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# Laboratory Performance Evaluation of Pavement Preservation Alternatives

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16. Abstract
This paper introduces a laboratory procedure for evaluating the performance benefits of pavement preservation alternatives and determining the least acceptable pavement conditions on which such treatments can be applied effectively. Two pavement preservation alternatives were evaluated: chip seal and microsurfacing. In addition, this paper presented a procedure for fabricating HMA samples treated with chip seals or microsurfacing for testing using a modified Overlay Test procedure. Three damage severity levels, representing varying pavement conditions, were also evaluated as part of this study: excellent condition with no cracks, low severity cracks (3 mm. wide), and medium severity cracks (6 mm. wide). The applicability of the introduced laboratory evaluation procedure was determined by assessing the sensitivity of the OT cycles to failure to capture the differences among the various samples. The least acceptable pavement conditions were determined based on cracking resistance improvements attained by applying preservation treatments. Analysis of Variance was also conducted to compare the difference among the tested sample groups. Based on testing results, it was concluded that the laboratory procedure for fabricating HMA samples treated with either a chip seal or a microsurfacing was found to produce consistent samples. This was the case because the bulk specific gravity values were similar providing evidence that the fabrication procedure results in comparable samples. The OT test was found to be sensitive to treatment type and damage severity level applied to tested samples; thus, it was successful at differentiating among samples. The OT test results show strong cracking resistance performance of undamaged samples applied with microsurface.

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# TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

# 1. INTRODUCTION

Pavement preservation is a method of preserving roadways and extending life by applying a treatment under the right conditions and at the right time in a pavement's life. Pavement preservation programs that are currently implemented rely heavily on field experience and field studies that use data from the LTPP SPS-3. HMA mixture properties and performance are important aspects of current roadway design practice. Performance testing on these materials is based on expected conditions that the materials will experience in the field and known correlations to full scale distress propagation. However, there is a clear gap in the proper mix design and properties of pavement preservation treatments and a lack of understanding for the proper application timing. The unique application methods and application timing of pavement preservation make it difficult for conventional HMA laboratory performance testing to be used on these treatments. Choosing the correct tests and creating samples that best represent the application of pavement preservation treatments in the field will be crucial in the future of pavement preservation testing.

However, the timing in which applying pavement preservation treatments is currently one of the biggest questions and problems researchers are aiming to answer. The performance of a pavement preservation treatment will likely have a lasting impact on whether or not that treatment will be used and applied in the future. Performance and life extension of pavement preservation materials depends greatly on the initial conditions of the roadway prior to treatment. There has been extensive research conducted on this topic using field data from LTPP SPS-3. Currently, there is a lack of laboratory-based research to determine the optimal timing for specific pavement preservation treatments. While field case studies rely heavily on data collected in the field, this approach requires extensive time and resources to come to useful conclusions.

In this study, the research team developed a method for: 1) producing Texas Overlay Tester samples applied with pavement preservation treatments to best simulate field application 2) determining the least acceptable conditions for pavement preservation treatment by testing un-distressed and distressed OT samples applied with pavement preservation treatments. Based on the literature review, the team decided to use chip seal and microsurfacing as the pavement preservation treatments to conduct the testing on. These treatments lack established cracking resistance tests and are among the most frequently used treatments.

The following report opens with the literature review in Chapter 2 which covers the current use, practice, and testing of pavement preservation treatments. Chapter 3 includes the material types and choices used in this study. Chapter 4 describes the sample preparation and testing regime. Chapter 5 covers the analysis of the data collected and the least acceptable conditions for applying the treatment. Chapter 6 includes the conclusion and recommendations.

# 2. LITERATURE REVIEW

## 2.1 General Literature Review Overview

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 life while keeping costs at a minimum [1]. 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 [1,2]. The use of pavement preservation treatments therefore ensures the protection of infrastructure assets while simultaneously allowing access to federal funding [3]. 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 [1,3]. 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 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 to use or apply these treatments correctly may deter many agencies from adopting these treatments in situations where rapid failure of the new treatment occurs [3]. It is therefore imperative that research and evaluation of collected data be used to improve the effectiveness and benefits of pavement preservation. While there has been some recent interest in laboratory testing and properties of treatments, there is a clear lack of comprehensive laboratory research regarding these topics and the laboratory based optimal timing studies.

## 2.2 Definition and Benefits of Pavement Preservation

Pavement preservation is a strategy used to maintain or improve roadway conditions 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 [1,4,5,6]. 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 [4]. Pavement preservation treatments also help to extend the life of pavement systems which helps reduce the costs incurred from pavement reconstruction [4].

The costs of maintaining transportation and roadway infrastructure have put a spotlight on pavement preservation treatments. The Moving Ahead for Progress in the 21$^{st}$ 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 [4]. Federal-aid funds are available to roadwork projects falling under pavement preservation and preventative maintenance done on highways [4]. 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 life of the pavement and should function as intended. They 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 SHA guidelines and programs [3]. It is therefore important to understand the different types and variations of pavement preservation treatments, how they can be used to address distresses and increase roadway conditions, how to determine the optimal timing to apply them, and the different strategies of their implementation. By compiling information from available sources and conducting further research, it is possible to improve pavement preservation design 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 the many pavement preservation treatments is necessary to choose versatile treatments that can be used and studied in a variety of circumstances.

### 2.3.1 Crack Sealing and Filling

Crack sealing is a pavement preservation treatment in which a bituminous material is used to fill in cracks and prevent moisture infiltration [1]. It is generally expected to last 2 to 6 years [1,2]. 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 [1,7].

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 [1,8]. Generally crack sealing is applied to cracks less than ¾”, while *crack filling* is used for cracks larger than ¾” [8]. 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 [8].

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 [8]. 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) [8].

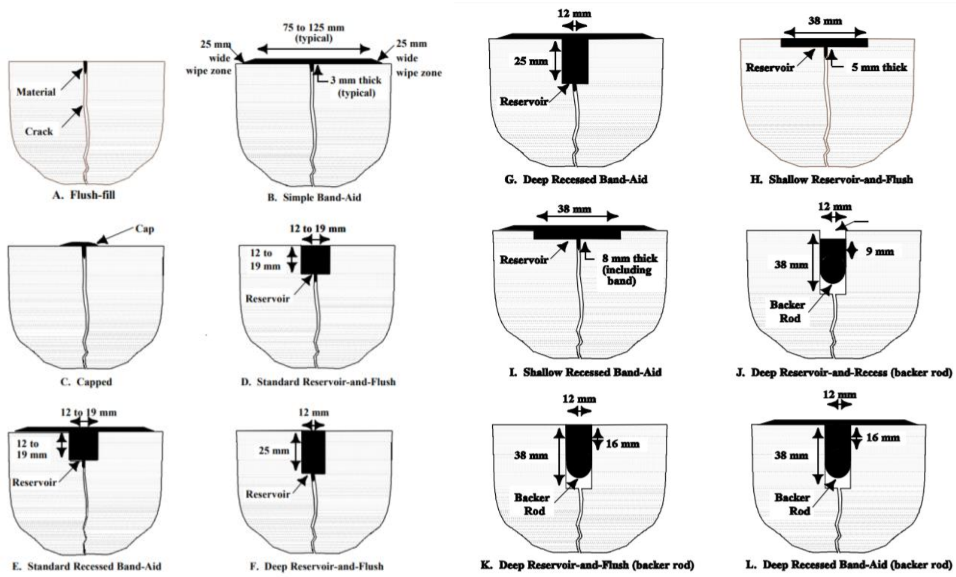



**Figure 1. Crack sealing and filling application approaches [9].**

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 [2,8]. As mentioned, crack sealing and filling benefits roadways by preventing moisture from infiltrating cracks.

### 2.3.2 Chip Seal

There are a variety 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 and aggregates are then rolled into the binder [2]. 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 chosen based on project specifications [2,10-13].

Chip sealing can provide from up to 4-7-year life extension to roadways [12]. 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 it is generally not used to address rutting [2,11]. 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 [2,11,14]. 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 [11].

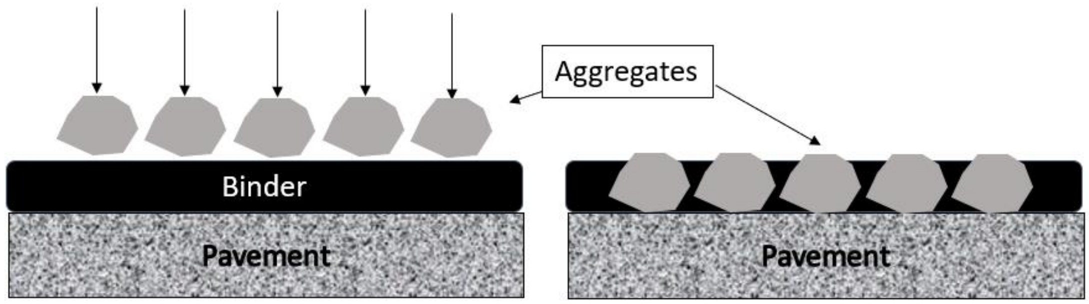



**Figure 2. Application of a Single Layer Chip Seal.**

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 that arise from the use of emulsion-based chip sealing include embedding and that using less binder may be necessary to avoid this issue on high volume roadways. In this case, modified emulsion binder may be necessary to ensure the aggregates do not dislodge. Rapid setting emulsions are used in most cases to ensure that the least time necessary for traffic control is needed [11]. 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 [11].

The use of emulsion binder is sufficient, as mentioned, for addressing minor cracking and protecting from moisture penetration. While emulsion binders are limited in scope by the pavement conditions, other binder types can be used to address different initial conditions and to provide varying outcomes. According to Caltrans's Flexible Pavement Preservation manual, pavement graded binders can be used to address varying degrees of climactic conditions and traffic volumes. This provides some flexibility in the use of chip seals as a pavement preventative measure as it allows users to choose chip sealing materials specific to their region. For example, rejuvenating binders can be used to penetrate and soften the existing pavement onto which the chip seal is being applied [2]. This is generally applied to asphalt concrete to target hardened surfaces due to oxidation, effectively restoring some flexibility to the underlying pavement [2]. Rejuvenating binders also helped to seal and improve cracking conditions in the roadways as they coat the walls of the cracks [2]. Asphalt rubber binder can also be used [2,13,15]. This type of binder contains high levels of both natural rubber and tire rubber [2]. In addition to the benefits provided by standard emulsion single chip sealing, using rubberized asphalt binder has a longer service life, provides resistance against reflective cracking, and resistance to oxidation [15]. Appropriate uses for asphalt rubber binder chip sealing include addressing cracking in structurally sound roadways, restore surface friction, and life extension of asphalt [15].

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 [2.11].

Chip seal variations include:

- **Single Chip Seal** – This type of chip seal is a single layer of aggregates rolled into a layer of either hot or emulsified 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 [11,16].
- **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 above. This method can be used for roadways experiencing higher loads when compared to the roadways single chip seals are used for [11,16].
- **Cape Seal** – This type of chip seal is a single chip seal layer followed by the application of a slurry seal [16].
- **SAMI** (Stress Absorbing Membrane-Interlayer) – This type of a chip seal is a single chip seal layer followed by a thin overlay [11].

While conventional methods such as single and double chip seal offer benefits of restored driving surfaces and roadway sealing, the use of methods such as cape seal and SAMI offer a more robust alternative and additional benefits to the chip seal [11.16]. The use of other materials and methods can further enhance chip seal performance such as the use of geotextiles, applying overlays, and the use of modified binders [2,11,16].

