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# A laboratory investigation of high polymer modified asphalt mixtures with softening agent

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**A LABORATORY INVESTIGATION OF HIGH POLYMER MODIFIED ASPHALT MIXTURES WITH SOFTENING AGENT**

by

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## Dedications

A special feeling of gratitude to my loving parents, Khaled Al Badr and Taghreed Jamal whose words of encouragement and push for tenacity ring in my ears and to my sister, Sara Al Badr who has never left my side for their support, patience, and help throughout my life.

This dissertation is dedicated to my fiancé, Reeman Tineh, for her love, patience, help, and continuous support throughout this journey, thank you for always being on my side.

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**Abstract**

Basel Al-Badr
A LABORATORY INVESTIGATION OF HIGH POLYMER MODIFIED ASPHALT MIXTURES WITH SOFTENING AGENT
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This study was initiated to evaluate the impact of aging and High Polymer Modified Asphalt (HPMA) binders containing a bio-based-oil softening agent (SA) on the rutting, cracking, and durability of asphalt mixtures. One control asphalt binder (PG 52-34), Styrene-Butadiene-Styrene (SBS) polymer modifier, and corn-oil SA were used to produce four asphalt mixtures including a control prepared using PG 52-34 binder and three modified mixtures were produced by blending PG 52-34 binder with different dosages of SBS and SA. The mixtures were tested using the Dynamic Complex Modulus (|E*|), Hamburg Wheel Tracking Device (HWTD), Flow Number (FN), Indirect Tension Cracking Test (IDEAL-CT), Semi-Circular Bend (SCB), Disk-Shaped Compact Tension (DCT), and Cantabro Durability tests. The impact of aging on cracking resistance was also evaluated by subjecting all mixes to short-, long, and extended-long-term aging levels. The Analysis of Variance (ANOVA) and post-hoc statistical analysis were also performed on the testing results. Based on testing results, SBS and corn oil SA increased the durability and rutting resistance of asphalt mixtures. At extreme low-temperature (i.e., -24°C), the use of SBS and corn oil SA improved the cracking resistance of asphalt mixtures; however, increasing the SBS and/or the SA dosage rates had a negative impact on their cracking resistance. Using balanced dosages (i.e., 7.5% and 7%) of SBS and corn oil SA led to the best improvement in durability, rutting, and short-term cracking performance.

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# Chapter 1

# Introduction

## Background

Asphalt binder plays a pivotal role in determining how asphalt mixtures and ultimately flexible pavements will perform in the field. Indeed, the properties of asphalt binders have a significant impact on the performance of asphalt mixtures. A potential approach to improve the properties of flexible pavements and extend their service life, especially in cold regions, is to produce asphalt mixes using highly elastic asphalt binder (HEB) that has better elastic property at low temperature (i.e., higher cracking resistance) compared to conventional asphalt binder. The use of HEB in asphalt pavement improves its ability to withstand harsh cold conditions and extends its service life. HEBs are usually produced by incorporating additives into asphalt binder and allow the additive to be homogenously distributed in the binder. Among the wide range of modifiers that can produce HEBs, polymers are the most commonly used additives to modify asphalt binders. The mechanism in which some polymer modifiers (mainly elastomers) reduce pavement distresses is through improving the "non-linear" response of mixtures. To elaborate more, blending polymer modifiers such as Styrene-Butadiene-Styrene (SBS) into asphalt binders leads to the formation of a thermoplastic rubber network within the asphalt binder (Bardesi et al., 1999). This network pins and reduces crack propagation in asphalt pavements due to the nature of cracks; since cracks propagate through the material's least resistance path, the PMA rubber network increases the difficulty for cracks to form and propagate (Timm et al., 2012). Besides the use of polymers in producing HEBs, previous studies (Neirouz, 2020; Xie et al., 2020) showed that the combination of SBS polymers and bio-based corn oil softening agent significantly improved the low-temperature properties of asphalt binder. In summary, the use of HEB is expected to improve the performance and extend their service life as well, especially in cold regions.

**Problem Statement**

Several researchers, highway agencies, and state departments of transportations (DOTs) also evaluated the performance of modified asphalt mixtures to improve the performance of asphalt pavements. Furthermore, previous studies (Neirouz, 2020; Xie et al., 2020) showed that modifying asphalt binder with a combination of SBS and corn-oil softening agent significantly improved the low-temperature properties of asphalt binder. However, further investigation is needed to evaluate the performance of asphalt mixes produced using these asphalt binders. In particular, the following points are not addressed in the literature:

- The performance of asphalt mixes produced using a combination of SBS polymer and corn-oil softening agent was not investigated by most studies,
- The impact of aging on the performance of asphalt mixtures produced using modified asphalt binder was not identified as well,
- The effectiveness of flexible pavements produced using HEB is not clear enough due to the use of high polymer content with softening agent to produce a modified asphalt mix.

Consequently, there is a need to investigate the laboratory performance of asphalt mixes produced using HEBs and to clearly understand the expected performance of these mixes in the field. Additionally, the effectiveness of using polymers and softening agents to produce highly elastic asphalt binder is still unclear. Therefore, conducting an appropriate investigation of asphalt pavements produced using HEB is necessary to bridge this gap in the current literature.

**Research Hypothesis**

This study investigates the hypothesis that using polymer and a softening agent in the asphalt binder's modification process to produce HEB can improve the cracking and rutting performance of asphalt mixes. The study also investigates the hypothesis that asphalt mixtures produced using HEB binder can improve their performance and extend their service life.

**Significance of Study**

The importance of this study is to develop innovative asphalt materials using a modified binder produced using a combination of SBS polymer and corn-oil softening agent. This was done by evaluating the laboratory performance of the produced asphalt mixtures in terms of durability, rutting, and cracking. The study also compared the impact of aging on the cracking performance of modified asphalt with conventional asphalt mixes. Such study will help select appropriate materials for constructing better performing pavements that will outperform conventional pavements and eventually provide cost-effective roadway and airfield solutions in cold regions. Moreover, the study will lead to a longer-lasting transportation infrastructure network. Based on the findings from this study, the following benefits will be offered to the Department of Defense (DoD):

- Selecting asphalt pavement's materials that will outperform conventional materials and be more cost-effective.
- Constructing longer-lasting and cost-effective transportation infrastructure in cold regions,
- Improving the infrastructure industry by developing sustainable pavements that can withstand the harsh cold environment under heavy traffic load,
- Revising and updating the current military engineering specifications (Tri-Service Pavements Working Group (TSPWG)) for selecting asphalt binder in cold regions.

**Goal & Objectives**

The goals of the study are:

a) Evaluate the impact of using SBS polymer-modified asphalt binder with corn-oil softening agent on the performance of asphalt mixtures.
b) Investigate the impact of different aging levels on the cracking resistance of asphalt mixtures.
c) Quantify the benefits of using modifiers in asphalt pavements and investigate if they are statistically beneficial.

The objectives of the study to achieve the goals are:

- Conduct a comprehensive literature review pertaining to HMA mixtures produced using highly elastic binders.

- Determine the appropriate long-term aging protocols for loose asphalt mixtures.

- Evaluate the performance of HMA mixtures produced with the selected modified binders.

- Conduct Statistical Analysis to quantify the benefits of using highly elastic binder in pavements.

**Research Approach**

In order to fulfill the goals and objectives of this study, the following tasks were conducted:

Task 1. Conduct a comprehensive literature review: This task included a comprehensive review of existing literature pertaining to modified asphalt mixtures and the design procedures of asphalt mixes. In addition, the laboratory and field performance of asphalt mixes produced using HEB, and its impact of different levels of aging on these mixtures will be determined.

Task 2. Determine long-term aging protocols for loose mixture: In this task, the optimum aging protocol for loose mixtures was determined. This task also involved a laboratory assessment of different aging protocols to determine the optimum aging protocol for further use in this study.

Task 3. Investigate the performance of HMA mixtures: In this task, a series of performance tests were conducted on modified asphalt mixtures to:

- Determine the impact of modification of dosage on the performance and volumetric properties of modified asphalt mixtures,

- Evaluate the intermediate and low temperature cracking, rutting, moisture susceptibility, and durability performance of modified asphalt mixtures at the different modification rates,
- Conduct a comprehensive evaluation of modified asphalt mixes' performance in mitigating fatigue, thermal, and fracture cracks. Furthermore, the impact of long-term aging on the cracking resistance of modified asphalt mixtures were investigated as well.

Task 4. Perform statistical analysis to evaluate the impact of polymer and softening modification rate on the performance of modified asphalt mixtures

Task 5. Prepare recommendations and future directions based on the findings and conclusions from this study.

## Chapter 2
## Review of Literature

### Introduction

For many years, the polymer modification of asphalt binder has become more common to improve their ability to mitigate the major causes for asphalt pavement failures, such as permanent deformation and cracking at high and low temperatures, respectively. Moreover, several studies were conducted to evaluate the performance of asphalt binders and mixtures produced using polymer modifiers. Due to their ability to improve the elastic property of asphalt binders, the use of polymer modified asphalt binder is more common in areas that experience significantly wide temperature ranges and heavy traffic load.

Asphalt binders age overtime and due to heat, oxidization, and other environmental factors. Aging increases the stiffness and rigidity of asphalt binder, causing it to fail and crack. A potential approach to restoring the properties of aged binder (i.e., RAP) and/or improve the asphalt binder's properties at low temperature is to use rejuvenators or softening agents (SA). Rejuvenators or SAs are liquids used to modify asphalt binders in order to improve their performance. The most used softening agents include aromatic oil, vegetable oil, corn oil, and others. Recently, a new modification approach of asphalt binder using a combination of polymer and softening agent was suggested and investigated by several researchers.

In this chapter, a summary of relevant literature-to-date pertaining to modified asphalt binders and mixtures is presented. In particular, this chapter includes an introduction on the use of polymer and softening agent modification in asphalt field, the used techniques to modify asphalt binder with polymers and softening agents, the impact of additives on the physical and rheological properties of asphalt binder, and a performance characterization of modified asphalt mixtures. A summary of the literature findings and their relevance to this study is also presented at the end of this chapter.

**Use of Polymers in Asphalt**

The word “Polymer” is derived from the Greek “Poly” means many, and “Mer” means units (many units). Polymers are mainly categorized into two main groups based on their production way: natural and synthetic (man-made) polymers. Due to their low density and cost as well as their good thermal and electrical insulation properties, polymers became widely involved in manufacturing. Natural polymers have been used for centuries in jewelry, clothing, and other applications. The most common examples of natural polymers are amber, wool, silk, and natural rubber. On the other side, the most common application of synthetic polymers is their use in producing light cars and airplanes and constructing thermally insulated buildings, besides their wide applications in the medical field in producing syringes, rubber gloves, and contact lenses. From a chemical perspective, a polymer can be described as a large molecule that consists of many smaller molecular units called monomers that are all linked together by chemical reaction (Kluttz, 2012).

Asphalt researchers were attracted by the wide use and the high cost-effectiveness of polymers in the manufacturing field. Consequently, several researchers investigated the potential of using polymers in the asphalt field as to improve its performance. Most of the conducted studies reported that polymers were able to enhance the asphalt properties such as enhancing its resistance to permanent deformation (i.e., rutting), besides improving its elastic property and ultimately the cracking resistance at low temperature, in addition to extend the service life of pavements (Lewandowski, 1994).

The polymers may also be classified based on their physical properties into two main groups: elastomers (rubber) and plastomers (plastic) according to Hines (1993). By understanding the properties of both groups, asphalt with elastomer modification is expected to resist deformation when it is loaded; however, when the load is released, its high recovery property allows it to recover quickly. Elastomers can also improve the elastic property and cracking resistance of asphalt binder and ultimately the flexible pavement at low temperatures (Hines, 1993). The most common elastomer modifiers include, but are not limited to, Styrene-Butadiene-Rubber (SBR), Styrene-Butadiene (SB), Styrene-Butadiene-Styrene (SBS), Styrene-Isoprene-Styrene (SIS), etc.

On the other side, plastomers have a tough, rigid, and a three-dimensional network that can resist deformations. When incorporating a plastomer polymer into the asphalt binder, it could increase its stiffness moduli and increase its strength when it is loaded (Hines, 1993). Polyethylene, polypropylene, Polyolefin (PO), Ethyl Vinyl Acetate (EVA), Polyvinyl Chloride (PVC), Ethylene Propylene (EPDM) are the most common, but not the only, examples of plastomers.

### *The Impact of SBS Polymer on Rheological and Physical Properties of Asphalt Binder*

The SBS polymer is a synthetic hard rubber made from two monomers: styrene and butadiene that are used in producing tire threads, soles of shoes, and other applications. The SBS polymer has also proven itself in improving the performance of asphalt binder and mixtures in several studies. Figure 1 illustrates a sample of SBS polymer.

