method provides agencies the ability to choose less effective preservation alternatives if budget constraints greatly limit spending capacity [10]. By

doing so, this study can provide potential users with an additional element for decision making that is not limited solely to life extension. This could be of particular interest when combined with the other models because it provides additional mechanisms to enhance decision making that will maximize both roadway life and cost savings.

Wei and Tighe (2004) [39] studied the use of pavement life extension and cost effectiveness of various preservation alternatives to develop a decision-making tree. The cost effectiveness of pavement management treatments were calculated by dividing the cost of the treatment by a calculated effectiveness (the effectiveness being found in a similar fashion as Haider and Dwaiket (2003) [11] by finding the area under the performance curve of treatments applied at different times in the pavement's life). By breaking the road networks in the target region based on various traffic load, pavement structure, and environmental factors, decision trees for these sections were developed based on cost effectiveness, which was calculated using roadway condition performance and life cycle costs [39]. The optimal timing for treatment was determined to be the year that has the most cost-effective value. The final decision tree took into account the most cost-effective timing for application of a wide range of preservation alternatives combined with various options dependent on cost, department restrictions, and local costs [39]. The decision trees allow agencies to decide which methods are best based on local standard performance thresholds, subgrade level, and cost.

The comparison of cost effectiveness between methods, roadway conditions, and optimal timing based on life extension appears to be the vital information sought after in each of these studies. What Wei and Tighe had done is combine this information into a versatile decision-making tree that allows users to make decisions based on location, cost,

and budgetary constraints. In another case, OPTime is a software that allows the use inputs specific to an agencies region and determine the best methods and timing to use pavement preservation treatments. This is ultimately the end goal of any pavement preservation study; to provide readers and users with valuable information to make cost effective and practical decisions based on their specific circumstances.

As seen in these studies, the application of available information and accepted modeling of roadway condition deterioration and performance can provide engineers with best estimates of optimal timing and cost efficiency. This aids in the improvement to the overall performance of treatments and pavement preservation as a whole. These studies are currently the most numerous methods of evaluation of treatment performance. This is likely due to the fact that there is plenty of field data that allows for this type of analysis. However, these models and studies depend heavily on roadway condition and performance data from the field to develop deterioration and effectiveness models. The selection of the pertinent and representative information to model roadway conditions also relies on field technician collection practices that may vary based on collection time, quantity of data, agency, and data reliability. In addition, this data generalizes and draws conclusions from the various treatments in a general manner; that is the variations in mixtures of a single treatment and respective performances are not taken into account. Although these methods of analysis are great for comparison of different types of treatments, these current studies lack differentiation within the same treatment. Studies of optimal timing of individual treatments based on material components such as binder, aggregate, and additives would further aid in the improvements to performance of each treatment and choosing the right time to use the treatment. Due to the focus on

comparisons of different treatments, there is a gap in increasing potential performance of specific pavement preservation treatments. The wide variation in costs, performance, and utility of these treatments means there should be conditions in which each of these treatments could be applied regardless of the differences among the performances of different treatments. Improvements and further research into to the way each treatment performs could also be linked to material selection and various distresses these materials undergo in the field.

2.5 Current State of Practice: Microsurfacing

Pavement preservation is a broad and general topic, which is apparent in the plethora of information available for treatment types, materials, and numerous studies of optimal timing. However, detailed information and treatment specific studies are also available for each treatment. The availability of this information on materials and studies is likely influenced by how common each treatment type is. The more information that is available to engineers and contractors, the more effectively each treatment can be used.

Perhaps one of the most versatile and widely applied treatment types currently used in the United States of America is microsurfacing [3] [4]. Based on respondents from surveys conducted by Vitillo et al. (2015) and Wang et al. (2011), microsurfacing is used by 64% and 72% of agencies, respectively. Many agencies provide specifications and guidelines for use of microsurfacing, mix design, and performance testing. Microsurfacing is currently being used in many states and by many agencies for both surface courses and rut filling [6], [40], [41], [8]. Specifications for states representing the four FHWA climactic zones can be found in Table 1. In addition to the many states that have standard specifications, Louisiana has a dedicated microsurfacing and chip seal

program. Microsurfacing use is widespread and is applied in a wide variety of climactic regions. Table 1 compares the mix requirements of states found in different climactic zones in The United States of America to the International Slurry Seal Association's guidelines. The International Slurry Surfacing Association's Recommended Performance Guidelines for Micro-Surfacing document A143 is the primary source for recommendations based on mix design, aggregate gradation, and performance [42]. This document provides microsurface composition and quality recommendation tests for aggregates, emulsion, surface texture, and mixture properties. These recommendations appear in many of the state agency guidelines for roadway design and are referenced to varying degrees [6], [40], [41], [8]. The specifications across states share commonalities in residual asphalt contents, mineral filler, polymer quantity in the asphalt, and application rates. It can be seen that for states such as Texas and Nevada where higher temperatures can be reached, the maximum residual asphalt content is kept lower than the other states. Recent experience in Minnesota has led to suggestions for updates in the minimum residual binder content from 5.5% to 7.5% [43]. This may indicate correlation with climate and region as far as binder quantities are concerned. However, prevailing similarities still exist. Use of specific gradations, emulsions, and other materials for microsurfacing varies state to state. The main functions for microsurfacing remain constant: provide a new driving surface, seal roadways, address raveling and oxidation, and filling of ruts [2].

Table 1

State Highway Agency Microsurface Mix Design Specifications

State	Application Rates	Emulsion	Residual Asphalt	Mineral Filler	Water	Polymer
ISSA	10-20 lbs/yd^2	CQS-1h	5.5% to 10.5% by dry wt. of dry agg.	0.0%-3.0%	As needed	3% minimum by bitumen wt.
Texas	15-20 lbs/yd^2	CSS-1p	6% to 9% by wt. of dry agg.	0.5% to 3% by wt. of dry agg.	As needed	3% minimum by bitumen wt.
New Jersey	16-22 lbs/yd^2	CQS-1h	5.5% to 11.5% by wt. of dry agg.	0% to 3% by dry weight of aggregates	As required	3% minimum by bitumen weight
Minnesota	To meet cross section requirements	CQS-1p or CQS-1hp	5.5% to 10.5% by wt. of dry agg.	0.25% to 3% by wt. of dry agg.	Not Specified	3% minimum by bitumen weight
Nevada	25 lbs/yd^2	MSE or MSE-h	5.5% to 9.5% by wt. of dry agg.	0.0% to 3.0% by wt. of dry agg.	Not Specified	3.5% minimum by mass of residual asphalt

2.5.1 Aggregates. Microsurfacing aggregate gradation generally comes in two forms: Type II and Type III. Microsurfacing aggregates are very fine 100% crushed stone [42]. Gradation recommendations based on the ISSA document A143 can be seen in Table 2. These recommendations suggest the use of Type II aggregates for urban and residential streets and airport runways, whereas Type III aggregates are used for interstate routes and to fill rutting. However, the use of these varying gradations can be different in

each state's guidelines, as these are only recommendations. For example, TxDOT only references one gradation, Type III, in Item 350 of their Standard Specifications for Construction and Maintenance of Highway, Streets and Bridges. Conversely, both NJDOT and MnDOT reference both types of aggregates. The major distinction in these two specifications is the use of Type II as surface coarse aggregates and Type III as rut filling aggregates.

Table 2

Gradation of Microsurface Type II and Type III Aggregates

Sieve Size	Type II (% Passing)	Type III (% Passing)
3/8"	100	100
#4	90-100	70-90
#8	65-90	45-70
#16	45-70	28-50
#30	30-50	19-34
#50	18-30	12-25
#100	10-21	7-18
#200	5-15	5-15

2.5.2 Binder type. The bitumen used in microsurfacing is a polymer modified emulsified binder [42]. Emulsified asphalt is a combination of water and asphalt dispersed using an emulsifying agent which creates a low viscosity asphalt [12]. The use of emulsified asphalt allows for mixing and application to take place within the same equipment and on site. Recommended requirements for the emulsified asphalt are provided in A143 from the ISSA and are typically included as specifications by state agencies. The residual binder after curing is recommended at 62% minimum by the ISSA. However, mix design methods from state agencies provide requirements for residual asphalt by weight of aggregates.

As can be seen in Table 1, there are a variety of different emulsions used by state highway agencies. In general, quick/rapid setting emulsions are used. The water in the emulsified asphalt chemically breaks with the general goal of being open to traffic within 1 hr. of application [8], [41]. The speed at which traffic is allowed back on the pavement is a primary advantage of using microsurfacing over slurry seals, as slurry seals break via evaporation which will be temperature and climate dependent.

2.5.3 Mineral filler, water, and polymer. Additional materials included in microsurfacing includes mineral filler (cement), water, and polymers. Each of these components serves a different role in the final product. The addition of cement contributes to the microsurfacing consistency allowing for easy pouring and spreading [12]. In addition, cement decreases curing time of the overall mixture by absorbing additional water and causes the emulsifying agent to break from the water more rapidly [12]. There are recommended minimum cement quantities provided in most state agency specifications which can be seen in Table 1. Water in the emulsified asphalt contributes to its low viscosity and ability to spread the microsurface, but additional water is used to further produce desired consistencies and homogenous mixtures. The addition of polymers to binder and emulsified asphalts help improve desired qualities of the emulsified asphalt. Typically, elastomeric polymers such as natural and synthetic rubber, styrene-butadiene-styrene (SBS), or crumb-rubber from tires [44]. When natural and synthetic rubbers are used (i.e. Latex), the polymer can be added pre or post emulsification and contributes to increased elasticity, and increased resistance to reflective cracking and resistance to deformation at high temperatures [45]. Typically, state agencies require a minimum of 3% polymer by weight of residual asphalt.

2.5.4 Application of microsurfacing. As mentioned above, the application of microsurfacing can be used as a surface course or to fill pavement deformation. In either case, the components of microsurface are all mixed on site in a slurry surfacing machine. The setup is intended to mix the components in the following order: aggregates, cement, water, and finally the emulsion [12]. These materials are then mixed in a pugmill and introduced to either a spreader box or a rut-filling box, depending on the intended application of the microsurfacing. Application rate depends primarily on the aggregate type and is controlled via the slurry surfacing machine. For surface courses, applications of up to three layers can be done [12]. Compaction of the final product is possible using one or two passes from a light pneumatic roller [12], [6]. However, not all agencies specify in their guidelines that compaction and rolling is required [8], [41]. Traffic provides much of the compaction of microsurfacing.

2.5.5 Performance testing. As mentioned previously, microsurfacing mix design, application, and performance guidelines are largely influenced by guidelines provided by the ISSA in A143. The performance testing typically employed by state highway agencies follows the recommended testing available in this manual which include tests for potential distresses of microsurfacing such as bleeding (TB109), compaction under traffic (lateral displacement) (TB147), aggregate loss (TB100), and moisture susceptibility (TB114) [42]. These performance tests appear to equate with distresses and problems microsurfacing faces in the field such as raveling, surface wear, stripping, and flushing [7]. However, cracking performance is often times not evaluated under SHA and ISSA specifications and guidelines despite the fact that cracking is one of the most commonly reported problems that microsurfacing faces [7] [46].

2.6 Current State of Material Testing of Pavement Preservation Materials

Laboratory testing is an important part in the design and application of the various materials used in the transportation system. Combining laboratory testing and field data can contribute to a robust and efficient system when applied to a pavement preservation program. Currently, however, there are few examples of specific mixture performance testing for pavement preservation treatments. Determining performance in the laboratory offers knowledge into which materials offer potentially better resistance to common distresses in the field such as rutting and cracking.

2.6.1 Need for performance testing. While there have been many studies into the performance and design of high performance thin overlays based on both laboratory and field performance, the same efforts are lacking for chip seals and microsurfacing mixtures. Despite this lack of laboratory research on performance measures of pavement preservation treatments, theoretical development of performance based specifications has not gone ignored. Chatti et al., (2017) [47] presented extensive information in the NCHRP Report 857 on how pavement preservation performance-related specification (PRS) should be developed. The authors stressed the importance of using acceptance quality characteristics (AQC) based on attributes specific to the preservation treatments and relating the performance to develop a PRS. Examples of microsurface attributes that are capable of developing PRS could be: texture, cracking, rutting, raveling, and bleeding [47]. One example the authors established is a PRS for not only chip sealing, based on aggregate-binder bonding and aggregate loss using the Vialit test, but also raveling, stripping, bleeding, and flushing [47]. Thin overlay performance can be evaluated in terms of cracking, rutting, and surface roughness, while microsurface performance can be

evaluated based on cracking, rutting, bleeding and stripping [47]. With this approach, a critical performance attribute of the pavement preservation treatment can be used to create specifications to determine acceptable limits and design criteria for the use of pavement preservation treatments [47].

2.6.2 Laboratory performance testing and effects on design. Currently, laboratory testing into treatments such as High Performance Thin Overlay (HPTO), an HMA layer, is most common likely due to its similarity in components and application when compared to traditional HMA mixes. A common test to evaluate the reflective cracking performance of HPTO layers is the Texas Overlay Tester. This test was developed in the 1970s for the evaluation of reflective cracking of HMA overlays, then updated in the 2000s to allow for use of smaller samples [48], [49]. In the case of TxDOT, overlays such as HPTO present less concern in the area of fatigue cracking, whereas reflective cracking pose the highest threat [49]. This makes tests such as the Texas Overlay Tester ideal when evaluating materials applied to existing surfaces which is the case for almost all pavement preservation treatments. For many thin HMA overlay applications, the other test often employed is the Hamburg rutting test. These two tests combined have been used extensively to design and compare performance of various thin overlays.

Scullion et al. developed a Crack Attenuated Mix (CAM) used as a thin surface overlay for maintenance and preservation methods [50]. The mix design for this material made use of both the Hamburg and Texas Overlay testing. These authors note that a lot of thin overlays are proprietary in nature and therefore there is a lack of literature regarding the testing used to develop these overlays. This has resulted in a gap in design methods.

The use of laboratory testing to standardize expected performance of mixtures for use in the field is a big step in improving the quality of pavement preservation treatments. The specifications laid out for performance of CAM mixes was further applied to Hot-Mix Cold-Laid Mix, Limestone Rock Asphalt Mixes, and Fine Grade Mixes [50]. Effects of using various aggregate types and mixes (fine DGM, fine SMA, and find PFC) in thin overlays was evaluated using the Hamburg wheel tracking test, overlay test, Cantabro test, Permeability test, skid and polishing resistance test, and tire pavement noise test [51]. Wilson et al. similarly developed recommendations for specifications for the mix design of thin overlays using these tests along with material standards based on their results. Further, they evaluated slurry overlays, including microsurface, using the Texas Overlay Tester, wet track abrasion, skid and polishing in an attempt to develop mix design specifications based on performance. All mixtures (including microsurfacing) had good performance in the wet-track abrasion test while microsurfacing performed worse than the other mixtures in the pull-off test. Based on the results of their study, the authors suggest further testing is required for data evaluation using the Texas Overlay Tester. Based on full scale evaluation, the observations suggested that while microsurfacing does show some resistance to reflective cracking, the treatments still fared worse than other mixes evaluated. The authors suggested further studies be conducted regarding these testing types on slurry-based overlays [51].

Mogawer et al. (2014) [52] conducted a study to develop and improve the design of high performance thin overlay for the Minnesota, New Hampshire, and Vermont department of transportations. This was done by using various performance tests used in asphalt performance testing such as the Texas Overlay Tester, Bending Beam Fatigue,

Semi Circular Bend, and Thermal Cracking Test (TRSST) and comparing to available mixes used by the mentioned SHAs. While no improvements for the specifications of the OT test could be made, specification changes for the beam tests were recommended to better represent field conditions. The team also suggested the use of additional testing such as the Semi Circular Bend test as part of the specifications for HPTO design.

While traditional hot mix treatments offer the possibility to easily implement existing asphalt laboratory tests to evaluate performance, there is a growing interest in laboratory evaluation of treatments such as chip seal and microsurfacing as well. A long-term study focusing on emulsion grading for binders used in chip seal and microsurface has been conducted and covered in NCHRP Report 837 [7]. The basis of this study was to correlate performance and binder grading. Grading of these materials will be correlated and validated using full scale construction of sections using the same materials. In order to do so, Kim et al., (2017) [7] identified primary distresses and performance measures for both chip seal and microsurfacing. For chip seal, the primary distresses are raveling, bleeding, cracking, stripping, and rutting [7]. For microsurface the primary distresses were identified to be cracking, raveling, bleeding, and rutting [7]. Kim et al., (2017) [7], then chose a wide range of emulsion types to use in the fabrication of chip seal and microsurface samples. To test chip seal performance, the team used the third scale model mobile load simulator (MMLS3) to evaluate as raveling (aggregate retention), mean profile depth (roughness), bleeding, and rutting. Additionally, the Vialit test, in which the surface of the treatment is struck with a metal sphere, was employed to measure aggregate retention. For microsurfacing, the authors used the wet track abrasion test to evaluate stripping potential, the MMLS3 was used to evaluate rutting and bleeding

potential, while the sand frame test and a glossometer were used to further evaluate bleeding. On the other hand, the locked wheel skid tester and British pendulum test were used to evaluate skid resistance, while the single edge notched bend test was used to evaluate thermal cracking. These performance tests were then compared to the rheological properties of the binders in an attempt to create performance grading criteria for the emulsion. The team found that chip seal aggregate loss and fracture energy of microsurface showed relationships to the dynamic shear modulus of the emulsion.

In addition to the use of performance tests to develop required specifications, laboratory studies have also been used to directly evaluate the performance of microsurfacing mixtures. In particular, evaluation of the cracking resistance of microsurfacing mixtures reinforced with fibers has been conducted in various countries using a variety cracking tests [53] [54]. Luo et al. (2019) evaluated the low temperature cracking performance using a universal tensile loading test of fiber reinforced microsurfacing mixtures at a dosage rate of between 0.10% and 0.20% by weight of aggregates. Cracking was evaluated through the use of a composite sample of microsurface added to a plate specimen. The team concluded that the use of fibers could be used to improve the low temperature cracking resistance of microsurfacing mixtures, with polypropylene showing the largest benefit. Jeffrey-Wright et al (2013) evaluated the tensile properties of glass fiber reinforced microsurface mixtures using a variety of laboratory tests including the ISSA TB146, a universal tensile test, AG:PT/T232 for tensile splitting strength, AG:PT/T233 for repeated tensile loading, and AS 2891.13.1 for resilient modulus. The team found that the fiber reinforced mixtures showed improvements over the control in all cases.

2.6.3 Full scale evaluation and effects on design. The Minnesota Department of Transportation (MnDOT) took the opportunity to evaluate performance of pavement preservation treatments on a stretch of the Minnesota Road Research Project mainline that was due for reconstruction. The ability for slurry seals and microsurfacing to reduce transverse cracking, top down cracking, and rutting was under prestressed conditions and was evaluated full scale on 500 ft. sections. Data was recorded over a three year span and included cracking observation, rutting, and IRI. In this project, the double seals without any crack sealing showed the best results in reducing transverse cracking while single and double slurry seals with crack sealing performed slightly worse. Sections receiving single layers of microsurfacing showed an increase in transverse crack severity [55]. A single layer of microsurfacing with crack repair and double microsurfacing layers performed best in reducing reflective top down cracking. Microsurfacing is also effective at filling in ruts [55]. The addition of microsurface kept most test sections below hazardous rutting levels [55]. The sections applied with microsurfacing required a second layer a year after data collection due to reflective cracking and ride quality issues [55]. Further evaluation by MnDOT has explored the various mix designs and materials used in microsurfacing [43]. The authors referenced the fact that its rut filling capabilities and relative stiffness are what tend to cause cracking issues, which in turn cause a perception that microsurfacing is an ineffective pavement preservation treatment. The conclusions of Cole and Geib, 2016, based on field inspection led to changes in their recommended mix design to softer base binders and increasing the low end of the quantity of emulsion in mixes.

The types of laboratory testing of pavement preservation materials are largely dependent on the distresses associated with each treatment. Chip seal issues are largely binder related such as bleeding and flushing. There have been serious considerations into the design and specifications for high performance thin overlays based on rutting and cracking performance. While it has been shown that work has been conducted on microsurfacing mixtures using laboratory tests and field observations, it is clear that there is a lot of room and interest in improving the cracking performance of microsurfacing. Attempts and recommendations for evaluating the cracking performance of microsurfacing have been a clear commonality in evaluations for specifications of microsurfacing as it is one of the major issues facing this treatment [43]. Therefore, continued evaluation of cracking performance of microsurface mixtures is both warranted and needed and would be of great interest to the engineering community.

2.7 Conclusion

Pavement preservation is a strong tool for extending pavement service life and avoiding costly reconstruction. The varied types of pavement preservation show just how many problems roadway systems face. While there have been comparisons of the various treatment types using LTPP SPS-3 data, laboratory testing can still use improvements to further understand how these treatments perform.

Performance and optimal timing applications are important factors in the way pavement preservation improves roadway durability and life. There has been little insight from a laboratory perspective in how pavement preservation materials can improve roadway systems or improve the mixtures themselves from a cracking perspective. This is despite the fact that cracking is currently one of the greatest challenges facing

pavement preservation treatments such as microsurfacing. It is one of the deciding factors in when to apply the treatment to roadways as can be seen in many SHA manuals and guidelines for pavement preservation application.