According to the NHCRP Report 680: Manual for Emulsion-Based Chip Seals for Preventative Maintenance, aggregate size, shape, gradation, cleanliness, moisture content, toughness durability, and porosity are all important aggregate characteristics to consider when choosing chip seals as a pavement preservation method. Interlocking and required binder quantities are affected by aggregate size, shape, and gradation [11]. Large aggregates will require more binder and in doing so offers better sealing to the roadway [11]. 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 [2,11,15]. Moisture content of aggregates is an important factor for both emulsion and asphalt rubber-based binders [11,15]. The ability for the aggregates to adhere to the binder is affected by the cleanliness and moisture content of the aggregates [11,15]. Asphalt rubber binder requires aggregates to be hot and pre-coated with asphalt prior to dispersion and rolling to ensure proper adherence [2,15]. According to the Caltrans Asphalt Rubber Guide, smaller chips around 9.5mm are recommended, while chip sizes up to 12.5mm can be used on lower volume roadways [15]. 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 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 [2,15,17]. According to the NCHRP Report 523, the thickness of a thin hot-mix asphalt overlay is between 0.75" and 1.5" [1]. Aggregates used in thin overlaying are generally less than 12.5mm NMAS [18]. 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 [7,17]. Thin overlays are not usually used to address structural failures, high levels of thermal cracking, or end of live pavements [1]. The life expectancy of thin overlays is 7 to 10 years [1]. 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 [2]. While selection criteria vary based on state agency policies, there are many visual and distress cues that can provide information on when to apply thin overlay. Thin overlay 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 [1,18]. Milling can be used to provide a suitable surface for the thin overlay, remove any deficiencies at the pavement surface, and supply recyclable material [1,17,18].

The three main types of thin overlay based on gradation of the aggregates are dense graded, open graded, and gap graded [2,7]. Asphalt binders, particularly pavement graded and modified binders, are chosen based on expected weather and traffic conditions [2]. Each combination and mixture offer various benefits as pavement preservation treatments. Dense graded thin overlays have a continuous aggregate gradation across all aggregate sizes [2]. They can be used to mitigate raveling, oxidation, minor cracking, minor surface irregularities, skid problems, and to waterproof pavement [2,7]. 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 [2,7].

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 [2]. Typical costs based on gradation are \$1.75 to \$2.00 per $yd^2$ for dense grade and \$1.25 and \$1.42 per $yd^2$ for open grade mixes [1].

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 [18]. This has led to a wide variety of thin overlay options which include:

- **UTBWC (Ultra-Thin Bonded Wearing Course, aka Novachip™)** – this is a thin overlay used by many state agencies as a pavement preservation method [17,19]. This method offers longer lasting life to the pavement, adds only a very thin lift, and reduced clearance adjustments [20]. It is an open graded HMA which makes use of a thick polymer modified emulsion tack prior to the application of the hot mixed asphalt overlay [17,19]. A study in Minnesota showed that after 7 years, roadway conditions and ride quality remain high using UTBWC, no weathering or raveling was witnessed [20]. The cost of this method in 2007 was estimated at \$4 per $yd^2$ [20]. One major drawback to this method is it requires unique equipment for application and is more expensive than typical thin overlay costs.
- **Dense Graded 4.75mm NMAS** – these mixtures can be used to decrease costs by reducing overlay thickness and provide quieter riding conditions [17,21]. Cooley and Brown (2003) found that 4.75mm NMAS mixtures are rut resistant and tend to be less permeable than larger NMAS [22]. In addition, Son et. al. (2016) 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 [23].
- **Open Graded Friction Course –** this is a thin overlay that increases water drainage on roads, increasing safety for drivers in regard to hydroplaning [24]. OGFC overlays using normal asphalt mixes tend to have low durability and strength [24]. Faghri et. al. (2002) using an addition of styrene-butadiene-styrene polymer that doubled the strength of OGFC mixes and increased permeability [24]. Islam et al. (2018) found that OGFC is more flexible and less susceptible to low temperature transverse cracking than regular asphalt concrete mixes [25]. A polymer modified OGFC overlay could make a good candidate for roadways often exposed to poor weather conditions.
- **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” [26]. Prior to application a tack coat is applied to ensure proper binding of the PPEST to the surface [26]. PPEST can be applied to roadways experiencing moderate cracking and adds about 4 to 6 years of life to the applied pavement [13].

Thin overlays can also be placed overtop of stress absorbing membranes (SAM) or stress absorbing membrane interlayers (SAMI) [2]. The effects of stress absorbing membrane interlayers on overlays was studied by Ogundipe et al. (2013) 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 [27]. Addressing cracking prior to the use of thin overlays or SAMI and SAM is important for its performance [2]. For roads with minimum cracking, SAM and SAMI can be placed underneath to strengthen the thin overlay [2].

### 2.3.4 Micro-surfacing, 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:

- **Slurry Seals** - are mixtures of well graded aggregates, asphalt emulsion and water that is spread over the pavement surface at a thickness of 10mm to 20mm using a squeegee or spreader box [1,6,8]. Slurry seals provide added surface friction, protects against moisture penetration, addresses raveling, minor cracking, and oxidation [1,8].
- **Micro-Surfacing** - 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 10mm and 20mm [1,2,6,8,28]. Application of microsurface is carried out by pouring the mixture onto the roadway using specially designed machinery. Microsurfacing provide added surface friction, protects against moisture penetration, addresses raveling, minor cracking, and oxidation [1,8]. Microsurfacing can also be used for filling of ruts based on aggregate type and the way in which it is applied to the roadway [1,8].
- **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 cracking [1]. However, fog seals may lower skid resistance on roadways and may not be good candidates when skid resistance is an issue [1].

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; micro-surfacing uses chemical breaking as the main mechanism for hardening, where slurry seals use thermal breaking [1,8]. 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, it lacks the surface friction benefits of micro-surfacing and slurry seals. Generally, these pavement preservation methods are initially used on roadways showing oxidation and/or minor cracking [1,8]. Micro-surfacing 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 [1,8]. Fog and slurry seals have expected life of 1 to 2 years and 3 to 5 years respectively [1]. Costs for slurry seal and micro-surfacing are roughly between \$0.70 and \$1.00 per yd$^2$ and between \$0.90 and \$1.70 per yd$^2$ respectively [1].

Ji et al. (2012) evaluated micro-surfacing based on various roadway conditions such as PCR and IRI. The team found that micro-surfacing is a cost-effective preservation method when applied to structurally sound roadways and help to address rutting and slows down the appearance of reflective cracking. However, micro-surfacing's ability to positively address PCR and IRI are limited [29]. This may be in part due to the roadway conditions pavement preservation treatments are applied on. Hajj et al (2011) used performance data to evaluate the effects of slurry seal. They found that the use of slurry seal greatly increases PCI when added between 3 and 9 years of pavement age and can extend the life of the pavement when applied at 3 years of age [30]. They surmised that the use of the slurry seal reduced aging effects on the roadway, further protecting it from thermal and fatigue cracking that could propagate due to aging [30]. The use of micro-surfacing 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 best choose 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 focus 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 [31-34]. 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.

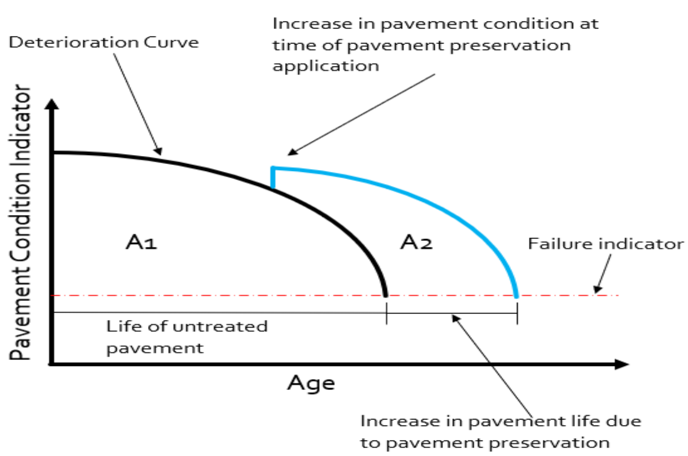



**Figure 4. Pavement condition deterioration with and without pavement preservation treatment.**

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 life of the pavement [1,31].

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 will determine the effectiveness or benefit-cost ratio of a pavement preservation treatment [1].

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 [1,31]. Maximizing the area of the post treatments curve ($A_2$ in Figure 4), is a basis on which optimal timing can be found [1,31]. 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 [1,31]. 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.

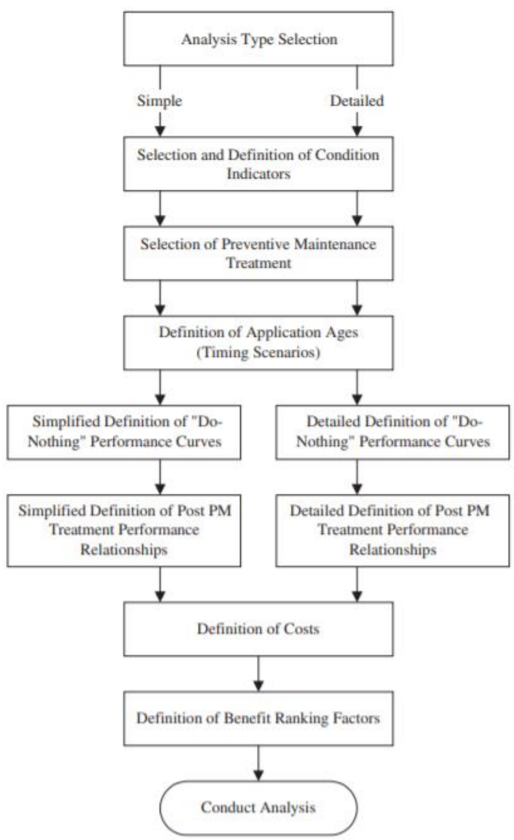



**Figure 5. Data input flow chart for OPTime [1].**

Haider and Dwaiket (2003) 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 came from 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 [31]. 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.

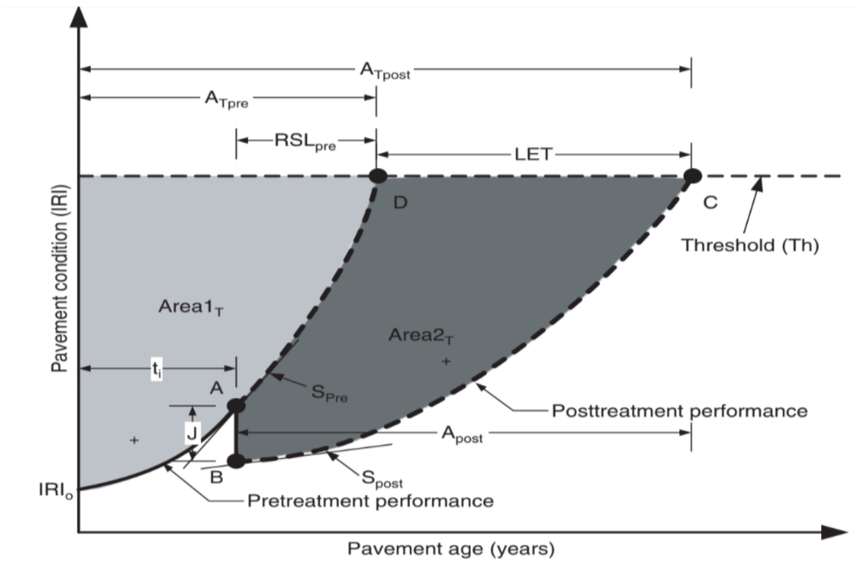



**Figure 6. IRI Deterioration vs. pavement age [31].**

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 [31]. By maximizing the areas in equations 1 and 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 [31].

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

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

Where,
Th = IRI Failure Threshold
$\alpha_1$ = Starting IRI Value
$\beta_1$ = Deterioration Rates of Performance Curves
$t_i$ = Treatment Application Time
$F_s$ = Post Treatment Slope Adjustment Factor
$F_J$ = Performance Factor After Treatment

This model focused solely on the international roughness index (IRI) as the determining factor in finding the optimal time [31]. The IRI levels pre and post preservation for different preservation methods determine the deterioration rates after application [31]. While limited by the fact that only the IRI shift from pre-treatment to post treatment determine the optimal timing of application, the model can be extended to other preservation alternatives [31]. 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) used an IRI deterioration to a failure threshold model that used traffic volumes (AADTT) and found optimal timing based on agency and user costs [32]. 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 [32]. 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 [32]. 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) method agree with Haider's and Dwaiket's (2003) model that better roadway conditions benefit from treatments later in the pavement's life, while poorer pavements benefit from treatments earlier in their life. This is further reinforced by the fact that roadways experiencing higher AADTT have longer life extensions if the pavement preservation methods are applied earlier in their life cycle [32]. 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) [32].