**Figure 1**

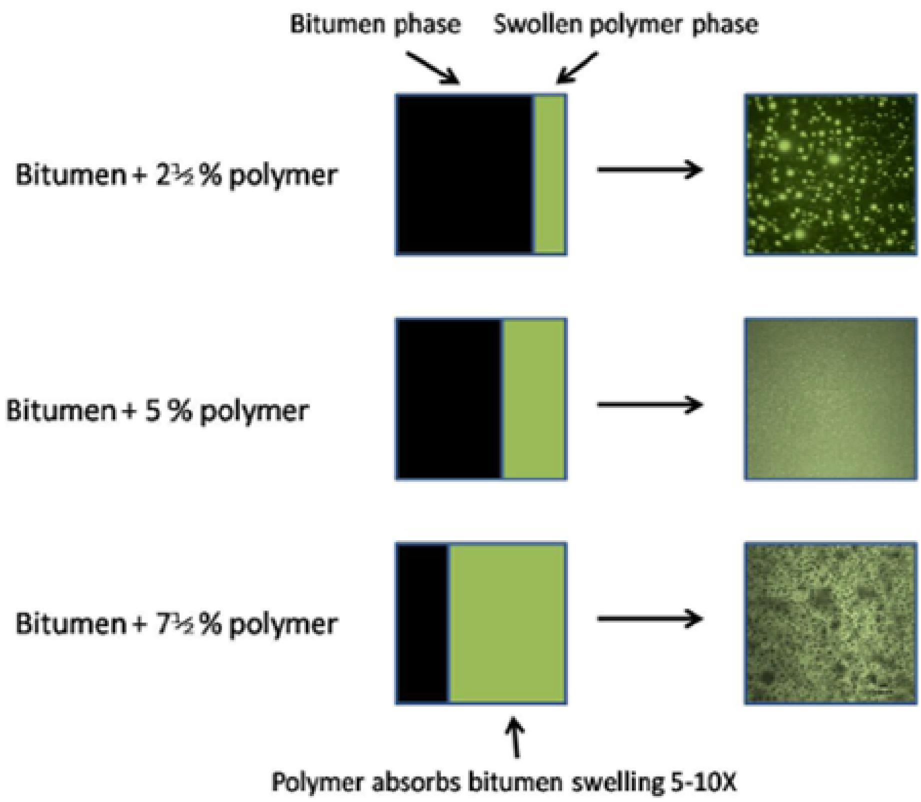
*Sample of SBS Polymer Modifier*

Polymer-modified asphalt (PMA) is a well-established product for improving the effectiveness of asphalt pavements. Indeed, the SBS polymer is the most used modifier to improve permanent deformation and cracking resistance of asphalt mixtures, besides its good dispersibility in asphalt binder. Conventional SBS modified binders typically include 2.5 – 3% SBS by weight of the base binder, while high SBS modified binder typically include 7% SBS or more.

The SBS polymer also showed a strong interaction with asphalt binder and it was observed that bitumen absorbs up to ten times of their own volume of less polar asphalt components (Morgan and Mulder, 1995). The relative proportion of swollen polymer and bitumen in addition to actual micrographs showing the dispersibility of SBS polymer into asphalt binder are shown in Figure 2. As illustrated in Figure 2, incorporating the typical SBS dosage (i.e., 2.5 – 3%) into the asphalt binder results in forming a partial continuous linking network within asphalt binder which leads to enhance its rutting and fatigue resistance. However, as the SBS dosage increases, it forms fully continuous links that lead to higher cracking and rutting resistance compared to lower dosage (Timm et al., 2012). To elaborate more, as a crack propagates through a composite material, its nature most likely leads it toward the least resistance path in the material by avoiding the rubbery tough phase and keep propagating through the weaker brittle phase. Therefore, higher SBS dosage shows more continuous links; thus, increase the difficulty of cracks to form and propagate (Timm et al., 2012).

**Figure 2**

*Dispersion of SBS Polymer in Asphalt at Different Loadings (Timm et al. 2012)*




Several researchers studied the rheological and physical properties of SBS modified asphalt binders. As an example, Sargand and Kim (2001) conducted a study to evaluate the rutting and cracking performance of SBS and SBR modified binders. Sargand and Kim (2001) reported that incorporating polymers (SBS or SBR) into asphalt binder enhanced the rutting and cracking resistance compared to the control (unmodified) binder. Another laboratory investigation was carried out by Airey (2004) to evaluate the performance of SBS modified asphalt binders. In conclusion, it was reported that increasing the SBS dosage in asphalt binder resulted in a more viscous binder and better compatibility that allowed the SBS to produce a continuous polymer network within the binder. Moreover, Airey (2004) reported that modified binder showed a better elastic response and higher stiffness at high temperatures, resulting in an improvement in rutting resistance compared to the unmodified binder. Andriescu and Hesp (2009) conducted a laboratory study to investigate high SBS polymer modified binder performance. Andriescu and Hesp (2009) reported that based on the Double-Edge Notched Tension test (DENT), a highly modified SBS polymer binder showed a significant enhancement in fracture energy at intermediate temperatures than conventional polymer modified binders.

In another study, Kim et al. (2010) utilized the Asphalt Binder Cracking Device (ABCD) test to investigate the low-temperature cracking resistance of modified binders with different SBS contents. Kim et al. (2010) reported that cracking temperature decreases as SBS content increases, especially when SBS content is more than 3%. Moreover, it was observed that the continuous low-temperature grade from Bending Beam Rheometer (BBR) test was unable to capture the improvement in low temperature cracking due to the use of SBS, since increasing SBS content reduced the low-temperature cracking resistance. Anderson et al. (2011) conducted a study to evaluate the performance of modified asphalt binders using 4% of SBS and 4% of EVA. Based on their testing results, it was reported that modified binder could improve the low-temperature cracking resistance compared to unmodified binders.

Florida Department of Transportation (FDOT) evaluated the performance of high polymer binder through Accelerated Pavement Testing (APT) (Greene et al. 2014). For comparison purposes, this study contained unmodified PG 67-22. An SBS modified binder with a PG 76-22, and a highly SBS modified binder with a PG 88-22 that included approximately 6% SBS polymer modifier, while PG 76-22 consisted approximately half modification dosage. In this study, five test sections were paved for APT test. These five sections were divided into two groups: three test sections were used to evaluate the rutting resistance, besides other two test sections those were utilized to evaluate their fatigue resistance. Based on the dynamic shear rheometer (DSR) results, Greene et al. (2014) reported that high polymer binder with PG of 82-22 exhibited the greatest elasticity, stiffness, and rutting resistance potential compared to other sections. In terms of the binder fracture energy test developed by the University of Florida, PG 82-22 binder exhibits greater fracture energy (i.e., higher cracking resistance) than PG 76-22 and PG 67-22 binders.

Recently, Shan et al. (2020) conducted a study to investigate the effect of SBS on the rheological properties of asphalt binder. In this study, the neat binder was modified with three different SBS dosages (i.e., 3%, 5%, and 7%). In this study, several performance tests were conducted to evaluate modified binders' performance such as stress sweep, frequency sweep, and large amplitude oscillatory shear stress tests. Based on their testing results, it was reported that incorporating SBS polymer into asphalt binder increased its nonlinearity and elastic properties, besides decreasing its fluidity, indicating its ability to improve both cracking and rutting resistance of asphalt binder.

***Techniques for Modifying Asphalt Binder with SBS Polymer***

The technique of incorporating polymers into asphalt binder was investigated by several researchers. For instance, the Federal Highway Administration (FHWA) published a study to investigate the compatibility and storage stability of polymer modified asphalt (Zubeck et al., 1999). In this study, the researchers reported two main interpretations of the compatibility of polymers and asphalt binders: the first one is the ability of polymers to remain distributed in asphalt binder without significant phase separation. The second one is that compatibility depends on the level of interaction between polymer and asphalt cement (Zubeck et al., 1999).

An important parameter to examine how success is the modifying process between asphalt binder and polymer modifier is called "compatibility." The incompatibility between asphalt and polymers leads to premature product failure due to rapid aging and property loss. However, good compatibility can be achieved when polymer modifier is soluble in asphalt binder and can maintain a homogenous distribution without significant phase separation. In fact, the modification process is considered successful (or compatible) if the modified asphalt binder exhibits typical homogeneity, ductility, cohesion, and adhesion properties.

Typically, polymer is blended with asphalt binder by incorporating polymers into asphalt binder at specific blending parameters (i.e., temperature and speed). Blending parameters have a strong influence on modified binder compatibility. For example, the blending temperature for polymer modified binders should be higher than the polymer's melting temperature to achieve better compatibility. Another method that is used to improve the compatibility of polymer modified binder is to use chemical bonds that have the ability to link two polymer chains together "cross-linking". In other words, the cross-linking approach is to add a material that can chemically react in the binder and link polymer chains together, which improves the homogeneity within the blended binder, and it becomes more rigid. Several materials can be used as cross-linker materials, such as sulfur powder used with SBS polymer modifiers.

In literature, different procedures were found in order to blend polymers with asphalt binder. For example, an investigation was carried out by (Saboo, 2015) to evaluate the performance of polymer modified binder. In this study, the optimum blending requirements (i.e., mixing time and temperature) was determined for two polymer additives (i.e., EVA and SBS). In addition to that, four different mixing temperatures (i.e., 160, 170, 180, and 190°C) and four different blending times (i.e., 20, 30, 40, and 60 minutes), besides five different shear rates (mixing speed) (i.e., 300, 600, 900, 1200, and 1500 rpm). A total of 80 combinations were produced for each modifier, and then the storage stability of each combination was tested to determine the optimum mixing requirements. In conclusion, it was observed that extending blending time, increasing mixing speed and temperature led to reducing the storage stability values, which indicates better compatibility between polymers and asphalt binder. In terms of SBS polymer, it was reported that increasing the shear speed resulted in a more stable binder. Moreover, Saboo (2015) observed that blending SBS polymers at temperatures below 170°C did not result in a storage stable binder. It was also reported that the influence of shear rate became more significant as the modification dosage increased (i.e., 7%).

In a recent study, Shan et al. (2020) modified neat binder with three SBS dosages (i.e., 3%, 5%, and 7%) by weight of asphalt binder. This study's modification process started by heating the asphalt binder at 180°C until it flows easily. After that, the SBS was added at a rate of 5g/min to the melted asphalt while mixed at a low shear rate of 500 rpm. After adding the required amount fully, a high shear mixer at 4000 rpm was used to blend the polymers with asphalt binder for two hours, followed by keeping the binder after blending another two hours in the oven at 180°C for compatibility purposes. In summary, several techniques of modifying asphalt binder with SBS polymer was followed in the literature, however, it is necessary to prove the compatibility between SBS polymer and asphalt binder for any used technique of modification.

***The Impact of Aging on Polymer Modified Binder***

Although the use of SBS polymer in asphalt binder, as was illustrated above, could significantly improve its performance, this improvement needs to be clarified more over the service life of asphalt pavements. Therefore, it is necessary to better understanding the performance of modified binders at long-term aging levels.

Several researchers studied the impact of aging on the performance of asphalt binders. For instance, Zhang et al. (2010) evaluated the influence of short- and long-term aging levels on polymer modified binder. In this study, SBS and SBS-sulfur modified binders were produced to investigate their performance. Moreover, several properties were evaluated in this study such as dynamic viscosity, thermal stability, and storage stability. In conclusion, Zhang et al. (2010) reported that incorporating SBS into asphalt binder improved its properties at short and long-term aging level compared to control binder. However, adding sulfur to SBS modified asphalt binder increased its aging susceptibility compared to SBS modified asphalt (without sulfur). Similarly, Huang (2008) reported that rubber-modified binder's elastic property improved with aging (at long-term aging level); indicating better performance compared to unmodified binder.

Tarefder and Yousefi (2016) conducted a study to evaluate the aging impact on polymer modified asphalt. In this study, the rheological, storage, loss, and bending stiffness properties were investigated. In addition to that, the aging impact on polymer modified binders was evaluated by utilizing RTFO and PAV aging methods in this study. Moreover, asphalt binder was modified using SB and SBS polymers to produce polymer modified binders at different dosages (i.e., 3, 4, and 5% by weight of base binder). The results of this study showed that increasing the polymer dosage led to reduce the aging susceptibility of polymer modified binder.

More recently, Yan et al. (2020) conducted a study to evaluate the impact of aging on the SBS polymer degradation for modified asphalt. In this study, an SBS modified asphalt binder was subjected to a total of 17 lab and field aging conditions. The SBS modified binder in this study was subjected to three laboratory aging levels including a long-term aging level using PAV and two short term aging levels using RTFOT and Short-term Oven Aging (STOA). The STOA aging method was done by producing a mixture of 3000 g and aging it in an oven at different specific temperatures (i.e., 163, 193, and 210°C) for two hours. After aging was done, the mix was cooled down, and the binder was extracted, recovered, and tested. On the other hand, field aging samples were taken from a pavement with 5% asphalt content and 9-years in service. In this study, and to characterize the degradation of SBS modified asphalt, the Attenuated Total Reflection Fourier Transform Infrared spectroscopy (ATR-FTIR) was applied. Moreover, a correlation between ATR-FTIR and DSR (MSCR) data was performed.

In conclusion, Yan et al. (2020) determined that polymer degradation is most likely to happen at short term aging level; suggesting that the degradation of polymer modified binder is susceptible to high temperatures at short term aging level, however, higher resistance at the long-term aging level is expected. Moreover, it was reported that the aging of polymer modified asphalt resulted in stiffer and more elastic binder; however, when polymer is degraded in asphalt binder, it showed less stiff and elastic binders. Both trends show the importance of polymer degradation and that polymer degradation is riskier on asphalt binder's properties than aging. Yan et al., 2020 also reported that RTFO and PAV aging methods resulted in less carbonyl growth compared to field-aged binders. These findings highlight the big need to investigate and reevaluate the RTFO and PAV aging methods.