While testing on microsurfacing has been conducted using laboratory asphalt testing as it relates to cracking, these tests are few. This is despite the fact that microsurfacing is one of the most common pavement preservation treatments [3], [4]. Microsurfacing is a versatile pavement preservation treatment type and its ability to address raveling, oxidation, minor cracking, and surface irregularities likely contributes to its widespread use. It is therefore imperative that further testing is conducted on microsurfacing. One of the most common distress types that microsurface currently faces is cracking [47], [7]. However, cracking performance tests are still not included in specifications for designing microsurfacing mixtures. The wide availability of cracking tests used in laboratory testing for asphalt performance offer a great starting point to begin evaluating the optimal timing of application and cracking performance of various microsurface mixtures. In addition, the development and use of polymer and fibers in HMA mixtures offer an opportunity to apply these technologies to improving microsurfacing cracking performance [56] [57]. In doing so, perceived and recorded failures in cracking may be mitigated in the future, and thus, enhance its performance and overall acceptance.

Chapter 3

Optimal Timing Laboratory Testing

One of the most widely studied and evaluated aspects of pavement preservation treatments is determining the optimal timing for application of various pavement preservation treatments [2] [9] [10] [11] [39]. The data provided for these studies typically comes from the LTPP SPS-3 which contains performance data of many different pavement preservation treatments. In addition, some state agencies have dedicated programs to treatments such as microsurfacing and chip seal [23]. This amount of experience and information informs industry decisions. Many guidelines and manuals created by state highway agencies offer decision making tools that provide engineers and contractors with acceptable roadway conditions on which to place specific pavement preservation treatments. An example of a decision making matrix can be seen in Figure 7. As it pertains to cracking, optimal timing in these cases is typically based on the cracking type and severity of cracking. These guidelines provide the expected performance of the pavement preservation treatment based on the pre-existing roadway cracking conditions.

The quantity of knowledge available pertaining to optimal timing for application of pavement preservation treatments makes this topic crucial to any pavement preservation study. It is clearly a vital piece in the overall understanding and best practices of pavement preservation. Therefore, in order to evaluate the cracking performance of microsurfacing mixtures, inclusion of and development of a laboratory test for the optimal timing was deemed necessary. The following sections describe the experimental plan, materials, sample fabrication, and data analysis.

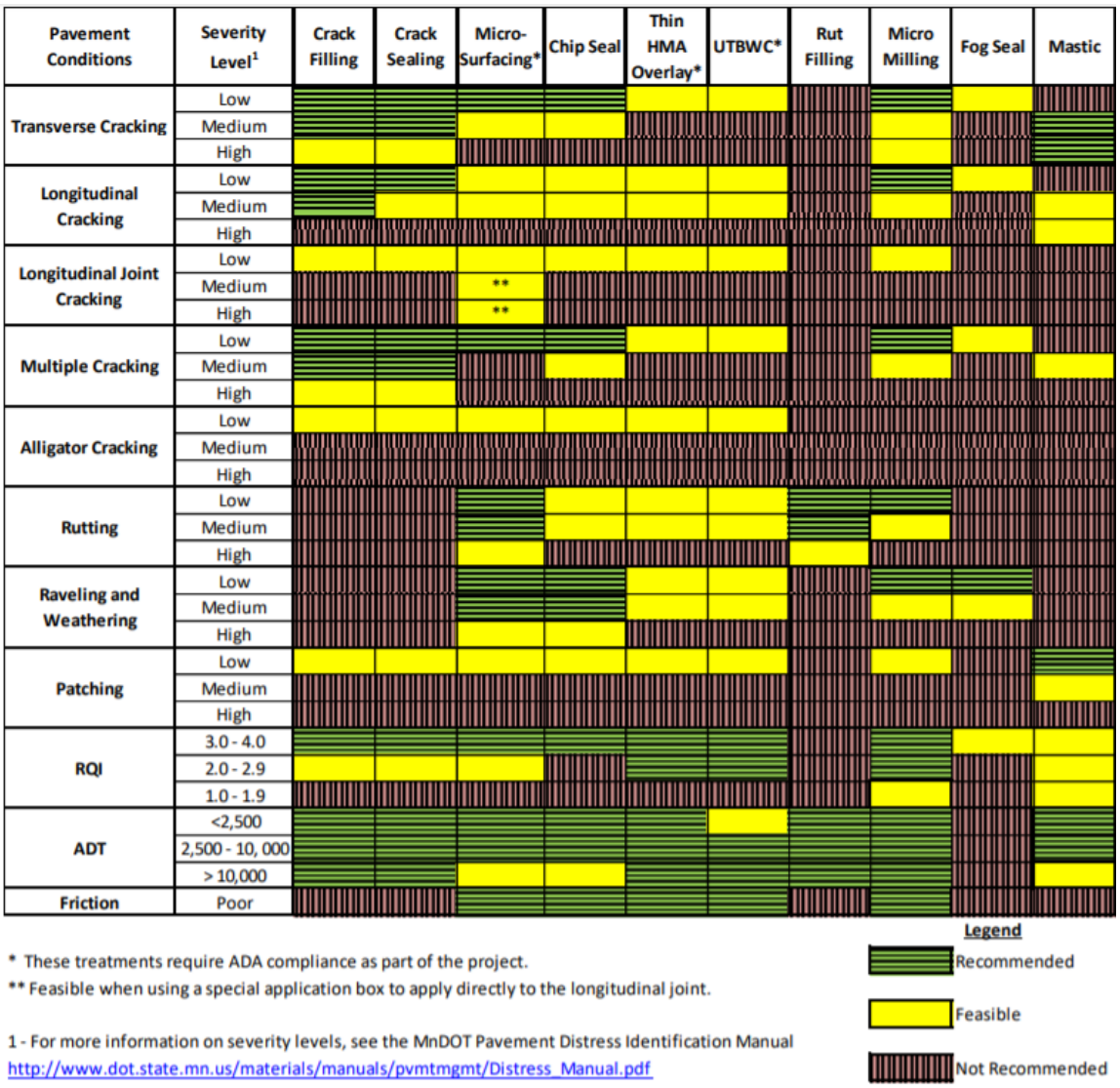

Figure 7. Decision matrix for pavement preservation treatments [41]

3.1 Experimental Plan

In order to evaluate optimal timing of pavement preservation treatments, two common materials were chosen. Microsurface, which is the focus of this study, was chosen because it is one of the most common treatment types and available information on expected performance is widely available. This would allow the cross reference of data obtained from laboratory testing with expected microsurface performance based on

available decision matrices. In addition, chip seal was chosen as it is also one of the most common treatments used. It also presents a different type of material with different practical uses when compared to microsurfacing and would offer insight into how asphalt laboratory tests may interact with different types of materials. The test set up required examination of tests, pavement preservation mix design and application in the field, and expected outcomes based on state highway agency manuals.

3.1.1 Materials. First, the material types for the treatments needed to be narrowed down. For reference on material types and quantities, FHWA and NJDOT manuals for roadway and bridge construction were used as a basis for application rates and material types. Table 3 and Table 4 represent the specified ranges and chosen quantities to use in this study. All materials were provided by local contractors. The chosen quantities aimed to represent the middle of the specifications from the NJDOT and FHWA recommendations, and application rates were converted for the surface areas of the asphalt samples used in this study.

Table 3

Microsurfacing Application Rates

Microsurface							
	Tack Coat	**Aggregates**	**Cement**	**Emulsion**	**Residual Asphalt**	**Water**	**Mixture**
Application Rate*	0.1 gal/yd^2	N/A	0% to 3% by weight of aggregates	N/A	5.5% to 11.5% by dry weight of aggregates	As Required	22 lb/yd^2
Quantity Applied to Sample	4.94 g	106.87 g	1.60 g	13.36 g	8.36 g	8.55 g	130.38 g

Table 4

Chip Seal Application Rates

Chip Seal			
	Tack Coat	**Aggregates**	**Emulsion**
Application Rate	0.1 gal/yd^2	21 lb/yd^2	0.35 gal/yd^2
Quantity Applied to Sample	4.94 g	124.37 g	17.29 g

3.1.2 Laboratory test: Texas Overlay Tester. As the dominant cracking mechanism experienced by pavement preservation treatments would be reflective cracking (as the material would be applied over potentially existing cracks present in the roadway), the Texas Overlay Tester was determined to be the most representative test. The Texas Overlay Tester is a cyclic loading test designed to evaluate reflective cracking [58]. Existing asphalt samples that have been epoxied to two plates are displaced to a controlled distance (typically 0.635mm) and then returned to the original starting position. The peak load is recorded during each cycle and the test is continued until the load recorded has dropped by 93% of the peak load of the first cycle which typically corresponds with full crack propagation [58]. Figure 8 shows a sample in the Texas Overlay Tester setup.

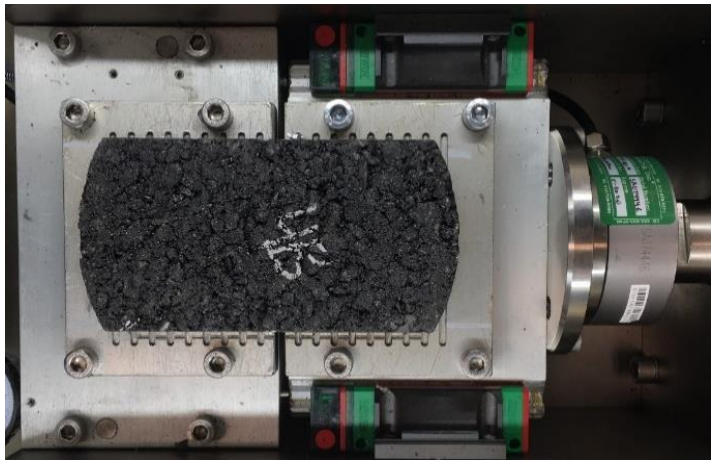

Figure 8. Texas Overlay Tester setup.

The choice to use this test was due to the fact that the crack propagation through the sample allows applied pavement preservation treatments on the top surface of the asphalt samples to experience crack propagation from the existing material. However, one primary modification was made to the testing standards: target displacement was set to 0.3mm. It was found during testing that the standard displacement caused the pre-notched samples to fully propagate in the first cycle. In addition, the displacement actuator would rapidly push the sample back together once the fully propagated crack had formed before continuing the displacement cycle. It was found that the displacement of 0.3 mm provided adequate cycles for the crack to propagate in all samples without erratic actuator responses. In a study conducted to improve OT testing and sensitivity, Walubita et al. (2012) used varying degrees of displacements and found that reducing displacement does not greatly affect variability of the results [58].

In order to determine the optimal timing for applying different pavement preservation treatments, samples to which the treatment was applied to were left without a distress (the control representing good pavement conditions), notched to a width of 3mm (low severity cracking) or notched to a width of 6mm (medium severity cracking). This would represent a roadway that had undergone varying levels of cracking and the performances of treated and untreated samples could be compared.

3.1.3 Sample production and materials. Sample production for this test was conducted in a way to simulate, as closely as possible, the application methods used in the field. Modified compacted asphalt samples were prepared to the specifications required for the Texas Overlay Tester and pavement preservation treatments were applied to the surface using the aid of 3D printed molds. These 3D molds were created to ensure the material applied to the surface of the sample was contained to the sample and did not flow over the sides. This is due to the fact that the emulsion binders have a low viscosity. Five samples per treatment (control [untreated], chip seal, and microsurface) were produced for each of the distress levels (no cracking, 3mm crack width, 6mm crack width) for a total of forty-five samples. The following describes the materials and production of these samples.

3.1.3.1 Asphalt sample: For this portion of the study, the hot mix asphalt used was an unmodified PG 64-22 binder with a 9.5 mm Nominal Maximum Aggregate Size provided by a local supplier. This would represent the roadway material on which the pavement preservation treatments were applied. The material was heated and compacted to a height of 150mm using the Superpave Gyratory Compactor.

The dimensions of the final compacted samples following NJDOT-B-10 specifications are 150mm x 76mm x 38mm +/- 0.5mm. Typical Texas Overlay Tester samples using NJDOT-B-10 are cut from the center of the core which result in samples that have smooth surfaces. For the purposes of this study, the final trimmed samples were slightly modified. The samples in this study were cut using the material from the top and bottom of asphalt samples compacted in a Superpave Gyratory Compactor. This helped to better simulate the surface texture of a roadway for purposes of applying pavement preservation materials to the samples. The aim of this modification was to simulate as close as possible the application of pavement preservation materials to existing roadways. The air voids of the final cut samples was 7 % +/- 1% air voids as per the specifications. The base asphalt OT sample thickness was not altered for any of the pavement preservation treatments for consistency and was kept at 38mm +/- 0.5mm.

Notching of the samples was conducted to simulate existing roadway cracking. The best method to introduce cracks was by notching using a saw. In this way, crack width could be controlled and standardized between samples. While it is possible to crack material using the Overlay Tester, variabilities between how the sample cracks makes it difficult to have a consistent representation of a crack from one sample to another. In addition, sample production and application of pavement preservation material would be difficulty on samples with fully propagated cracks. Initial testing of the notched samples determined that the cracking does propagate to the artificially placed notches, which allows the subsequent tensile loading to be applied to the pavement preservation treatments on the surface. A notched Texas Overlay sample can be seen in Figure 9**.**

Figure 9. Notched asphalt sample.

In order to apply the pavement preservation treatments, a 3D printed plastic mold was used to encase the OT sample and prevent the treatments from flowing off the surface. A silicone based water sealant was used around the edges of the OT sample to ensure the emulsion based treatments were contained to the surface of the asphalt. Additional silicone sealant was placed down the corners of the sample as this was found to be a frequent point of leaking. The mold was then placed around the sample and clamped from the rounded ends of the sample to lock the mold. A tack coat was then applied to the surface of the asphalt sample as per the requirements from the FHWA and NJDOT construction guidelines for microsurfacing and chip seal. Tack coat is applied to the surface at a rate of 0.10 gal/yd^2 (which equates to approximately 8g of tack coat for the surface area of the sample) and spread using a small spatula to ensure the entire surface of the sample was covered. It was found that applying the tack coat in three separate columns and spreading from these starting locations produced the most even application of the tack coat. Spraying the tack coat using a spray bottle was attempted; however it was found that the spray bottle would clog. Asphalt samples encased in molding and with tack coat applied can be seen in Figure 10A and Figure 10B.

A) 

B) 

Figure 10. Texas Overlay Tester in 3D Printed Mold. A) 3D Mold Surrounding OT Sample B) Tack Coat Applied

3.1.3.2 Chip seal. In practice, chip seal is applied by first laying down either hot or emulsified binder and then rolling aggregates into the binder. The chip seal materials used in this study were a 1/4 in. chip seal aggregate provided by a local contractor and a polymer modified CRS-2 quick set chip seal emulsion binder was used.

Once the tack coat applied to the asphalt sample had become tacky to the touch, the chip seal emulsion binder was poured on the surface and spread using a spatula. A spray bottle was attempted to be used for the emulsion; however, it was found that this emulsion clogged the spray bottle. The aggregates were then prepared by wetting the aggregates with

2% water by weight of aggregates and then hand-mixing for 30 seconds. The aggregates are immediately added to the surface by evenly dispersing the aggregates across the entire surface of the sample.

The aggregates were rolled into the emulsion using a PVC pipe that had been cut to a length of 76mm and coated with three layers of duct tape to prevent cracking of aggregates. The duct tape was wetted to reduce the adhesion of binder to the roller. The goal of rolling was to embed the aggregates and produce a flat surface. Rolling aligned the aggregates in a manner that the surface of the samples had flat and level surfaces as seen in Figure 11. A ten-pound weight was used on top of the PVC pipe to keep the rolling procedure consistent from sample to sample. This weight was found to be sufficient to embed the aggregates and produce a well aligned aggregate surface.

Figure 11. OT Sample with chip seal applied. A) Chip Seal in Mold B) Level Chip Seal Surface

The sample was then cured to allow water to leave the emulsified binder. Originally 65^{o}C was used for curing, however it was found that the emulsion would become viscous. In addition, it was found that at 65^{o}C, the molds would begin to warp and become soft. The sample was cured at 35^{o}C for 24 hours inside the molds.

For cracked samples, the application procedure is the same with the exception of the pouring of the emulsions. The emulsion was poured into four columns, two on either side of the crack and then spread using a spatula. Emulsion was also spread into the notched portion of the sample.

3.1.3.3. Microsurface. In this study, the microsurfacing mixture included a quick setting highly-polymer-modified emulsion binder (CQS-1hp), type I/II Portland cement as a mineral filler, water, and Type II microsurfacing aggregates. The residual binder after distillation of the emulsion was 66.9%. The mix design for this material was produced in the lab using 1.5% mineral filler by weight of aggregates, 12.5% emulsion binder by weight of aggregates, and 8% water. These proportions were used based on the NJDOT standard specifications [6] for microsurfacing mix design and recommendations from experienced local material testing laboratories. The water content to reach the consistency for pouring matched recommendations from local laboratories and contractors and resulted in a mixture that was easy to pour into the molds.

After the tack coat applied to the asphalt sample was tacky to the touch, the preparation of the microsurfacing mixture began (approximately one hour). The aggregates and cement were thoroughly mixed together, followed by addition of the water, and further mixing. After mixing of the aggregates, water, and cement the emulsion was poured into the center of the mixture and mixed for 30 seconds. A total of 135g of mixture was

produced to ensure the target quantity of 130.38g of mixture could be poured onto the samples.

The mixture was then poured onto the surface of the asphalt sample. The mixture was spread as evenly as possible to ensure a smooth surface and as little variation from one end of the sample to the other. The sample was then left to cure at room temperature for 24 hours. The silicone was then carefully removed from the sample and mold using a razor blade.

After the silicone was removed, the sample was cured at 65^{o}C for 48 hours. After curing, the sample was ready for testing. The final microsurface sample can be seen in Figure 12.

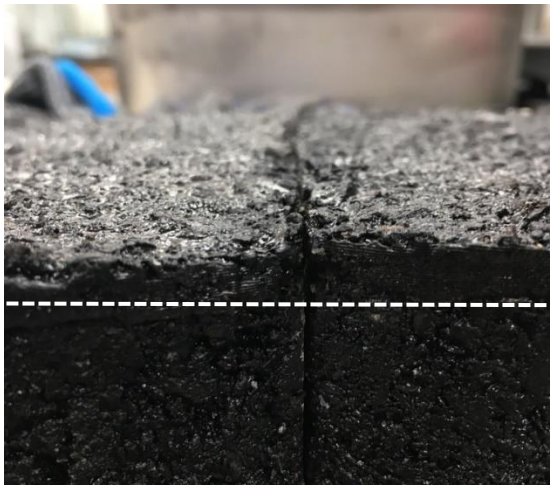

Figure 12. Final microsurface application surface.

3.2 Results and Discussion

The results of the Texas Overlay Tester were used to evaluate the effectiveness of chip seal and microsurfacing at different distress levels. This was conducted to evaluate the optimal timing of the materials and determine the ability of the test to recognize the presence of the pavement preservation material. The primary outcome for the Texas Overlay Tester is the cycles to failure. This was the first way in which the optimal timing for microsurface and chip seal application was evaluated. However, other methods of evaluation have been tested by Walubita et al (2012). In particular, these attempts were set forth to improve repeatability and variance of the results, which are known to be high using the cycles to failure parameter. For purposes of this test, the additional method used was the use of a pseudo-tensile work indicator using the area under the load reduction curve.

3.2.1 Cycles to failure. Cycles to failure was used as the first and primary performance indicator of the pavement preservation treatments at each of the three different distress levels. Five samples were run for each material (control, chip seal, and microsurface) and distress level (no distress, 3mm crack width, 6mm crack width). The number of samples was tested based on Walbuita et al.'s (2012) recommendations of testing five samples and using the three with the lowest coefficient of variance. Results of these tests can be seen in Figure 13**.**

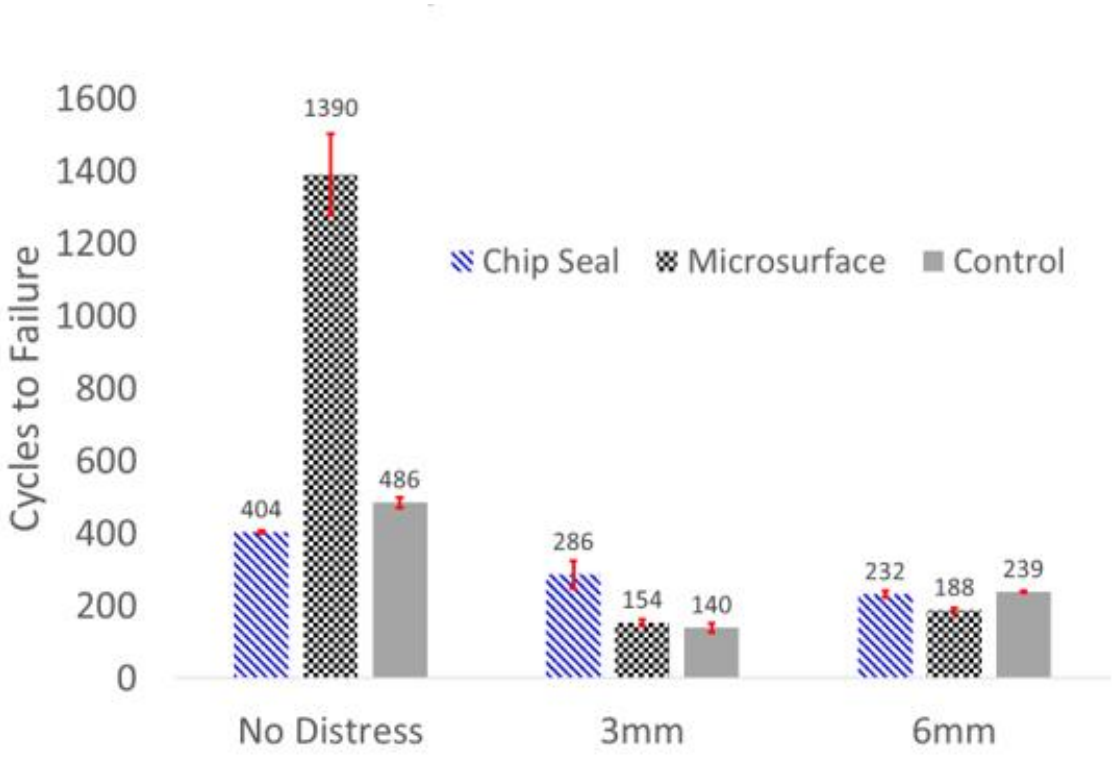

Figure 13. Cycles to failure of Texas Overlay Tester results based on treatment and distress type.