Wang et al. (2012) 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) [33]. Using these factors, crack seal, chip seal, micro-surfacing, thin overlay, and NovaChip were compared to find the varying degrees of benefits based on the application years [33]. 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 [33]. 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 [33]. 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 [33]. 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) 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) 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 [34]. 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 [34]. 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 can provide engineers with best estimates of optimal timing and cost efficiency. 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, and data reliability. However, these models could be applied to laboratory studies as well. The use of pavement conditions and distresses to determine optimal timing for applications allows data collected in a laboratory setting to be applied using a benefit curve. These benefit curves could be used to evaluate performance of a pavement preservation treatment against variations in distresses applied in lab tests that measure resistances to rutting and cracking.

## 2.5 Current State of Performance 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 material specific performance testing and field correlations.

Despite the lack of laboratory research on performance measures of pavement preservation treatments, development of performance based specifications has not gone ignored. Chatti et al. (2017) presented extensive information in the NCHRP Report 857 on how pavement preservation performance-related specification (PRS) should be developed. The authors stress the importance of using acceptance quality characteristics (AQC) based on attributes specific to the preservation treatments and relating the to performance to develop a PRS. Examples of microsurface attributes that can be used to develop PRS could be texture, cracking, rutting, raveling, and bleeding [35]. One example the authors establish is a PRS for chip sealing based on aggregate-binder bonding and aggregate loss using the Vialit test, but also raveling, stripping, bleeding, and flushing [35]. Thin overlay performance can be evaluated based on cracking, rutting, and surface roughness [35]. Microsurface performance can be evaluated based cracking, rutting, bleeding and stripping [35]. With this approach, a critical performance attribute of the pavement preservation treatment can be used to create specifications to determine acceptable limits for the use of pavement preservation treatments [35].

A long term study focusing on emulsion grading for binders used in chip seal and microsurface and correlating them to performance measures has been conducted and covered in NCHRP Report 837 [36]. 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. 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 [36]. For microsurface the primary distresses were identified to be cracking, raveling, bleeding, and rutting [36]. Kim et al. 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, 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 team used the wet track abrasion test to evaluate stripping potential, the MMLS3 was used to evaluate rutting and bleeding potential, the sand frame test and a glossometer were used to further evaluate bleeding, the locked wheel skid tester and British pendulum test were used to evaluate skid resistance, and 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.

The Minnesota Department of Transportation took the opportunity to evaluate pavement preservation treatment performance 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 was evaluated full scale on 500 ft. sections. 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 [37]. A single layer of microsurfacing with crack repair and double microsurfacing layers performed best in reducing reflective top down cracking (JJ). Microsurfacing is also effective at filling in ruts [37]. The addition of microsurface kept most test sections below hazardous rutting levels [37].

## 2.6 State agency guidelines, reports, and manuals

Based on the various studies and modeling of the effectiveness and life extension capabilities of pavement preservation in Sections 2.4 and 2.5, it is necessary to develop efficient strategies to implement these techniques to benefit transportation infrastructure. Considering the increasing popularity in using pavement preservation techniques, it is important to identify the various methods, choice criteria, and variations between different state agencies when it comes to their pavement maintenance programs. These programs can lay a foundation for other state agencies seeking to improve their roadways. The extent to which these various agencies differs is great which can be seen in this section.

Many state agencies have detailed manuals and guidebooks to assist users in choosing the proper pavement preservation and preventative maintenance methods. Other states include chapters in their pavement manuals briefly covering pavement preservation and the various techniques that can be used. It should be noted that the separate definitions of pavement preservation and preservation maintenance make a distinction between pavement preservation as a robust program employing pavement maintenance to maintain good roadway conditions [4]. Many of the manuals reference the FHWA's 2005 memorandum defining pavement preservation as "a program employing a network level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety and meet motorist expectations" [38]. There are certain aspects are similar across various pavement preservation programs and guides which are as follows [2,39-41]:

The objectives of pavement preservation programs:
1) Preserve investments put into pavement systems
2) Maintain a good pavement condition and LOS

The benefits of using pavement preservation include increased:
1) Pavement performance
2) User satisfaction
3) Costs saved on life and condition of pavement
4) Safety of the pavement

The process for selecting the proper treatment:
1) Gather visual conditions of pavement and data available on pavement conditions.
    a. This may include testing
    b. Information gathered should include: pavement age, pavement type and materials, and traffic volumes and types
2) Analyze gathered information on pavement conditions
3) Determine which pavement preservation methods are feasible for the pavement conditions
    a. Compare these methods based on cost, distresses addressed, and pavement conditions
4) Select the treatment

The following pavement preservation and pavement preventative maintenance manuals are not the sole agency guidelines in existence, but they do include agency guideline manuals and handbooks that contain some of the most extensive information.

### 2.6.1 California [2]

Caltrans has an extensive pavement preservation guidelines of any state agency. The document contains 13 chapters on various pavement preservation techniques. The document begins with chapters offering background on distresses and various pavement materials (asphalt binders, asphalt emulsions, cutback asphalts, polymer modified binders, asphalt rubber, and aggregates). There is an entire chapter devoted to treatment selection that makes the distinction between the need for preventative maintenance and rehabilitation/reconstruction. The document makes the reoccurring and important distinction that the only treatment a well-constructed and new roadway will require is pavement preservation.

The four main factors in deciding a treatment are listed as [2]:
1) To make sure the technique chosen will improve distresses.
2) That the pavement is prepared in a way that the treatment can be applied.
3) That the treatment is cost effective.
4) That the treatment can be carried out before the distresses change or get worse.

The overall objective of the selection process is to first visually and analytically determine the roadway conditions in order to determine the appropriate methods based on cost and life extension. Visual inspections of the pavement and survey forms should be used to make these assessments. The document states clearly that optimal timing and cost effectiveness are important factors in determining the appropriate pavement preservation condition and references several options and models in determining these factors. Feasible treatments for current conditions can then be chosen using matrices such as that found in Figure 7. Cost effectiveness of available options should then be compared and analyzed to determine the best option.

The remainder of the document is devoted to the various pavement preservation options that should be considered. These include crack sealing, patching and edge repair, fog and rejuvenating seals, chip seals, slurry seals, micro-surfacing, thin overlays, bonded wearing course, interlays and in-place recycling. Each preservation method chapter provides in depth information regarding materials, mix designs, distresses addressed, construction, trouble shooting, variations within each technique and under which climate conditions to use the treatment. These sections also include flow charts, decision making procedures, diagrams, photos, standards, and technical information. The information is clearly gathered from a wide variety of sources and each chapter is well referenced.

### 2.6.2 Minnesota [39]

A document entitled MnDOT Pavement Preservation Manual dated 2018 contains guidelines for choosing pavement preservation methods and it is stated that "the document should be used throughout the Department" [39]. The document contains general background on pavement preservation and references the FHWA memorandum regarding pavement preservation.

The selection steps for choosing the appropriate pavement preservation method appear to be designed to ensure that pavement preservation is chosen based on available information of pavement condition, optimal timing and methods, and to avoid using pavement preservation where it will either be inefficient or unwarranted (old pavements or structurally deficient roadways). The process begins with gather data regarding the current conditions of the roadway in question. Past data, software, traffic levels, and condition indicators can used to evaluate the current situation [39]. Then, potential treatment candidates are determined based on these conditions. A matrix is available, as seen in Figure 7, to help match potential treatments capable of being applied to roadways under certain levels of rutting, cracking, oxidation, friction, raveling, etc. The best treatment is then chosen based on cost effectiveness. While the manual does not specify the method to determine effectiveness, it mentions that cost versus benefit is commonly used by other agencies. Use of the data collected in the state's pavement management system is encouraged.

The document lists crack filling, rout and seal cracks, micro surfacing, seal coats, thin overlay, ultra-thin base wear course, micro milling, and fog sealing as available preservation methods [39]. Each preservation method has a section devoted to explaining various aspects of that particular method including specifications, cost, general treatment descriptions, application practices, conditions addressed, additional considerations, recommendations, alternative treatments, expected life, and photographs.

### 2.6.3 Illinois [41]

Chapter 52 of Illinois's Bureau of Design and Environmental Manual covers the state's pavement preservation strategy. Like many other manuals it immediately defines pavement preservation based on FHWA's memorandum. The benefits of pavement preservation are stressed as being protecting pavement investments and maintaining good pavement conditions [41].

Optimal timing of treatment application is stressed along with knowledge of the varying factors affecting pavement deterioration such as traffic, environment, materials, and moisture [41]. Proper application of the correct treatment at the right time can help prevent or mitigate distresses and fix minor surface distresses [41]. The chapter provides a list of pavement problems that are slowed and corrected by pavement preservation; the document also includes a list of distresses that are indicators it is too late for pavement preservation. The steps in determining the proper treatment type are identical to Minnesota's list. Pavement conditions are gathered using field surveys, historical data, current pavement distress data, and through the use of the state's pavement management system (PMS). Pavement management systems are stressed several times as an important tool in pavement preservation. The gathered data is then evaluated to determine if pavement problems are common or excessive in the area of interest. So long as distresses are not extreme, pavement preservation treatments can be considered. Treatments are then selected based on existing conditions using a matrix similar to the one in Figure 7.

The constraints affecting making the correct choice are identical to Minnesota's preservation guide (contractors, available materials, agency practices, time of year, costs, user preferences, noise, downtime, and surface friction) [39,41]. Like the Caltrans and Minnesota guides, the Illinois preservation guide includes charts to aid in the selection of pavement preservation methods based on distress types. Detailed information regarding the pavement preservation methods is also given; these methods include crack filling, crack sealing, fog seals, sand seals, slurry seals, micro-surfacing, chip seals, cape seals, cold in-place recycling, hot in-place recycling, SMART overlay (Surface Maintenance at the Right Time), half-SMART overlay, ultra-thin bonded wearing course, and cold milling [41].

### 2.6.4 South Dakota [42]

The South Dakota Preservation Guidelines contains extensive selection charts based on both distresses and pavement preservation methods. The steps in deciding the correct pavement preservation treatments are similar to those above. Pavement condition and information must be gathered and evaluated to ensure distress levels are not too extreme for the use of specific pavement preservation treatments [42]. The use of SSDOT's Enhanced Pavement Management-System is encouraged to gather distress levels. Excessive distresses (distress levels that present poor conditions for certain pavement preservation treatments) must be taken into consideration when using pavement preservation [42]. The selection matrices are each devoted to one of the following distresses: fatigue cracking, transverse cracking, patching, block cracking, rutting, IRI, D-cracking/ASR, joint spalling and corner cracking. Each chart comes with severity readings for each distress making it easy for a user to determine the extent to consider at which the condition of the pavement is currently at. The pavement preservation methods included in the guidelines are: crack sealing, diamond grinding, full-depth repair, cross stitching, sub sealing, pavement jacking, fog seals, scrub seals, rejuvenation, spray patching, micro-surfacing, rut filling, chip seal, thin overlay and cold milling [42]. Additional considerations must be taken into account when choosing methods such as pavement preparation, pavement markings, traffic control, treatment sequencing, and rumble strips [42]. However, the manual does not specify how to take these into account.