**The Softening Agent's in Asphalt Modification**

Rejuvenators or softening agents (SAs) are naturally occurring or engineered products divided into two main groups: organic and inorganic. The most common SAs are corn oil, aromatic extract, vegetable oil, waste vegetable oil, and other wide range of oils. From an asphalt perspective, softening agents are defined as an additive agent capable of reducing the viscosity and brittleness of asphalt binder, which leads to improve its cracking resistance at low temperature.

In 1988, The U.S army and air force (TM, 1988) evaluated the addition of rejuvenators on asphalt binder. They reported that rejuvenators reduced the skid resistance of asphalt pavement for up to one year. For that reason, the use of rejuvenators was mainly used on parking lots, low traffic, and low speed designed pavements. Rejuvenators were also used in low-weight air-craft vehicles (60,000 pounds or less). The use of rejuvenators can also delay the need for bituminous surface treatments for up to two years. The same study (TM, 1988) recommended that rejuvenators are applied in temperatures above 20°C so that rejuvenators penetrate more into asphalt pavement and cure sooner than in colder temperatures.

Several studies (Zaumanis et al., 2014; Ali et al., 2016; Ji et al., 2017; Elkashef and Williams, 2017; Ahmed et al., 2020) were conducted recently to evaluate the benefits that can be drawn from incorporating SA into asphalt binder. Most of these studies proved that the different types of rejuvenators (e.g., waste vegetable oil, organic oil, distilled tall oil, aromatic extract, waste engine oil, etc.) were able to reduce both high and low performance grade (PG) of asphalt binder, suggesting an enhancement in cracking and fatigue resistance and more rutting susceptibility. Also, it was proved that softening agents were able to counter the negative impact of aging on asphalt mixtures containing RAP material in several studies.

***The Impact of SA on the Physical and Rheological Properties of Asphalt Binder***

In literature, several studies (Zaumanis et al., 2014; Ji et al., 2017; Elkashef and Williams, 2017; El-Shorbagy et al., 2019; Ahmed and Hossain, 2020) were conducted to compare different types of rejuvenator in order to counter the negative impact of aging on asphalt binder. For instance, Zaumanis et al. (2014) evaluated the impact of using six different types of rejuvenator (i.e., Waste Vegetable Oil, Waste Vegetable Grease, Organic Oil, Distilled Tall Oil, Aromatic Extract, and Waste Engine Oil) on rutting resistance, moisture susceptibility, workability, fatigue cracking, and low temperature cracking. The results showed that all rejuvenator linearly reduced the high and low PG of asphalt binder. In addition to that, the organic products require lower dosage to reach the PG target compared to petroleum products. Furthermore, aromatic extract outperformed other types of rejuvenators. These findings indicate that using rejuvenators in asphalt binder improved its cracking resistance and increased its rutting susceptibility.

Another study was conducted by Ji et al. (2017) to determine the feasibility of using vegetable oil-based rejuvenators for RAP mixes as an alternative to the standard heavy fuel oil-based rejuvenators. In this study, five rejuvenators content were used after blending them with aged binder (extracted RAP binder) at different dosages (i.e., 2, 4, 6, 8, and 10% by weight of base binder). On the other hand, an unmodified PG 64-22 binder was used as control binder. Several performance tests were conducted in this study including DSR, rotational viscosity, and BBR tests to evaluate the blended binder's properties. The result showed that vegetable oil (corn oil and soybean oil) at a dosage between 6 to 8% by weight of base binder could enhance the low temperature performance of asphalt binder.

Another study was conducted by Elkashef and Williams (2017) to evaluate the impact of different dosages of Soybean rejuvenator (i.e., 6% and 12%) aged binder (RAP extracted binder) on mechanical properties of binder. In this study, a neat binder with a PG58-28 was used to produce as a control binder and was blended with aged binder as well. Several performance tests were conducted in this study to characterize the binder's properties such as frequency sweep test, and linear amplitude (LAS) tests. Based on their testing results, soybean-derived rejuvenator was found to have better cracking resistance and lower rutting resistance.

In 2019, a laboratory evaluation of using waste oils as rejuvenators or softening agents was studied by El-Shorbagy et al. (2019). In this study, a virgin binder was used as control binder, while Waste Cooking Oil (WCO) and Waste Engine Oil (WEO) were blended in this study with aged binder (RAP extracted binder) at different dosages (3.5-4.0%) and (5.5-6.0%) for WCO and WEO, respectively. Several performance tests in this study were conducted such as penetration, softening point, Brookfield viscosity, DSR, and BBR tests to evaluate the performance of asphalt binder. On the other hand, the chemical composition of these binders was investigated using Fourier Transform Infrared Spectroscopy (FTIR) and Energy Dispersive X-ray (EDX), besides Scanning Electron Microscopy (SEM) imaging technique that was applied to evaluate the quality of rejuvenated binders. El-Shorbagy et al. (2019) reported that rejuvenators could significantly enhance the properties of aged binder according to FTIR and SEM/EDX results. Based on DSR and BBR results. It was also observed that rejuvenated aged bitumen had less tendency to short-term aging.

Recently, a study was conducted by Ahmed and Hossain (2020) to investigate the effectiveness of using waste cooking oil (WCO) as a rejuvenator to improve the properties of aged binders. Ahmed and Hossain (2020) reported that increasing the WCO dosage reduced its softening point and viscosity, indicating less resistance to rutting.

***Techniques for Modifying Asphalt Binder with SA***

Since softening agents are usually liquids (oil), the use of softening agents in asphalt binder is usually done by adding the required amount of softening agent to a preheated asphalt binder when it is in a high viscous state, and then, by stirring the blend up to get a homogenous blended binder.

Typically, different techniques are used to incorporate softening agents into asphalt binder. In fact, the different techniques to incorporate the softening agent into asphalt binder might be at room temperature or at a higher temperature, while asphalt binder is at high viscosity state (i.e., at high temperature). Afterwards, the blend is stirred up manually for a few minutes or using a low-shear mixer to produce a homogenous blend.

Although main studies were conducted pertaining to rejuvenators were conducted on RAP binders to restore their virgin binder's properties, the findings can show the different techniques that were used to incorporate rejuvenators into asphalt binder. As an example, Zaumanis et al. (2013) evaluated the addition of rejuvenators on 40% and 100% RAP contents. In this study, two different rejuvenator dosages were used (18.3% and 9% by mass of asphalt). The addition of rejuvenators was after heating the asphalt binder for 40 minutes at 135°C.

Ji et al. (2017) evaluated the addition of three different rejuvenators (fuel oils, corn oil, and soybean oil) on asphalt binder extracted from RAP material. In this study, rejuvenator dosage rates were 0.0%, 2.0%, 4.0%, 6.0%, 8.0%, and 10.0%. Also, the study evaluated unaged PG 64-22 and RTFO+PAV aged, extracted asphalt binders. Rejuvenators were added on a recovering temperature of 130°C using a mixer for 30 minutes at a speed of 200 rpm.

**Performance Characterization of Highly Polymer Modified Asphalt Mixtures**

A key factor in determining how asphalt pavements will perform within the field are the properties of asphalt binders. In particular, asphalt binders influence the ability of hot mix asphalt (HMA) to resist cracking and rutting. To elaborate more, asphalt mixtures with stiffer binders have higher rutting resistance and it is recommended in high temperatures. In comparison, softer binders are recommended in cold regions due to their ability to resist cracks more than stiff binders.

Due to their substantial impact on pavement performance, researchers have evaluated and recommended using varying asphalt binder modifiers that would improve HMA performance. For instance, Polymer-modified asphalt binders (PMAs) are well-known for their ability to reduce the severity and extent of pavement distresses and extend pavements' service life, in comparison to neat unmodified binders. The mechanism in which some polymer modifiers (mainly elastomers) reduce pavement distresses is through improving the "non-linear" response of mixtures. To elaborate, blending polymer modifiers into asphalt binders leads to the formation of a thermoplastic rubber network within the asphalt binder (Bardesi et al., 1999). This network pins and reduces crack propagation in asphalt pavements, also reported that because cracks propagate through a material's least resistance path, the PMA rubber network increases the difficulty for cracks to form and propagate (Timm et al., 2012).

Previous section illustrated the performance of asphalt binder due to modifying it with SBS polymer and softening agent. However, this section focuses more about the performance of asphalt mixtures produced using highly elastic binders, especially, high polymer modified asphalt mixtures (HPMAs) that were produced by incorporating different high dosages of SBS polymer and corn-oil bio based softening agent.

*Performance of Mixtures Prepared Using Modified Asphalt Binders*

Evaluating the performance of asphalt mixtures produced using High Polymer Modified Asphalt (HPMA) has been attracting several researchers. As an example, a field investigation of pavement sections constructed using modified (with SBS) and unmodified (control) asphalt mixtures was carried out by Von Quintus et al. (2007). In this study, the selected sections' performance data were derived from Long-Term Pavement Performance (LTPP) and the National Center of Asphalt Technology (NCAT) databases. Based on their results, Von Quintus et al. (2007) reported that pavement sections constructed using SBS modified mixtures showed lower cracking and rutting distress compared to unmodified mixtures. Besides rutting and cracking performance enhancements, the use of PMAs also improves the resistance of asphalt mixtures to thermal (or low temperature) cracking. In conclusion, Von Quintus et al. (2007) observed that using SBS modified mixtures led to 5 to 10 years increment in pavement service life.

In another study, Hamed (2010) evaluated the fatigue performance of SBS modified mixes by producing mixtures with four different dosages of SBS: 3%, 5%, 7%, and 10% by weight of the base binder. It was noted in this study that increasing the SBS dosage by more than 5% did not significantly improve the performance of asphalt mixtures. In the same manner, it was noticed that using low SBS dosage (less than 5% by weight of base binder) showed similar behavior to unmodified mixtures. In conclusion, Hamed (2010) observed that using SBS polymer in asphalt mixtures led to a significant improvement in fatigue behavior compared to the controlled mix. Another study that was conducted by Kim et al. (2012) to characterize the fracture properties of asphalt mixtures, it was reported that cracking temperature, as measured using the Asphalt Binder Cracking

Device (ABCD), decreases with increasing the SBS dosage within asphalt binder. This was the case when SBS dosage was 3% or more by weight of binder.

Various researchers also studied the use of high polymer modified asphalt binders (HPMAs) due to the benefits reported when using PMAs. An HPMA binder is typically produced by adding a polymer modifier at dosages exceeding 3% by weight of the base binder. In the National Center of Asphalt Technology (NCAT), a field and laboratory investigation of HPMA was carried out by Timm et al. (2012) to evaluate the HPMA performance and their structural capacity. Based on the testing results, Timm et al. (2012) reported that HPMA mixtures (7.5 SBS by weight of base binder) showed higher fatigue cracking and rutting resistance compared to a control mixture that was prepared using a PMA binder with 2.8% SBS dosage. In terms of fatigue cracking, it was reported that HPMA binder produced using 7.5% SBS showed greater number of cycles resulted in 45 times more improvement in mix's fatigue cracking resistance compared to control mixture. On the other hand, it was reported that HPMA mixture showed better rutting resistance compared to control mixtures based on the Asphalt Pavement Analyzer (APA) device and the Flow Number (FN) tests.

In another study, Timm et al. (2013) conducted a field evaluation of HPMA and control mixtures over a couple of years period. An HPMA mixture was prepared by incorporating 7.5% SBS polymer into asphalt binder and a controlled mixture that was prepared by adding 2.8% SBS dosage in asphalt binder was tested. In results, Timm et al. (2013) reported based on Hamburg Wheel Tracking Device (HWTD) results that HPMA mixtures had less moisture susceptibility compared to control mixtures (i.e., higher SIP values compared to control mixtures). In terms of field performance of HPMA, Timm et al. (2013) reported that sections those produced using HPMA showed a significant enhancement in rutting resistance, in addition to a significant improvement in the ride quality compared to control sections. Overall, Timm et al. (2013) observed that mixtures produced using HPMA had higher tensile strength, rutting resistance, fatigue cracking resistance, and better riding quality compared to control mixtures.

Mogawer et al. (2012) conducted a study to evaluate the use of HPMA in high-performance thin overlay (HPTO) using Warm Mix Asphalt (WMA) technology and with incorporating high Reclaimed Asphalt Pavement (RAP) content into the HPTO mixes. To summarize, Mogawer et al. (2012) reported that using HPMA as HPTO negatively affected its cracking resistance as was obtained by the overlay test compared to control mixtures. It should be mentioned that the authors reported that this reduction in HPMA performance might be due to the increment in mixture's stiffness due to binder's modification.

Kim et al. (2013) conducted a study to evaluate the fatigue properties of HPMA mixtures using four-point bending beam fatigue tests and indirect strength tests. The results showed that crack resistance for SBS modified asphalt mixtures was significantly improved at 10°C by a factor of 1.32 and 1.18 at 20 °C, which would result in higher fatigue life. Kim et al. (2013) also reported that SBS modifiers' roles in retarding fatigue crack growth were more significant than crack initiation when the indirect tensile was conducted. On the other hand, Kim et al. (2013) observed that SBS modifiers had the ability to reduce the rate of micro-damage accumulation, resulting in an improvement in the SBS modified mixture's cracking resistance compared to unmodified mixtures.