Based the results, it can be seen in cases where the asphalt samples that have no distress and have been treated with microsurfacing have an increase of 244% cycles to failure when compared to the control. This indicates that the test is picking up on the presence of the microsurfacing material on the sample, and that the microsurfacing is reinforcing the asphalt sample in a way that benefits the overall structure. The theorized mechanism at work for the later conclusion is that as the crack propagates to the surface of the original asphalt sample, the load bearing potential of the asphalt decreases (i.e. the load is dropping during each cycle). While the loads recorded early in the test will be primarily due to the asphalt sample, the later loads will be more influenced by the microsurface as the crack reaches closer to the surface of the material and the ability for

the remaining asphalt to resist tensile loading decreases. It is in this zone where the microsurface is likely presenting the highest benefit. This could be due to the stiffness of the microsurface, which would be strong enough to offer some reinforcement during each cycle. On the other hand, it can be seen that chip seal offered no benefit for the undistressed sample when compared to the control. This is likely due to the fact that chip seal is not a cohesive mixture. Due to the failure criteria of the Texas Overlay Tester being determined mostly by the stiffness of the asphalt (which would be much higher than that of the binder), the chip seal layer may not be reinforcing the sample.

For the low severity cracking (3mm width crack), only the chip seal showed improvement to the cycles to failure. This may be due to the fact that the binder is laid first, which effectively enters, coats, and seals the crack which help bond the two asphalt interfaces during the displacement from the cyclic loading. The microsurface, on the other hand, has both binder and aggregate entering the crack which provides less bonding than the chip seal. When cross sections of the samples were taken, it was seen that only binder entered the crack for the chip seal, validating the hypothesis. The cross-section of the microsurface showed that aggregates and binder (i.e. the mix) entered the crack. This theory was compared to evidence and results of the medium severity cracking (6mm width crack). Neither chip seal or microsurface improve upon the cycles to failure when compared to the control. Cross sections of the chip seal sample showed that the aggregates and binder both entered the crack (i.e. due to the fact that the crack was wider). This would, in turn, act more like the microsurfacing and offer less bonding with the sides of the crack due to the presence of the aggregates instead of pure binder.

3.2.2 Area under the load displacement curve. While cycles to failure is a traditional method of evaluating the performance of samples using the Texas Overlay Tester, it can often present outcomes that are highly variable. As mentioned above, the samples used to evaluate cycles to failure were the three samples of each category that presented the lowest coefficient of variance. The high coefficient of variance between samples that is produced by using this method of evaluation has led to alternative methods of analyzing the data produced from this test [58]. Due to the low thickness of both microsurface and chip seal, an alternative method for isolating the performance of these treatments was warranted. In particular, the case of chip seal control samples and distressed samples show a lack of performance enhancements.

Therefore, an alternative analysis method for this study to further understand the cracking performance of these pavement preservation materials when applied to distressed asphalt samples was introduced. To do this, evaluation of the tensile work performed on each sample to cause failure was investigated. In this case, the area underneath of the cyclic load reduction curve was determined using the trapezoidal method. This effectively shows the area under the load reduction curve. These values were then divided by the cross sectional area of each sample to account for the increased cross sectional areas of the treated samples. Higher tensile work indicates better performance. Figure 14 shows the results of this evaluation. In this case, all samples are taken into consideration.

The results seen in Figure 14 show that in conditions with no distress, both microsurface and chip seal outperform the control. This is in contrast to the results using cycles to failure as the performance indicator. These values indicate that the addition of

pavement preservation to the samples increases the work required to fail the sample, and therefore that the treatments are performing in a way that increases the cracking resistance of the overall sample. In this case, microsurface performs better than the chip seal. This is likely due to the mixture being a more homogenous and an overall stiffer material.

Under the 3mm crack width condition, microsurface can be seen to outperform the control and chip seal slightly outperforms the control. Based on these results, the application of microsurface to roadways experiencing low cracking levels will resist the full propagation of the existing crack to the surface of the pavement for a time. Chip seal only slightly improves cracking performance in this case. In fact the 95% confidence level of chip seal in this case shows the improvement may overshadow any effects the chip seal has on the sample.

In regards to the 6mm width cracking condition, neither sample outperforms the control, indicating that this cracking width is too extreme for the pavement preservation treatments to show effects on the samples and that based on these results reflective cracking could propagate early in the treatment's life.

While analysis of performance directly compared to the control samples is a traditional approach, the composite nature of these samples could be more complex than the data alludes to. For instance, it can be seen from Figure 14 that the cracking resistance of microsurface and chip seal treated samples decreases with increasing crack severity level. Analysis of microsurface and chip seal performance excluding the controls should also be considered due to the fact that the composite nature of the samples may make it difficult to assess the impacts the pavement preservation materials would have on the

structure of the overall sample. For example, during the curing stage of each sample, the loss of volatiles from the asphalt would stiffen the entire sample. In particular this would affect the top, bottom, and side exposed surfaces of the asphalt. However, the chip seal and microsurface would effectively seal the top surface portion of the asphalt. This could cause a difference in the stiffness of the asphalt where the bottom portion of the sample (pure asphalt) is stiffer than the surface. The failure criteria of the test is determined by the initial cycle's peak load, which will be largely determined by the stiffness of the lower portion of the asphalt. However, as the crack propagates from the bottom of the sample towards the top of the sample, the crack will eventually reach a region of the sample where the material is less stiff than the bottom of the sample (due to the protective nature of the pavement preservation treatment). If this region has been protected from aging during curing due to the application of a pavement preservation treatment, then this could be affecting the overall composition of the asphalt portion of the sample. This concept is particularly compelling when considering the relatively soft nature and thin lift of a chip seal compared to the asphalt. The existence of such a soft material would offer very little value in reinforcement of the asphalt base. The protective nature of the material when it comes to aging of the asphalt, however, and the increased work required to fail the samples could be an indicator of the ability of these materials to combat aging in addition to their cracking resistance capabilities.

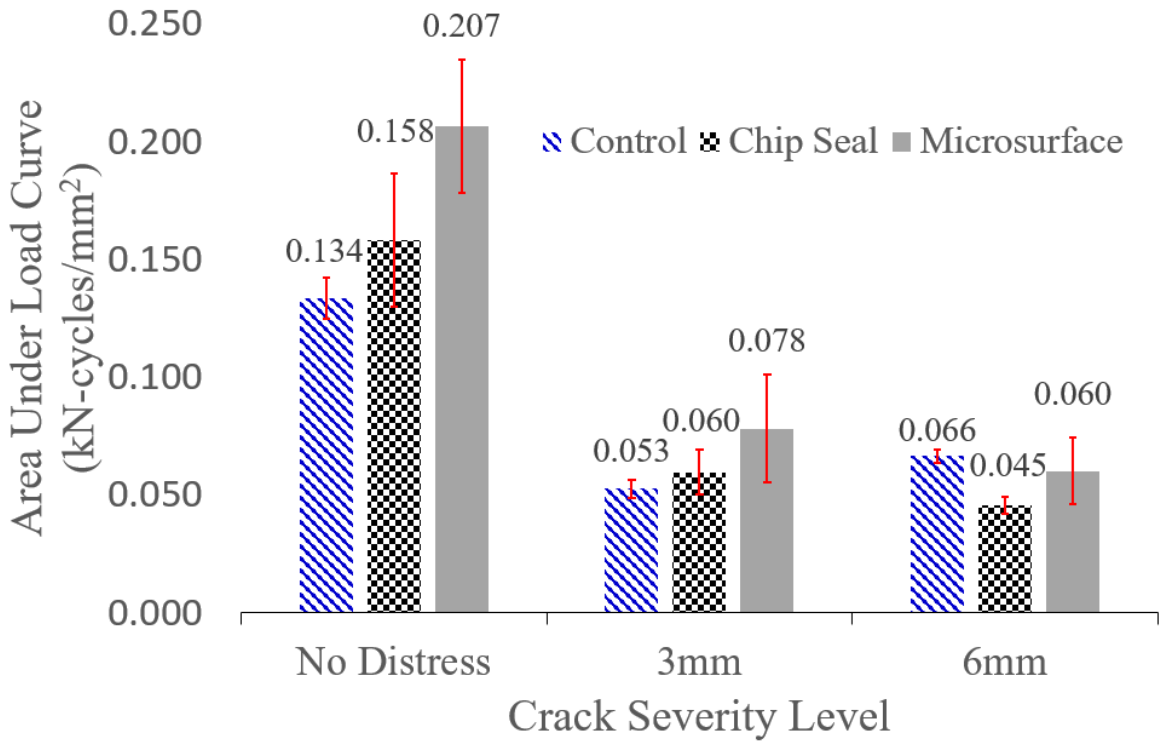

Figure 14. Area under load reduction curve to identify optimal timing.

3.3 Conclusion

Based on the results of this test it would appear that the Texas Overlay Tester can be used to evaluate certain pavement preservation treatments. In particular, the microsurface applied to undistressed samples showed the greatest performance in both cycles to failure and area under the load reduction curve. In addition, using the area under the load reduction curve showed promising signs of this test set up validating current practice in application of treatments such as chip seal and microsurfacing to roadways in good condition in terms of cracking. However, the lack of knowledge into the way composite materials perform in the Texas Overly Tester present some interesting caveats to analysis of the data. Comparison to a control may not be the best way to evaluate the optimal timing for use of the pavement preservation treatments. To factor out the

different effects each treatment may have on the overall structure of the asphalt sample, comparison within a treatment type across distress levels may be the best course of action. In this case, a diminishing performance was seen with increasing crack width. In the parameters of this study, this test only evaluated optimal timing based on cracking. Future studies could evaluate these based on rutting, aging, raveling, etc.

The results and analysis of this optimal timing study have been submitted for potential journal publication and were part of a project funded by the University Transportation Council. This test and set up paved the way for further microsurfacing testing as part of this thesis, namely seeking improvements to cracking performance of microsurfacing mixtures. This study helped determine that laboratory tests have potential for evaluating other performance mechanisms for microsurfacing. It provided in depth knowledge into how to produce microsurface mixtures in the laboratory that accurately represent the mixture in the field. As cracking is currently one of the largest problems facing microsurface, evaluation into improving cracking performance of microsurface mixture is a logical next step.

Chapter 4

Description of Materials Used for Microsurfacing Samples

Microsurfacing mixtures exist in different forms based on region and agency, though in general are used for both rut filling and surface courses. In the next portion of this study, a base microsurface mixture designed for surface courses was used. The aggregates used were of the Type II gradation which consisted of fully crushed stone and stone sand. Portland cement Type I/II was used as the mineral filler and mixed into the Type II aggregates. Water was added after mixing of the aggregates and cement to pre-wet the aggregate mixture and help increase mixability and lower the viscosity of the final mixture. For the binder, a polymer modified CQS-1h emulsion was used. Two different emulsions based on polymer content were used. The polymer quantities of 3% and 6% were calculated based on the weight of the residual binder content of the emulsion. The polymer (a synthetic rubber latex [SBR]) was provided by the emulsion supplier and mixed with the emulsion in the lab. While 3% is the minimum requirement based on SHA specifications [6], the upper range of 6% polymer was chosen based on studies evaluating effects of polymer on binder performance and recommendations from local contractors [44], [59]. In addition, glass fibers were used in two of the four mixtures to evaluate the potential to improve cracking performance. While glass fibers are not part of the mix design of microsurfacing, there has been interest in its use in microsurfacing [56]. Typically, fibers have been used successfully to improve cracking characteristics of asphalt in laboratory testing for both intermediate and low temperature cracking [60], [61]. It was therefore determined that there is potential to increase the cracking resistance of microsurfacing.

The following sections describe in detail the characteristics of the materials used in this study. The mix proportions used were based on the New Jersey Department of Transportation Updated Standard Specifications for Road and Bridge Construction 2007 microsurfacing mix design. ISSA and NJDOT mix design specifications along with the mix design used in this study can be seen in Table 5.

Table 5

NJDOT Mixture Design Specifications and Study Mixture Design

Application Rates Based on Guidelines and Specifications						
Mixture Type	Aggregates	Emulsion	Water	Mineral Filler	Fiber	Polymer
ISSA A143	Type II or Type III	CQS-1h (5.5% to 10.5% residual asphalt)	As needed for consistency	0.0% to 3.0%	N/A	3% minimum
NJDOT	Type II or Type III	CQS-1h (5.5% to 11.5% residual asphalt)	As needed for consistency	0.0% to 3.0%	N/A	3% minimum
Study	Type II	CQS-1h (8.5% residual asphalt)	6% by dry wt. of agg.	Type I/II Cement (1.5% by dry wt. of agg.)	Glass Fibers 0.3% by dry wt. of agg.	SBR
Quantities Use in Study						
Mixture Type	Aggregates	Emulsion	Water	Mineral Filler	Fiber	Polymer
Control	2300g	292.3g	138g	34.5g	N/A	3% wt. polymer by wt. asphalt
Fiber Reinforced (3%WF)	2300g	292.3g	138g	34.5g	7g	3% wt. polymer by wt. asphalt
Polymer Enhanced (6%NF)	2300g	292.3g	138g	34.5g	N/A	6% wt. polymer by wt. asphalt
Fiber Reinforced and Polymer Enhanced (6%WF)	2300g	292.3g	138g	34.5g	7g	6% wt. polymer by wt. asphalt

4.1 Aggregates

In this study, Type II microsurfacing aggregates were used for the mixture which can be seen in Figure 15. NJDOT specifies that microsurfacing aggregates must be manufactured stone sand and crushed stone. The aggregates were obtained from a local supplier that provides these materials for microsurfacing projects in New Jersey. As the materials and testing were conducted using New Jersey materials, application rates, and mix design, the New Jersey Department of Transportation Updated Standard Specifications for Road and Bridge Construction 2007 was used to ensure the material gradation fell within the acceptable limits. To ensure the materials obtained followed the Type II (and not Type III) gradation, wet and dry sieving in accordance with AASHTO T 11 and AASHTO T 27 was performed. The gradation used in this project along with the specification limits can be seen in Figure 16.

Figure 15. Type II microsurfacing aggregates (largest aggregate 9.5mm).

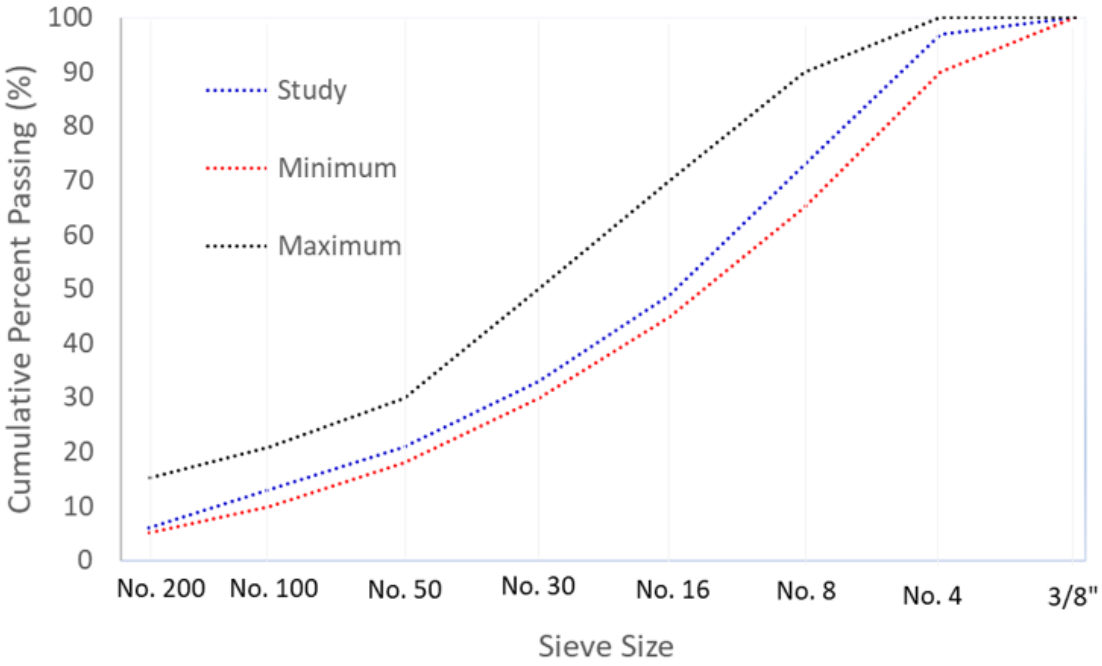

Figure 16. Gradation of type II aggregates.

The gradation of the original aggregate samples received and tested were used as the representative gradation throughout the stud. It was found that the gradation from bag to bag varied which affected the mixability of the final mixture (i.e. the mixture was no longer liquid after two minutes of mixing). This presented problems in pouring the final mixtures into the molds. Therefore, the gradation displayed in Figure 16 was kept constant by adjusting the gradation using sieved microsurfacing aggregates. This ensured consistency between samples when new bags of materials were obtained.

4.2 Binding Agent

In this study, a latex-polymer modified quick setting cationic CQS-1h emulsified asphalt was used. The base binder had a PG grading of 64-22. Two different polymer

quantities were used in this study, 3% and 6% added to the emulsion based on residual asphalt content mass. A synthetic rubber (styrene-butadiene rubber [SBR]) was used in this study and added post milling in the desired quantities in the laboratory. Penetration of the final emulsions was tested to ensure it met the required penetration values of between 40 and 90. The binder residue was recovered after the addition of the SBR using ASTM D7497. Both the 6% polymer and 3% polymer emulsions had average penetration values of 50.9dmm and 51.6dmm respectively. These proportions of polymer are based on the mass of polymer and the mass of the residual asphalt content. The emulsified binder was provided by a local supplier. This material is used in microsurfacing projects in New Jersey and conforms to the same standards in the New Jersey Department of Transportation Updated Standards Specifications for Road and Bridge Construction-2007. The binder was provided in 2-5 gallon quantities as needed. It was ensured that samples prepared for the same performance tests used the same batch of emulsified asphalt. Large obtained quantities were avoided to minimize evaporation and aging of the emulsion from sample to sample. The emulsions were stored in 2L plastic containers and were stirred every other day and before every use.

4.3 Additives-Portland Cement

A type I/II Portland cement was used in the microsurfacing mixture. The percentage seen in Table 5 was based on the dry weight of aggregates. The cement was mixed in with the aggregates prior to the addition of water to the mixture. This ensured the cement would not clump and follows the process order when microsurfacing is mixed in the application equipment for field use. The cement aids in stiffening the mixture and also aids in reducing the curing time of the microsurface mixture.

4.4 Additives-Fibers

In this study, some microsurfacing mixtures were reinforced using fiber additives. While polypropylene and other fiber types have been researched in other countries [53], alkali resistant fibers are used in microsurfacing in the United States of America. The alkali resistance of glass fibers makes them compatible and unreactive when added to asphalt and have similar specific gravities when compared to aggregates. The fibers used for this study were alkali resistant glass fibers cut to ¼" length as seen in Figure 17. The standard accepted requirements call for an application rate of fibers of between 0.2% and 0.4% by dry weight of aggregates. In this study, the amount of fibers used in the mixtures was 0.3% of the dry weight of aggregates. Table 6 presents the fiber properties for those used in this study.

Table 6

Alkali Resistant Glass Fiber Properties

Material	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Softening Point (^oC)	Density (kg/m^3)	Property
¼" Pre-chopped glass fibers	1700	72	860	2680	Alkali and acid resistant

Figure 17. ¼" Glass fibers.

4.5 Mixtures

Four separate mixtures were evaluated in this study. These can be seen in Table 7 along with the G_{mm} of each mixture obtained according to AASHTO T 209. The control mixture is based on proportions of the various materials midway in the required mix design found in Table 5**.** It can be seen that the G_{mm} values of the different mixes show a trend, that in both cases the 6% polymer based binder has a higher maximum specific gravity. That is, of the two mixes without fibers, the 6% polymer content sample has a higher G_{mm} than the 3%, and for the fiber samples the 6% polymer content sample had a higher G_{mm}. However, these values are relatively close regardless of the mixture.

The mixing procedures and descriptions are discussed in a separate section. The laboratory cracking performance of three mixes a) 6%-No Fiber [6%NF]; b) 6%-With Fiber [6%WF], and c) 3%-With Fiber [3%WF]) were compared with the control.

Table 7

Mixture Types and Maximum Specific Gravities (G_{mm})

Mix (Polymer Content-Fiber)	Maximum Specific Gravity (G_{mm})
3%-No Fiber (Control)	2.465
3%-With Fiber (3%WF)	2.451
6%-No Fiber (6%NF)	2.478
6%-With Fiber (6%WF)	2.458

Chapter 5

Sample Production and Testing Plan

5.1 Overview of Sample Production

Sample production was based on the tests that would be performed and the desired makeup of the sample and was reliant on several key factors that must be considered.