### 2.6.5 Pennsylvania [43]

Pennsylvania's Publication 242-Pavement Policy Manual contains a chapter on pavement preservation guidelines. The beginning of Chapter 12 lists 17 pavement preservation treatments including asphalt rejuvenators, sealers, crack sealing, crack filling, scrub seals, sand seals, chip seals, cape seals, slurry seals, micro surfacing, profile milling, ultra-thin friction course, thin overlays, mill and resurface, ultra-thin bonded concrete overlay of asphalt, hot in-place recycling, and cold in-place recycling [43]. The manual stresses AASHTO's definition of pavement preservation and strict adherence to the fact that it must be a longer term planned strategy to maintain proper roadway conditions. The document provides very general guidelines on the conditions for which pavement preservation treatments should be used under. Safety is a major consideration when choosing pavement preservation as an option. Treatments that enhance the safety for users is encouraged, while treatments that reduce safety in any way are barred from use [43]. However, the document does not define how to determine these safety considerations. This manual, however, does not include a matrix to aid decision making as do the other documents listed in this literature review. Rigid pavement preservation methods are also listed. General and technical guidance is provided to ensure the users maintain their projects under proper pavement preservation protocols.

### 2.6.6 New Mexico [40]

Another state with an extensive pavement maintenance manual is a document titled The New Mexico Department of Transportation's Pavement Maintenance Manual. The manual opens by discussing the growing importance of pavement preservation and maintenance. It also addresses the FHWA memorandum which clearly provides definitions and goals of pavement preservation. The manual presents an in depth look at various distresses that occur in pavements. The list of treatment options is quite extensive, including but not limited to crack sealing, crack filling, full depth crack repairs, fog sealing, chip sealing, slurry sealing, scrub seals, micro surfacing, cape sealing, overlays, Novachip overlays, hot in place recycling (HIR), and cold recycling overlays [40]. The manual also addresses concrete pavement preservation methods. Each method is accompanied by an extensive description of the background on the method and details on the various materials and application methods for each technique. Much of this manual references FHWA resources on pavement preservation.

### 2.6.7 Michigan [44]

Michigan has a pavement maintenance program in place. The document is entitled Capital Preventative Maintenance and includes guidelines for implementing preventative maintenance treatments. The manual contains an extensive list of pavement maintenance techniques including but not limited to HMA crack treatment, concrete crack treatment, joint resealing, chip seals, micro-surfacing, ultra-thin overlay, paver placed surface seal, thin overlays, and surface milling and overlay [44]. Interestingly, the document also includes emerging pavement treatment technologies including polymer injection slab stabilization, ultra-thin bituminous overlay-high volume, fibermat (SAMI), TruPave Engineered paving mat, and longitudinal joint stabilizer [44]. The document provides definitions for the user to understand the various types of maintenance. It also stresses the use of Pavement Management Systems as a source of valuable information in determining the proper type and time of maintenance technique.

Current roadway conditions and gathering initial information is the first step in determining the correct pavement preservation treatment [44]. Once the data has been evaluated, the possible treatments are selected by using a matrix similar to that in Figure 8, where current roadway conditions indicate potential performance of specific pavement preservation treatments. Selection is based on efficiency and cost, however the manual lacks a method of doing so. The document provides various pavement conditions that should be present when selecting specific pavement conditions. Each section devoted to each maintenance technique includes timing for application (based on remaining service life) and expected life additions to the pavement. Like many other documents, it is stressed that the optimal use of preventative maintenance techniques relies on applying them to roadways with good structural integrity.

### 2.6.8 New York [45]

Preventative maintenance is included as a 41-page chapter (chapter 10) of New York’s pavement design manual. Also included in this manual is a chapter on choosing a treatment type based on pavement evaluation (chapter 3). The entirety of the manual is meant to provided designers with NYDOT policies and guidance on pavement projects [46]. The manual specifically states that life cycle cost analysis does not have to be part of the decision-making process for making a decision between which preservation maintenance technique to use.

The manual breaks preventative maintenance into three main types: nonstructural overlays, minor pavement repairs, and drainage [45]. The nonstructural overlays and minor pavement repairs consist of preventative maintenance techniques similar to other agencies such as chip seal, slurry, micro-surfacing, thin overlay, and crack sealing in addition to paver places surface treatments, 6.3mm polymer modified HMA, and surface preparations [45]. However, the manual does not make any reference to “pavement preservation” and continuously classifies these as pavement maintenance. Descriptions of each technique is available along with the conditions for choosing the particular methods.

### 2.6.9 New Jersey [47]

Currently there is a lack of pavement preservation use and specifications in the state of New Jersey. While there are recommendations and specifications for the materials used for microsurfacing, slurry seal, and thin overlay, there are no guidelines on when to use these treatments (47). Specifications were being explored under FHWA-NJ-2015-11 for the use of pavement preservation treatments. The report conducted a thorough survey of other highway agency specifications and decision making tools and compiled them for evaluation and consideration for future use in New Jersey [6]. The report notes that a robust pavement preservation system may draw more contractors to the state which would help to grow pavement preservation options in the state [6].

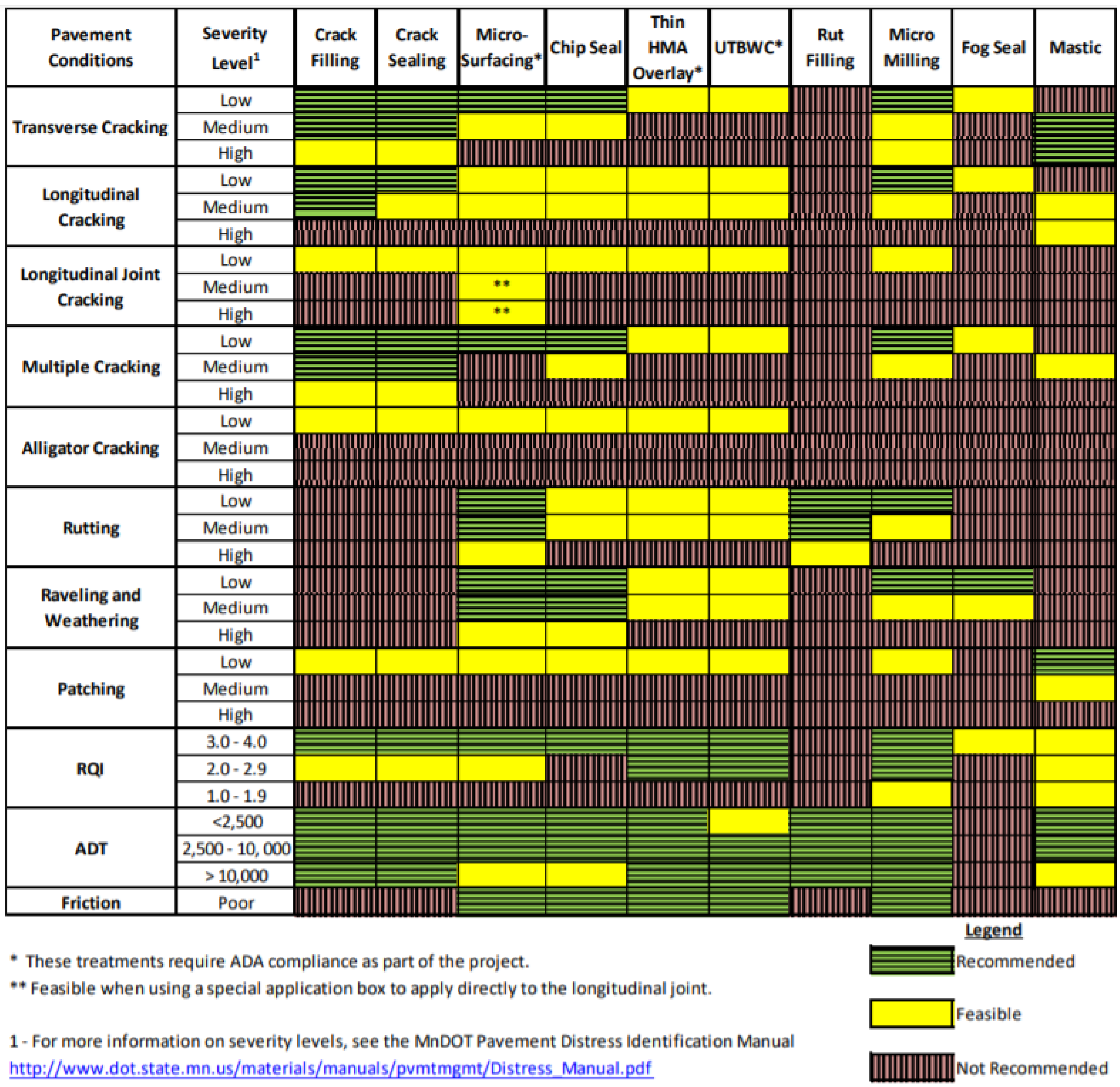



**Figure 7. Selection Matrix from MnDOT Pavement Preservation Manual [39].**

## 2.7 Summary

The available state agency guidelines on pavement preservation and their respective programs shows just how important pavement preservation is. Cost savings, funding, and condition of roadways are all major factors in the advancements of pavement preservation. States like California, Illinois, and Michigan among others stress the objectives, benefits, and data required in order to choose the best methods. These parameters are a common theme and could be considered for any pavement preservation program in addition to parameters that may be specific to the site or regions being studied.

LTPP SPS-3 had been a starting point in compiling accessible information regarding preservation methods; however the pavement condition indicators are not shared across all agencies. The various studies and models for cost effectiveness and optimal timing already conducted using this information shows how useful concise and comprehensive data can be. The study carried out by Wang et al. (2012) show that state agency data can also be used to evaluate pavement preservation method effectiveness.

LTPP SPS-3 formed a basis for which agencies can extract reliable and cohesive information. However, for each state agency to form their own programs, additional research would help to further strengthen pavement preservation programs. In addition to the objectives, benefits and required data, the pavement preservation techniques used across the various state agencies and for the LTPP SPS-3 study are also similar. Thin overlay, slurry seal, microsurfacing crack seal, and chip seal were listed in most of the manuals and guidelines mentioned in this paper. In addition to these, states also use slurry seal, scrub seals, cold-in-place recycling, hot-in-place recycling, cape sealing, Novachip, and fog sealing.

A lack of materials testing and laboratory performance evaluation presents a gap in pavement preservation research. While field data is vital to improving pavement preservation programs, quick and efficient means of determining material performance would aid in providing confidence to SHAs and contractors looking to include pavement preservation in their pavement management programs. Mix design and performance testing have been a key part in asphalt roadway design and can be applied to pavement preservation materials. In light of the conducted literature review and lack of laboratory testing, performance properties of microsurfacing and chip seal were chosen to be evaluated in this study. The similarity in their form (the material fully covering the existing surface), effectiveness (based on field studies), range of functions (seal cracks, waterproof roadways, rut filling, and restoring driving surfaces), and range of costs make these treatments excellent candidates to evaluate for use in further research. By conducting laboratory testing on these materials, a greater understanding of these treatment’s properties and capabilities can be gleamed. This study will aid in expanding the knowledge base of these materials and fill in the gaps related to determining the conditions under which these treatments should be applied.

# 3. DESCRIPTION OF MATERIALS

Optimal timing and application of pavement preservation methods depends on pavement condition and cost. Selection of the correct pavement preservation methods to test depends on a detailed analysis of these factors. Studies that have been conducted to determine the effectiveness of these materials also help to determine the best treatments to use. Reports evaluating pavement preservation practice can be used to choose the most commonly effective treatments. By combining these resources, it is possible to make an accurate determination of which methods should be further evaluated in this project using laboratory testing.

A study based on surveys sent to various state agencies by the Kentucky Department of Transportation conducted by Wang et al. (2011) compiled information regarding state agency use of pavement preservation methods used and expected life expectancy based on engineering judgement of the respondents. Of the responses, 83% of the states had a thin overlay program, 86% had a crack filling/sealing program, 83% had a chip sealing program, 21% had a slurry seal program, and 72% had a microsurfacing program. Slurry seals were the least used of the major methods despite being included in the SPS-3 survey [5]. The most commonly chosen methods agreed with an NJDOT sponsored report, report FHWA-NJ-2015-011 that surveyed state DOT agencies and found the four most common pavement preservation methods as chip sealing, crack sealing, microsurfacing, and thin overlay [5,6].