As a part of the Florida Department of Transportation (FDOT), Greene et al. (2014) conducted a study to evaluate the effect of increasing the polymer content of asphalt binders in terms of rutting distress. In this study, Greene et al. (2014) selected three asphalt binders: an unmodified PG 64-22 binder, a PG 76-22 binder with 3% SBS content, and a PG 82-22 binder with 6% SBS content. Assessing the effect of HPMA was investigated in this study by characterizing the performance of both asphalt binders and mixtures. In terms of asphalt mixture's characterization, the Indirect Tension Test (IDT) was conducted to evaluate these mixtures' cracking resistance. Greene et al. (2014) reported based on IDT testing results that mixtures produced using high dosage of SBS modification (i.e., PG 82-22) showed the better cracking resistance compared to other mixtures, followed by mixtures that were produced using PG 76-22 and PG 64-22, respectively. On the other hand, and based on a full-scale accelerated pavement testing study, Greene et al. (2014) reported that sections containing HPMAs (i.e., PG 88-22 in this study) had higher fracture energy and lower rut depth when compared to those produced using PG 76-22 and PG 64-22 binders. Greene et al. (2014) also reported that the section containing HPMA binder had approximately seven times more fatigue life than containing PG 76-22 asphalt binder.

In a funded project by the Virginia DOT, Bowers et al. (2018) investigated the laboratory and field performance of HPMA mixtures in Virginia. In this study, the field samples were taken from mixtures that were placed over a milled asphalt pavement. The DCM test was conducted in this study to determine the complex modulus and phase angle of asphalt mixtures under different frequencies over a range of temperatures. The four-point BBF test was also conducted in this study to investigate the fatigue life of asphalt mixtures. In addition to that, the Overlay Test was utilized to investigate its cracking resistance. In summary, Bowers et al. (2018) reported that mixtures prepared using HPMA binders had approximately 40 to 50 times higher fatigue life than control mixtures. Habbouche et al. (2018) also reported similar findings further highlighting that HPMA binders enhanced the rutting and cracking resistance of asphalt mixtures.

***The Impact of Long-Term Aging on HPMA Mixtures***

The cracking resistance of asphalt mixes is highly influenced due to heat, oxidation, and other environmental factors, in other words, due to aging. Aging is one of the main defects that contributes to the total deterioration of asphalt pavements. To elaborate more, as asphalt mixtures age, they become stiffer and have less relaxation capability, leading to increased cracking potential. From a chemical perspective, oxygen reacts with certain molecules through the aging process of asphalt binders leading to form polar functional groups called carbonyl and sulfoxide compounds (Petersen, 2009). In addition, this chemical process influences the flexibility and the stiffness of asphalt mixtures (i.e., increase of complex modulus and decrease of phase angle).

The purpose of aging asphalt mixes in the lab is to simulate the field aging on laboratory produced asphalt mixes. This will help to predict the performance of asphalt pavements in the field over their service life. Typically, asphalt mixes can be aged by keeping them at a constant high temperature in an oven for a specific time. In particular, aging is done following one of two protocols: aging a compacted asphalt specimen or aging a loose HMA mixture before compacting it. Furthermore, a wide range of aging conditions (i.e., temperature and time) were followed in previous studies. In the following subsections, the relevant findings in both aging methods are discussed, besides understanding each method's advantages and disadvantages.

***Compacted Specimen Aging***

As an example of aging compacted HMA specimen, Bell et al. (1994) conducted a study to evaluate aging methods for asphalt mixtures. Based on their testing results, Bell et al. (1994) proposed an aging protocol that was conducted on loose HMA mixture at 135°C for four hours to simulate short-term aging during mixing, storage, and compaction process on actual construction practice. On the other hand, and in order to simulate the long-term aging, Bell et al. (1994) suggested to age compacted HMA specimens for different durations at 85°C. In conclusion, Bell et al. (1994) reported that the long-term aging recommended in AASHTO R30 standards (5 days at 85°C) represents 7 to 10 years of aging in the field.

Similar to Bell et al. (1994) study, Brown and Scholz (2000) conducted a study to investigate the best short- and long-term aging simulation of loose HMA mixtures. Brown and Scholz (2000) noticed that short-term aging of loose mixture at 135°C increases the stiffness of asphalt mixtures by 9% to 24% per hour of aging. In conclusion, Brown and Scholz (2000) observed that oven aging for two hours at 135°C represents aging during mixing, loading, and transporting that happens in the construction field. In terms of long-term aging, Brown and Scholz (2000) compared the stiffness modulus of laboratory aged mixtures with samples were taken from the field. In summary, Brown and Scholz (2000) reported that aging compacted specimens for five days in the oven at 85°C represents 15 years of aging in the field for pavements in the US.

In literature, a numerous number of different aging conditions (i.e., aging temperature and duration) were utilized. Table 1 illustrates a summary of compacted HMA specimen's aging protocols found in the literature. As shown in Table 1., the different aging conditions included a wide range of temperatures between 60 to 163°C, while the aging durations ranged between 5 hours and 20 days. However, most of the studies did not carry out a field validation of the proposed aging method.

**Table 1**

*Aging Procedures for Compacted Asphalt Specimens*

| Aging Temperature (°C) | Aging Duration | Reference |
|---|---|---|
| 110-120 | 16 hours | Van den Bergh (2011) |
| 60 | 48 hours | Nicholls (2006) |
| 60 | 20 days | Hayicha et al. (2003) |
| 85 | 5 days | Bell et al. (1994) |
| 2 days at 60 +<br>5 days at 107 | 7 days | Von Quintus et al. (1992) |
| 163 | 5 hours | Mugler (1970) |

In literature, several problems were reported regarding the laboratory aging of compacted specimens. As an example, Reed (2010) noticed changing in air void distribution of asphalt specimen as a problem of aging a compacted specimen which happens most likely due to the slumping of compacted asphalt specimens. In order to minimize slumping, the NCHRP 9-23 project (2005) suggested a technique to preserve the specimen from slumping by wrapping the specimens in a wire mesh and hold them in place by three clamps. The development of an aging gradient through the thickness of compacted specimen is another problem that is associated with long-term aging. For instance, Partl et al. (2013) noticed a change in the compacted samples' size and shape during the aging process. This was found to influence the testing results and their variability due to the change in their air void content.

***Loose Mix Aging***

Similar to aging a compacted HMA specimen, several researchers studied the potential of age loose asphalt mixtures. Most of the studies recommended aging loose mixtures to simulate the aging of asphalt pavements instead of aging compacted specimens (Mollenhauer and Mouillet 2011, Van den Bergh 2011). This technique was mainly suggested due to its benefits compared to aging a loose asphalt mix. The primary advantages of aging loose asphalt mixture include the following:

- Uniform aging distribution through an HMA specimen compared to aging a compacted HMA specimen, since air and heat can easily circulate inside loose asphalt mixture.
- Solve the slumping problem that is caused when aging a compacted HMA specimen.

- Increasing the area of binder surface exposed to oxygen which leads to increase the rate of asphalt's oxidation. Therefore, less time is needed in this case compared to aging a compacted asphalt mix.

For example, Von Quintus et al. (1988) conducted a study to simulate long-term field oxidation by aging loose asphalt mixtures at 135°C in a forced draft oven for 8, 16, 24, and 36 hours. Afterward, the binder in aged mixtures was extracted and recovered using penetration and viscosity tests. Similar short-term aging levels between the laboratory-aged materials and field samples taken from batching plants were reported based on the testing results. However, the laboratory-aged materials exhibited significant variability. Based on these results, Von Quintus et al. (1988) recommended short-term aging of loose mixtures at 135°C in a forced draft oven for four hours before compaction.

Another study was carried out by Van den Bergh (2009) with the goal of replicating RAP material. Van den Bergh (2009) conducted an experimental program for laboratory aging of loose asphalt mixtures. In this study, several mixtures were short-term aged in an air ventilated oven at 130°C for three hours and then long-term aged at 90°C for extended times. Binder aging was evaluated by determining the increase in the ring and ball (R&B) softening point, the dynamic shear modulus, and the carbonyl and sulfoxide indices. In terms of carbonyl and sulfoxide indices, a plateau was reached after seven days of long-term oven aging, but the rheological properties did not reach such a plateau after seven days. Afterward, these results were compared with the ones for binders extracted from seven- to ten-year-old pavement sections (Van den Bergh, 2011). Based on this comparison and in order to simulate 7 to 10 years old asphalt mixes, two procedures for aging (producing RAP materials) using a standard forced draft oven in the laboratory were recommended, as follows:

- Short-term aging at 130°C for 3 hours following long-term aging at 90°C for 168 hours (7 days).
- Short-term aging at 134°C for 4 hours following long-term aging at 85°C for 168 hours (7 days).

Under the National Cooperative Highway Research Program (NCHRP) project number 09-54, Kim et al. (2018) investigated the long-term aging of asphalt mixtures for performance testing and prediction. In this study, Kim et al. (2018) evaluated several aging approaches at different temperatures ranging from 70°C to 135°C for 12 and 24 hours. Kim et al. (2018) also reported that for certain asphalt binders: there was a significant change in the relationship between binder rheology and chemistry properties when the aging temperature increased from 95°C to 135°C. In addition, it was reported that aged mixtures at 135°C experience less fatigue resistance than those were aged at 95°C. Therefore, this study recommended to age loose asphalt mixes at 95°C as the optimal loose mix conditioning temperature.

More recently, Chen et al. (2018) conducted a laboratory investigation to select a loose mix aging protocol for the NCAT top-down cracking test. In this study, the field aging of asphalt mixtures was characterized using cumulative degree-days (CDD) which were defined as the accumulation of daily maximum temperature throughout a mixture’s service life. Chen et al. (2018) depended in their study on a performance data collected from over 80 existing pavements that experience top-down cracks. In results, it was found that top-down cracks were usually initiated when the CDD value exceeds a critical limit of 70,000 CDD. Four loose mix aging protocols were investigated in this study and tested using the DSR, BBR, and FTIR tests. The four tested protocols consist of 6-hr, 12-hr, and 24-hr of aging at 135°C, besides 5-days of aging at 95°C. Based on testing results, it was observed that 8-hour aging at 135°C was most representative of 5-days aging at 95°C for loose mixtures. Chen et al. (2018) also recommended using 8-hour at 135°C to simulate aging in the field. Furthermore, Chen et al. (2018) reported that aging a loose mix for 5-days at 95°C simulated 48,000 to 80,000 CDD at field, however, aging for 6-hr, 12-hr, and 24-hr at 135°C represented 48,000, 80,000 to 157,000, and more than 235,000, respectively. This study's findings allow researchers to simulate the field aging anywhere by knowing the maximum daily temperature at that area.

In summary, asphalt mixtures can be subjected to long-term aging in terms to simulate the field aging on laboratory mixes by following two main methods: age a compacted asphalt specimen or a loose asphalt mixture sample. Table 2 shows a summary of long-term aging methods, as was obtained from the literature review.

**Table 2**

*Aging Procedures for Loose Asphalt Specimens*

| Short-term Aging | | Long-term Aging | | Aging Equipment | Reference |
|---|---|---|---|---|---|
| Temp. (°C) | Duration | Temp. (°C) | Duration | | |
| - | - | 95 | 5 days | Oven | Chen et al. (2018) |
| | | 135 | 6 hours | | |
| | | 135 | 12 hours | | |
| | | 135 | 24 hours | | |
| - | - | 95 | 5 days | Oven | Kim et al. (2018) |
| 135 | 4 hours | 90 | 20 hours | PAV | Mollenhauer and Mouillet (2011) |
| 135 | 4 hours | 85 | 7 days | Oven | Van den Bergh (2011) |
| 130 | 3 hours | 90 | | | |
| 135 | 4 hours | 85 | 7-9 days | Oven | De la Roche et al. (2009) |
| 135 | 1.5 hours | 60 | 14 days | Oven | Piérard and Vanelstraete (2009) |
| Mixing Temp. | 2 hours | 80 | 7 days | Oven | Read and Whiteoak (2003) |
| 135 | 4 hours | 100 | 24 hours | Oven | Such et al. (1997) |
| - | - | 160 | 16 hours | Loose hot mix in sealed tin in oven | Van Gooswilligen (1989) |

**Summary of Literature Review**

An extensive and thorough review of the literature was conducted on the use of SBS polymer and corn-oil softening agent in asphalt binders and mixtures. A majority of the research investigates the impact of SBS polymer and corn-oil additives on the properties of asphalt binders and mixtures in terms of rutting, cracking, and stability performance. The different protocols of aging asphalt mixtures were also investigated in this research with evaluating the impact of aging on the properties of modified asphalt binders and mixtures. The findings from the studies on using SBS polymer and corn-oil SA in asphalt pavements are as follows:

- A potential approach to improve the performance of asphalt pavements in cold regions is to modify asphalt binder with a combination of polymer and a softening agent.
- The use of SBS polymer in asphalt binder improved the rutting and fracture performance of asphalt mixtures, besides improving the asphalt binder's aging resistance.
- Using softening agents such as corn-oil in asphalt binders and mixtures enhanced their cracking resistance at low temperatures by approximately 10-50% of its original resistance to cracking (i.e., low PG temperature) depending on the rejuvenator's type and dosage.
- The compatibility between additives and asphalt binder is a key parameter to examine how successful the modification process is.

- Cracking resistance of asphalt binder is sensitive to aging. Therefore, several protocols were proposed in the literature to simulate the field aging on laboratory-produced mixtures in order to investigate the performance of asphalt mixes in field.