1. The microsurfacing mixtures and samples are produced in a way that closely represents the field to maintain proper material composition for laboratory testing.
2. The methods for sample fabrication are convenient to produce and consistent in their makeup to reduce variability between samples and allow testing within a reasonable timeframe.
3. The trimming of the samples produces test specimens that have not gone under undue stresses or aging due to the trimming process, storage, or transportation.
4. The tests chosen provide pertinent information to the goals and objectives of the study.

In order to test the ways in which polymer and fibers can be used to improve microsurfacing cracking performance, first a procedure for sample production must be formed. However, there are currently no standardized methods of microsurface sample production for laboratory performance testing using the Texas Overlay Tester or Semi-Circular Bend test. Therefore, the ways in which microsurfacing is mixed and made in the field were used to produce the samples and are described as follows.

5.2 Production of the Mixture

First, it was determined that production of microsurfacing samples should follow as closely as possible the method in which it is produced in the field. The use of a slurry surfacing machine produces the mixture starting with the aggregates, followed in order by the addition of cement, water, and finally the emulsified binder [12]. Therefore the mix in the lab was produced in a similar fashion which is outlined below.

5.2.1 Step 1: Prepare aggregate sample as per design gradation. The aggregates are weighed out in a mixing bowl to the specified quantity for production of the desired test (see testing plan for mixture proportions). These aggregates follow the gradation laid out in Chapter 3. Pouring of aggregates into the mixing bowl must be done gently to reduce the loss of fines in the air. In addition it was found that the aggregate gradation had an impact on the mixability and curing time of the microsurface. It was crucial to control the gradation throughout the process to ensure the final samples were consistent for each round of testing.

5.2.2 Step 2: Add and mix cement to aggregates. The cement was then added to the aggregates using the specified quantity in Chapter 3. The cement and aggregates were thoroughly and mixed by hand for one minute. It was found that due to the fines and cement, mechanical mixing caused too much loss of material to the air. Therefore mechanical mixing for this process is not recommended.

5.2.3 Step 3: Add and mix water to aggregate/cement mixture. The water was then added to the aggregate/cement mixture using the specified quantity in Chapter 3. The addition of water was conducted gently to not disturb the fines in the aggregate/cement mixture. Water was spread over as much of the surface area of the

mixture as possible and concentrating the water in specific locations was avoided. Hand mixing was conducted again to prevent the agitation of fines in the mixture. Thorough mixing was considered complete when dry aggregates and cement could no longer be spotted in the mixture and an additional thirty seconds after.

5.2.4 Step 4: Add emulsion to wet mixture. The emulsion was then added to the mixture using the specified quantity in Chapter 3. The emulsion as added over as much surface area of the aggregate/cement/water mixture as possible. Hand mixing until all aggregates and cement appeared to be covered in emulsion was conducted prior to mechanical mixing (approximately 30 seconds).

5.2.5 Step 5: Add fibers to emulsified mixture. Fiber was added in quantities found in Chapter 3 after thorough hand mixing and after all of the aggregates appeared to be covered in emulsion as described in Step 4. Note that only two of the four mixtures called for the addition of fibers. Half of the fibers were spread over the surface of the mixture and hand mixed, followed by the second half of the fibers and hand mixed (approximately 30 seconds of mixing required).

5.2.6 Step 6: Mix final sample. Final mixing was conducted using a mechanical asphalt stirrer. As mentioned in Step 4, hand mixing was conducted prior to mechanical mixing. This was necessary due to the liquid consistency of the mixture and it was found that without hand mixing, separation occurred and clumping of uncoated aggregates congregated at the bottom of the mixing vessel. Mechanical mixing was conducted for two minutes. It should be noted that a liquid consistency should be maintained after two minutes of mechanical mixing. This was found to be dependent on emulsion quantity, water quantity, and aggregate gradation.

5.3 Sample Production

In the field, microsurface application is conducted by spreading the mixture over the surface of the existing asphalt. While rolling is required in some state highway agency manuals [6] it is not mentioned in all state highway agencies manuals [41], [8] and in some cases is mentioned as not being required at all [62]. In addition, there is little research into the effects that compaction has on the performance of microsurfacing [1]. For this study, production of the samples was conducted by pouring the mixture into customized molds. The pouring and subsequent curing of the samples, rather than compacting to a targeted density, was selected as the most representative way to allow the mixture to behave as microsurfacing would in the field. As the standard Superpave Gyratory Compacted samples is the most common way to produce laboratory specimens for the various available tests, it was determined that the molds used to house the microsurfacing mixture should be of the same dimensions (i.e. a 150mm diameter cylinder). This would allow for the production of microsurfacing samples to be tested in many different asphalt based laboratory tests. In addition, it offered a simple and convenient way to ensure the production of the material is consistent from batch to batch and also consistent for the different tests that would be conducted. The following is the sample production procedure.

5.3.1 Step 1: Mold preparation. First, the molds were placed around an asphalt core cut from a SGC sample to a height of 38mm. The asphalt had silicone placed around its circumference to seal the mold to it. Transparency paper was then placed on the bottom and sides of the mold to prevent the microsurfacing from peeling when the molds are removed. The molds were further sealed with more silicone.

5.3.2 Step 2: Laying of the microsurface mixture. The mixtures were poured into the mold to a height of 70mm. The transparency paper in Step 1 were cut to a height of 70mm. Controlling the height of the sample ensured each mixture was produced and poured into the same volume.

5.3.3 Step 3: Curing. The samples were cured to allow for adequate moisture removal. The first day the samples stayed in the mold at 25^{o}C to allow the material to take the intended shape. The samples were then taken out of their molds and placed in an oven at 60^{o}C for 48 hours. Finally the samples were cured at 25^{o}C for an additional 24 hours prior to trimming.

The 70mm height chosen for the samples allowed for the production of specimens to be used in the intended laboratory tests while still providing sufficient room to trim the surface and bottom portions of the final sample. Curing of the samples took place over four days. Mold preparation and final samples can be seen in Figure 18**.**

A)  B) 

C) 

Figure 18. Sample preparation. A) Molds with transparency paper B) Microsurface poured in mold C) Final sample

Production of long beams was attempted; however it was found that transport of such samples is risky as the material would bend easily, damaging the integrity of the samples for testing. The use of a cylinder allowed for the transport and preparation of the samples without risking damage to the material and structure.

While the choice of molding and dimensions was laboratory based, the choice of how to produce samples with consistent and reliable densities was driven by several factors. First, unlike hot mixed asphalt, the construction of microsurfacing does not consider or control for final density and air voids in the field. In addition, conventional laboratory compaction methods for asphalt are problematic for microsurfacing mixtures. Mixtures of the consistency used in the field have large quantities of water in them and the Superpave Gyratory Compactor forces much of the water out. In addition there is no proper sealing mechanism to keep the water in the molds which allows much of the emulsion to run out of the mold. The forcing of the water out of the microsurface mixture rather than being allowed to cure naturally is problematic as the curing process largely determines bonding of asphalt to aggregates [44]. By forcing the water out of the mixture prior to proper curing, the overall final composition of the mixture is deviated from what would be expected in the field.

Due to these factors, the use of the customized molds without gyratory compaction was determined to be the best method to produce laboratory cured mixtures to represent field mixtures. This method was theorized to not only be more representative of curing in the field, but also avoided damage to laboratory equipment.

5.4 Test Plan

The objective of this study is to evaluate how the addition of and increased dosage of specific materials (fiber and polymers) to enhance asphalt cracking performance can be applied to improving the cracking resistance of microsurfacing mixtures. This study does not seek to change the current State Highway Agency guidelines on mix design of microsurfacing. Instead, the use of these limitations is employed and not deviated from.

The scope of this study only encompasses a comparison of the cracking performance of these mixtures using asphalt laboratory cracking tests (i.e. mechanistic evaluation only) when compared to a typical microsurfacing mixture. As standardized methods of evaluating the cracking performance of microsurfacing do not exist, it is necessary to use pre-existing tests developed for other applications. The final (post-curing) makeup of microsurfacing is similar to asphalt concrete (binder and aggregates) and therefore these tests serve as the primary source for evaluating cracking performance of microsurface.

To test the cracking resistance of the various mixtures it was determined that the tests selected should meet several factors:

1. The tests are sufficient to test the cracking performance of all the mixtures.
2. The test samples are easy to produce and production is not be overly difficult or time consuming using microsurfacing materials.
3. The final prepared microsurface samples are robust and able to withstand the criteria of the test while being able to record necessary data for collection and analysis.

To the first part, many tests were considered including bending beam fatigue, ITS, SCB, and Texas Overlay Tester. Bending Beam Fatigue was ruled out as an option due to the thickness and length of the samples required. Without compaction, microsurface remained highly flexible and both transportation and set up of the test could likely lead to bending of the beam, potentially impacting. In addition, ITS test was ruled out due to the soft nature at intermediate temperatures of the final samples and quantity of material required for testing. This could likely lead to strange results where deformation may occur without crack propagation.

5.5 Texas Overlay Tester-TEX-247-B

The most representative of the tests was determined to be the Texas Overlay Tester. The Texas Overlay Tester was designed and is used to evaluate reflective cracking in asphalt overlays [49]. As microsurface serves as a very thin overlay on asphalt roadways and may often be applied to cracked pavement, this test offered the most representative example of cracking for microsurface mixtures. Reflective cracking will also be a common distress for microsurfacing as it is applied to roadways several years into the pavements life [1]. In addition, the use of small samples meant that the transport and integrity of the samples could be kept during trimming, air void determination, and gluing to the OT plates. Finally, examples of the use of OT testing on microsurfacing samples has been conducted and therefore considered a reasonable test for evaluating the performance of microsurfacing [50].

The Texas Overlay Tester tests the resistance to reflective and fatigue cracking of asphalt samples through the cyclic displacement and subsequent recording of the load measured during the displacement. Each cycle's displacement is 0.06mm. Failure criteria for this test is 93% reduction of the initial recorded peak load. Traditional samples for OT tests are cut from Superpave Gyratory compacted samples. The first two cuts produce a cylindrical sample with a thickness of 38mm and 150mm diameter which can be seen in Figure 19A. The third and fourth cuts produce a sample with a width of 76mm which can be seen in Figure 19B. Tolerance for the specimen's dimensions are +/- 0.5mm and are typically compacted to 7.0% +/- 1.0% air voids. The standards for this test are TEX-248-F.

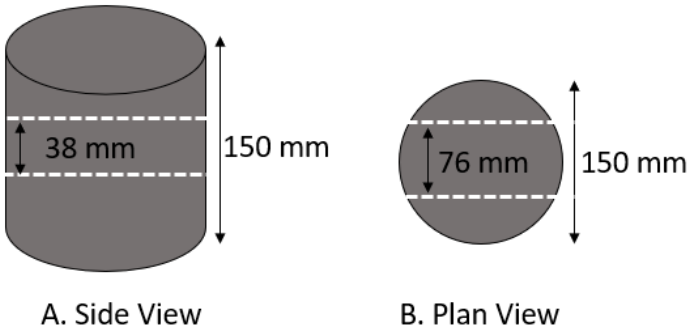

Figure 19. Specimen trimming for standard Texas Overlay Tester samples. A) Surface trimming-two cuts B) Edge trimming-two cuts

However, 38 mm is thicker than surface courses of microsurface. Therefore, an adjustment was made to the dimensions of the samples. While microsurfacing can be very thin, typically the strategy of laying down at a thickness slightly larger than the largest microsurfacing aggregate is conducted [7]. In addition, multiple layers of microsurfacing can be laid down up to ¾ (19mm)" [7]. This thickness was chosen as the target sample thickness for several reasons:

1) Samples of about 9.5mm (single layer) are very thin and ran the risk of both harm to the operator during specimen trimming and damage to the sample when transporting.
2) 19mm is exactly half the standard specification for the OT test.
3) Samples of 19mm would give more cycles to failure, and theoretically less variation in the results as larger samples tend to produce less variability [49].

In order to produce these samples, 70mm samples of microsurfacing mixture were produced based on the description in the sample production section. Trimming of the

samples started with trimming the sample to the 76mm width as seen in Figure 20A. Then 5mm portions were removed from both ends as seen in Figure 20B. The remaining middle portion was trimmed to three 19mm thick samples as seen in Figure 20C. Final samples can be seen in Figure 21.

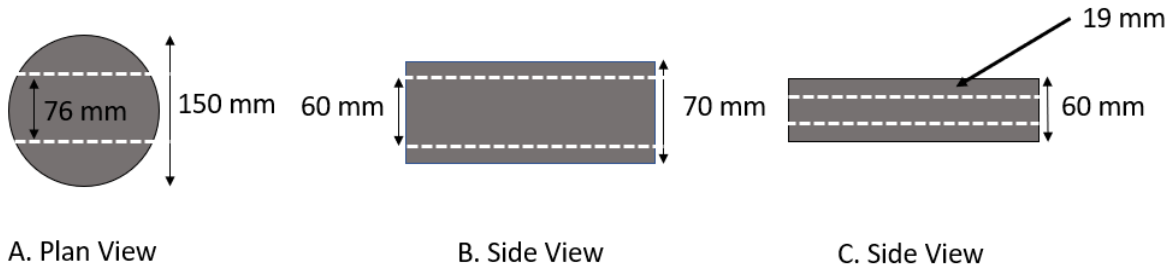

Figure 20. Trimming of samples for this study. A) Edge trimming- two cuts B) Surface trimming- two cuts C) Final trimming- three cuts

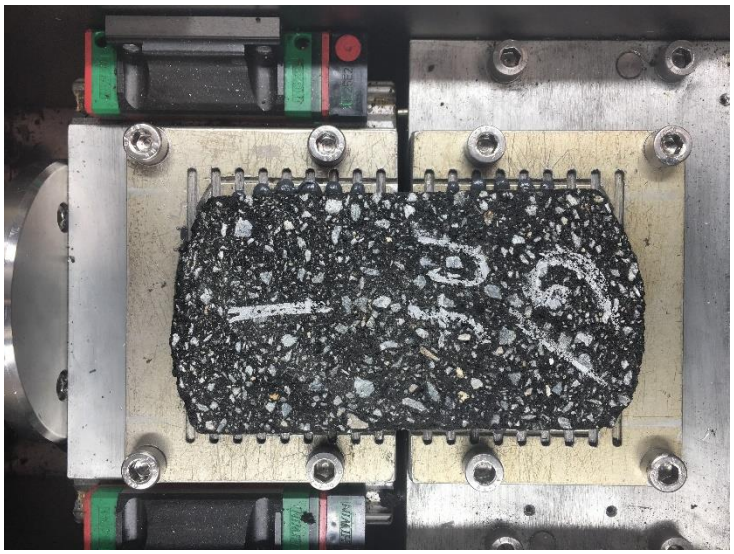

Figure 21. Final OT microsurface test specimen.

Traditional data analysis for the Texas Overlay Tester uses the number of cycles to reach the failure criteria. However, this method can lead to high variance among samples [49]. Other methods for analysis include calculating area under the load reduction curve and crack propagation rate by fitting a power function to the data to obtain a parameter from the representative equation as seen in Equation 3 where *y* is the normalized load, *x* is the cycle, and *a* is the crack propagation rate. For this method, the are is normalized by dividing the loads recorded by the first load reading.

$$y = x^{a} \qquad \text{Equation 3}$$

5.6 Semi Circular Bend Test-AASHTO TP 124

A secondary test used to analyze the cracking performance of the microsurface mixtures was the Semi Circular Bend Test in accordance with the AASHTO Standard TP-124-16. This test was chosen as a way to measure the resistance of each mixture to the initiation of cracking. The robust nature of the samples (50mm thick semicircular samples) which do not deform under its own weight (as the bending beam fatigue test samples would be prone to) were found to be easy to produce. In addition, the introduction of a notch to the specimen means crack propagation point is controlled and the low stiffness of the sample does not hinder crack initiation (the surface of the sample where the load is applied may deform under loading in a test such as ITS).

The results from this test may be used to corroborate the data gathered from the Texas Overlay Tester, which is a representative test for the reflective cracking aspects of microsurfacing. However, the Texas Overlay Test is prone to high variance among

samples [49]. The use of multiple tests was considered to validate or compare the results as a standardized method for cracking performance determination of microsurfacing does not exist. In addition, the data gathered from SCB testing can offer several cracking parameters such as fracture energy, fracture toughness, and stiffness. Overall, the test is primarily used to determine a mixture's cracking resistance.

Traditional specimens are compacted or trimmed from Superpave Gyratory Compacted samples to a thickness of 50mm. The specimen is cut in half along the flat surface axis and a notch is introduced along the axis of symmetry 15mm into the specimen. Specimen preparation can be seen in Figure 22. For this study, specimens were cut from the center of a 70mm thick sample and prepared according to the standard specifications. The specimen is seated in the apparatus and loaded along the axis of symmetry. The displacement is controlled via a linear variable displacement transducer (LVDT) and the load measured along the load line. Displacement is conducted at a rate of 50mm/min. Final study specimen in loading cell can be seen in Figure 23.

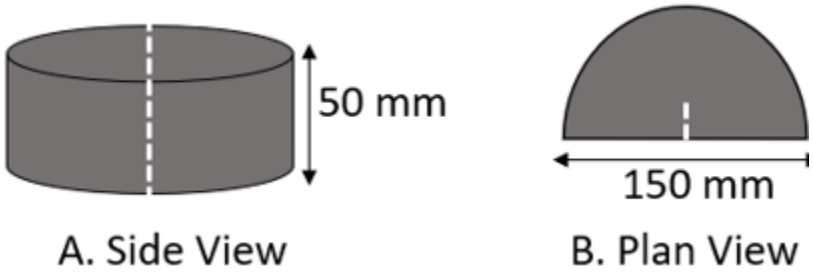

Figure 22. SCB specimen preparation.

Figure 23. Microsurface SCB specimen.

Peak load is one of the primary outputs of this test, used to indicate the maximum load the mixture could tolerate before crack initiation. Work in a fracture test is a parameter to characterize the cracking resistance of samples using the SCB test. It is calculated by finding the area under the load line displacement versus load curve. Integration of these curves over the range of displacement can be used to determine work of fracture (W_f) as seen in Equation 4 where u is the displacement, P_1 is a third degree polynomial representing the pre-peak load data, and P_2 is an exponential function representing post peak load data. It is used to find fracture energy (G_f), which can be used to characterize the cracking resistance of tested specimens. It is determined by dividing the work of fracture determined in Equation 4 by the ligament area ($Area_{lig}$) as seen in Equation 5.

In addition, Illinois Center for Transportation and University of Illinois at Urbana-Champaign developed a software to fit and analyze curves to SCB data and present the fracture energy.

$$W_f = \int_0^{u_0} P_1(u)du + \int_{u_0}^{u_{final}} P_2(u)du \quad \text{Equation 4}$$

$$G_f = \frac{W_f}{Area_{lig}} x10^6 \quad \text{Equation 5}$$

In addition, data obtained from the SCB test can be used to evaluate the Flexibility Index (*FI*) of a mix which identifies mixes more susceptible to premature cracking. It is calculated by dividing the fracture energy (G_f) by the post peak slope which can be seen in Equation 6 where *m* is the post peak load slope at the inflection point and *A* is a conversion for scaling (0.01).

$$FI = \frac{G_f}{|m|} xA \quad \text{Equation 6}$$

It was found that some of the samples were prone to cracking during the pre-load. It appeared that the loading overshoots the 100N preload condition and would then relax. Therefore, the preload was set to 25N, which was found to prevent cracking in the samples during preload. It appeared this load was sufficient to seat the sample for the test as the first readings recorded increasing loads. There were two samples whose first

readings were not increasing. The loads that were not increasing were likely due to improper seating of the sample. The data for these samples was trimmed to the first data point for which the subsequent data point had a load greater than the previous reading.

5.7 Semi Circular Bend Test (Low Temperature)-AASHTO TP 105

As a last test in the laboratory cracking performance evaluation of microsurface mixtures, a thermal cracking test was conducted. This was due to two main factors:

a) Thermal cracking is a potential issue facing microsurfacing [7] and should be included in an evaluation that involves the cracking resistance of microsurfacing mixtures.
b) Tests run at lower temperatures will increase the load at which samples crack which would address some shortfalls seen in tests run at intermediate temperatures.

For the purposes of this test, AASHTO TP 105 was chosen as the test at which to run low temperature cracking on the microsurface samples. The test and outputs of this test are similar to AASHTO TP 124. Except that the thickness of the sample (25mm instead of 50mm), the load rate is controlled by the crack mouth opening (CMOD), testing temperature (0^{o}C vs 25^{o}C) and the notch depth (12.5mm vs 15mm). To evaluate this test for microsurface, the LVDT loading rate of 12.5mm/min was used instead of using the CMOD. This was found to produce consistent and recognizable loading curves and the loading rate for cold temperature cracking has been cited in literature [63].

The samples for this test were created using the standard mold and sample production for the other tests, and therefore the final material would have the same

composition as the other tests. Sample production was identical to the as seen in Figure 23 with the exception of the final thickness. The main outputs for this test are peak load and fracture energy.

5.8 Test Matrix

In this study, the three total tests were run on each of four mixtures to compare the cracking performance of three "enhanced" mixtures to a standard control microsurface. This resulted in a final testing matrix as seen below in Table 8.