Peshkin and Hoerner (2005) compiled an extensive report on current pavement preservation practices and studies in order to develop pavement preservation specifications for the National Cooperative Highway Research Program. In this report they included relevant reports pertaining to the pertinent and recent pavement preservation research, programs, and needs. Based on the surveys distributed to SHAs and the research the team conducted, the most common pavement preservation treatments were found to be crack sealing, chip seals, microsurfacing and slurry seals, sand seals, rejuvinators, thin overlays, and open graded friction courses [48].

Due to the abundance of microsurfacing programs in use, microsurfacing is a top candidate for pavement preservation testing due to the availability of sufficient practice and data. Louisiana's chip seal and microsurfacing program were evaluated by Shah et al. (2002). Using pavement management system data and visual observation of test sections the team compared the two preservation methods in addition to effects of pre-treatment conditions, traffic, and age. Using PCI as the pavement indicator, the team found that after 52 months the median PCI for chip seal treated sections was 75 and 75% of the sections were in good to excellent condition. For microsurfacing, the median PCI was 85 after 60 months and almost all sections were considered good to excellent. Microsurfacing therefore maintained better pavement conditions through its life, however it is costlier than chip sealing. This makes microsurface another good candidate for testing as it may offer increased benefits when compare to chip seal.

The treatments selected in this study were chip seal and microsurface. These treatments were selected based on surveys conducted in previous studies covered in the literature review and various field performance studies [5,6]. These two treatments represented similar application methods (use of emulsified binders and applied in ultra-thin layers) but are different in their cost and uses. The materials used in this study were aggregates, binders, and mixtures obtained from local suppliers that follow specifications in accordance with local and federal highway agencies. Specific mix designs and application rates fell within ranges specified by local and federal highway agencies. Descriptions of the sample production process can be found in the subsequent sections.

### 3.1 Hot Mix Asphalt

The hot mix asphalt used for this study was an unmodified PG 64-22 binder with a 9.5 mm Nominal Maximum Aggregate Size provided by a local supplier. This material provided the base for the application of the pavement preservation materials. The samples were compacted in the lab using the Superpave Gyratory Compactor Mold. A CSS-1h emulsified tack coat was applied to the surface of compacted asphalt samples and cut OT samples prior to the application of the pavement preservation treatment at a rate of 0.10 gal/yd$^2$ as per NJDOT standard specifications [47].

### 3.2 Microsurfacing

Microsurfacing is an ultrathin layer applied to the surface of asphalt in order to seal the roadway and restore driving surfaces [35]. In this study, the microsurface mixture included a quick setting polymer-modified emulsion binder (CQS-1hpm), type I/II Portland cement as a mineral filler, water, and Type II microsurface aggregates which are used in surface course microsurfacing. The residue after distillation of the emulsion binder 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 [47] for microsurface 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. Figure 8 shows the consistency of the final mixture prior to pouring.

(a) (b)

**Figure 8. Microsurface Mixture and Application to OT Sample. (a) Mixture and (b) Mixture Applied to OT Sample**

### 3.3 Chip Seal

Chip seal is applied by laying down either hot or emulsified binder and rolling aggregates into the binder. This method is generally used to seal transverse cracks and improve riding quality [35]. The chip seal materials used in this study were a 1/4 in. chip seal aggregate provided by a local contractor which is used in local projects. Additionally, it was chosen for the benefits that smaller aggregates offer in chip sealing including reduced ride noise and windshield cracking [11]. A polymer modified CRS-2 quick set chip seal emulsion binder was used. It is important to note that the tack coat and emulsion binders were stirred on a daily basis to ensure separation did not occur. The quantities applied for the emulsions were converted from the application rates into mass quantities using the supplier's specific gravity of 1.01. This allowed the application to be measured to the nearest 0.01g using a balance. In this way, the application rate could simulate standard specifications and be kept constant across the various samples. Figure 9 shows the aggregates used and final product.

**(a)** **(b)**

**Figure 9. Chip Seal Aggregates Rolled into Emulsified Binder on OT Sample. (a) ¼ in. Aggregates and (b) Emulsion and Binder Applied to OT Sample**

# 4. DETERMINING LEAST ACCEPTABLE PAVEMENT CONDITIONS FOR PRESERVATION TREATMENTS

The process of evaluating the performance benefits of pavement preservation treatments requires establishing a procedure for fabricating and testing samples that are representative of how such treatments are applied in the field. Such a procedure is essential to comparing the performance of untreated and treated samples. A laboratory performance test procedure must also be selected based on the treatment applied and the potential benefits it offers to existing pavements. The details of the procedure proposed for evaluating the performance benefits (mainly cracking resistance benefits) and determining potential conditions at which pavement preservation treatments should be used is presented in the following subsections.

## 4.1 Step 1: Select a Laboratory Performance Test

Depending on the type of pavement preservation treatment being evaluated and their performance benefits, the first step of the proposed procedure is to select a proper laboratory test for assessing the performance of untreated (control) and treated samples. Such testing was used to determine the increase in performance (e.g., cracking resistance) due to the application of a preservation treatment. To elaborate more, when applying a microsurfacing layer to an existing pavement structure, for example, the performance benefits attained are sealed cracks. Therefore, for microsurfacing applications it is suitable to determine the increase in cracking resistance when the treatment is applied. This can also be translated into a potential number of years by which a microsurfacing treatment is expected to extend a pavement layer (i.e., if the life of a typical layer made of the surface HMA mix is known).

In this study, chip seals and microsurfacing treatments were evaluated for their cracking resistance when applied to an HMA layer. For this reason, the selected performance test was a modified version of the Texas Overlay Tester (OT) test as seen in Figure 10. The OT also offers a good representation of the distresses the pavement preservation treatments would experience in the field. For example, the treatments are going to be applied to roadways years after their construction when distresses have begun to appear. The treatments will therefore likely be applied to roadways with existing cracks. Reflective cracking will be a distress type that pavement preservation treatments will likely be exposed to as the existing cracks and propagating cracks will move through the upper layer from the existing asphalt. As commonly known, the OT involves applying a constant displacement load (i.e., 0.6 mm. at 0.1 Hz) and recording the force required to apply such displacement. The test continues until a 93% reduction of the peak tensile load (recorded for the first cycle) is reached. The OT samples are produced by cutting cylindrical specimens to a final sample size of 150 mm. x 76 mm. x 38 mm. Modifications were made to the testing procedure to ensure successful testing of samples in this study, in particular the pre-cracked samples. Under the normal testing conditions (0.6mm displacement), the pre-distressed control samples would crack straight through on the first cycle. Abrupt actuator movements were causing the sample to fail from the first cycle. This corrective method appeared to cause the test to run longer than the controls. The displacement load was reduced from 0.6 mm. to 0.3 mm to address these premature sample failures. This modification was reported to not affect the variability of OT test results [47]. In addition, it yielded results that were expected, namely the pre-distressed samples failed sooner than the non-distressed samples.

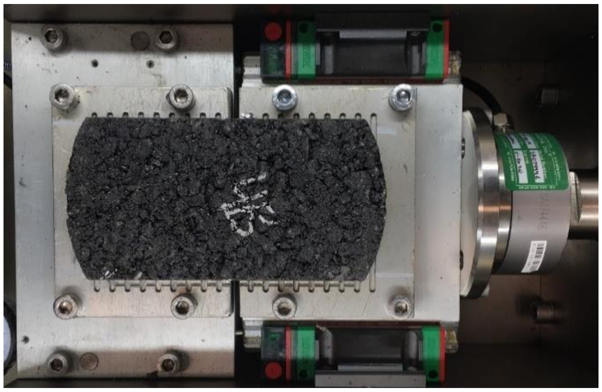


**Figure 10. Texas Overlay Tester Instrument with Modified Untreated Sample.**

### 4.2 Step 2: Select Pavement Condition Thresholds

It is commonly known [1, 31-32] that the degree to which a pavement preservation treatment extends the life of a flexible pavement structure heavily depends on the condition of such structure before the application of the treatment. That is, if the pavement structure is in poor condition, a preservation treatment may not significantly extend the life of such a pavement and, in fact, the treatment may be ineffective from a cost perspective. Since one of the functions of both chip seal and microsurfacing is to seal cracks, a reflected crack from the original pavement through the preservation treatment to the surface would mean it is failing to carry out one of its primary functions. In addition, cracks existing at the surface will likely increase IRI values and contribute to an all-around rougher ride, effectively reducing another major function of these treatments which is to restore driving conditions. The existing pavement condition affects the performance of the pavement preservation treatment. Therefore, to determine the least acceptable conditions at which a particular treatment can be applied while still being beneficial, pavement condition thresholds must be defined.

Since the proposed evaluation approach is laboratory-based, pre-cracked treated samples can be assessed. By doing so, the test samples will simulate a field sample. The severity of a crack can be established using the Long Term Pavement Performance (LTPP) Distress Identification Manual thresholds or currently established state based thresholds. As an example, to determine if a chip seal is applicable when medium severity cracks are present in the existing pavement, samples can be pre-cracked and tested at widths ranging between 6 mm. to less than 19 mm. [49]. For the OT samples prepared as part of this study, HMA OT samples were pre-cracked to have a depth of 9.5 mm as seen in Figure 11. This was done using a hand saw with an adjustable blade depth to maintain consistent depth across the sample. The width of the blade would produce cuts 3mm wide. To produce the 6mm cuts, an initial cut was made with the saw and the remaining width was shaved away slowly with the saw. Measuring was done frequently to ensure the cut was not made too wide.

It is recommended to conduct testing (Step 4) on samples prepared at two crack severity levels; low severity (3 mm. to less than 6 mm. wide) and medium severity (6 mm. to less than 19 mm. wide), as that would allow for determining the least acceptable distress severity level a preservation treatment can be applied. In addition, samples without cracks represent the pavement early on in its life and can used as both a control for comparison, and satisfy the scenario of using the treatment within the first few years of the pavement life.

**Figure 11. Distressed HMA Sample.**

### 4.3 Step 3: Fabricate Samples Representative of Field Treatment Application Procedures

A procedure for fabricating laboratory “treated” samples is also necessary to facilitate performance comparisons with untreated mixes. Depending on the selected performance test, samples can be fabricated using standard procedures. A pavement preservation treatment is then applied to the samples.

For this study, the OT test was selected for evaluating the cracking resistance of HMA mixtures treated with either a chip seal or a microsurfacing preservation treatments. The procedures employed for fabricating samples using both preservation treatments are presented in the following subsections. For both treatments, the control (HMA) OT samples were first compacted using a Superpave Gyratory Compactor (SGC). The HMA samples were then cut to the standard OT sample size as specified in Tex-248-F and NJDOT-B10 of 38 mm x 76 mm x 150 mm. An air voids level of 7 ± 1% was targeted for the control HMA OT samples. It is also noted that the samples were obtained from the outer third, as opposed to middle, of the SGC specimen in order to ensure a rough surface is present, similar to field conditions, when applying the selected preservation treatments. OT samples are generally smooth on both faces as the outer portions are cut away. This does not accurately represent the conditions onto which a pavement preservation treatment will be applied.

To facilitate the application of both treatments, a 3D printed plastic mold (seen in Figure 12) was fabricated and used to encase the HMA OT samples. A silicone based water sealant was also applied around the edges of the OT samples (Figure 12a) to prevent the emulsion from exiting the mold by effectively sealing it. Additional silicone sealant was placed down the corners of the sample as this was found to be a point from where the chip seal and microsurface emulsion frequently would frequently escape the mold. For application of asphalt emulsions, the quantity of materials used was determined based on the surface area of the sample and standard application rates [47,48]. An asphalt emulsion tack coat (CSS-1h) was used prior to application of the pavement preservation treatment. The tack coat was applied to the surface at a rate of 0.10 gal/yd$^2$ (Table 1) and spread using a small spatula (Figure 12b) to ensure the entire surface of the sample was covered. It was found that by applying the tack coat in three separate columns and spreading from these starting locations produced the most even surface and ease of spreading as seen in Figure 12c and Figure 12d. Spraying the tack coat using a plastic spray bottle was attempted; however, it was found that the spray bottle would clog fairly quickly hindering the application. Additional sample fabrication details for each preservation treatment are provided in the following subsections.