Therefore, due to the limited literature on the use of softening agent with high polymer modified asphalt binders in flexible pavements, there is a need to investigate the impact of high polymer modified binder with softening agent on the performance of asphalt mixtures. Also, previous research highlighted the importance of assessing the negative impacts of aging on the cracking performance of asphalt mixtures and that such impacts can potentially be countered through the use of softening agents. Current studies in literature also did not assess the potential for using softening agents as part of the binder modification formula for potentially improving the performance of long-term aged asphalt mixture produced using HPMA. This study bridges this gap in the current literature.

## Chapter 3

## Materials and Experimental Plan

A description of materials, such as additives to produce highly modified asphalt mixtures is presented in this chapter. This chapter also discusses the adopted laboratory testing approach for evaluation of the performance of modified asphalt mixtures. In particular, this chapter provides a discussion of the utilized materials and the procedures employed for producing highly elastic binders to be used in producing HMA mixtures. Moreover, this chapter includes the HMA mix design and the procedures followed for producing highly elastic modified asphalt mixtures. In addition, this chapter includes the procedure followed to characterize the performance of modified asphalt mixtures.

### Modified Asphalt Binder Materials and Preparation

In this study, a neat asphalt binder of PG52-34 was used to produce control (unmodified) mixture and was also used to produce modified asphalt binders those were then used to produce asphalt mixtures. The neat soft binder used in this study was selected due to its soft nature; thus, it may exhibit better cracking resistance in cold regions. On the other side, the following materials were utilized in the study to produce modified asphalt binders:

1- Corn-oil Softening Agent: The used corn oil in this study was selected because of its ability to improve the cracking resistance of asphalt binders and mixtures in previous studies (Zaumanis et al., 2014; Xie et al., 2018).
2- SBS Polymer: A thermoplastic elastomer SBS polymer was used in this study and it was Kraton D-0243 which is a clear, deblock copolymer based on styrene and butadiene with a polystyrene content of 33%.

3- Sulfur Powder: The sulfur powder in this study was incorporated into the modification process of asphalt binder at low dosage (i.e., 0.1% by weight of base binder) to reduce the separation between asphalt binder and modifiers.

Four binders were produced in this study to evaluate the impact of polymer modified asphalt with softening agent on the performance of asphalt mixtures. The four types of asphalt binders included a control binder and three modified binders. The modification rates of asphalt binders used in this study were selected based on a preliminary conclusion was drawn at earlier stage of the study (Xie et al., 2020). The results in Xie et al. (2020) study showed that selected modification rates were compatible and showed a significant enhancement in the performance of HPMA binder compared to neat binder.

Consequently, based on Xie et al. (2020) results, this study included the best three performed modified asphalt binders were produced by incorporating different SBS polymer and corn-oil SA. In this study, first modified binder was produced by blending neat asphalt binder with 7.5% of SBS and 7% of corn-oil SA, the second modified binder included 7.5% of SBS and 14% of corn-oil SA, and the third binder was modified with 10% of SBS and 14% of corn-oil SA. It should be noted that all dosage rates were determined by weight of base binder. Furthermore, to improve the compatibility between additives and base binder, 0.1% of sulfur powder by weight of base binder was incorporated into the modified asphalt binder.

The modification process as recommended by the material's provider consisted of five main steps as follows:

1- Heating up the base binder at 280°F for two hours or until it flows easily.

2- Adding the softening agent to the base binder based on the modification dosage (percentage by weight of base binder).

3- The blend was stirred manually for five minutes and then kept in the oven for 10 to 15 minutes at the same temperature (i.e., 280°F).

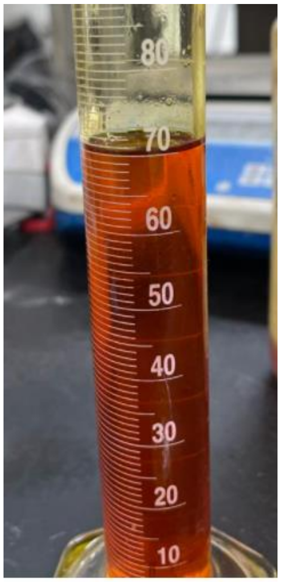
4- Preparing the required amount of SBS polymer and sulfur powder at this stage to be added to the blend. The SBS dosage was a percentage by weight of base binder and varied depending on the modification rate (i.e., 7.5% or 10%), while 0.1% of sulfur powder by weight of base binder was added to the blend.

5- At this stage, a high shear mixer was used to blend the additives together. The blending was done at 4000 rpm for four hours at 340-350°F.

**Figure 3**

*Materials Used in Preparing Modified Asphalt Binder*

a) SBS Polymer b) Sulfur Powder




c) Corn-Oil Softening Agent

**Figure 4**

*Shear Mixer Used to Blend Additives with Asphalt Binder*


a) Shear Mixer

b) Shear Blade

## Asphalt Mixture Materials and Mix Design

A dense-graded airfield mix was utilized in this study to produce control and modified HMA mixtures. The aggregate's gradation was designed based on Superpave procedures and Federal Aviation Administration (FAA) P-401 specifications (Circular, 2009). The FAA specifications were followed in this study due to their similarity with the US Army Corps of Engineers (USACE) HMA mix specifications for airfield.

In order to prepare asphalt mixtures in this study, a diabase aggregate type was utilized and mixed with four different asphalt binders as was illustrated in the previous section. Figure 5 illustrates the gradation and control points for P-401 mixes. The blend was prepared with a 12.5 mm Nominal Maximum Aggregate Size (NMAS), which is used typically as a surface course. This aggregate gradation was selected from a previously FAA approved P-402 Job Mix Formula (JMF) obtained from a local contractor.

After mixing the aggregate blend and asphalt binder, compacted specimens were prepared according to AASHTO 312 and using the Superpave Gyratory Compactor (SGC). The optimum binder content of asphalt mixtures was determined at a design gyration level ($N_{des}$) of 50 gyrations (P-401 specifications), with a targeted air voids content of 3.5±0.5%, and a minimum Voids in Mineral Aggregates (VMA) of 15%. Four types of mixtures were produced in this study including a control mix (prepared with neat binder) and three modified asphalt mixtures produced using modified binder as was described in the previous section (i.e., PG 52-34 blended with 7.5% SBS and 7% SA, 7.5% SBS and 14% SA, and 10% SBS and 14% SA). Table 3 illustrates the mixture ID, modification rate, and volumetric properties.

**Figure 5**

*FAA P-401 Aggregate Gradation*

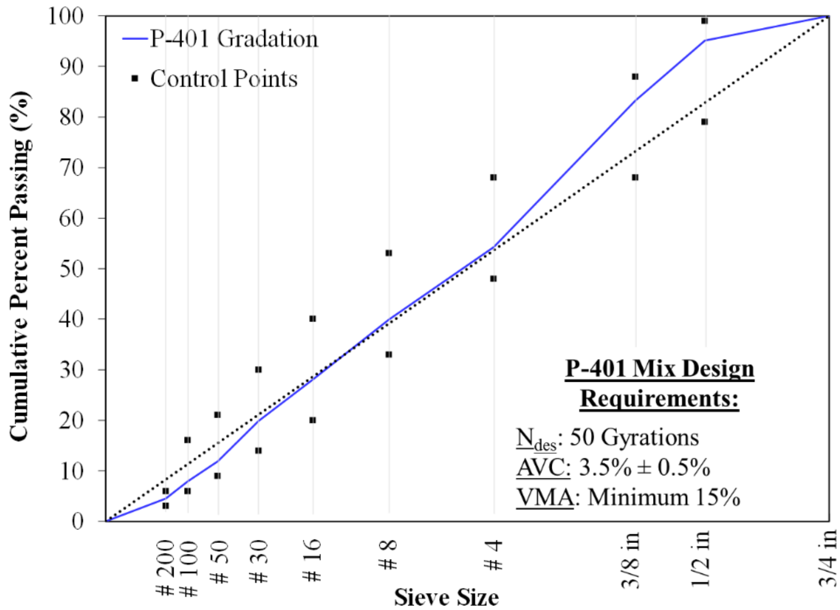


**Table 3**

*The Optimum Binder Content of Modified Asphalt Mixtures*

| Mix ID | Asphalt Mix Design Results | | | |
|---|---|---|---|---|
| | Modifier | Opt. Binder Content (%) | VMA (%)* | Avg. Air Voids (%)* |
| **Control** | Neat Binder | 5.5 | 16.6 | 3.36 |
| **7.5-SBS-7-SA** | 7.5% SBS + 7% SA | 5.5 | 16.5 | 3.30 |
| **7.5-SBS-14-SA** | 7.5% SBS + 14% SA | 5.5 | 16.8 | 3.77 |
| **10-SBS-14-SA** | 10% SBS + 14% SA | 5.5 | 16.5 | 3.35 |

* Min. VMA is **15%** and target air void content is 3.5 ± 0.5%

## Experimental Plan

The experimental plan in this study was designed to investigate the impact of incorporating SBS polymer and corn-oil softening agent into asphalt mixtures on the performance of asphalt mixtures. In particular, the experimental plan included a characterization of the dynamic modulus, durability, rutting, and cracking properties of modified asphalt mixtures. In addition, the study includes an investigation of the impact of loose asphalt mix aging on the properties of asphalt binder. Furthermore, the cracking resistance of asphalt mixtures in this study was investigated at three different aging levels (i.e., short, long, and extended long-term aging levels) to evaluate the impact of aging on the cracking resistance of modified asphalt mixtures. In this study, several performance tests were utilized to characterize the fatigue, low, and intermediate temperature cracking resistance of modified asphalt mixtures. The following subsections summarize the performance test protocols in more details.

***Dynamic Complex Modulus (|E*|, AASHTO T342)***

The Dynamic Complex Modulus was utilized to investigate the linear viscoelastic properties of the control and modified asphalt mixes. According to AASHTO T342, the test was conducted at various temperatures (i.e., -10, 4, 21.1, and 37.4°C) and loading frequencies (i.e., 0.1, 0.5, 1, 5, 10, and 25 Hz). At a target air voids level of 7 ± 0.5%, three replicate samples from each mix were produced by coring and cutting Superpave gyratory compacted large samples. The final dimensions of cored samples were 150-mm. height and a 100-mm. diameter. A sigmoidal model was used to fit all data by developing a master characteristics curve at a reference temperature of 21.1°C. The value of |E*| at low frequencies provide insights into the performance of mixtures at high temperatures (mainly rutting), while those at high frequencies help in assessing mixes' performance at low temperatures (mainly cracking).

***Hamburg Wheel Tracking Device (HWTD, AASHTO T 324-19)***

The goal of the HWTD test is to investigate the permanent deformation characteristics and moisture susceptibility of the control and highly modified asphalt mixtures. At a target air void content of 7 ± 0.5%, three replicates (a total of six gyratory specimens) for each mix were tested. The asphalt specimens had dimensions of 150-mm. diameter and 75-mm. height. Furthermore, a steel wheel was utilized in this test to apply a load of 702N on top of compacted asphalt mixtures. The samples were loaded while they were submerged in water at a temperature of 40°C. This temperature was selected due to the use of soft asphalt binders in this study. Testing was terminated when a sample reached a total of 20,000 loading cycles or when the maximum rut depth in the sample reached a maximum rut depth of 12.5 mm. The difference in surface elevations at five different points along the sample were calculated after each cycle to determine the rut depth. The main parameters determined by the HWTD were the Stripping Inflection Point (SIP), rut depth values, and number of cycles to failure. The lower SIP and higher rut depth values for an asphalt mix indicates its higher susceptibility to rutting and moisture induced damage.

***Flow Number (FN) or Repeated Load Permanent Deformation (AASHTO T 378)***

The Flow Number (FN) test was utilized in this study to investigate the rutting resistance of asphalt mixtures produced in this study. In this test, one cycle was completed by applying a haversine load pulse at 0.1 second on a specimen followed by a 0.9-second rest period which in total equals one second for one cycle. Due to the use of soft binders in this study, the testing temperature selected for this test was 37°C instead of 54°C as was recommended by the AASHTO T378. The test was continued for several cycles to determine the cumulative permanent deformation and number of cycles to failure (i.e., the FN). The FN value indicate how a mixture is rutting resistant where the higher FN indicates higher resistance to rutting. At a target air voids content of 7 ± 0.5%, three replicates for each mix were prepared. It is noted that the samples prepared for the |E*| were utilized to conduct the FN test after completing all required |E*| testing.

*Indirect Tension Asphalt Cracking Test (IDEAL-CT) at Intermediate Temperatures (ASTM D8225-19)*

The IDEAL-CT test was utilized in this study to investigate the cracking resistance of the unmodified and modified asphalt mixtures at intermediate temperature. The selected intermediate temperature based on the PG grade of base binder (i.e., PG52-34) was calculated according to the ASTM D8225-19 to be 13°C. This test consists of applying a constant displacement load at a rate of 50 mm/min to break the specimens. The asphalt specimens were compacted at a height of 62 mm with a 150 mm diameter and target air voids of 7 ± 0.5%. Three replicates for each type of mixtures and aging level were produced and tested. Using the recorded load vs. displacement curve, various cracking performance measures can be identified from this test. Specifically, the strength to fracture (or Indirect Tensile Strength, ITS) and the Cracking Test Index (CT-Index) were measured. Higher ITS and CT-Index values indicate better resistance to fatigue cracking.