Table 8

Testing Matrix

	Test Samples		
Mixture	**Texas Overlay Tester**	**Semi-Circular Bend Test-Intermediate Temperature**	**Semi-Circular Bend Test-Low Temperature**
3%NF	6	6	4
3%WF	6	6	4
6%NF	6	6	4
6%WF	6	6	4

Chapter 6

Data Analysis

In this study, the evaluation of cracking performance of microsurfacing utilized three cracking concepts. The first cracking measure considered was the ability of each mixture to resist crack initiation. To achieve this goal, the semi-circular bend test was utilized. The properties of peak load and fracture energy were used to evaluate the resistance of a mixture to the initiation of cracks when compared to the control mixture. Second, the ability of a mixture to resist crack propagation after the initiation of the crack was considered. This was evaluated using the Texas Overlay Tester, which measures the number of cycles required to fully propagate a crack through the test sample. Third, the resistance of each mixture to resist cracking at lower temperatures was evaluated. As the mechanism for low temperature cracking is typically due to the internal tensile stress built up within the material, the main mechanism to evaluate would be a resistance to crack initiation. To this end, reflective cracking would not play a significant role when compared to the appearance of transverse cracking due to low temperatures. The Semi Circular Bend test at low temperatures was used to evaluate the resistance of each mixture to crack initiation at low temperature. Using these three tests allows specific evaluation of different cracking mechanisms microsurface may be subject to. In addition, the air voids of each sample were taken into consideration. As the production of specimens remained the same for all mixtures, differences in air voids based on mixture could impact performance both in the lab and in the field as the current construction process does not consider final densities or air voids in quality control.

6.1 Air Void Analysis

The procedure for producing the samples of microsurfacing were evaluated based on the final trimmed air void values. In this way, it could be determined if air voids changed based on the day of sample production. Table 9, Table 10, and Table 11 presents the mixtures, sample types, and final air voids. It can be seen that using this production method, air voids within specific mixtures remained relatively constant. The main exceptions are samples 5 and 6 from Table A of 6%NF and 6%WF. Since these were made using the same material and on the same day, it is thought that the emulsion may have come from the end of the container and had been produced almost a week after the final 6% polymer samples had been produced. In addition there would have been more headspace in the container. This could result in the evaporation of more water from the emulsion, resulting in a higher binder content in the final samples. In addition, the 3%WF samples across all samples had relatively higher air voids than the other samples. Since each sample was produced the same way and without compaction, this mixture appears to be presenting higher air voids due to the components. This is especially true considering the 6%WF samples contained fiber but did not see higher air voids. This may be due to the increased polymer content which aids in aggregate bonding [64], and therefore increased homogenous integration of the fibers into the mix.

Table 9

Air voids of Semi-Circular Bend Test (Intermediate Temperature) Specimens

Mixture	1	2	3	4	5	6	Average
3% NF	37.5%	37.6%	37.6%	37.1%	36.2%	37.0%	37.2%
3% WF	37.1%	37.1%	39.7%	39.7%	38.1%	39.0%	38.3%
6% NF	36.1%	36.3%	37.2%	36.6%	30.9%	31.0%	35.4%
6% WF	36.8%	35.8%	38.7%	38.8%	32.9%	31.8%	36.6%

Table 10

Air voids of Semi-Circular Bend Test (Low Temperature) Specimens

Mixture	1	2	3	4	Average
3% NF	36.3%	36.4%	36.5%	35.3%	36.1%
3% WF	38.3%	38.1%	37.6%	37.4%	37.9%
6% NF	35.3%	34.4%	35.6%	35.7%	35.3%
6% WF	36.4%	37.2%	36.4%	35.9%	36.5%

Table 11

Air voids of Texas Overlay Tester Specimens

Mixture	1	2	3	4	5	6	Average
3% NF	34.9%	36.2%	36.3%	34.7%	35.8%	36.2%	35.7%
3% WF	37.8%	38.4%	38.2%	35.3%	35.9%	36.3%	37.0%
6% NF	33.1%	34.6%	34.6%	33.1%	34.5%	34.3%	34.0%
6% WF	33.1%	35.1%	35.9%	33.6%	35.6%	35.9%	35.9%

Figure 24 presents the averages of all trimmed samples. It appears that within a mixture and across different types of test samples, the air voids are consistent (i.e. low variability). This is promising as it shows the consistency of the production method for these samples. In addition, it lowers the chances that performance of test samples will show variation due to air voids. However, this may need to be reconsidered for 3%WF samples, where air voids are consistently higher than all other samples. This may have an impact on the final performance. The consistency of sample production across all

mixtures means the impacts these materials have on the final volumetrics would likely occur in full scale production. This means the performance differences, if attributed to air voids alone, would still apply in full scale production because there are no target air voids or densities when laying microsurface in the field. This means each mix would go through the same laying (and compaction if used) process and these inherent differences caused by the different materials present would be applicable.

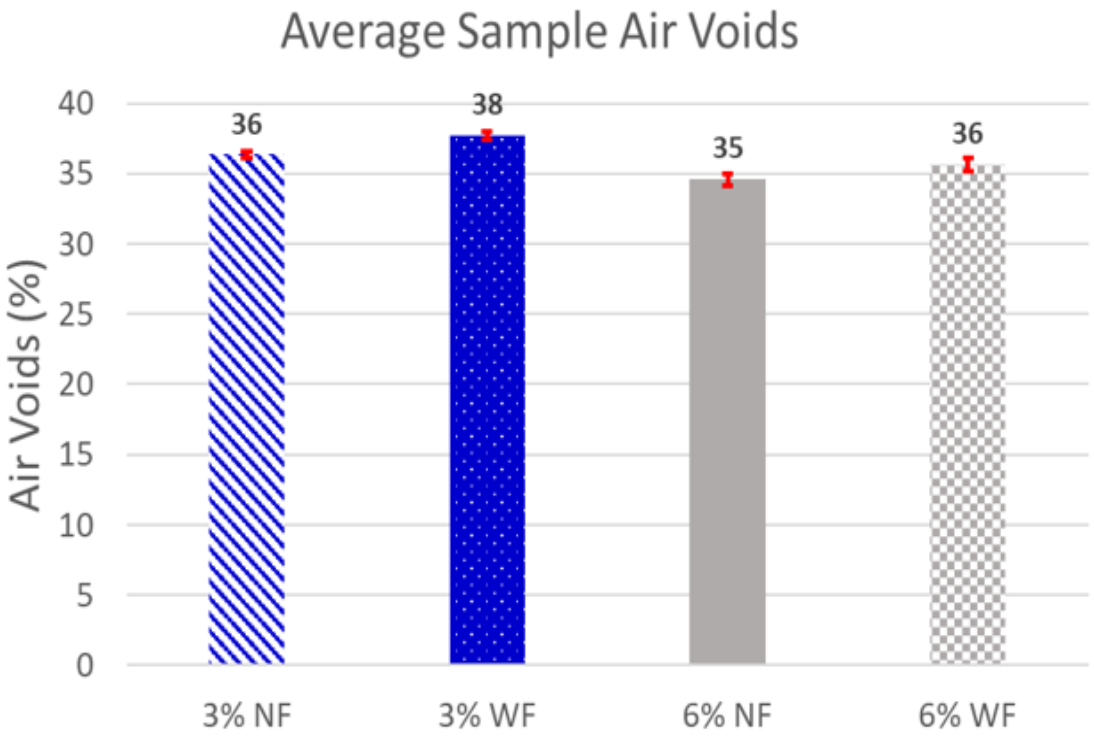

Figure 24. Average air voids of all tested samples.

6.1.1 Statistical analysis of air voids. To further evaluate the air void contents of the various mixtures, One Way ANOVA was conducted to determine if the differences

were statistically significant. The resulting p-value determined that the difference in the means was significant (0.038). Post-hoc analysis was then used to determine which mixtures showed significant difference in means, which showed that 3%WF and 6%NF were significantly different. However, no other combination of mixtures presented this result. It would therefore need to be considered during analysis that comparisons of performance between these two mixtures may be a result of the air void differences. As mentioned above, these differences were likely a result of the different materials used rather than a difference in the sample production procedure, as the procedure was identical for all mixtures.

6.2 Semi-Circular Bend Test (Intermediate Temperature)

The first cracking mechanism evaluated using cracking performance testing was resistance to crack initiation. This required a test that would be able to determine the overall strength of a material. For this, the Semi Circular Bend (SCB) test was used. The standardized methods for evaluating the performance of SCB data include indicators such as peak load, fracture energy, and flexibility index. Peak load is the maximum load recorded during the load vs. displacement curve. Fracture energy is the energy released by the sample as cracking occurs and is obtained by calculating the area under the load vs. displacement curve [65]. Fracture energy was evaluated in two ways in this study. The first was to evaluate the fracture energy up to the peak load to represent resistance to crack initiation. The second was fracture energy over the entire test (to failure condition of 0.1kN) to represent resistance to crack initiation and propagation. The higher these values, the more crack resistant the mixture would be considered. The flexibility index is measured by taking the fracture energy and dividing it by the post-peak curve's slope at

the inflection point. In this study, peak load and fracture energy were used as the methods for evaluating the resistance to crack initiation of microsurfacing mixtures, as a large portion of the data required consists of the pre-crack initiation region. The flexibility index and fracture energy to failure was mainly used as a way of quantifying the materials overall resistance to cracking, which would include properties of both crack initiation and propagation. The fracture energy (entire test) and flexibility index were used as a comparison to test results from the Texas Overlay Tester to identify if the SCB results could potentially quantify post cracking behavior of the mixtures that represent crack propagation. The primary goal of SCB at intermediate temperatures was to evaluate pre-crack properties of the mixtures. A numerical method (trapezoidal rule) was used to calculate the area under the load vs. displacement curve. It should also be noted that the use of the tool provided by the Illinois Center for Transportation (IFIT) was attempted. IFIT is a software tool provided by the Illinois Center for Transportation that allows users to input collected data, which then fits curves to the entered data and provides fracture energy and flexibility index as outputs. The Illinois Center for Transportation developed flexibility index as a means for quantifying fracture resistance in asphalt mixtures containing RAP and RAS and is now subsequently used in AASHTO TP-124 [66]. These outputs would be calculated based on Equation 4 and Equation 5 which, through analytical integration methods, calculates the area under the load curve and the post peak slope at the inflection point.

The standard AASHTO TP-124 states that data should be cut off at 0.1kN after the peak. This method was employed when attempting to use IFIT. It was noted that this leaves much of the post peak data out of the calculations as seen in Figure 25, which is

unique to this study due to the relatively low load outputs. Traditional asphalt samples would have much of the post peak data exist above the 0.1kN mark. In addition, two samples from the same testing day for the 6%WF did not reach 0.1kN. A phenomenon was witnessed where the load increased prior to the 0.1kN threshold. This is theorized to be happening due to the softer nature of the samples, where crack propagation does not happen quickly as it would in a more brittle asphalt sample. Instead crack propagation may be happening during large horizontal displacement, causing the seating mechanism to press against the side of the seat housing. This causes an increase in the load readings and had been witnessed in several test samples. Therefore, for post-crack fracture energy and flexibility index, using IFIT presented two main obstacles. First, evaluating all samples at 0.1kN cut off was not feasible. Two samples would have to be removed from analysis in order to accomplish this. In addition, increasing the cut off load caused issues with IFIT software where the outputs could not be calculated for several control samples. It is hypothesized that this was due to a lack of data sufficient to create a post-peak curve with an inflection point within the data range, or lacked data points to produce a uniform curve from pre-peak load to post-peak load. This would likely be due to the fact that the standard AASHTO TP 124 states that the pre-peak conditions can be fit with a third degree polynomial, while the post-peak curve can be fit with an exponential function. The inflection point of the post-peak exponential function may be occurring beyond the data recorded. Differences in material composition when compared to HMA may also be contributing to IFIT incompatibility with these results. Issues with IFIT software have been witnessed in other studies [67]. To avoid the removal of so many data points from the analysis, it was determined to use the trapezoidal method as the numerical analysis

method to evaluate the area under the loading curve. This allowed for a uniform analysis method that could use all data sets and sufficiently provides the necessary data to achieve the goal of using SCB to evaluate cracking performance of microsurfacing mixtures.

Since the I-FIT software could not be used for the flexibility index, it was determined that another method for post-crack slope would need to be applied. The post-peak slope at the inflection point is used as a way to quantify post peak behavior. In Figure 25, it can be seen that from the peak to the 0.1kN cut off point, the data mostly takes a linear form. This was also evident in the R-Square values of lines fit to this data (22 samples had R-square values greater than 0.97, 1 sample had R-square of 0.94, 1 sample had R-square of 0.90). It was therefore determined that the post-peak behavior would be quantified using the slope of the line that fit this data. The inflection point of a polynomial with such limited data would be highly dependent on the exact point of inflection, for which the slopes at each point vary greatly. This was the case even for data sets that had load readings well below the 0.1kN cut off. Therefore, the slope of fitted linear lines was deemed to be sufficient as the slope of this line was bound to the data recorded.

Twenty-two of the data sets were cut off at 0.1kN, while three data sets from 6%WF samples were cut off at 0.12kN, 0.11kN, and 0.11kN. Since the analysis method uses the trapezoidal method, it was determined that this would produce conservative results for the 6%WF samples as it removes area from under the curve. Results of analysis are below.

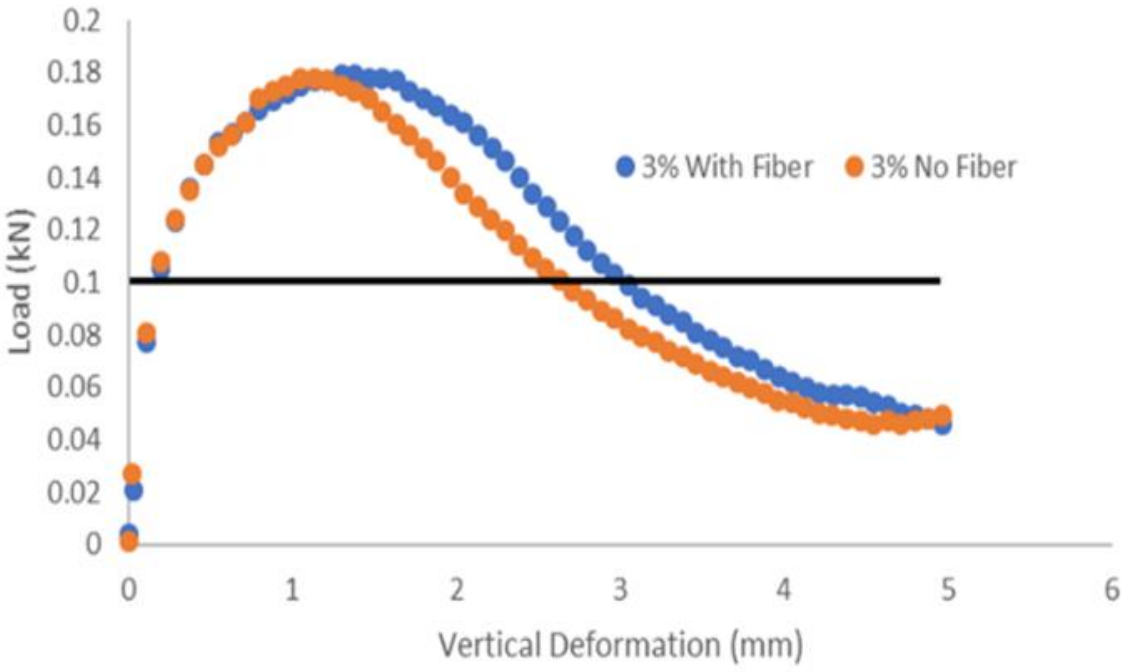

Figure 25. Load curves of 3%NF and 3%WF samples.

6.2.1 Performance indicators. The performance indicators for this study the peak load, fracture energy, and flexibility index. The use of peak load and fracture energy to peak load represented the primary use for the SCB test in this study, to evaluate the mixtures susceptibility to crack initiation. Flexibility index and fracture energy to failure were used as a way to evaluate overall fracture resistance, including propagation. For this analysis, all 6 samples for all 4 mixtures were evaluated using ANOVA and Post-Hoc analysis. ANOVA analysis was utilized to evaluate if there was a significant difference in the means of all the mixtures tested. Post-Hoc analysis was utilized to evaluate any performance improvements that may be occurring between the enhanced samples and control samples, but also between enhanced samples and another enhanced sample. In

this way, it could be determined which mixture was performing best in resisting the initiation of cracking.

Figure 26A, Figure 26B, Figure 26C, and Figure 26D show the results of testing. Table 12, Table 13, Table 14, and Table 15 show the results of the results of the Post Hoc analysis.

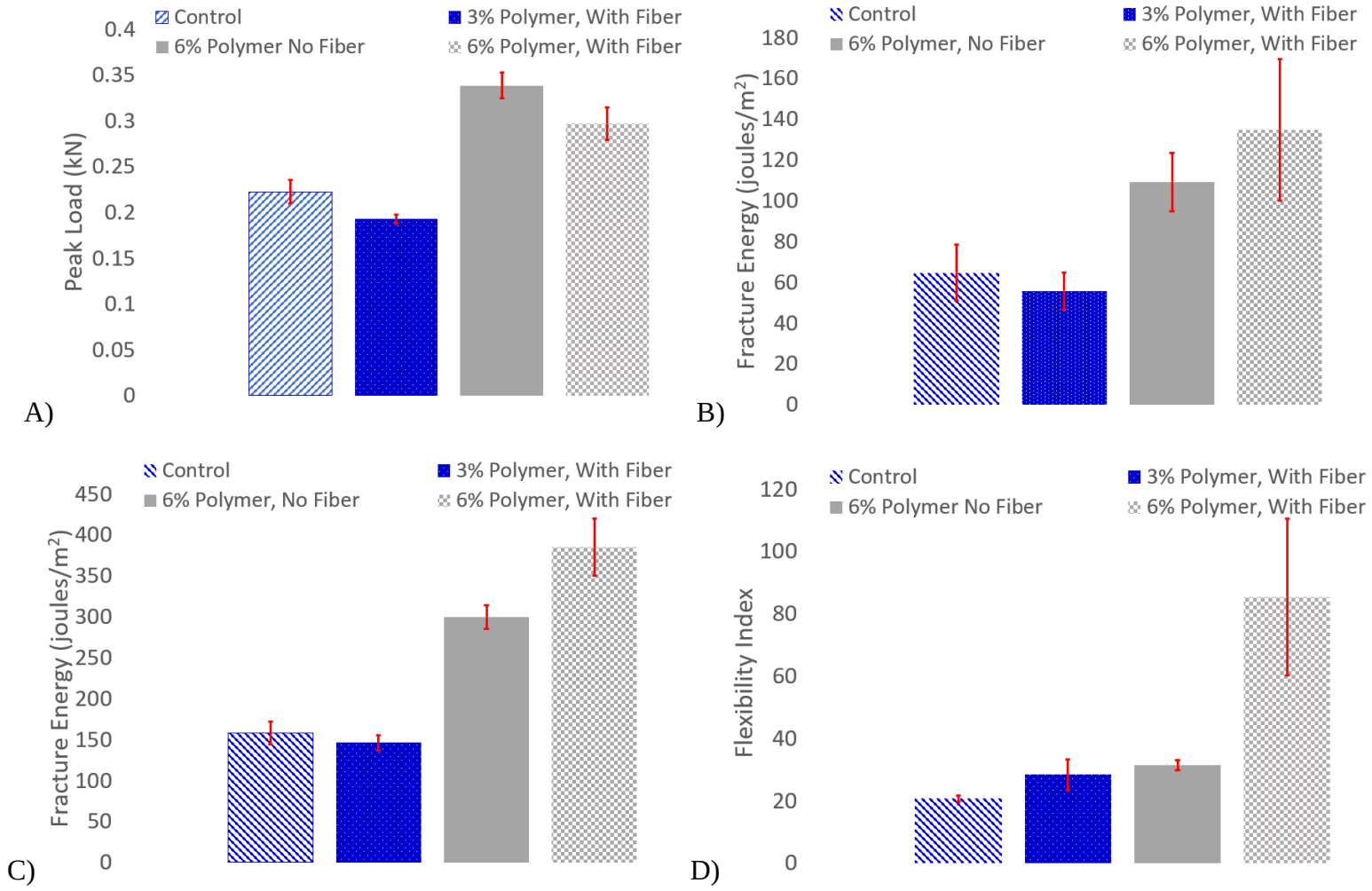

Figure 26. Crack performance indicators for SCB. A) Peak load B) Fracture energy pre-peak C) Fracture energy to failure D) Flexibility index

6.2.2 Peak load analysis. Figure 26A shows that the 6%NF and 6%WF mixtures both outperform the control in peak load by 52% and 33% respectively. The 3%WF mixture actually has a 13% lower peak load than the control. These initial observations suggest that the strongest candidate mixture in resisting crack initiation is the 6%NF. Table 12 shows that both the increases in peak load performance of the 6%NF and 6%WF are significant with p-value of 0.000 and 0.001, respectively when compared to both the control and 3%WF samples with both p-value of 0.000. It is also observed that the samples with fibers slightly underperformed the mixtures without fibers of the same polymer content. This would initially suggest that fibers reduce the capabilities of a mixture to resist crack initiation. However, the Post-Hoc analysis shows that these differences are not significant. It must be considered that these outcomes may be due to the increased air void levels of the samples as seen in Table 9. However, as the air voids are a result of the same production procedure, the addition of fibers may be negatively impacting volumetrics, and therefore performance.