**Table 1. Microsurfacing and Chip Seal Application Rates Implemented in this Study**

| **Microsurfacing** | | | | |
|---|---|---|---|---|
| Property | Tack Coat | Aggregates | Cement | Mixture |
| App. Rate* | 0.1 gal/yd$^2$ | N/A | 0% to 3% | 22 lb/yd$^2$ |
| Qty. Applied | 4.99 g | 106.87 g | 1.60 g | 130.38 g |
| Property | Emulsion | Residual Asphalt | Water | |
| App. Rate* | N/A | 5.5% to 11.5% | As Required | |
| Qty. Applied | 13.49 g | 8.44 g | 8.55 g | |
| **Chip Seal** | | | | |
| Property | Tack Coat | Aggregates | Emulsion | |
| App. Rate** | 0.1 gal/yd$^2$ | 21 lb/yd$^2$ | 0.35 gal/yd$^2$ | |
| Qty. Applied | 4.99 g | 124.37 g | 17.47 g | |

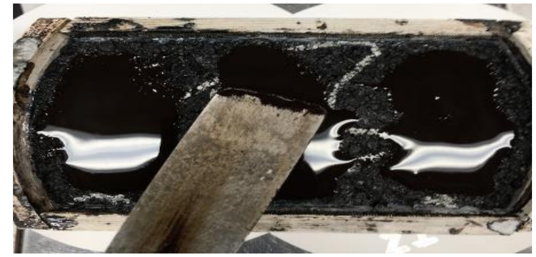
* Based on NJDOT Specifications [47] **Based on FHWA Specifications [48]

### 4.3.1 Fabrication of Chip Seal Treated Samples

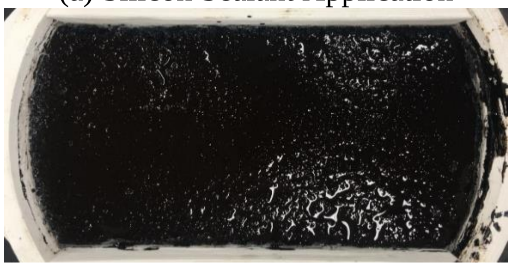
First, tack coat was applied to the surface of the pre-cut OT sample. Before the application of the emulsion binder, the tack coat must be dried to the point it was "tacky" to the touch as is described in the Updated Standard Specifications for Road and Bridge Construction [47]. Once the tack coat had dried, the aggregates for chip seal were then wetted with water (i.e., adding 2% by aggregate weight to dry aggregates) followed by hand-mixing for 30 seconds. The wetting of the aggregates follows the standard specifications laid out by the FHWA for aggregate preparation prior to the use of chip seal aggregates with emulsion based binder [49]. Then, the chip seal asphalt emulsion (CRS-2) was poured on the surface of the sample at a rate of 0.35 gal/yd$^2$ and was spread using a spatula (Figure 12e); in a similar manner to tack coat application. The total emulsion (SG=1.01) applied to the surface of the OT sample was approximately 17.47 g (Table 1). After the emulsion is spread evenly, the wetted aggregates are immediately placed and rolled to the surface at a rate of 21 lb/yd$^2$ (Figure 13f). The application of the aggregates should take place as soon as possible after the application of the emulsion binder to ensure the binder does not stiffen. The total quantity of aggregates used for the OT sample was 124.37 g. The aggregates were rolled into the applied emulsion using a PVC pipe that was cut to a length of 76 mm. and coated with 3 layers of duct tape to prevent aggregate cracking due to rolling. The duct tape was wetted to reduce adhesion of the binder with the applied emulsion. The implemented rolling approach aligned the aggregates flat on the surface of the sample (Figure 12g). It is noted that a ten pound weight was used on top of the PVC pipe to keep the rolling procedure consistent from one sample to another. The samples were cured in an oven at a temperature of 35°C for 24 hours inside the plastic molds before demolding. It is noted that a higher curing temperature was attempted (i.e., 64°C); however, at this temperature the emulsion was flowing around the aggregates, leaked out of the molds, and warped the molds. This can be seen in Figure 13 in a cross section of the chip seal pre and pose curing. The final sample surface can be seen in Figure 14.

(a) Silicon Sealant Application

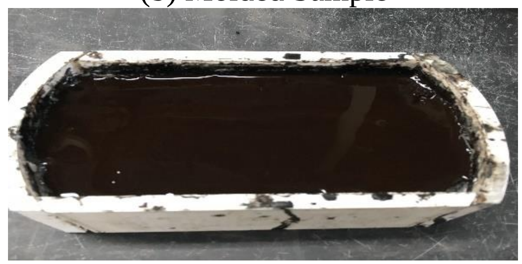
(b) Molded Sample



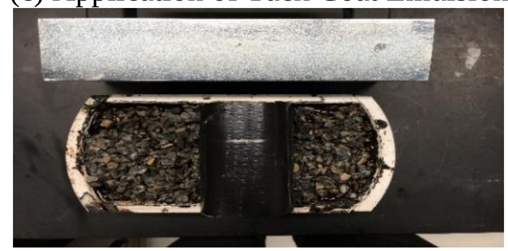
(c) Application of Tack Coat Emulsion



(d) Curing Tack Coat Layer



(e) Application of Chip Seal Emulsion



(f) Application & Rolling of Chips

(g) Final Chip Seal Treated OT Sample

(h) Microsurfacing Mixing Process

(i) Pouring & Spreading Microsurfacing Mix

(j) Final Microsurfacing Treated OT Sample

**Figure 12. Laboratory fabrication of HMA OT samples treated with a chip seal or a microsurfacing preservation treatments.**

(a) (b)

**Figure 13. Chip Seal Curing at 65ºF.**
**(a) Pre-curing and (b) Post-curing**

**Figure 14. Surface of Chip Seal Treated Sample.**

### 4.3.2 Fabrication of Microsurfacing Treated Samples

For microsurfacing treated samples a microsurfacing mix (Figure 12h) is first prepared. This mix included type I/II Portland cement, aggregates, water, and asphalt emulsion at proportion illustrated in Table 1. The tack coat was applied to the OT sample in the same manner as the chip seal sample. When the tack coat dried, the microsurface mixture was prepared. The aggregates and cement were dry-mixed together to ensure the cement was well distributed within the Type II aggregates. Next, the water was applied to the mixture and stirred by hand for 30 seconds to ensure the water was distributed well within the mixture. Finally, the emulsion was added to the center of the mixture and stirred by hand for 30 seconds. The mixture is poured on top of a molded sample, ensuring the mixture remains well distributed as it pours out. The mixture had a tendency to separate when it was being poured. It was found that using a smaller pouring vessel reduced this problem. The mixture was added to the surface down the middle of the sample. The mixture was then spread using a spatula. To ensure an even surface and consistent thickness, a caliper was used to measure the distance from the top of the mold to the mixture surface. If the mixture was uneven, the mixture was spread using a spatula to compensate the lower areas using material from the higher areas and then leveled to obtain a smooth surface. The use of the 3D molds ensured the distance from the top of the mold was the same around the sample's edge. A total of 130.38g of microsurfacing mix was poured and spread on all samples (Figure 12i). The sample was then left for 24 hours at room temperature (25ºC) to cure. A razor blade was used to separate the edges of the mold from the placed microsurface mix. It was observed that if the razorblade was not used, the microsurface would break off in areas where the binder had attached to the mold. The silicone was then removed using a razorblade. Additional curing in an oven at 65ºC for 48 hours was also applied to ensure the emulsion is fully cured before testing (Figure 12j). Final microsurface samples can be seen in Figure 15. In addition, a cross section of the distressed with a 3mm wide crack can be seen in Figure 16. This was done to see if the material was entering the crack.

**Figure 15. Final Microsurface Samples.**

**Figure 16. Microsurface Presence in 3mm Crack.**

### 4.4 Step 4: Test Treated Samples and Determine Least Acceptable Conditions for Applying a Preservation Treatment

Laboratory performance testing is then conducted to determine the performance benefits of using a pavement preservation treatment with respect to reflective cracking. It is recommended to conduct testing on various sets of undamaged samples prepared with and without the application of treatments. The exposure of a pavement preservation treatment to existing cracks can vary depending on different roadway conditions. The reflection of these cracks and performance of the treatment will be altered depending on the existence of cracks and severity of cracking. As mentioned earlier, two damage severity levels (low and medium) as defined in the LTPP Distress Identification Manual at minimum are recommended.

Once performance testing is conducted, statistical analyses (e.g., Analysis of Variance, ANOVA) can be conducted to determine the significance of differences in performance among treated and untreated groups of samples; taking into consideration the damage severity levels. The least acceptable pavement condition (i.e., distress state) at which a specific pavement preservation treatment is applied can then be determined by comparing performance improvements. These improvements are obtained by comparing treated undamaged and damaged sample groups compared to the untreated control group. The least acceptable pavement condition level (i.e., excellent condition with no damage, low damage severity, or medium damage severity) at which a pavement preservation treatment can be applied is therefore defined as that showing performance benefits in comparison to the untreated control samples due to the application of a preservation treatment.

### 4.5 TESTING PROGRAM

Testing was conducted on microsurface and chip seal samples to evaluate the applicability and practicality of the proposed procedure for evaluating the performance benefits of pavement preservation treatments. As discussed in the previous section, undamaged untreated control samples, damaged untreated samples, and damaged treated samples were tested using a modified OT test procedure. Table 2 presents the overall testing program completed as part of this study. The following performance comparisons can be made among the various sample sets highlighted in Table 2:

Quantifying the performance benefits obtained by applying a chip seal or a microsurfacing layer on undamaged samples (i.e., excellent pavement condition with no cracks). This is possible through comparing the performance results for Set B and the Control sample.

- Evaluating the performance benefits obtained by applying a chip seal or a microsurfacing layer on low severity cracked samples (i.e., samples pre-cracked to a width of 3 mm. and a depth of 9.5 mm.). This is possible through comparing the performance results for sample sets C and D.
- Quantifying the performance benefits obtained by applying a chip seal or a microsurfacing layer on medium severity cracked samples (i.e., samples pre-cracked to a width of 6 mm. and

a depth of 9.5 mm.). This is possible through comparing the performance results for sample sets E and F.

- Determining the least acceptable pavement condition at which the application of a chip seal or a microsurfacing treatment can be applied with the treatment is still showing improvement in performance. This is possible by comparing Set B, Set D, and Set F to the control samples set.

**Table 2. Testing Program Conducted To Evaluate the Performance Benefits of Chip Seals and Microsurfacing Pavement Preservation Treatments.**

| **Sample Set** | **Preservation Treatment** | | | **No. of Samples*** |
|---|---|---|---|---|
| | **No Treatment** | **Chip Seal** | **Micro-surfacing** | |
| Untreated, undamaged (Control) | ✓ | | | 5 |
| Treated, undamaged (Set B) | | ✓ | ✓ | 10 |
| Low severity cracking, untreated (Set C) | ✓ | | | 5 |
| Low severity cracking, treated (Set D) | | ✓ | ✓ | 10 |
| Medium severity cracking, untreated (Set E) | ✓ | | | 5 |
| Medium severity cracking, treated (Set F) | | ✓ | ✓ | 10 |
| Total No. of Samples | | | | 45 |

* Number of Overlay Tester samples fabricated for each set.

# 5 LEAST ACCEPTABLE CONDITIONS FOR PAVEMENT PRESERVATION: RESULTS, ANALYSIS, DISCUSSION

This section presents a discussion of the results obtained as part of this study. Specifically, the following subsection provide a discussion of the applicability and practicality of the proposed approach, assessment of pavement preservation performance benefits, and statistical analysis results.