*Semi-Circular Bend Test (SCB) at Low Temperatures (AASHTO TP 124-18)*

The goal of conducting the SCB test was to evaluate the cracking resistance of all mixtures at low temperatures (i.e., 0°C). The asphalt specimens were fabricated by cutting a gyratory compacted specimen (150 mm diameter with 50 mm) in half. The samples were then notched (each half) to guide the crack propagation towards the center of asphalt specimen and to target required notch depth and width, that is, 12.5 and 1 mm, respectively. Three samples were produced for each mix type to target an air void content of 7 ± 0.5%. The test was conducted at 0°C by applying a constant displacement load of 12.5 mm/minute on asphalt specimens until break. Using the load versus displacement curve the fracture energy, fracture toughness, and flexibility index were measured using the SCB test. Higher fracture energy, toughness, and flexibility index values indicate that asphalt mixtures are more resistant to cracking.

***Disk-Shaped Cracking Test (DCT) (AASHTO T322)***

The DCT test was utilized in this study to evaluate the cracking resistance of control and modified asphalt mixtures at extreme low temperature (i.e., at -24°C). The DCT test was conducted by subjecting a circular specimen with a single edge notch to a tensile load. The asphalt mixtures (control and modified) were compacted to have a 150 mm. diameter, 50 ± 5 mm. thick, and a target air void content of 7 ± 0.5%. Afterward, two loading holes were fabricated with 25-mm. diameter for each. Between these holes, a notch was fabricated along the specimen's diameter and a flat surface at the crack mouth was cut at 90° ± 5° to the notch. The applied tensile load was controlled by controlling the crack mouth opening displacement (CMOD) and maintaining a constant load rate of 1.0 mm/min on tested samples. All samples were conditioned at testing temperature (i.e., -24°C) for 16 hours. After that, the fracture energy (cracking resistance) of asphalt mixtures was calculated by determining the area under the load vs. CMOD graph. Using It is noted that the higher fracture energy value refers to more propagation cracking resistance.

***Cantabro Durability Test (AASHTO TP108)***

The durability of modified and unmodified asphalt mixtures was assessed using the Cantabro Durability Test. Three replicates for each mix type were compacted at 50 gyrations reaching a height of 115 ± 5 mm and meeting a target air void content of 3.5 ± 0.5% and then placed in the Los Angeles Abrasion (LA Abrasion) device. The test was conducted on asphalt mixes by testing them separately and subjecting each one to 300 revolutions at a speed of 30-33 revolutions per minute. Afterwards, the Cantabro Loss was calculated by determining the percent abrasion loss of compacted asphalt mix samples based on its weight before and after the test. Lower percent materials loss values indicate that asphalt mixtures are more durable (more resistant to breaking down under loading).

***Aging Levels Applied for Cracking Tests***

In order to investigate the impact of aging on the cracking resistance of highly modified asphalt mixtures, three aging levels were used to age these mixtures to evaluate the impact of short, long, and extended long term aging levels on the cracking resistance of asphalt mixtures. According to a study by Chen et al. (2018), the long- and extended-long-term aging protocols simulate 10 and 20 years of pavement's service life in Alaska, respectively. Field aging in Alaska conditions was utilized because the base binder used in this study is representative of those typically used in the state. The different aging levels were selected in this study to assess the impact of loose asphalt mix aging on the performance of asphalt mixtures. The use of the different aging levels also allows to better understand the benefits of using highly modified asphalt binders containing softening agent. The employed aging levels in this study were as follows:

- *Short-Term Aging:* Loose mix aged at compaction temperature for 2 hours before samples were compacted;
- *Long-Term Aging:* Loose mix aged at 135°C for 8 hours before samples were compacted; and,

- *Extended-Long-Term Aging:* Loose mix aged at 135°C for 12 hours before sample were compacted.

**Figure 6**

*Images of the Experimental Plan for Evaluating the Performance of Asphalt Mixtures*

DCM and FN Tests

HWTD Rutting Test

Cantabro Durability Test

IDEAL-CT Cracking Test

SCB Cracking Test

DCT Cracking Test

**Table 4**

*Summary of the Experimental Plan for Evaluating the Performance of Asphalt Mixtures*

| Laboratory Test | Relevant Specifications | Tested Aging Level | Testing Temperature | Distress Measured | No. of Samples |
|---|---|---|---|---|---|
| **Dynamic Complex Modulus** | AASHTO T342 | ✓ Short-Term | -10, 4, 21.1, and 37.4°C | ✓ Fatigue Resistance<br>✓ Rutting Resistance | 12 |
| **Hamburg Wheel Tracking Device** | AASHTO T324-19 | ✓ Short-Term | 40°C | ✓ Rutting Resistance<br>✓ Moisture Susceptibility | 24 |
| **Flow Number (FN)** | AASHTO T378 | ✓ Short-Term | 37°C | ✓ Rutting Resistance | 12 |
| **Cantabro Test** | AASHTO TP108 | ✓ Short-Term | Room Temperature | ✓ Durability | 12 |

| Laboratory Test | Relevant Specifications | Tested Aging Level | Testing Temperature | Distress Measured | No. of Samples |
|---|---|---|---|---|---|
| **Indirect Tension Test** | ASTM D8225-19 | ✓ Short-Term<br>✓ Long-Term<br>✓ Extended Long-Term | 13°C | ✓ Cracking Resistance (Intermediate Temperature) | 36 |
| **Semi-Circular Bend Test** | AASHTO TP 124-18 | ✓ Short-Term<br>✓ Long-Term<br>✓ Extended Long-Term | 0°C | ✓ Cracking Resistance (Low- Temperature) | 36 |
| **Disk-Shaped Cracking Test** | AASHTO T322 | ✓ Short-Term<br>✓ Long-Term<br>✓ Extended Long-Term | -24°C | ✓ Cracking Resistance (Low-Temperature) | 36 |
| **Total Number of Tested Samples = 168 Samples** | | | | | |

# Chapter 4

# Laboratory Results and Analysis

The purpose of this chapter is to discuss the results of laboratory performance of highly modified asphalt mixtures. This chapter presents the laboratory results on the impact of using high polymer modified asphalt (HPMA) with corn-oil softening agent on the durability, rutting, moisture, and cracking resistance of asphalt mixtures. The impact of aging loose asphalt mixture on the cracking resistance is also discussed in this chapter.

## Impact of HPMA on Asphalt Mixture's Durability

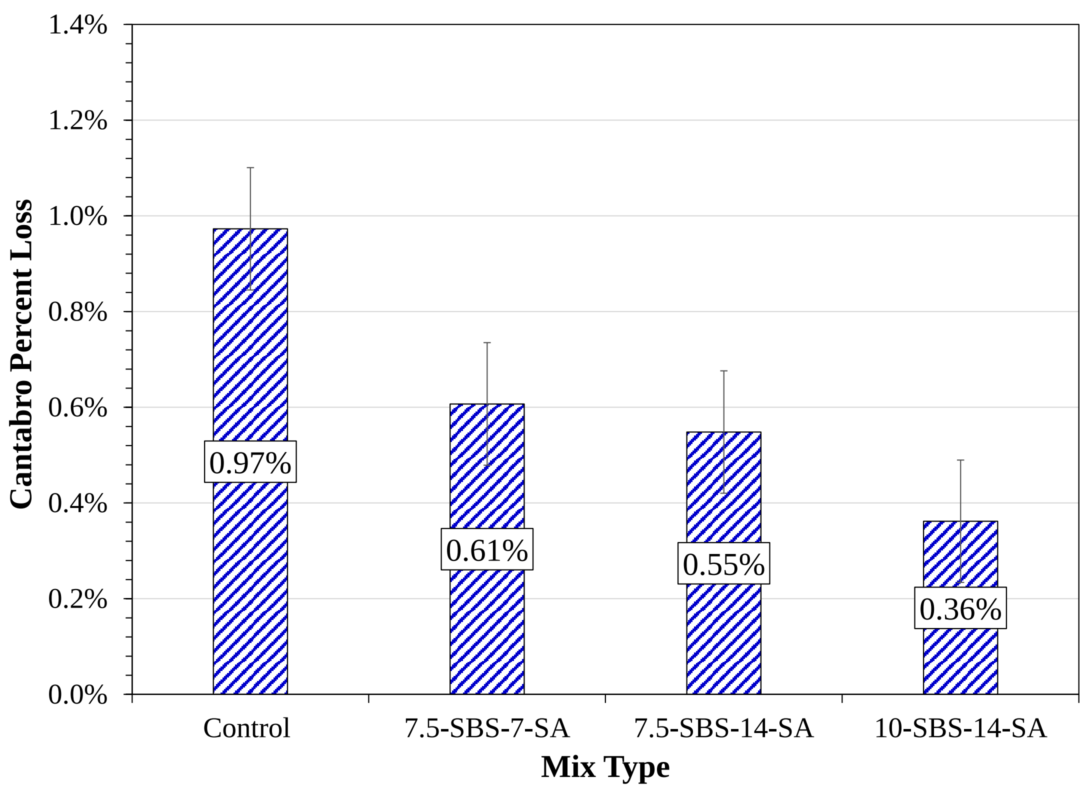
The durability of asphalt mixtures was investigated in this study as mentioned before by subjecting asphalt specimens to 300 revolutions in the LA Abrasion device. The specimen's weight before and after the test were used to calculate the Cantabro Percent Loss which indicates how hard it is to break the specimen, in other words, how durable is the asphalt mix. It is noted that the less Cantabro Percent Loss indicates the more durable mix (higher resistance to breaking down).

The Cantabro Percent Loss values of the tested asphalt mixtures in this study are shown in Figure 7. As illustrated in Figure 7, all modification dosages improved the durability of asphalt mixes. In particular, incorporating SBS polymer and corn oil SA into the asphalt mixtures reduced their Cantabro Loss from 40 to 60% compared to unmodified mix. These findings indicate that using SBS with corn oil SA had more resistance to breakdown, in other words, the SBS and SA additives enhanced the durability of asphalt mixtures. The results also show that the modified mix with 7.5-SBS-7-SA had a slightly higher Cantabro Loss (within 0.1-0.2%) compared to the 7.5-SBS-14-SA mix, however, as the SBS dosage increased to 10%, the Cantabro Loss decreased by

34 to 40% of its value for both mixes those were modified with 7.5% SBS. This indicates that the improvement in asphalt mix's durability was attributed to the use of SBS polymer in modified mixes.

**Figure 7**

*Results of the Cantabro Durability Test (Cantabro Loss)*




**Effect of HPMA on the Viscoelastic Properties of Asphalt Mixes**

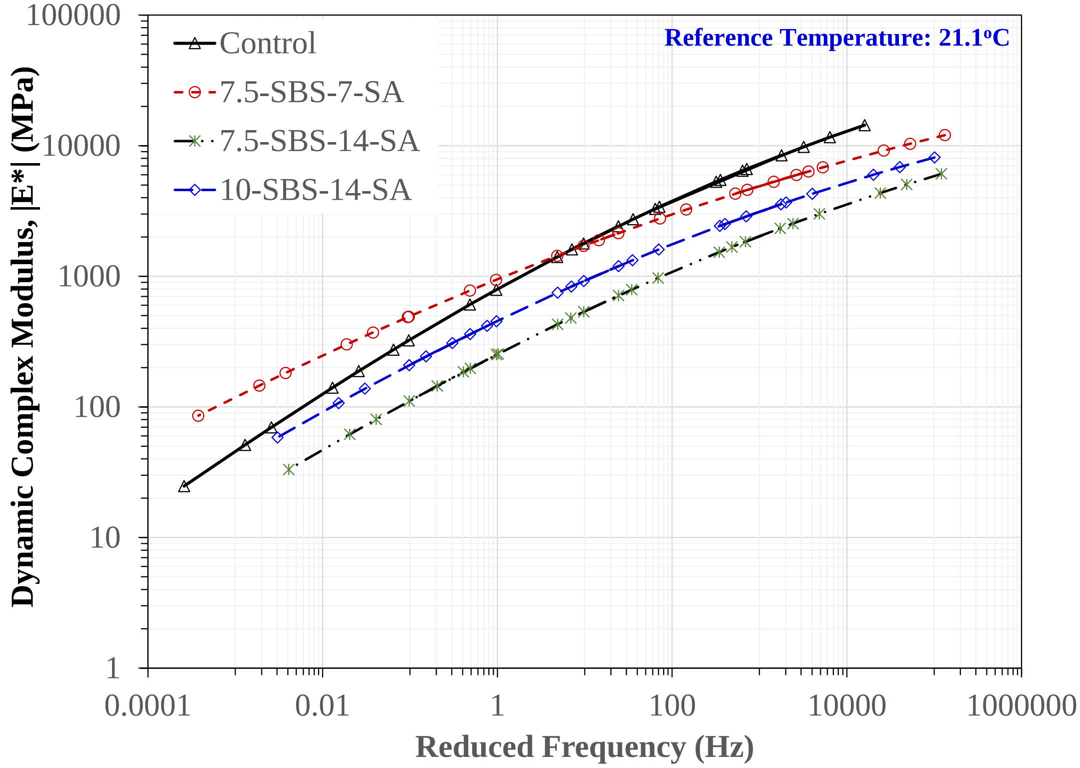
The DCM test was utilized mainly in order to investigate the impact of using high SBS polymer with softening agent in asphalt mixtures on their viscoelastic properties. The DCM testing was done by subjecting the asphalt specimens to a sinusoidal axial compressive stress at a wide range of frequencies (i.e., 0.1, 0.5, 1, 5, 10, and 25 Hz) and at different temperatures (i.e., -10, 4, 21.1, and 37.4°C). The applied stress and the resulting recoverable axial strain response of the specimen was measured and then used to calculate the dynamic modulus (|E*|). Afterwards and based on the time-temperature superposition theory, the |E*| and δ results at the different temperatures were shifted horizontally to a reference temperature of 21.1°C to develop master curves for |E*| values as illustrated in Figure 8. Figure 8 shows the |E*| master curves for all tested samples at a reference temperature of 21.1°C. It is noted that due to the shifting, the results at a higher temperature will have a lower reduced frequency, while results at colder temperature will have higher reduced frequencies. The "reduced frequency" term refers to the resulted frequency after shifting. Consequently, the |E*| values obtained at high reduced frequencies provide insights on the cracking resistance of asphalt mixes at cold temperature, however, their resistance to permanent deformation at high temperature can be seen at low reduced frequencies.