6.2.3 Fracture energy to peak load analysis. Figure 26B shows that both 6%NF and 6%WF have higher fracture energies than the control (69% and 108% increase respectively. The 3%WF did not have a statistically significant lower fracture energy than the control (14% decrease). Table 13 shows that the difference in fracture energy of the 6%NF and 6%WF samples when compared to the control were statistically significant (p-value of 0.003 and 0.000 respectively. Based on these values, the 6%WF was the strongest mixture when compared to the control. The difference in fracture energies of the 6%NF and 6%WF is not statistically significant, though there appears to be a minor increase in fracture energy of the 6%WF over the 6%NF. These results indicate that the

higher polymer content mixtures are always the higher performing samples. The addition of fibers to the control does not aid in either crack initiation or overall crack resistance. However, at 6%, the fibers may be having a slight impact. When considering both peak load and fracture energy to peak load, it appears that the two samples with the 6% polymer based binder have increased strength and resistance to crack initiation when compared to the control.

6.2.4 Fracture energy to failure analysis. Figure 26C shows that both 6%NF and 6%WF have higher fracture energies than the control (89% and 143% increase respectively). The 3%WF does not appear to have a significantly lower fracture energy than the control (8% decrease). The 6%NF and 6%WF have visibly higher cracking performance indicators than the control. While the scope of this study was not to determine the best polymer contents for fibers, it would appear that higher polymer contents may have a positive effect on the performance of mixtures with fibers. This is seen more with fracture energy, which is used in this study as the overall cracking performance. While peak load is used to signify resistance to crack initiation, fracture energy to failure is used as an indicator of overall cracking performance, including crack initiation and crack propagation.

Table 14 shows that the increase in fracture energy of the 6%NF and 6%WF mixtures is statistically significant when compared to both the control (p-values of 0.002 and 0.000 respectively) and the 3%WF mixture (p-values of 0.000 and 0.000 respectively). The decrease in fracture energy of the 3%WF mixture is not significant when compared to the control. The same observations for fracture energy to peak load could be made when evaluating the performance of the 6%NF and 6%WF, that is the

presence of the polymer appears to be playing a major role in the performance of these mixtures.

6.2.5 Flexibility Index. Figure 26D shows the results of the flexibility index. It can be seen that the control has the lowest flexibility index of all mixtures. 3%WF and 6%NF have similar flexibility indices. This is in stark contrast the peak load and fracture energy, where the 6%NF has higher values than both the control and 3%WF. This may suggest that while the 6%NF mixture's increased polymer content is aiding in conditions leading to the crack initiation, it is doing little in the way of post crack conditions. However, the overwhelming increase of performance seen in the 6%WF material is dominating the scale of improvement.

Table 15 shows that within this data set, the 6%WF mixture is the only significant improvement to flexibility index when compared to the control. However the difference is not statistically significant when compared to the 6%NF mixture.

Table 12

Post-Hoc Analysis of SCB Peak Load

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	0.029	0.499	No
	6%NF	-0.116	0.000	Yes
	6%WF	-0.007	0.010	Yes
3%WF	Control	-0.029	0.499	No
	6%NF	-0.145	0.000	Yes
	6%NF	-0.104	0.000	Yes
6%NF	Control	0.116	0.000	Yes
	3%WF	0.145	0.000	Yes
	6%WF	0.041	0.224	No
6%WF	Control	0.074	0.010	Yes
	3%WF	0.104	0.000	Yes
	6%NF	-0.041	0.224	No

Table 13

Post-Hoc Analysis of SCB Fracture Energy to Peak Load

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	9.05406	0.839	No
	6%NF	-44.389	0.003	Yes
	6%WF	-69.874	0.000	Yes
3%WF	Control	-9.054	0.839	No
	6%NF	-53.443	0.000	Yes
	6%NF	-78.928	0.000	Yes
6%NF	Control	44.389	0.003	Yes
	3%WF	53.443	0.000	Yes
	6%WF	-25.485	0.122	No
6%WF	Control	69.874	0.000	Yes
	3%WF	78.928	0.000	Yes
	6%NF	25.485	0.122	No

Table 14

Post-Hoc Analysis of SCB Fracture Energy to Failure

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	11.889	0.983	No
	6%NF	-141.212	0.002	Yes
	6%WF	-226.945	0.000	Yes
3%WF	Control	-11.889	0.983	No
	6%NF	-153.101	0.001	Yes
	6%NF	-238.834	0.000	Yes
6%NF	Control	141.212	0.002	Yes
	3%WF	153.101	0.001	Yes
	6%WF	-85.733	0.069	No
6%WF	Control	226.945	0.000	Yes
	3%WF	238.834	0.000	Yes
	6%NF	85.733	0.069	No

Table 15

Post-Hoc Analysis of SCB Flexibility Index

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	-7.70904	0.981	No
	6%NF	-10.633	0.952	No
	6%WF	-64.687	0.022	Yes
3%WF	Control	7.709	0.981	No
	6%NF	-2.924	0.999	No
	6%NF	-56.977	0.049	Yes
6%NF	Control	10.633	0.952	No
	3%WF	2.924	0.999	No
	6%WF	-54.053	0.066	No
6%WF	Control	64.687	0.022	Yes
	3%WF	56.977	0.049	Yes
	6%NF	54.053	0.066	No

6.2.6 Impact of air voids on the outcome of performance. As a final analysis of the SCB data, air voids were considered in the impact on the performance. This was conducted due to the fact that two samples from the 6%NF and 6%WF categories were well below the other samples of all categories which can be seen in Table 9, samples 5 and 6. It is hypothesized that this occurred due to a large headspace in the binder-container for these samples as it was the last of the emulsion from that particular container. This meant that the binder had not only been used and stirred more often, but also that water may have been able to evaporate from the emulsion. This would cause an increased quantity of binder in the final sample, therefore decreasing air voids. Asphalt performance is strongly linked to air voids and therefore to mitigate the effects that lower air voids may have on performance, the samples with the highest air voids were removed from this analysis for the control and 3%WF samples, while the lower air void samples were removed from the 6%NF and 6%WF. The removal of the highest air void samples for the control and 3%WF mixtures may not properly represent the performance of these

mixtures as there did not appear to be a significant difference among the air voids for these mixtures. This was mainly conducted to evaluate what sort of potential impacts air voids could possibly be playing on the performance. Further studies would be required to confirm any impacts the air void values may be having on microsurfacing mixture performance under these conditions.

Four total samples of each mixture were evaluated for cracking performance using the same One Way ANOVA and Post-Hoc Analysis as the previous section. Table 16 shows the final average air voids of these samples. One Way ANOVA analysis showed that there is no significant difference among these samples ($p=0.452$) for air void. One Way ANOVA does show that without normalizing air voids, there is a significant difference among the samples ($p=0.038$). Figure 27 and Table 17, Table 18, and Table 19 show the results of the SCB testing and Post-Hoc Analysis. One Way ANOVA analysis showed that the results of both peak load and fracture energy were significant when the air voids are normalized ($p=0.000$ and $p=0.001$ respectively).

Table 16

Average Air Voids for SCB Testing (Air Voids Normalized)

Mixture	Average Air Voids for Analysis (%)	Average Air Voids of Samples Removed (%)
Control	36.8	37.5
3%WF	37.6	39.7
6%NF	36.7	31.0
6%WF	37.7	32.3

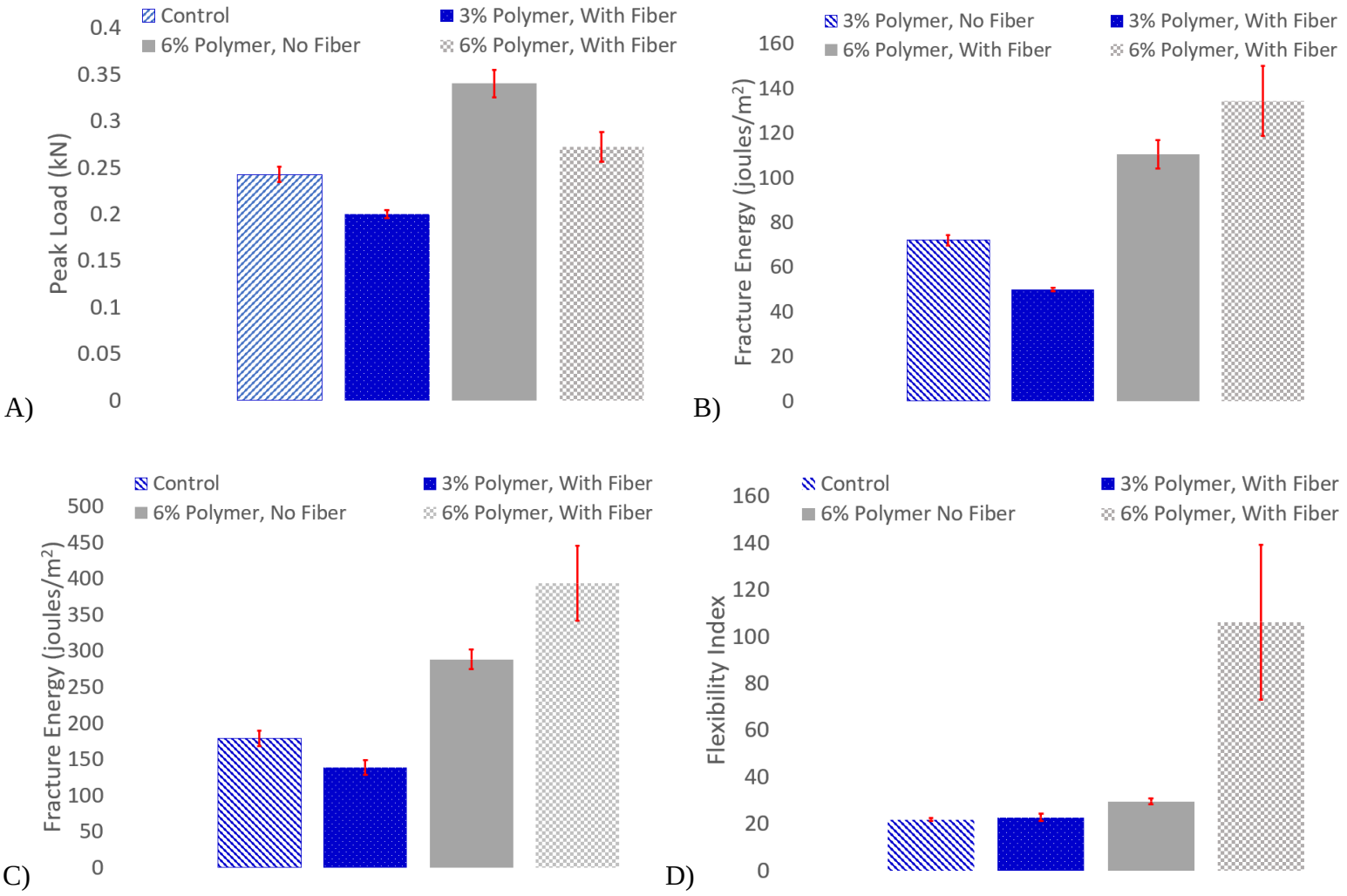

Figure 27. Crack performance indicators for SCB (air voids normalized). A) Peak load B) Fracture energy to peak C) Fracture energy to failure D) Flexibility index

6.2.6.1 Effect on peak load. Figure 27A shows that there is an increase in peak load of the 6%NF over the control by 45%, while the 6%WF increase in peak load over the control is only 16%. The 3%WF has a peak load that is 15% lower than the control, indicating a drop in performance. Therefore, the presence of fibers may actually be hindering cracking performance of microsurfacing mixtures at this polymer concentration level. The 6%WF also presents a 20% lower peak load than the 6%NF. This further indicates a decrease in performance as it pertains to peak load when fibers are included in the mixture. Initial analysis of peak load results indicates that only the 6%NF mixture provides a substantial improvement to cracking performance as it pertains to peak load and crack initiation. Table 17 shows that it is the only sample to present statistically significant improvements to peak load when compared to the control (p-value of 0.002). The post-hoc analysis further validates Figure 27A because the 6%NF also provides significantly higher peak loads than the other two mixtures. Statistically, the 6%WF only outperforms the 3%WF sample as it pertains to peak load. Based on these results, the best mixture in hindering crack initiation is the 6%NF sample. Furthermore, it appears that the addition of fibers to microsurfacing mixtures can actually hinder the ability of microsurfacing to resist crack initiation. This is in contrast to the peak load significance seen in Table 12, where both the 6%WF and 6%NF samples had significantly higher peak loads. This suggests that air voids had an impact on the peak load values.

6.2.6.2 Effect on fracture energy to peak load. Figure *27*B shows that the 6%NF and 6%WF mixtures both have improved fracture energy values when compared to the control of 49% and 86% respectively. The 3%WF sample had a 31% reduction. However based on post-hoc analysis seen in

Table 18 only the 6%WF mixture's increase was statistically significant. The difference between the peak load and fracture energy to peak load outcomes may suggest that both mixtures present increased strength when compared to the control, even at the same air void levels. This would be an important point as any compaction these treatments would go under in the field due to traffic would still show the greatest crack initiation resistance in the 6%NF and 6%WF samples even at similar air void levels.

6.2.6.3 Effect on fracture energy to failure. Figure 27C shows that the 6%NF and 6%WF mixtures both have improved fracture energy values when compared to the control of 68% and 130% respectively, and therefore appear to have improved overall cracking resistance. Initial observations suggest that the 6%WF mixture, while underperforming in peak load when compared to 6%NF, is overall more resistant to cracking. While the use of SCB in this study did not intend to make conclusions based on post-crack parameters, its inclusion is helpful as it represents the increased time it may take for the crack to initiate and also propagate. As with peak load, Figure 27C shows that the 3%WF sample has a reduced fracture energy rating. Table 19, however, shows that the only significant improvement to fracture energy when compared to the control is seen in the 6%WF mixture (p-value of 0.003). The results of fracture energy will be corroborated with the Texas Overlay Tester. The Texas Overlay Tester is the primary indicator in this study of post-cracking performance. These results suggest that the air voids of the 6%NF and 6%WF samples may have had an impact on fracture energy.

6.3.6.4 Effect on flexibility index. Figure 27C shows that the 6%WF sample greatly outperforms all other mixtures in terms of flexibility index. It can be seen that there is a slight increase of the 6%NF mixture over the control and 3%WF mixture.

However, Table 20 shows that the only significant improvement over the control is 6%WF (p-value of 0.047). This outcome matches the analysis when all samples were analyzed and suggests the difference in air voids of the samples did not affect the outcome for flexibility index. However, this could be solely due to the scaling of these values.

Table 17

Post-Hoc Analysis of SCB Peak Load (Air Voids Normalized)

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	0.035	0.416	No
	6%NF	-0.105	0.002	Yes
	6%WF	-0.037	0.371	No
3%WF	Control	-0.035	0.416	No
	6%NF	-0.140	0.000	Yes
	6%NF	-0.072	0.029	Yes
6%NF	Control	0.105	0.002	Yes
	3%WF	0.140	0.000	Yes
	6%WF	0.068	0.039	Yes
6%WF	Control	0.037	0.371	No
	3%WF	0.072	0.029	Yes
	6%NF	-0.068	0.039	Yes

Table 18

Post-Hoc Analysis of SCB Fracture Energy to Peak Load (Air Voids Normalized)

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	22.121	0.446	No
	6%NF	-38.400	0.083	No
	6%WF	-62.236	0.005	Yes
3%WF	Control	-22.121	0.446	No
	6%NF	-60.521	0.006	Yes
	6%NF	-84.357	0.00	Yes
6%NF	Control	38.400	0.083	No
	3%WF	60.521	0.006	Yes
	6%WF	-23.835	0.385	No
6%WF	Control	62.236	0.005	Yes
	3%WF	84.357	0.00	Yes
	6%NF	23.835	0.385	No

Table 19

Post-Hoc Analysis of SCB Fracture Energy (Air Voids Normalized)

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	32.652	0.899	No
	6%NF	-116.843	0.117	No
	6%WF	-222.210	0.003	Yes
3%WF	Control	-32.652	0.899	No
	6%NF	-149.495	0.036	Yes
	6%NF	-254.862	0.001	Yes
6%NF	Control	116.843	0.117	No
	3%WF	149.495	0.036	Yes
	6%WF	-105.366	0.172	No
6%WF	Control	222.210	0.003	Yes
	3%WF	254.862	0.001	Yes
	6%NF	105.366	0.172	No

Table 20

Post-hoc Analysis of SCB Flexibility Index (Air Voids Normalized)

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	-0.914	1	No
	6%NF	-7.722	0.992	No
	6%WF	-84.432	0.044	Yes
3%WF	Control	0.914	1	No
	6%NF	-6.807	0.995	No
	6%NF	-83.518	0.047	Yes
6%NF	Control	7.722	0.992	No
	3%WF	6.807	0.995	No
	6%WF	-76.710	0.072	No
6%WF	Control	84.432	0.044	Yes
	3%WF	83.518	0.047	Yes
	6%NF	76.710	0.072	No

6.3 Semi-Circular Bend Test (Low Temperature)

The Semi-Circular Bend test (AASHTO TP105) was used to evaluate the cracking performance of the microsurface mixtures at low temperatures. The outcome for low temperature cracking was crack initiation. Crack propagation was not considered in this study at low temperatures as it is hypothesized that full depth transverse cracking at low temperatures of microsurfacing would likely take place rapidly due to the thin nature of microsurface lifts. Therefore, only peak load and fracture energy of the SCB test following the standard AASHTO TP 105 was considered. The test was run at 0^{o}C with a load displacement rate of 12.5mm/min. Again, the use of IFIT was attempted, however it gave unexpected results such as negative fracture energies or fracture energies well beyond practical values. This may have to do with the data points, which vary greatly from standard asphalt mixes and could produce unlikely results using a model designed for asphalt. Therefore, the trapezoidal method for calculating fracture energy to failure and fracture energy to peak load was used. It was noted from Table 10 that the 3%WF

samples contained higher air voids than all other samples. In addition, flexibility index was also calculated. It was theorized that this parameter may not be as vital at low temperatures than intermediate temperatures. Microsurface is a very thin layer, and low temperature cracking is typically caused by a failure in the material to resist tensile stress build up due to a quick drop in temperature. Post crack properties of a mix of a layer so thin may not play a role in the failure of this material. Regardless, the method for calculating the post peak slope used a third degree polynomial, as there was sufficient data after the peak load for a discernable curve to form to the failure criteria of 0.1kN. The second derivative of the polynomial was used to determine the x-value of the inflection point, which was then used to find the y-value. These points were then plugged into the first derivative of the polynomial to determine the post peak slope.

One Way ANOVA analysis showed that there was a significant difference in the air voids of the 3%WF mixture when compared to the control (p-value of 0.003) and also the 6%NF mixture when compared to the 3%WF and 6%WF samples with p-values of 0.000 and 0.027, respectively. This again shows that there is an inherent difference in the volumetrics of microsurfacing mixtures when air voids and density are not controlled for. Therefore the outcome of performance testing can be assumed to be the expected result of using these mixtures in the field when all are laid the same.

6.3.1 Effect on peak load. Figure 28A shows the peak loads of all four mixtures. The 6%NF and 6%WF both have higher peak loads than the control with 15% and 20% increases, respectively. The 6%NF and 6%WF peak loads appear to be similar. As was the same with the SCB test at intermediate temperature, the 3%WF sample had the lowest peak load of all mixtures. Post-hoc analysis was used to determine how each mixture

compared to the control in peak load, and also among each other. It was found that only the 6%WF mixture presented significance with a p-value of 0.025 results when compared to the control as seen in Table 21. While the 6%NF mixture presented a relatively low p-value (p=0.0825), the difference in the averages and low variance among the samples was likely a driving factor in the peak load of the 6%WF showing verifiable significance.

6.3.2 Effect on fracture energy. Figure 28B and Figure 28C shows the fracture energy values for all four mixtures. While the 6%NF and 6%WF show an average increase in fracture energy compared to the control, ANOVA showed they were not statistically significant ($p<0.050$).

6.3.3 Effect on flexibility index. Figure 28D shows the results of the flexibility index for the low temperature SCB test. The control in this case shows the highest mean, however ANOVA analysis showed that there was no significance in these results (p=0.936). ANOVA analysis of this also showed no significance (p=0.901).