## 5.1 Applicability and Practicality of the Proposed Performance Evaluation Procedure

The applicability and practicality of the proposed laboratory procedure for evaluating the performance benefits gained due to the use of pavement preservation treatments depends on two main factors: (1) the ability to produce samples in the laboratory consistently and (2) the OT test is sensitive enough to capture the differences among the various sample types. Figure 17 presents the OT testing results for control, chip seal treated, and microsurfacing treated samples. The data presented are for samples of each damage severity level and treatment condition. The changes made to the displacement (0.6 mm. to 0.3 mm.) of the OT test and modification to the samples still present a load vs. cycle trend consistent with what is typically seen when the test is run using typical settings [49]. As illustrated in Figure 17, the control, untreated samples with no crack applied (Figure 17a) had similar (within a 100 cycles) number of OT cycles to failure than those obtained for the chip seal treated samples (Figure 17b) and significantly lower than those obtained for the samples treated with microsurfacing (Figure 17c). With the introduction of a 3 mm. wide crack into the OT samples, it can be seen from Figure 18 that the OT cycles to failure for the untreated samples (Figure 17a, 155 cycles) was lower than that for those treated with a chip seal (Figure 17b, 314 cycles). Figure 17c also shows that the 3 mm. cracked samples treated with a microsurfacing had similar OT cycles to failure (147 cycles) when compared to the 3 mm. cracked but untreated samples. In addition, Figure 18 shows that the number of OT cycles to failure was similar for all treated and untreated samples when a 6 mm. wide crack was pre-applied. These observations clearly suggest that the modified OT was sensitive enough to capture the difference among samples based on damage severity level and the application of a treatment. Therefore, it can be concluded that the proposed approach was applicable to, at a minimum, chip seals and microsurfacing.

To highlight the consistency in preparing treated samples using the procedures described previously, the Bulk Specific Gravity ($G_{mb}$), as determined using AASHTO T 166, for all treated and untreated samples were compared (Figure 17d). It is noted that the $G_{mb}$ values were utilized, as opposed to air voids, because of the difficulty associated with determining the Maximum Theoretical Specific Gravity ($G_{mm}$) of the samples treated with chip seal or microsurfacing. As shown in Figure 17d, the bulk specific gravity of the treated and untreated samples were relatively similar; indicating that the treatment did not have an impact on the air voids of the samples. Similarity among the $G_{mb}$ values also suggests that samples can be produced with good consistency and repeatability. By comparing the error bars (standard deviation) among each group of samples, it can be seen from Figure 17d that the standard deviation is relatively small in each group of samples. This further indicates that the treated-undamaged as well as the treated-damaged samples can be prepared consistently in the laboratory using the proposed procedures.

Overall, the results presented in Figure 17 show that the proposed approach for quantifying the benefits of pavement preservation treatments is applicable and practical. This is the case because treated-damaged and treated-undamaged samples were consistently produced. The OT test was also sensitive to changes in the condition of the samples.

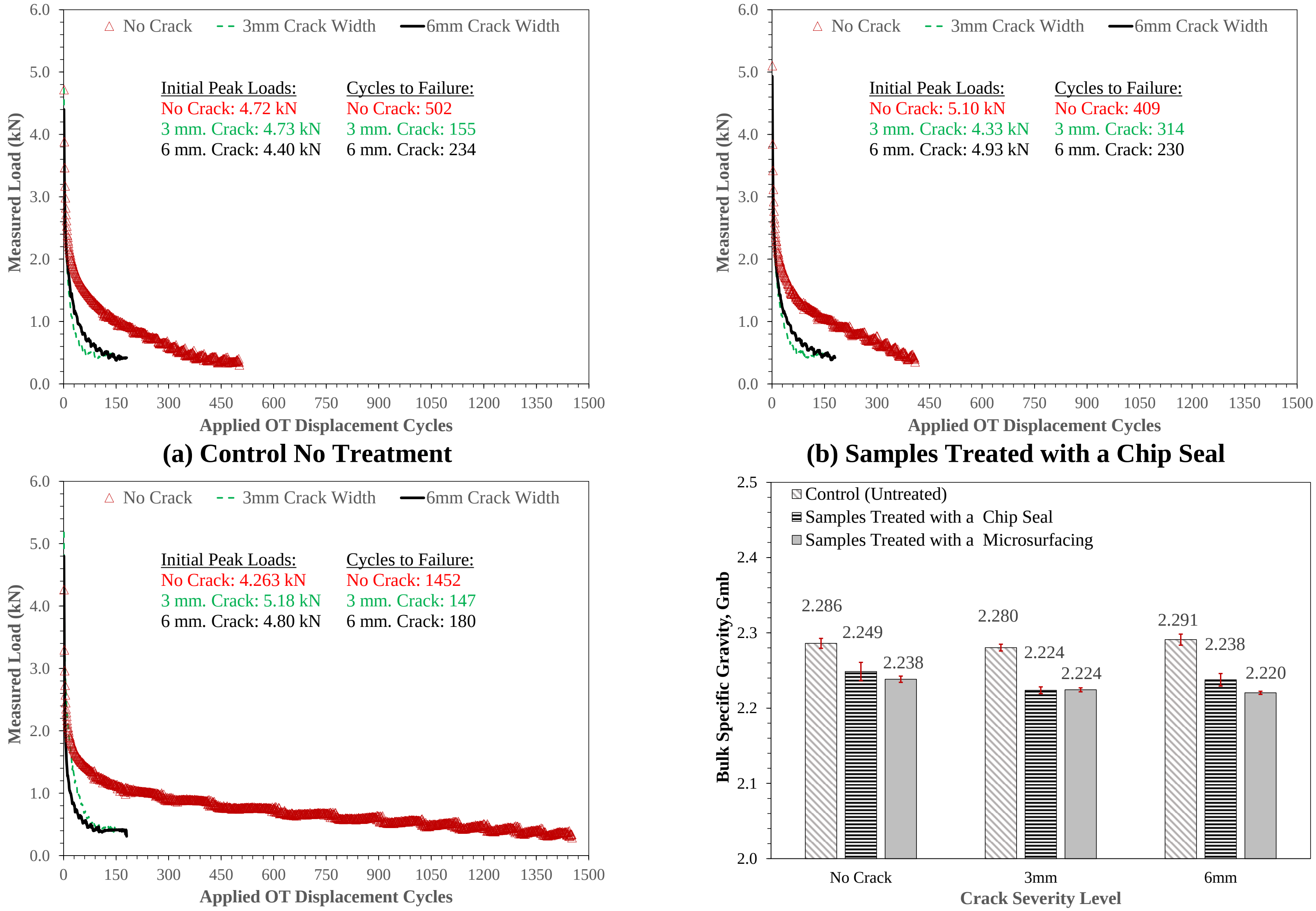
### 5.2 Assessment of Pavement Preservation Performance Benefits

Figure 18 presents the OT number of cycles to failure for all sample sets tested as part of this study along with performance benefits attained from applying pavement preservation treatments. This was done using a benefit factor, where the number of cycles to failure for a treated sample is divided by the control cycles to failure. A benefit factor >1 indicates the treatment enhanced cracking performance of the entire sample. As can be seen from Figure 18a, for undamaged samples (i.e., no crack state), the number of OT cycles to failure for the samples treated with a microsurfacing layer was significantly higher than that obtained for the control (untreated) samples. The control and chip seal treated samples had similar OT cycles to failure (Figure 18a). These observations indicate that the application of a chip seal does not necessarily improve the cracking resistance of surface asphalt pavement layers. On the other hand, these results indicate that applying a microsurfacing treatment on roadways with excellent condition leads to an overall improvement in the cracking resistance of HMA treated with microsurface.

When a low severity crack (3 mm. wide) is applied to the samples, the performance benefits obtained from chip seals and microsurfacing treatments change based on the OT cycles to failure results which are presented in Figure 18a. To elaborate more, Figure 18a shows that the OT cycles to failure for the untreated and microsurfacing treated samples were relatively similar (a difference of 14 cycle). These observations indicate that microsurfacing may not be suitable for even low severity cracked pavements as there are no improvements in cracking resistance (not cost effective treatments). The main reason as to why there are no improvements in cracking resistance with respect to cycles to failure when a microsurfacing treatment is applied on cracked samples is believed to be due to the poor adhesion between the crack sides and the microsurfacing mix, which does not deter the crack propagation.

In the case of the chip seal treated samples, slight improvements in cracking resistance, when compared to 3 mm. cracked-untreated samples, can be observed. Figure 18a shows that the chip seal treated samples (with 3 mm. wide cracks) had slightly higher OT cycles to failure than the untreated samples. This is an interesting result because it suggests that the application of chip seals might be more suitable when the low severity cracks are present than when the pavement is in an excellent uncracked condition. These observations are believed to be reasonable because of the mechanism by which a chip seal is applied. When applying a chip seal to low severity cracks (3 mm. in this case), the first step is the application of the asphalt binder emulsion. When applied, the emulsion fills the crack; establishing a bond between the emulsion and the sides of the crack that helps in increasing the cracking resistance in comparison to samples with no chip seals applied. For a 3 mm. crack, the aggregate chips do not enter the crack; thus, keeping the bond between the asphalt emulsion and the crack sides intact. Figure 18a also shows that samples cracked using 6 mm. wide cracks had similar OT cycles to failure. This was the case for all sample sets; untreated, treated with chip seals, and treated with microsurfacing. For medium severity (cracks that are 6 mm. wide); therefore, these observations indicate that neither chips seals (1/4 in. aggregate size) nor microsurfacing preservation treatments are suitable because there are no performance improvements attained from them. In other words, applying these treatments under medium severity conditions is not cost effective. In these cases, the crack propagation is not halted by the pavement preservation treatment in a way that significantly adds cycles to the sample. Crack propagation from the underlying pavement through the pavement preservation results in an unsealed roadway and increased IRI, effectively reducing two of these treatments functions. In addition, while the cracking resistance slightly improved due to chip seal application on low severity cracked samples, the same application on medium severity did not lead to appreciable improvements. This is mainly attributed to the presence of aggregate chips inside the crack compromising the bond between the crack sides and the chip seal emulsion and presenting a weak point around which the crack can continue to propagate up through the material which can be seen in Figure 19.

To further understand the benefits attained from chip seals and microsurfacing treatments, a Benefit Factor (BF) values was defined as the ratio of number of OT cycles to failure for treated samples to those for untreated samples while keeping the crack severity level constant. Figure 18b presents the BF values obtained for the samples treated with a chip seal and microsurfacing. As shown in this figure, the microsurfacing treatment was the most beneficial for samples with no cracks (2.9 times the control samples). Figure 18b also shows that the chip seal resulted in a BF 2.0 for samples with low severity cracks. These observations further enforce the observations made from Figure 18a.