As shown in Figure 8, the results of |E*| for the control mix are higher than those obtained for the 7.5-SBS-14-SA and 10-SBS-14-SA. This reduction in the modulus is mainly attributed to the use of high corn-oil SA dosage (i.e., 14%) in the modified mixture. These results also suggest that incorporating 7.5 or 10% of SBS with 14% of softening agent improve the cracking resistance of asphalt mixtures at low temperatures (i.e., lower |E*| values at high reduced frequencies) and increase their rutting susceptibility at high temperatures (i.e., lower than control |E*| values at low reduced frequencies). This further highlights that incorporating higher dosage of SBS polymer improves the rutting resistance of modified asphalt mixtures, but it increases its susceptibility to cracking.

With regards to the 7.5-SBS-7-SA mix's results, the |E*| values at low temperature (i.e., high reduced frequencies) are lower than those for the control mix, while the |E*| values are higher than those obtained for the control mix at high temperatures (i.e., low reduced frequencies). This indicates that using this modification dosage rates (i.e., 7.5% SBS and 7% SA) enhances the rutting resistance at high temperature as well as the cracking performance at low temperatures. Furthermore, by comparing the |E*| values for all mixes, it is observed that increasing the SA dosage improves the cracking resistance of asphalt mixtures and increased the rutting susceptibility. Furthermore, by comparing the |E*| values obtained for all mixes, it can be seen that using a modification dosage of 7.5% SBS and 7% of SA resulted in the best improvement in both cracking and rutting performance.

**Figure 8**

*Results of the Dynamic Complex Modulus (|E*| Master Curves)*




## Impact of HPMA on Rutting Resistance of Asphalt Mixtures

In order to investigate the impact of HPMA on the rutting resistance of asphalt mixtures, the FN and HWTD tests were utilized in this study. The FN was determined by subjecting asphalt specimens to a 0.1 second of haversine load followed by a 0.9 rest period to complete one loading cycle. The test was continued for several thousand cycles or until the tested sample was failed to determine the cumulative permanent deformation and the FN number. The FN value represents the number of cycles to failure where higher number of cycles represents higher rutting resistance. The FN values obtained for all mixtures as well as the HWTD results are illustrated in Figure 9a and Figure 9b, respectively.

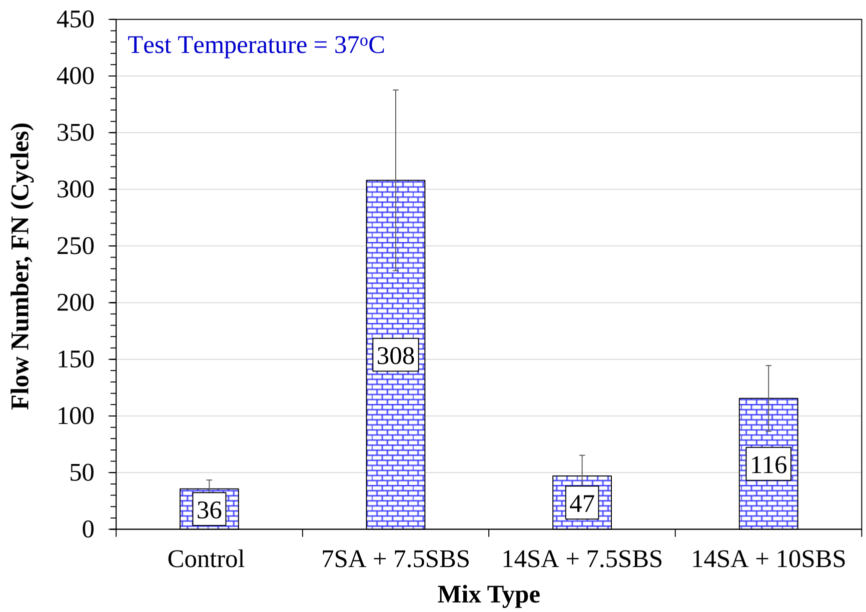
As illustrated in Figure 9a, all three modified mixtures have a higher FN values than those obtained for the control mix. This finding suggests that using a combination of SBS and corn oil SA in asphalt binder leads to improve the rutting resistance of asphalt mixtures. Figure 9a furthermore shows that the FN value for the 7.5-SBS-7-SA mix was the highest compared to all other mixtures which indicate that this modification dosage leads to the best improvement in terms of rutting resistance. Moreover, the FN results indicate that the SBS polymer is the main factor leading to improve the rutting resistance of asphalt mixtures. This can be clearly seen when comparing the FN values obtained for both mixes (i.e., 7.5-SBS-7-SA and 7.5-BS-14-SA). In other words, increasing the corn oil SA dosage from 7% to 14% reduced the FN value (i.e., rutting resistance) to 15% of its value at the mix modified with 7% of SA. Similarly, increasing the SBS dosage from 7.5% to 10% (i.e., 7.5-SBS-14-SA to 10-SBS-14-SA) improved the rutting resistance of asphalt mixtures to two times of its resistance (FN value) compared to those obtained for the 7.5-SBS-14-SA mix.

The results of the HWTD test are presented in Figure 9b. As illustrated in this figure, it can be seen that all modified mixtures have lower rut depth values ranging from 20% to 60% than that obtained for the control mix. This highlights that incorporating a combination of SBS and corn oil SA into asphalt binder improves the rutting resistance of asphalt mixtures produced using these modified binders. The results in Figure 9b also show that the 7.5-SBS-7-SA mix had the lowest rut depth values compared to all other mixes; suggesting that using this modification rate led to the best improvement in rutting performance compared to other mixtures. It is noted for the control mix and the 7.5-SBS-14-SA mix that the average rut depth is less than 12.5mm and they did not reach the maximum cycles (i.e., 20,000 cycles); this is the case because the HWTD has five sensors at the centerline of the tested specimens at different locations; thus, if any sensor reads a rut depth of 12.5 mm the test will automatically stop.

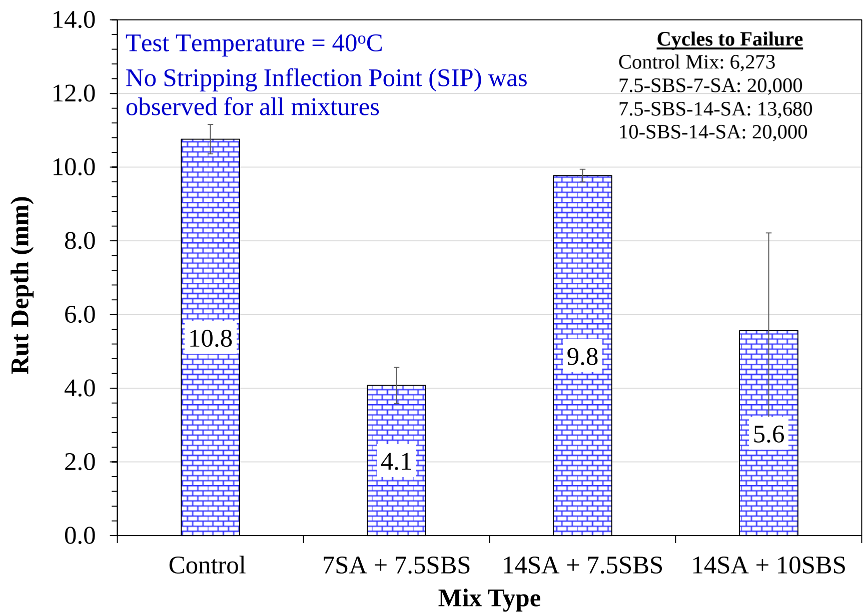
When comparing all mixtures together, it can be observed that the SBS was the main factor responsible for improving the rutting performance of asphalt mixtures, while incorporating more SA in the asphalt mix decreased the rutting resistance of asphalt mixtures. This is mainly because increasing the SA dosage from 7% to 14% (i.e., 7.5-SBS-7-SA and 7.5-SBS-14-SA mixes) approximately doubling the measured HWTD rut depths. On the other side, increasing the SBS dosage from 7.5% to 10% (i.e., 7.5-SBS-14-SA and 10-SBS-14-SA mixes) reduced the rut depth values obtained for the mix with higher SBS dosage. Nevertheless, despite the expected negative impacts of SAs on the rutting resistance of asphalt mixtures, the results presented in Figure 9b show that the use of SBS counteracted the corn oil's impact on rutting resistance, leading to better overall rutting resistant asphalt mixtures. As a result, it can be concluded that corn oil and SBS polymer can be used successfully to improve the rutting resistance of asphalt mixtures. It is important to also note that no Slope Inflection Point values were observed for the control and modified asphalt mixtures. This suggests that the predominant mode of failure all the mixes experienced is rutting and no moisture damage.

**Figure 9**

*Results of the Rutting Performance Tests: a) Flow Number Test, FN (Cycles to Failure) and b) HWTD Measured Rut Depths*




**a)**




**b)**

## Impact of HPMA on the Cracking Resistance of Asphalt Mixtures

Three performance tests were utilized in this study to evaluate the cracking resistance of HPMA mixtures including the IDEAL-CT, SCB, and DCT tests. These performance tests were also used to characterize the aging impact on the cracking resistance of asphalt mixtures by subjecting asphalt mixtures to three different aging levels (i.e., short, long, and extended long term aging levels).

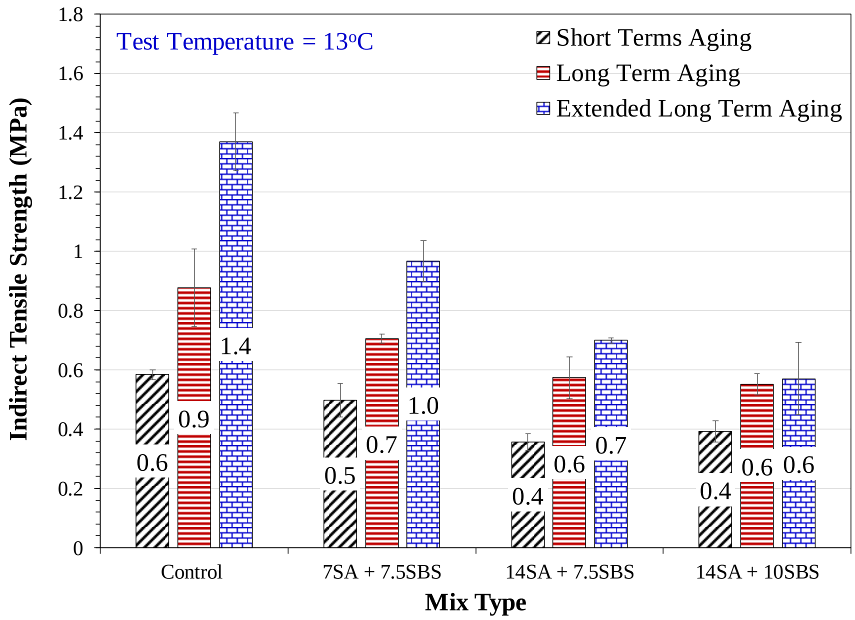
## IDEAL-CT Results

The results of the IDEAL-CT test for three modified asphalt mixtures and the control mix at the three aging are presented in Figure 10a and Figure 10b. Figure 10a presents the IDEAL-CT ITS values for the control and modified mixtures tested at the three aging levels (short-term, long-term, and extended-long-term). As can be seen from Figure 10a, the control mixture had higher average ITS values than all the modified asphalt mixtures. This was the case for all aging levels tested. The reduction in ITS values for the modified mixes is mainly attributed to the corn oil SA used in the modified asphalt binder in these mixtures. These ITS observations may indicate that the control mix has a higher cracking resistance at intermediate temperatures than the modified mixes. It should be noted; however, that ITS values alone do not always relate to improved cracking performance and they should be interpreted with other cracking indices. The ITS is only a measure of a mixture's strength and not necessarily always a good predictor of asphalt mixes' cracking in the field. In addition, the impact of loose mix aging on ITS can be evaluated by comparing the ITS values for the mixes tested at short-, long, and extended-long-term aging levels. The ITS values for all mixes increased with increase in loose mix aging period. With more aging, the asphalt mixtures become “stiffer”; thus, explaining the observed increases in ITS values with aging. These results also provide further evidence that ITS is not a good predictor of asphalt mixes’ cracking performance. This is the case because it is commonly known that as asphalt mixtures age, their cracking resistance is reduced. Therefore, higher ITS values at more severe mix aging levels are not representative of increased cracking resistance.