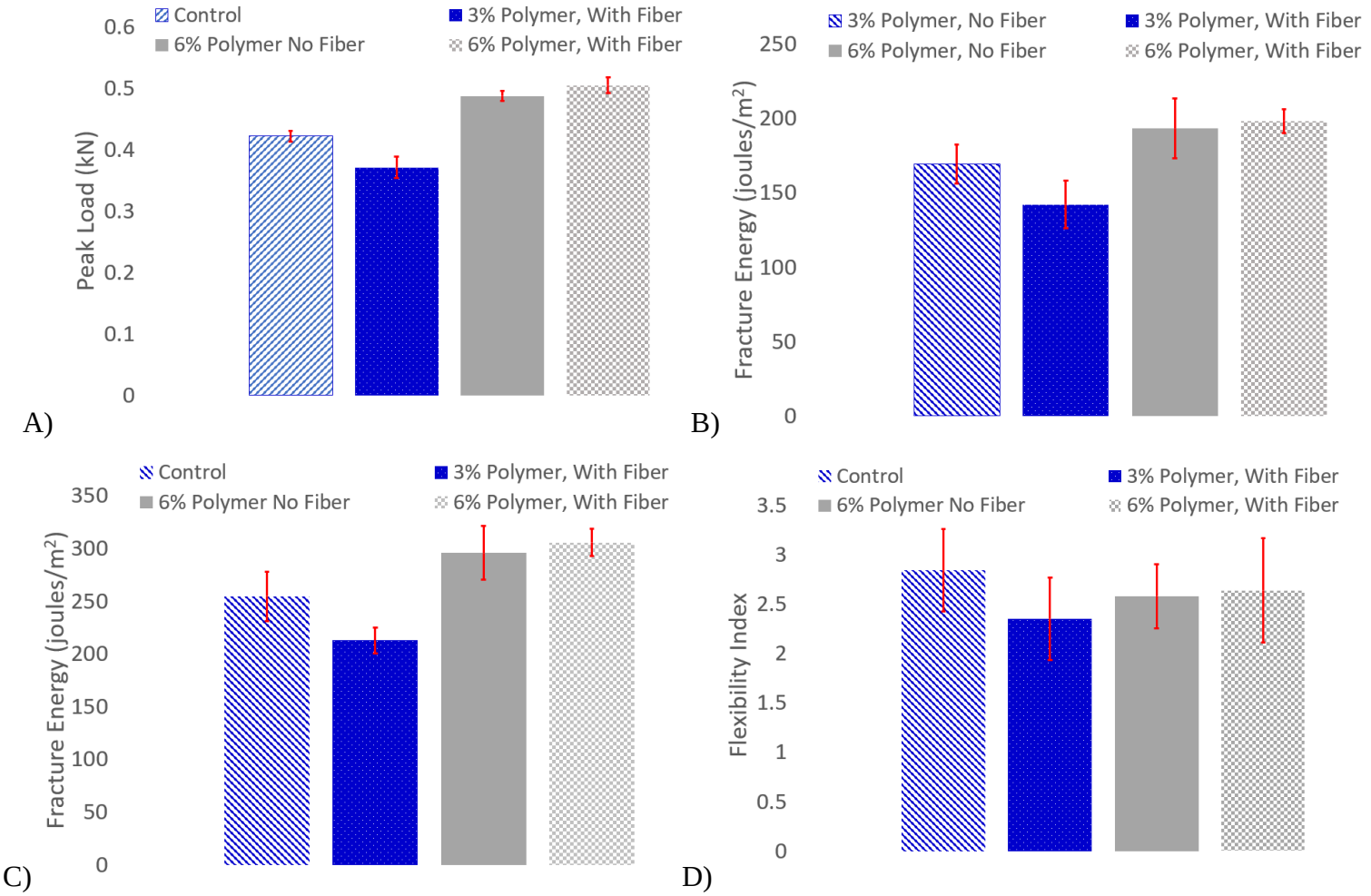

Figure 28. Crack performance indicators for SCB at low temperature. A) Peak load B) Fracture energy to peak load C) Fracture energy to failure D) Flexibility index

Table 21

Post-Hoc Analysis of SCB at Low Temperature Peak Load

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	0.051	0.214	No
	6%NF	-0.065	0.086	No
	6%WF	-0.0827	0.025	Yes
3%WF	Control	-0.051	0.214	No
	6%NF	-0.116	0.002	Yes
	6%NF	-0.133	0.001	Yes
6%NF	Control	0.065	0.086	No
	3%WF	0.116	0.002	Yes
	6%WF	-0.017	0.886	No
6%WF	Control	0.082	0.025	Yes
	3%WF	0.133	0.001	Yes
	6%NF	0.017	0.886	No

6.4 Texas Overlay Tester

The second cracking mechanism evaluated in this study was reflection cracking. In order to do this, the Texas Overlay Tester was employed. The standardized method for evaluating cracking performance using the Texas Overlay Tester is the number of cycles required to meet the failure criteria. For standard asphalt samples, the failure criteria is a 93% reduction in the peak load recorded during the first displacement cycle. This is used as it generally signifies full failure of the sample [58]. However, two observations were made during the testing of these samples. The first was that full crack propagation appeared to be occurring at load reductions of approximately 85% to 88% in samples with 3% polymer. Therefore, the traditional 93% reduction in load as the failure criteria would not be accurate for the samples produced in this study. The second observation was that the control sample's load reduction curve would level off after reaching these load drops as seen in Figure 29. In this figure, the load spends over 5000 cycles above

88% load reduction, only ever reaching a max load reduction of 90.8%. It is theorized the load would not reduce below these points due to healing. It was observed that by taking a fully broken sample, it could be pressed back together by hand, and it would stay bonded even under the forces of gravity. Therefore, it may be that the OT could only cause cracking in these samples to a specific point due to the healing effects caused by the OT tester pushing the samples back together. Healing has been witnessed in microsurfacing during full scale studies during which the cracks seem to disappear in warmer weather [43].

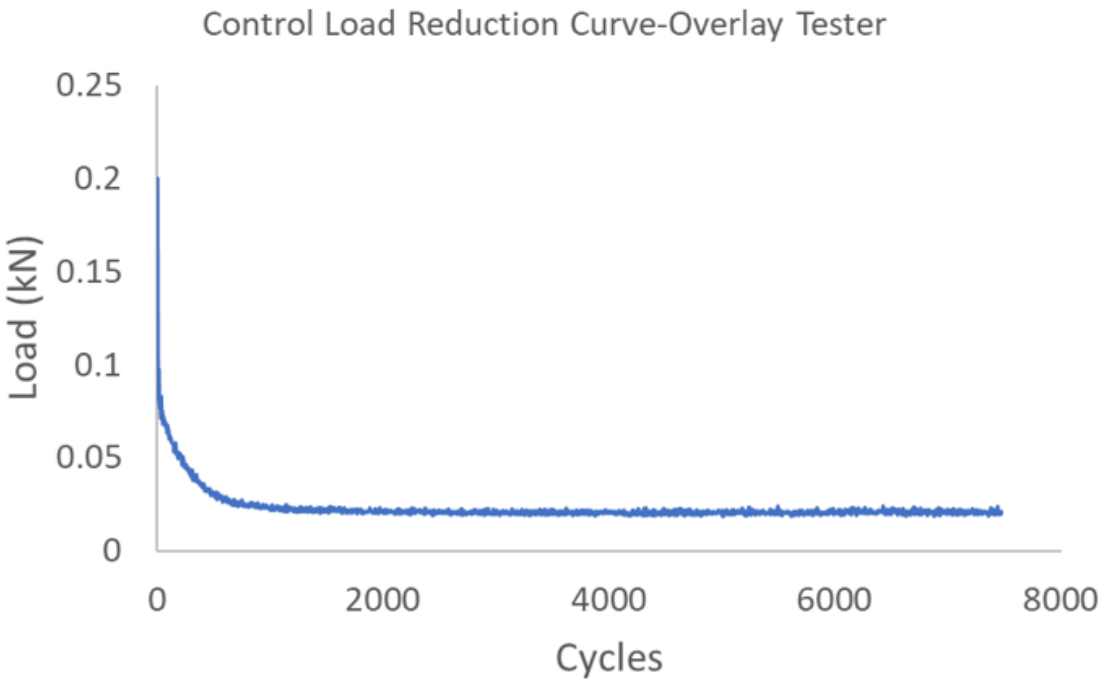

Figure 29. Load reduction curve of control sample.

Based on the observations from the control (i.e. that the samples were failing at around 88% reduction), the tests were limited to 2000 cycles to ensure that mixtures performed better than the control would reach failure (full cracking) before test

termination. Failure, for this case, was originally thought to be when the material reached 88% reduction in load. However, when the 6%NF and 6%WF samples were run, the samples were reaching around 75% to 77% load reduction maximum within the 2000 cycle limit. In addition, several samples did not reach above 70% reduction in load by the 2000^{th} cycle. Two hypotheses were developed from these results. First and foremost, the 6%NF and 6%WF samples were superior to the control because the failure load reduction based on the control was not being reached.

The second hypothesis is that these materials were experiencing full crack propagation at a lower load reduction. The second hypothesis required observations of the samples during testing, and it had been determined that full crack propagation was generally taking place between 75% and 77%. It appeared that the failure criteria based on load reduction and crack propagation could be dependent on the material type. The load reduction curves could help estimate these failure points of the samples by evaluating areas in the graph where the load reduction curve flattened. The load at which most curves leveled out at was around 0.057kN, which equated to about 75% load reduction in those samples that never reached the observed failure criteria (i.e. the load was still dropping by the end of the 2000 cycle limit). It is thought that the samples would have leveled off at this value regardless if allowed to run longer. This is not surprising, however, as the peak loads for these samples were all very similar and therefore the materials would share similar load reductions at specific loads. Figure 30 shows the leveling off of the load for several 6% polymer samples**.** Confirmation of this theory, however, would require a separate study.

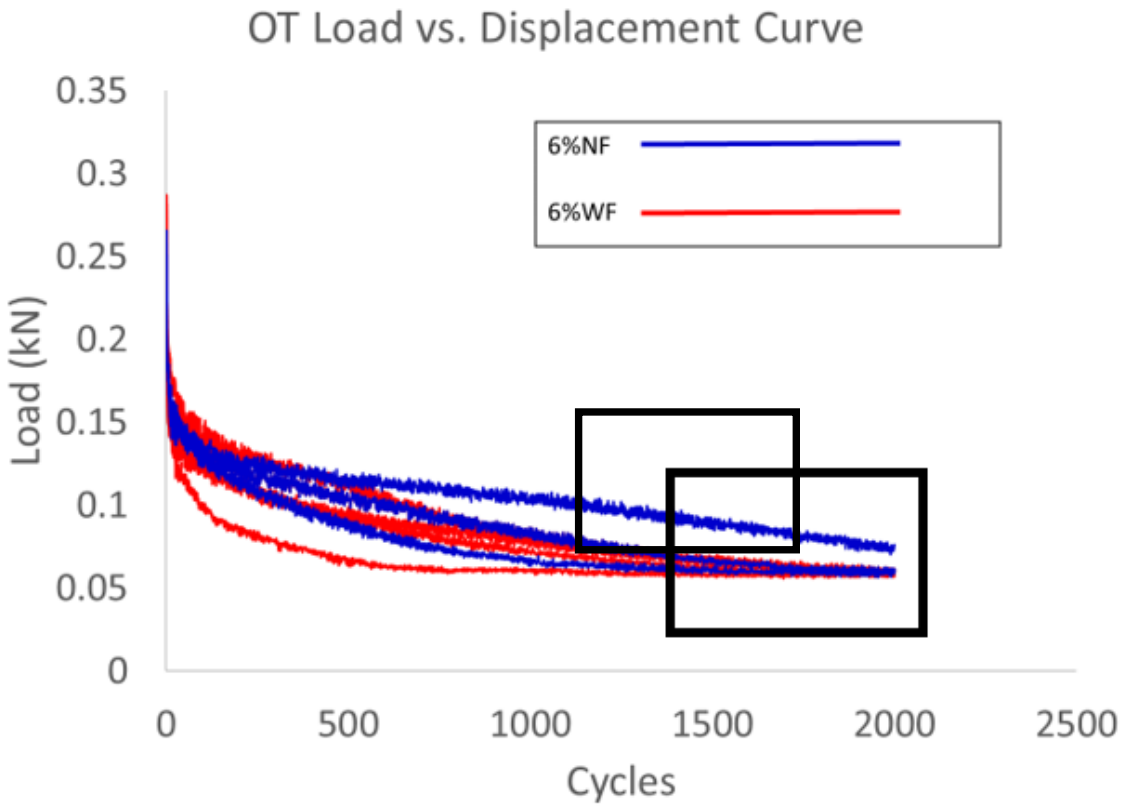

Figure 30. OT load data for 6%NF and 6%WF cycles load leveling.

These observations led to three different data analysis methods to evaluate failure and performance. The first method was to use the cycles to failure to reach a specific load reduction. In the control and 3%WF (i.e. mixtures with a base emulsion polymer content of 3%), failure was set to be 85%. Choosing the lower value ensured weaker samples that failed at this level would not continue counting cycles. The 6%NF and 6%WF (i.e. mixtures with a base emulsion polymer content of 6%) failure was set to be 75%. It was noted that some of the 6%NF samples didn't reach the 75% reduction in the allotted 2000 cycles, and so were included in this analysis with a value of 2000 cycles as the failure.

The second method of data analysis was to evaluate the area under the load reduction curve as a tensile-work indicator. This method was described by Walubita et al. (2012) and found to neither significantly improve nor harm the coefficient of variance of data for cycles to failure. It was determined to be a proper indicator for this study due to clear differences in peak load, load curves, and failure conditions as can be seen in Figure 31. . This indicator could capture the differences in how each mixture is reacting to cyclic loading.

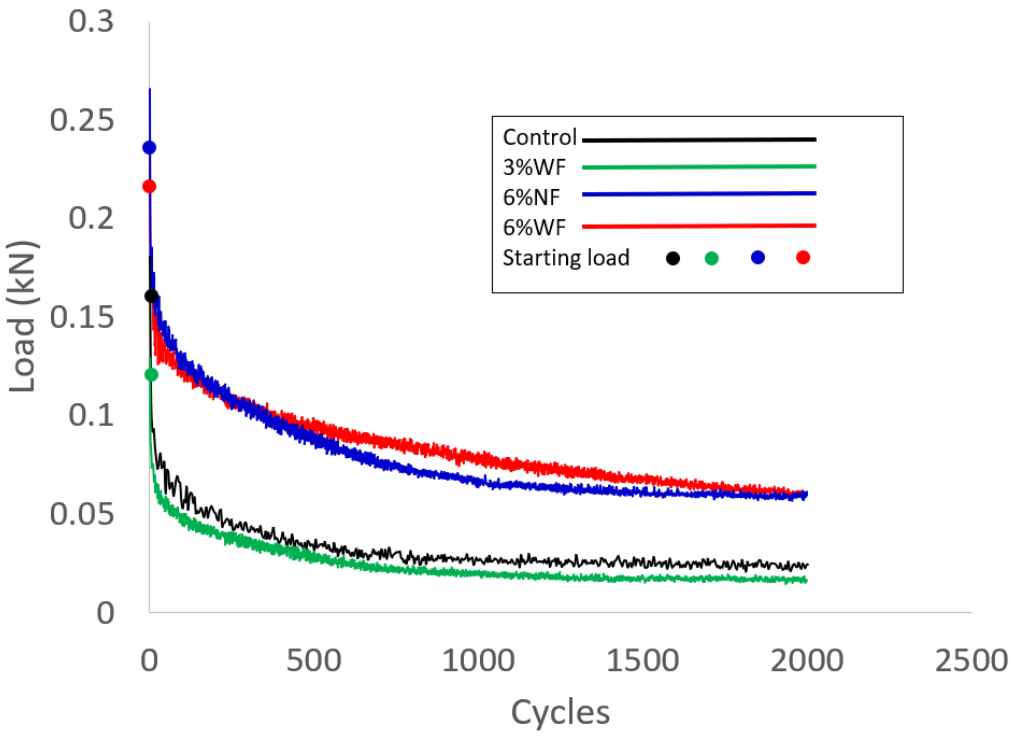

Figure 31. Representation of load reduction curves for Texas Overlay Tester.

The third analysis method was the use of a power function to fit the data from which the raised variable power represents the crack propagation rate as seen in Equation 7 where *y* is the load, *x* is the cycle number, and *a* is the crack propagation rate.

$$y = x^a \qquad \text{Equation 7}$$

The lower the crack propagation rate, the more resistant the mixture is to crack propagation. This indicator was explored by Walbuita et al. (2012) and is used in a different form in Tex-248-f. For this method, the loads are normalized by dividing each load by the first load recording. This provides a benefit to this study by evaluating the rate at which the load drops irrespective of the starting peak loads. The differences in starting peak loads and subsequent loading as seen in Figure 31 would largely favor certain mixtures. While this information contains important properties of the different mixtures, the crack propagation rate indicator allows for a more direct method of evaluating the rate at which load is dropping without being largely influenced by the peak load.

6.4.1 Peak load. Figure 32A shows the average peak loads recorded during the first cycle of the overlay test for each mixture. As can be seen, both the 6%NF and 6%WF mixtures outperform the control with peak loads 29% higher and 27% higher respectively. The peak load of the 3%WF mixture is a 20% decrease from the control. Table 22 presents the post-hoc analysis of the peak loads. It can be seen that the 6%NF and 6%WF peak load values are statistically significant when compared to the control (p-values of 0.014 and 0.025 respectively). The comparisons of these mixtures to the control

are similar to the peak loads comparisons found in the SCB test. This helps validate the results from each test as the peak load of both tests are recorded at the point of crack initiation, and therefore the mixtures are not performing drastically different up to the crack initiation point in these tests.

6.4.2 Cycles to failure. Figure 32B shows the cycles to failure of the different mixtures. The cycles to failure were based on load reductions specific to polymer levels in the emulsion based on crack propagation observation (85% for 3% polymer and 75% for 6% polymer). It can be seen that even with the lower load reduction failure criteria, both the 6%NF and 6%WF have increased cycles to failure over the control of 550% and 333% respectively. The 3%WF mixture has increased cycles to failure over the control of 39%. Table 23 shows the post-hoc analysis of this indicator. The increase of cycles to failure of the 6%NF and 6%WF over the control is statistically significant (p-values of 0.000 and 0.017 respectively). This shows that these two mixtures are both more resistant to crack propagation and reflective cracking. However, the 3%WF mixture does not show a significance in the increase of cycles to failure over the control.

6.4.3 Area under the load curve-500 cycles. Figure 32C shows the area under the load curve of the four mixtures up to the 500^{th} cycle. 500 cycles was chosen because the 85% reduction in peak load for the control samples had almost all been reached by this point (with the exception of one sample). This was deemed appropriate as going any further beyond this failure would give the 6%NF and 6%WF samples a greater advantage for this performance indicator. As the base concept of this study is to compare the mixtures to the control, then the proposed mixtures only have to outperform the control to be considered better mixtures, and therefore basing the criteria on the control's

performance is reasonable. In addition, the area under the load curve was divided by the cross-sectional area of each sample as is typically done for energy and work calculations. This ensures that if the data is being affected by small differences in the cross-sectional areas of the samples, this could be accounted for in the overall performance. The 6%NF and 6%WF mixtures had an increased performance of 329% and 194% when compared to the control. The 3%WF mixture had a decreased performance of 15%.

Table 24 shows the post-hoc analysis of the area under the load reduction curve. The 6%NF and 6%WF mixtures both have statistically significant increases to the area under the load reduction curve over the control (p-values of 0.000 and 0.000 respectively). This shows that more work was required to propagate the crack through the samples, and therefore the 6%NF and 6%WF mixtures are better at resisting reflective cracking. It is possible that the area under these curves will be heavily in favor of the 6% polymer mixtures as the load curves have higher peak loads and level off at a higher load as seen in Figure 31.

6.4.4 Crack propagation rate. Figure 32D shows the crack propagation rate. It can be seen that both 6%NF and 6%WF have reduced crack propagation rates of 60% and 47% respectively. These reductions are significant based on post-hoc analysis as seen in Table 25 (p-values of 0.00 and 0.003 respectively). This data suggest that the crack propagated through the mixture at a slower rate. These values agree with the results based on the parameters of failure chosen for cycles to failure and lend strength to the choice of the failure parameters based on both indicators. The 3%WF mixture did not show any significant difference when compared to the control. The use of crack propagation rate accounted for the potential issues from observation based failure and the differences seen

in the loading patterns that would affect the outcomes of both cycles to failure and area under the load reduction curve. This also helps support the choices made in evaluation methods for these parameters.