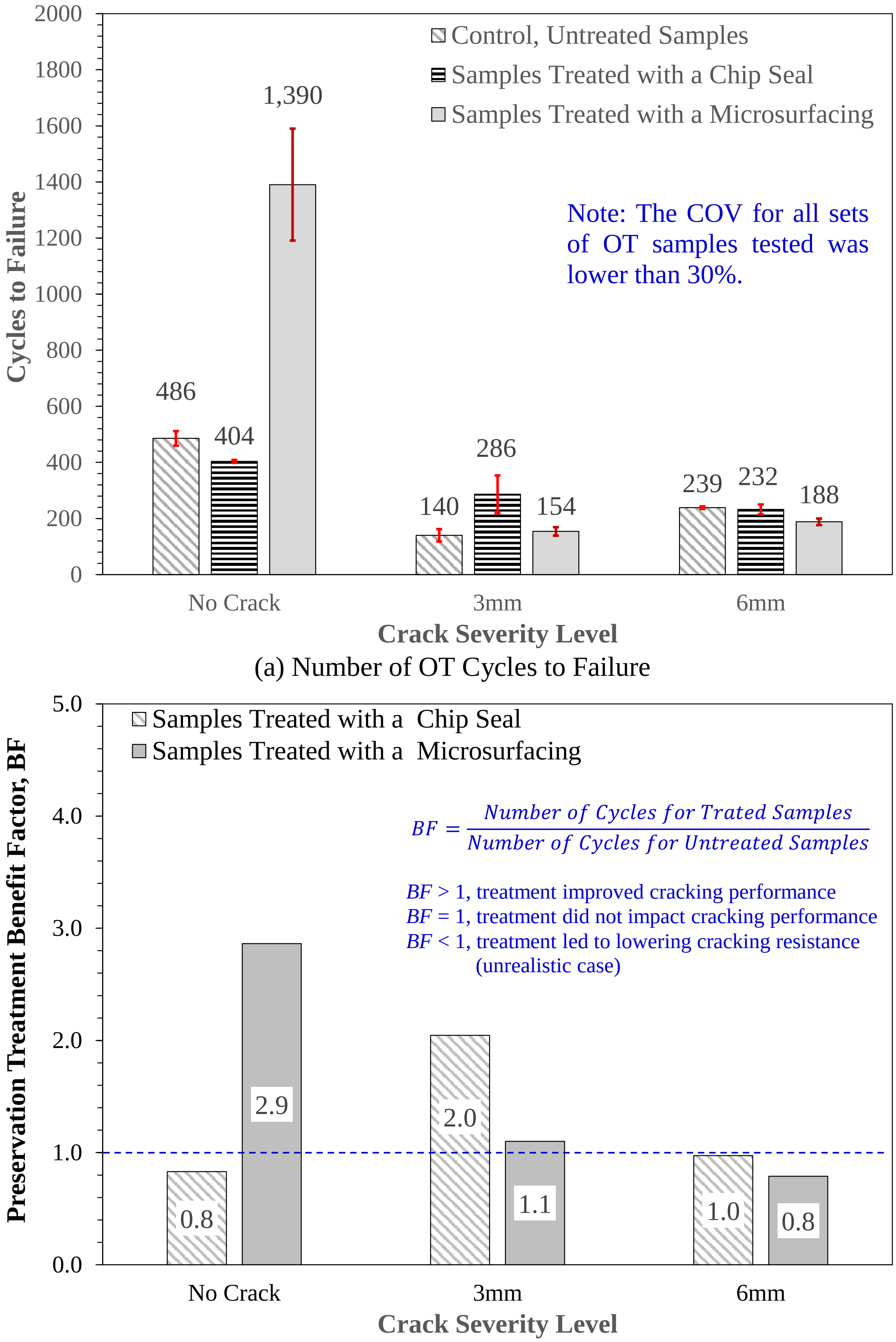

**(a) Control No Treatment**

**(b) Samples Treated with a Chip Seal**

**(c) Samples Treated with a Microsurfacing**

**(d) Bulk Specific Gravity**

**Figure 17. Load vs. number of OT cycles for: (a) control untreated samples, (b) samples treated with a chip seal, (c) samples treated with a microsurfacing treatment, and (d) Bulk Specific Gravity.**




(a) Number of OT Cycles to Failure



(b) Benefits of Treated Samples

**Figure 18. Overlay test results: (a) OT cycles to failure for treated and untreated samples and (b) performance benefit factor.**

(a)

(b)

**Figure 19. Aggregate Presence in Distressed Samples:**
**(a) 3mm Crack and (b) 6mm Crack**

## 5.3 Statistical Comparisons and Determination of Least Acceptable Pavement Condition

ANOVA was conducted to evaluate the statistical significance of treatment type and crack severity level on cracking performance (or OT cycles to failure). Table 3 presents the ANOVA results with multiple comparisons between the different treatments and crack severity levels considered in this study. As shown in Table 3, crack width, treatment type and their interaction were found to significantly (p-value < 0.05) impact the OT cycles to failure, with crack width being the most significant factor (F-value = 22.163 and p-value = 0.0). This provides statistical evidence that the OT test was sensitive to varying treatment types and crack severity levels.

Table 3 also presents the multiple comparison across treatment types (when crack width is kept constant) and across crack severity levels (when treatments are kept constant). From the multiple comparisons across treatment type it can be seen (Table 3) that the different in mean between the untreated and microsurfacing treated samples was significant (p-Value = 0.007 < 0.05). The OT number of cycles to failure were also similar for untreated and chip seal treated samples as well as those samples treated with chip seals and microsurfacing (p-value < 0.05 for both cases). Similarly, from the crack severity level multiple comparisons, it can be seen from Table 3 that introducing a crack (either 3 mm. or 6 mm. wide) significantly impacted the OT cycles to failure; regardless of applying or not applying a pavement preservation treatment.

To determine the least acceptable condition on which a chip seal or microsurfacing treatment can be applied, only treatments that showed a statistically significant improvement in cracking performance are considered. For this case, the application of a treatment will not lead to improving performance and therefore may not be cost effective. Since only the microsurfacing treatment had a significant improvement in performance when compared to the untreated condition (Table 3), it is the only treatment for which the least acceptable pavement condition is determined. Understanding that this treatment significantly improved the cracking resistance of the HMA mix when there was no crack present (i.e., when a crack was present the difference in performance due to the application of a microsurfacing treatment was insignificant). Therefore, it can be concluded that it is best to apply microsurfacing treatments on pavements that have no visible cracks to reap the performance benefits of this treatment effectively.

**Table 3. Analysis of Variance (ANOVA) Results.**

| **Factor** | | **F-Value** | **p-Value** |
|---|---|---|---|
| Intercept | | 149.827 | *0.000* |
| Crack Width | | 22.163 | *0.000* |
| Treatment | | 5.448 | *0.009* |
| Crack Width * Treatment | | 3.193 | *0.024* |
| **Multiple Comparisons (Treatment Type)** | | | |
| **(I) Treatment** | **(J) Treatment** | **Mean Diff. (I – J)** | **p-Value** |
| Untreated | Chip Seal | -95.27 | 0.503 |
| | Microsurface | -274.40* | *0.007* |
| Microsurface | Chip Seal | -179.13 | 0.099 |
| **Multiple Comparisons (Crack Severity)** | | | |
| **(I) Treatment** | **(J) Treatment** | **Mean Diff. (I – J)** | **p-Value** |
| No crack | 3 mm. Crack | 468.27 | *0.000* |
| | 6 mm. Crack | 503.27 | *0.000* |
| 6 mm. crack | 3 mm. Crack | 35.00 | 0.910 |

# 6 SUMMARY AND CONCLUSIONS

This study presented a laboratory procedure for evaluating the cracking resistance and determining least acceptable conditions on which pavement preservation alternatives can be applied cost effectively. Two pavement preservation alternatives; namely chip seal and microsurfacing, were evaluated in this study. Three damage severity levels, representing varying pavement conditions, were also evaluated as part of this study; excellent condition with no cracks, low severity cracks (3 mm. wide), and medium severity cracks (6 mm. wide). In addition, this paper presented a procedure for fabricating HMA samples treated with chip seals or microsurfacing for testing using a modified OT test (i.e., using a 0.3 mm. displacement as opposed to 0.6 mm.) and modified OT samples. The applicability of the introduced laboratory evaluation procedure was determined by assessing the sensitivity of the OT test to capture the difference among the samples. The least acceptable pavement conditions were determined based on cracking resistance improvements attained by applying preservation treatments.

Based on all testing results and the subsequent statistical analyses conducted as part of this study, the following conclusions were drawn:

- The laboratory procedure for fabricating HMA samples treated with either a chip seal or a microsurfacing was found to produce consistent samples. This was the case because the $G_{mb}$ values were similar providing evidence that the fabrication procedure results in comparable samples.
- The OT test was found to be sensitive to treatment type and damage severity level applied to tested samples; thus, it was successful at differentiating among samples. This is mainly attributed to the different OT cycles obtained for the different sample conditions (i.e., untreated-undamaged, untreated-damaged, treated-undamaged, and treated-undamaged). ANOVA results also showed that treatment type and crack width (or damage severity) had a significant impact on OT cycles to failure.
- For undamaged samples with microsurfacing applied, the OT cycles to failure significantly increased when compared to those obtained for the untreated-undamaged samples. The benefit factor for this case was nearly three times greater; indicating that the cracking resistance improved three times due to the application of a microsurfacing. This was not the case for treated-damaged samples. Overall, these results suggest that the use of microsurfacing on roadways that show no visible cracks (excellent condition) provides the greatest benefit to the roadway in terms of cracking resistance. This is further supported by the ANOVA results, which showed that microsurfacing OT cycles to failure is statistically significant when compared to untreated samples.
- In the case of damaged samples (either with 3 mm. or 6 mm. crack widths) treated with microsurfacing, there was no significant change in the OT cycles to failure due to the application of the preservation treatment. These results also indicate that the least acceptable pavement condition for microsurfacing is excellent condition with no cracks. Based on these results, microsurfacing may not be a viable option for roadways with visible cracking. It is noted that these results are limited to the materials and tests used in this study (i.e. application

rate and mixture proportions); thus, additional research is still needed to verify these conclusions for different microsurfacing mixtures.

- The chip seal treated samples did not show an increase in OT cycles to failure when compared to the untreated samples. This was the case for medium severity damaged (i.e., those with 6 mm. wide cracks) as well as undamaged samples. ANOVA results also showed that the difference in OT cycles to failure was not significant among these groups of samples. This indicates that the addition of chip seal does not improve the cracking resistance of asphalt in these conditions. Based on these results, it would appear that the propagation of cracks through the chip seal material from underlying cracks may occur at the same rate regardless of cracking severity. Therefore it will always be best to use emulsion based chip seal on roadways with minimum crack severity.
- The lack of addition of cycles to the control sample due to chip seal does not indicate, however, that chip seals should not be used and do not offer benefits. For example, roadways with no cracks will take longer to propagate through the asphalt and into the chip seal. The purpose of this study was to evaluate the cracking resistance of these materials under specific circumstances. The crack propagation cycles of the untreated distressed samples simply gives a benchmark on which to evaluate any additional cycles the chip seal would offer. While chip seal does not appear to be crack resistant based on the parameters of this study, the realized benefits of chip seal (seal roadways, slow asphalt aging, and restoring surface friction) would be most apparent when the roadway has lower crack severity. If chip seal is applied to a cracked roadway, the crack propagation will reach the chip seal surface rapidly and reduce its function.
- In the case of low severity cracked samples treated with a chip seal, there was a slight improvement in the OT cycles to failure when compared to the untreated sample. This suggests that under low severity cracking levels, chip seal may offer some benefits in terms of cracking resistance by sealing cracks. To elaborate more, the chip seal emulsion provides bonding with the sides of the crack; ultimately sealing it. ANOVA results; however, has showed that this improvement in OT cycles to failure for low severity cracked samples treated with a chip seal was not significant. Similar to microsurfacing, this study is limited to the materials used; thus, additional research is needed to evaluate various chip seal materials and determine the least acceptable pavement conditions on which these treatments can be applied.

## 6.1 Future Work

Laboratory testing of pavement preservation treatments could be an integral part of pavement preservation programs. However, the ability to test these materials is limited by the types of tests that exist and the unique material applications and materials used. This study presented a technique for determining the least acceptable pavement conditions for the application of pavement preservation treatments. While the results based on this study show that the least acceptable pavement conditions for microsurfacing would be a roadway with no distress, this is based on only a single microsurface mixture and application rate. Future work to build upon the basis of this study could include:

- Using higher application rates and various mixtures to see if the sensitivity of this method can capture these changes in the output data. In addition the use of higher application rates may allow the test to capture the effects of this material being applied to the OT samples.

- The sensitivity of the test to the addition of microsurface to these OT samples has other implications and applications. These include possibility to test the cracking resistance of different microsurfacing mixtures to determine the optimal mixtures for cracking resistance. This could in turn be combined with modified APA rut testing samples to determine balanced mix designs for optimum microsurface and chip seal mixtures.
- Different evaluation methods of the data can be used to evaluate the performance of these materials. While cycles to failure is an indication for performance of asphalt mixtures and resistance to cracking, the new sample production methods may require different analysis techniques to best capture the benefits and performance of microsurface and chip seal. Fracture energy and work done using the curves obtained from these tests may hold valuable information in the evaluation of the performance of these materials.

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