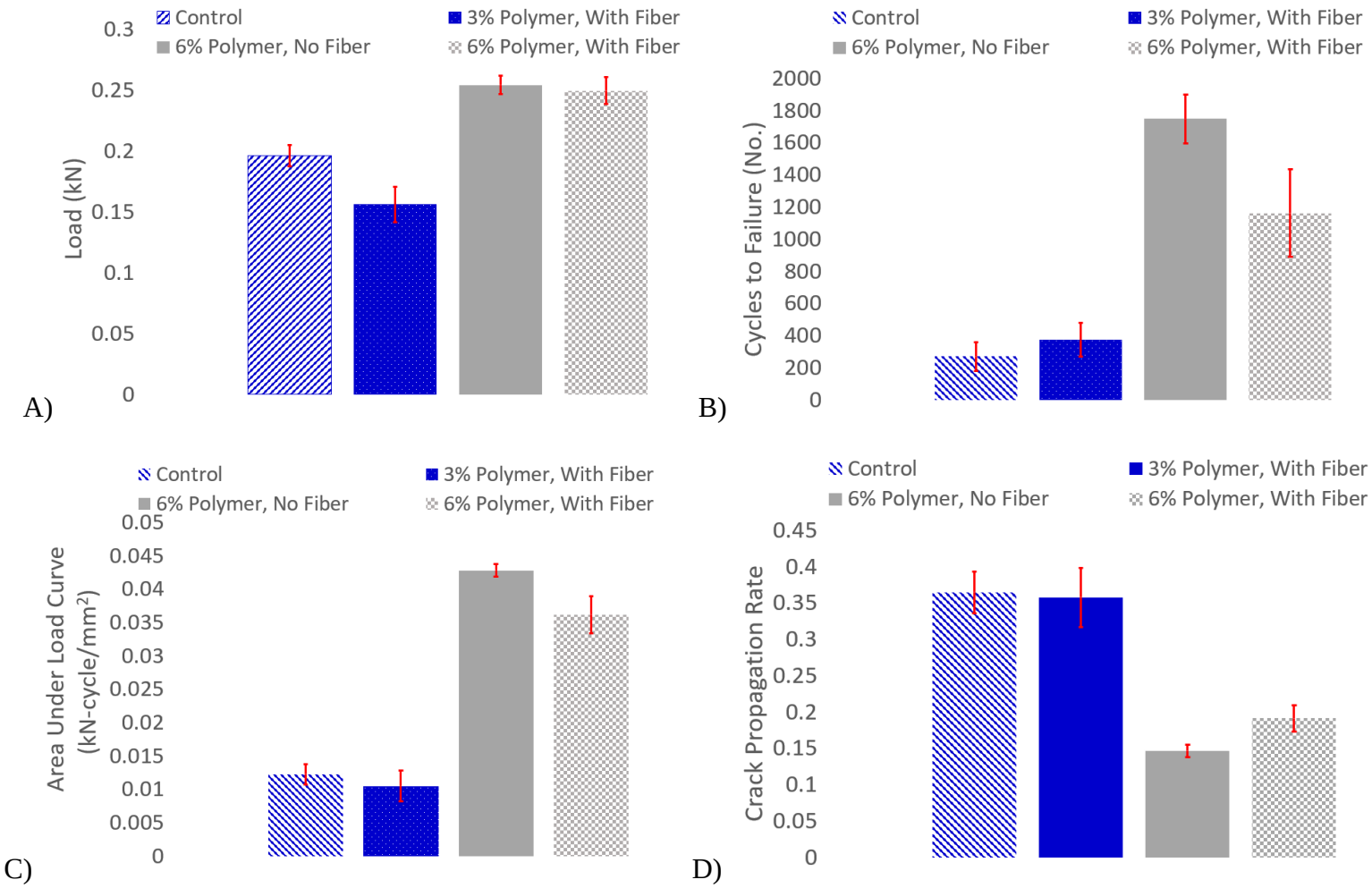

Figure 32. Crack performance indicators for Texas Overlay Tester. A) Peak Load B) Cycles to failure C) Area under curve D) Crack propagation rate

Table 22

Post-Hoc Analysis of Texas Overlay Tester Peak Load

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	0.040	0.119	No
	6%NF	-0.058	0.014	**Yes**
	6%WF	-0.053	0.025	**Yes**
3%WF	Control	-0.040	0.119	No
	6%NF	-0.098	0.000	**Yes**
	6%NF	-0.094	0.000	**Yes**
6%NF	Control	0.058	0.014	**Yes**
	3%WF	0.098	0.000	**Yes**
	6%WF	0.005	0.993	No
6%WF	Control	0.053	0.025	**Yes**
	3%WF	0.094	0.000	**Yes**
	6%NF	-0.005	0.993	No

Table 23

Post-Hoc Analysis of Texas Overlay Tester Cycles to Failure

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	-103.833	0.980	No
	6%NF	-1478.500	0.000	**Yes**
	6%WF	-892.167	0.017	**Yes**
3%WF	Control	103.833	0.980	No
	6%NF	-1374.667	0.000	**Yes**
	6%NF	-788.333	0.038	**Yes**
6%NF	Control	1478.500	0.000	**Yes**
	3%WF	1374.667	0.000	**Yes**
	6%WF	586.333	0.164	No
6%WF	Control	892.167	0.017	**Yes**
	3%WF	788.333	0.038	**Yes**
	6%NF	-586.333	0.164	No

Table 24

Post-Hoc Analysis of Texas Overlay Tester Area Load Reduction Curve

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	0.002	0.945	No
	6%NF	-0.031	0.000	**Yes**
	6%WF	-0.024	0.000	**Yes**
3%WF	Control	-0.002	0.945	No
	6%NF	-0.032	0.000	**Yes**
	6%NF	-0.026	0.000	**Yes**
6%NF	Control	0.031	0.000	**Yes**
	3%WF	0.032	0.000	**Yes**
	6%WF	0.007	0.197	No
6%WF	Control	0.024	0.000	**Yes**
	3%WF	0.026	0.000	**Yes**
	6%NF	-586.333	0.164	No

Table 25

Post-Hoc Analysis of Texas Overlay Tester Crack Propagation Rate

Mixture		Mean Difference (I-J)	Sig.	Significant?
Control	3%WF	0.007	0.998	No
	6%NF	0.218	0.000	**Yes**
	6%WF	0.172	0.003	**Yes**
3%WF	Control	-0.007	0.998	No
	6%NF	0.210	0.000	**Yes**
	6%NF	0.165	0.005	**Yes**
6%NF	Control	-0.218	0.000	**Yes**
	3%WF	-0.210	0.000	**Yes**
	6%WF	-0.045	0.711	No
6%WF	Control	-0.172	0.003	**Yes**
	3%WF	-0.165	0.005	**Yes**
	6%NF	0.045	0.711	No

Chapter 7

Summary of Findings, Conclusions, and Recommendations

This study aimed to use asphalt cracking tests in the laboratory to determine if three mixtures could be used as microsurfacing. The control mixture was based on NJDOT control specifications. The three mixtures used combinations of materials often used to improve asphalt performance and studied in asphalt testing. These included a glass fiber reinforced mixture (0.3% fibers by mass of aggregates), a mixture with increased polymer levels in the emulsion using styrene-butadiene rubber (6% polymer by weight of residual asphalt content), and a mixture combining the fibers and high polymer emulsion. These materials have been applied to varying degrees in the use of full scale microsurfacing projects.

A new sample production method was developed in order to produce testing samples that could be manufactured consistently and be trimmed for use in the chosen tests. It was found that this method produced final trimmed specimens with consistent air voids within mixtures. The semi-circular bend test was employed to evaluate the fracture resistance of the mixtures and determine the ability of each mix to resist crack initiation at both low and intermediate temperatures. Peak load, fracture energy, and flexibility index were evaluated for each mixture. The Texas Overlay Tester was used to evaluate the resistance of each mixture to crack propagation. ANOVA and post-hoc pairwise analysis was employed to determine which mixtures had improved cracking parameters when compared to the control.

7.1 Summary of Findings

-Evaluation of the air voids among the samples showed a maximum coefficient of variance value of 5.1% within each mixture and between all mixtures (Coefficient of Variance value of 5.2%). However, ANOVA analysis detected significance among the means of the samples (p=0.00). Post-hoc analysis showed that there was statistical significant difference in air voids of laboratory compacted mixtures between the 6%NF mixture and 3%WF mixture.

-For each test's final trimmed specimen, the 3%WF had the lowest average air voids and the 6%NF had the highest air voids (2.5% to 3% difference). The control and 6%WF samples had similar air voids (0.2% to 0.6% difference) and fell between the 3%WF and 6%NF mixtures.

- SCB test at intermediate temperatures results showed that the 6%WF and 6%NF mixtures had higher peak load compared to the control based on post-hoc analysis (significance values of 0.010 and 0.000 respectively). When air voids across the samples were considered in the analysis (i.e. the two samples with the lowest air voids of the 6%NF and 6%WF mixtures were removed from analysis and the two samples with the highest air voids of the control and 3%WF were removed from analysis), only 6%NF had a significantly higher peak load based on post-hoc analysis (significance = 0.002) when compared to the control.

-SCB testing at intermediate temperatures showed that 6%NF and 6%WF samples had higher fracture energy to peak load values than the control based on post-hoc analysis (p-values of 0.003 and 0.000 respectively). When air voids across the samples were considered, only the 6%WF had higher fracture energy to peak load through post hoc

analysis. The 6%NF did have an overall higher average fracture energy to peak load when compared to the control. The 3%WF mixture had a lower mean when compared to the control, though this was not significant based on post-hoc analysis.

- SCB test at intermediate temperatures showed that the 6%NF and 6%WF samples had higher fracture energy to failure values than the control based on post-hoc analysis (p-values of 0.002 and 0.000 respectively). When air voids across the samples were considered, only the 6%WF had higher fracture energy to failure through post hoc analysis, though the 6%NF did have a higher fracture energy over the control by 68%. The 3%WF mixture had a lower mean when compared to the control, though this was not significant based on post-hoc analysis.

-SCB test at intermediate temperatures showed that only the 6%WF sample had higher flexibility index when the air voids were normalized. All mixtures showed improvements in comparison to the control based on the average flexibility index.

-SCB test at low temperatures showed that the 6%NF and 6%WF had increased average peak load values compared to the control. However only 6%WF was statistically significant in post-hoc analysis.

-SCB test at low temperatures showed that the 6%NF and 6%WF had higher average fracture energy to peak load and higher fracture energy to failure values. However, post-hoc analysis showed no improvements.

-SCB test at low temperatures showed no change in flexibility index between mixtures. The differences among all samples were found to be not statistically significant in all cases.

-Texas Overlay Tester results showed that 6%NF and 6%WF mixtures have higher peak loads than the control based on post-hoc analysis (p-values of 0.014 and 0.025 respectively), higher cycles to failure than the control based on post-hoc analysis (p-values of 0.000 and 0.017 respectively), higher area under the load curves (p-values of 0.000 and 0.000), and lower crack propagation rates (p values of 0.000 and 0.003).

7.2 Conclusions

-The laboratory testing sample for evaluating pavement preservation techniques produced consistent samples for testing in overlay tests. The test methods were deviated from the published specifications to measure consistent properties of microsurface and its application methods typically replicated in the field.

-The contents of each mixture appeared to have an impact on the final air voids of each sample. The addition of fibers to the mixtures without changes to other parameters such as emulsion, cement, and water content appeared to have a negative impact on the air voids and performance of microsurfacing. Since application in the field is not controlled for final density and air voids, this mixture could expect to see lower density in the field. This increase in air voids may be due to a need for increase in emulsion and binder content in the mixtures. If the binder is absorbed by the aggregates, this would leave less binder to incorporate the fibers into the overall structure of the samples. In addition, the curing process through which water leaves the mixture could create air pockets around the fiber strands. The use of higher polymer contents within the emulsion appeared to have a positive impact on air voids (i.e. lower air voids) when compared to all other mixtures. This may be due to the potential for polymer to increase adhesion of the binder to the aggregates, forming a tighter structure between the aggregates within the

overall structure. The increase to air voids from the polymer and decrease from fiber introduction could also be seen in the fact that the 6%WF sample fell somewhere between the polymer enhanced mixtures and fiber reinforced mixtures, which was comparable to the control. These outcomes are significant for microsurfacing in general, as the lack of control of final density means that the as-laid density of microsurfacing could determine performance.

-The test results show some consistency in the different parameters evaluated across the different tests. For example, the peak load from the Texas Overlay Test results show similar trends (6%NF and 6%WF perform better than the control and 3%WF) as the chosen crack initiation performance indicators from the Semi Circular Bend test such as the peak load and fracture energy to peak load. The same observations are made for the fracture energy to failure of the Semi Circular Bend test at intermediate temperatures (6%NF and 6%WF perform better than the control and 3%WF). This suggests that the crack initiation and crack propagation indicators of these tests may share commonalities and help support the conclusions made.

-Based on the peak load and fracture energy parameters of the SCB test at intermediate temperatures and Texas Overlay Tester, the 6%NF and 6%WF have higher crack resistances when compared to the control. This indicates that the presence of the increase polymer contents in microsurfacing mixtures results in a greater required load to initiate cracking. In these cases, it is likely that the increased quantity of SBR in the binder is increasing the tensile strength of the 6%NF and 6%WF samples. The addition of polymers is cited as increasing a binder's overall tensile strength through the increased bonding of the binder to the aggregates and forming a load absorbing layer around

asphalt particles [44]. In this case, however, the 6%WF has a lower peak load than the 6%NF sample. In addition, the 3%WF has a lower peak load than the control. This shows that the presence of fibers in a sample may reduce the load required to initiate cracking. This could be due to the increased air voids that were seen in the fiber based mixtures when compared to the samples with the same polymer contents. The peak load will be largely determined by the strength and overall structure of each sample which may be negatively affected by the introduction of fibers. This would likely results in an overall reduction in peak load.

-Based on fracture energy of the SCB test at intermediate temperatures, 6%NF and 6%WF mixtures proved to require greater overall energy for cracking to initiate and propagate. In particular, the 6%WF sample improves the overall fracture resistance of the mixture based on fracture energy and flexibility index. The presence of both increased polymer and fiber have a positive impact on the mixtures' ability to resist crack initiation and propagation when compared to the control. As mentioned previously, the data suggests the existence of increased SBR quantities is having a positive impact on the sample's ability to resist cracking. However, the 3%WF sample does not improve fracture energy, indicating that the presence of more polymer is enhancing the reinforcement capabilities of the fibers for the 6%WF mixture. While the 3%WF mixture did not show improvements to fracture energy and flexibility index, it is interesting to note that the 6%WF did have larger average fracture energy values and flexibility when compared to the 6%NF. The increase in area under the load curve could potentially be due to the presence of fibers through the cross sectional area of the sample as the crack propagates, slightly increasing the load required to propagate the crack. The higher

polymer content may be promoting incorporation of the fibers to the overall structure. If this is the case, the crack propagation through such a large cross sectional area (comparatively say to the OT test) would likely come in contact with fibers that have better binder and polymer coating more frequently. This could explain the increased fracture energy and flexibility index values of the 6%WF samples. Based on flexibility index of the SCB test at intermediate temperatures, the 3%WF, 6%NF, and 6%WF all have higher fracture resistance when compared to the control. However, the 6%WF mixture is the best performing mixture and shows the only significant improvements based on post-hoc analysis. This indicates that the combination of higher polymer contents and fiber reinforcement of microsurfacing mixtures may be improving pre and post crack conditions based on the SCB test parameters. When comparing the results of both the OT and SCB results for crack propagation, the SCB shows that the average values for the 6%WF are higher in SCB results and not for OT. It is therefore difficult to make a solid conclusion on the use of fibers in microsurfacing based on these results.

-Based on the peak load of the SCB test at low temperatures, the 6%NF and 6%WF samples both have higher cracking resistance and pre-crack conditions. However, only the 6%WF show significant results. This indicates that at low temperatures, the presence of increased polymer contents and fiber reinforcement may improve the mixture's ability to resist crack initiation. This parameter is vital to the cracking resistance of microsurface during rapid cooling events, as it indicates the ability of the microsurface to resist the onset of cracking. However, crack propagation due to cyclic cold temperature events may not be captured in this test as microsurface can go through

healing phases during warm events. Despite this, the thin nature of a microsurface layer likely makes it more susceptible to cracking during a single cold temperature event.

-Based on the fracture energy and flexibility index of the SCB at low temperatures, none of the mixtures had significantly higher overall cracking resistance than the control. This indicates that post-crack propagation occurs quickly across all mixtures at low temperatures.

-Failure criteria for the Texas Overlay Tester may need to be reconsidered for different materials. If full crack propagation determines failure criteria, then materials that are not traditional HMA mixes may need different failure criteria for comparative studies. Direct comparison of new materials and/or composite materials to control samples may require additional analysis methods and strategies. As this study did not focus on using the Texas Overlay Tester to compare microsurface to HMA, close attention was paid to the crack propagation and load reductions. This was necessary to evaluate the data gathered in a manner that met the objectives of using the Texas Overlay Tester, which was to evaluate crack propagation and reflective cracking.

-Based on peak load, cycles to failure, area under the load curve, and crack propagation rate from the Texas Overlay Tester, both the 6%NF and 6%WF are more resistant to reflective cracking and crack propagation. The increases to these indicators when compared to the control are much higher than those seen in the SCB (i.e. the percent increase of performance over the control). This shows that this test is more sensitive to the ability of the material to resist cracking due to cyclic loading (i.e. traffic). In addition, the consistency of the test results across all indicators for 6%NF and 6%WF (i.e. 6%NF outperformed 6%WF in each case) suggests that SCB post crack indicators

may not be suitable for judging the potential for resistance to crack propagation as the mechanics of the Texas Overlay Tester better represent the field loading that would propagate cracks. The presence of increased SBR quantities is likely playing a vital role in the increase to the performance indicators of these mixtures when compared to the control. The increased tensile strength and elasticity that polymers offer to asphalt would be of particular importance under repeated loading. This would not only help the mixtures to offer more resistance, but also for the binder to maintain its load bearing capacity longer through improved elasticity. It was noted that the 6%WF mixture did not have higher averages for crack propagation indicators through the Texas Overlay Test. This could be due to the decreased sample size. This may have an impact on the likelihood that the crack would propagate to or through fibers incorporated into the overall mixture. This is opposite to the SCB test, where the increased cross sectional area would increase the likelihood of fibers falling in the path of the crack propagation.

7.3 Recommendations

Based on the conclusions, the recommendations are as follows:

While the use of microsurfacing has been shown to improve pavement life and condition based on studies using collected data such as that from LTPP SPS-3 data, improvements to current microsurfacing mix design can address inherent and frequent problems witnessed in microsurfacing surface courses such as cracking. The tests and data analysis conducted in this study show that improvements to cracking resistance can be realized through improvements such as increased polymer content in emulsion through the use of laboratory testing. The combination of increased polymer content in emulsion and

addition of fibers performed better than the control, however this may be due to the presence of the increased polymer content.

As it pertains to the materials used in this study, use of an emulsion containing 6% SBR by residual binder weight can be used to improve the resistance of microsurfacing to crack initiation and reflective cracking. While minimum polymer contents are currently part of microsurface mix design in many SHA roadway and pavement preservation manuals, increases to these levels may improve the effectiveness of microsurfacing based on cracking performance. In addition, overall cracking resistance of microsurface may be improved through the addition of fibers to microsurface mixtures containing an emulsion with at least 6% SBR by residual binder weight. It was noted that the 6%WF mixtures did not show a statistical difference when compared to the 6%NF mixture. Therefore, most of the benefits seen from the 6%WF mixture may be due to the polymer content.

The use of such mixtures have potential for resistance to both reflective cracking and crack initiation based on the testing results. The higher resistance to the tensile stresses caused by existing cracks would be better resisted by a material with higher crack initiation resistance. In addition, the potential to resist top down cracking may be higher based on both SCB and OT results. While top down cracking was not directly explored in this study, the 6%NF and 6%WF show an overall higher strength than the control which would offer some resistance to such cracking as the tensile loading is applied at the surface of the material. These mixtures both have increased performance in all indictors from OT when compared to the control as well, indicating these mixtures have potential to slow crack propagation

Post crack behavior of the 6%WF mixtures in this study based on SCB testing favors situations during which the crack would take time to propagate to the surface. The lower peak load means of the 6%WF mixture show it may be more susceptible to crack initiation than the 6%NF mixture, but overall may be more resistant to cracking based on fracture energy and flexibility. However the Texas Overly Tester better represents the loading patterns that would cause crack propagation and SCB results for crack propagation in microsurfacing mixtures should be further evaluated. The use of fibers without increased polymer levels may have negative impacts on the performance where a typical mixture would be used in its stead. Use of fibers without increased polymer contents shows no advantage in any of the parameters tested in this study when compared to the control. In addition, while 6%WF mixtures outperformed the control, it did not outperform the 6%NF mixture based on Texas Overlay Tester results. Therefore, the use of fibers did not improve the crack propagation rate.

While the use of the 6%NF and 6%WF had higher means than the control for crack testing at low temperatures, post-hoc analysis did not show these values to be significant. Therefore, where thermal cracking is the prime concern for failure in microsurface layers, the use of the proposed mixture in this study cannot be used to address this mechanism. However, the proposed mixtures did not show a decrease in these performance parameters, and therefore use should not be discredited where reflective and fatigue cracking are problems in the underlying pavement.

7.4 Future Work

The focus of this study was to evaluate cracking performance of proposed mixtures when compared to a standard microsurface mixture. This required the development of a sample

production method, in addition to different evaluation methods of the obtained data. Sample production methods and new data evaluation methods should be further developed for microsurfacing mixtures. In addition, the obtained cracking performance results from the lab should be corroborated with full scale data.

- The production methods used to mold and cure the test specimens produced varying air void values in the final trimmed samples. These values should be compared to values of fresh microsurfacing layers applied in the field to verify the resulting data obtained in this study. This would further aid in the validation of the results obtained for purposes of mixture performance comparisons.
- The outcomes of this study suggest there may be optimal polymer contents for the use of fibers. In addition, the differences in performance of the control to the 6%NF sample suggest that polymer content can impact the cracking performance of microsurface mixtures. Further evaluation of optimal cracking performance based on polymer levels could lead to a minimum suggested polymer content for microsurfacing of both fiber reinforced and non-fiber reinforced microsurfacing mixtures.
- The evaluation of the samples in this study focused on the material's early life (i.e. uncompacted). Performance of these materials may change later in life due to densification of the materials due to traffic. Therefore, a study evaluating these materials at different compaction levels would aid in later-life performance comparisons of the proposed mixtures. It was considered that due to the current practice of microsurface construction of not controlling final densities, a compacted performance comparison could require gyration level or controlled loads rather than

targeted air voids for performance at higher microsurfacing densities. A method for compacting microsurfacing for laboratory testing could take into consideration the fact that microsurfacing densifies under traffic loading, and that after initial curing of the microsurfacing layer would be impacted through repeated loading.

- Validation of the results of this study could be corroborated with the construction of full scale test sections. Validation using full scale test section production would also reinforce the sample production, test methods, and data analysis methods used in this study. This would allow further evaluation of the cracking performance in future microsurfacing mixture studies. The failure criteria for microsurfacing mixtures, based on the results of this study, may need to be changed for tests such as SCB and OT. In particular, the OT failure criteria of 93% appears to be insufficient for microsurfacing mixtures.

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