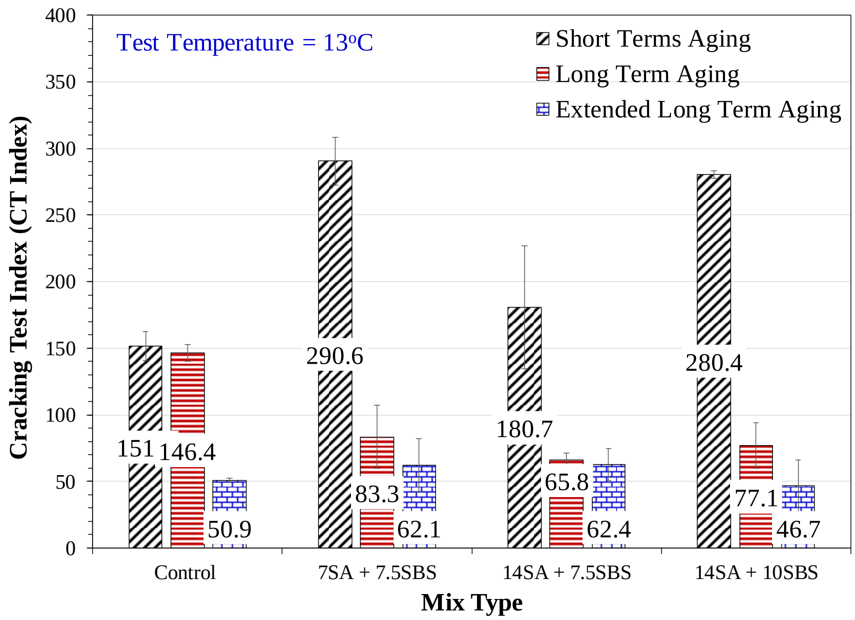
Figure 10b shows the CT-index values for all mixes. As illustrated in this figure, the CT-index values for the modified mixtures tested after short-term mix aging are higher than those of the control mix. This was the case for all SBS and corn oil SA combinations of dosages. This CT-Index observation suggests that the modified mixtures have a higher cracking resistance, during their early life, than the control mix; highlighting the short-term cracking resistance improvements attained by modifying asphalt binders with SBS and corn oil SA. For long-term aging, the CT-Index values (Figure 10b) for the modified mixtures were lower than that obtained for the control mix. In the case of extended-long-term aging, the CT-Index values for the control and modified mixtures were similar (within 11 points). These observations indicate that mixture aging affects the cracking resistance of asphalt mixtures produced using asphalt binder modified with SBS and corn oil SA. The results in Figure 10b also show that aging affects all modified mixtures, regardless of SBS and corn oil SA dosages, similarly (i.e., CT-Index for these mixes are relatively the same for long- and extended-long-term aging levels). Overall, it can be concluded from the CT-Index results that the use of SBS and corn oil SA help improve the fatigue cracking resistance (at intermediate temperatures) of asphalt mixture during early life; however, as the mixtures age these improvements are negated.

**Figure 10**

*Results of the IDEAL-CT Cracking Test: a) IDEAL-CT Indirect Tensile Strength (ITS) and b) CT-Index*




**(a)**




**(b)**

**SCB Results**

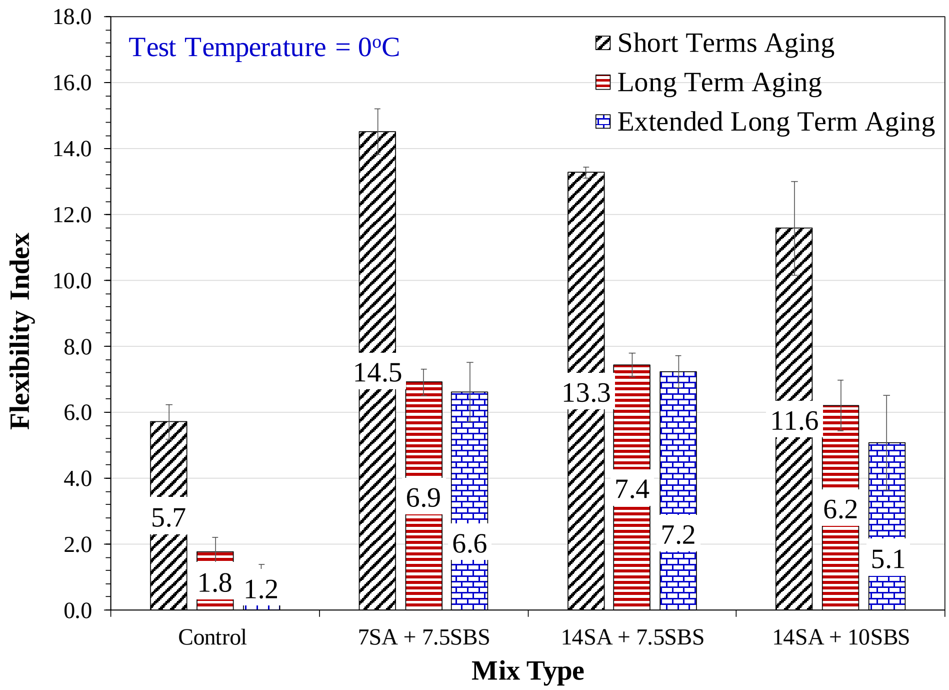
With regards to low-temperature cracking resistance, Figures 11a, 11b, and 11c present the Flexibility Index (FI) values, SCB fracture energy and fracture toughness, respectively, for all mixtures tested at the three loose mix aging levels considered in this study. The results in Figure 11a show that all modified mixtures have higher FI values compared to control mix by two, three, and five times approximately at short, long, and extended-long aging levels, respectively. It is also shown that increasing the SBS dosage from 7.5% to 10% reduced the FI value (cracking-related damage). This indicates that at low-temperature the HPMA mixes have lesser crack-related damage at all aging levels compared to the control mix. Furthermore, increasing the aging level from short to extended-long term aging reduced the FI value for the control mixture to 21% of its original value, however, the FI value for the HPMA mixtures was reduced to 45-55% of its original value (at short term aging). This indicates that over time the cracking resistance for HPMA mixtures are more stable than control mix with increasing the aging level. To elaborate, this stability suggests that aging does not have a significant influence on the performance of HPMA mixtures.

In terms of fracture energy values obtained using SCB test, Figure 11b show that the control and the 7.5-SBS-7-SA had similar SCB fracture energy values (within ≈300 joules/$m^2$) for samples tested at short-term aging. The other two modified mixes (7.5-SBS-14-SA and 10-SBS-14-SA) had lower fracture energy values. These results indicate that preparing asphalt mixtures using binder modified with balanced SBS and corn oil SA dosages of 7.5% and 7%, respectively leads to mixtures with statistically similar low-temperature cracking resistance to that of the control mix. The results also show that adding more softening agent or SBS polymer (10% SBS and 14% corn oil) had a negative impact on the SCB fracture energy; suggesting these high dosages are not effective at improving the low-temperature cracking resistance of asphalt mixtures. The impact of aging can also be evaluated by comparing the fracture energy values (Figure 11b) for mixtures tested at long- and extended-long-term aging. As shown in Figure 11b, all mixes had similar fracture energy values for samples tested at long- and extended-long-term aging levels. This indicates that the low-temperature cracking resistance for the modified and control mixtures at long term aging were statistically similar. The impact of aging is also less pronounced on the mixes containing 14% corn oil SA. This may be because the high dosage of the softening agent effectively neutralizes the aging impacts and keeps the fracture energy values, regardless of aging level, relatively similar (within 100 to 300 joules/$m^2$).

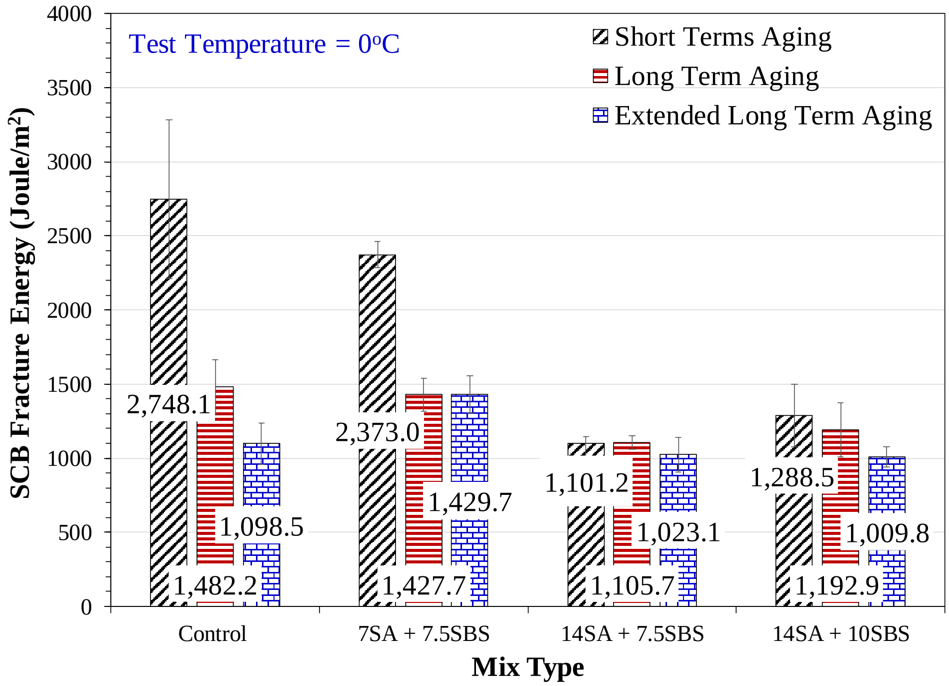
The fracture toughness as measured using the SCB for all mixtures tested at the three aging levels is presented in Figure 11c. The results in this figure show that the control mix had the highest fracture toughness values followed by the 7.5-SBS-7-SA mix. The other two modified mixes (i.e., 7.5-SBS-14-SA and 10-SBS-14-SA) had similar toughness index values but were lower than the control and 7.5-SBS-7-SA mixes. This was the case for all three loose mix aging levels considered in this study. These observations suggest that low-temperature cracking, as predicted by the SCB fracture toughness, for the modified mixtures is lower than that for the control mix. This in turn indicates that the use of SBS and corn oil softening agent, regardless of the dosages used, reduces the low temperature cracking of asphalt mixtures as lower energy to initiate a brittle failure around the crack tip (or lower fracture toughness) is needed for these mixtures. The impact of aging, as shown in Figure 11c, on fracture toughness for all mixture seems to be negligible as the fracture toughness for each of the mixes is similar (within 4 to 8 MPa MPa·m$^{0.5}$) regardless of aging level evaluated.

**Figure 11**

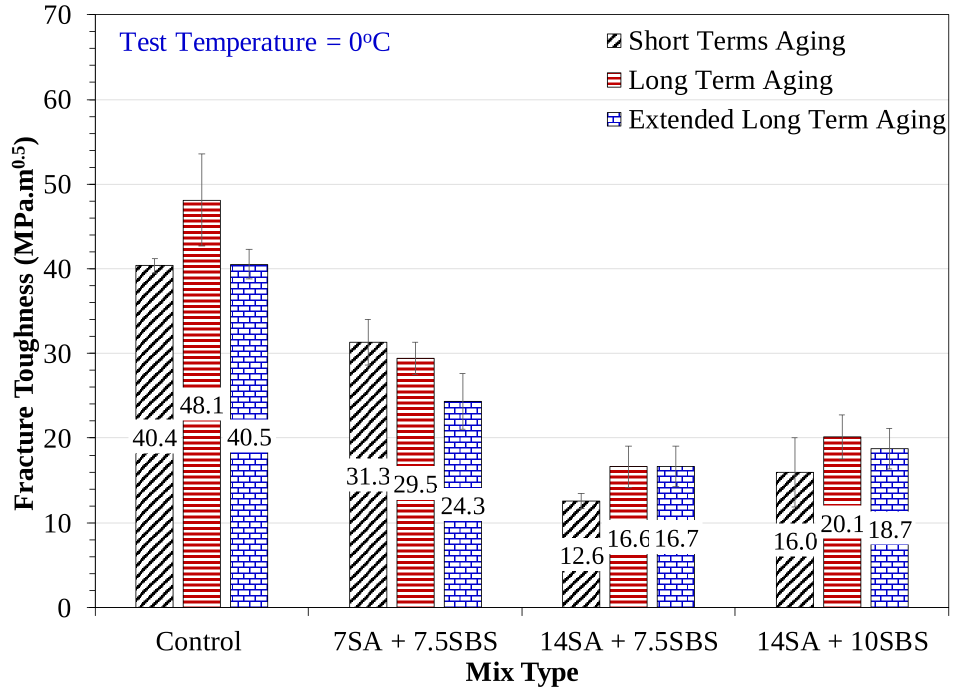
*Results of the SCB cracking test: a) Flexibility Index (FI), b) SCB Fracture Energy, and c) SCB Fracture Toughness*




**(a)**


Test Temperature = 0°C
Short Terms Aging
Long Term Aging
Extended Long Term Aging
SCB Fracture Energy (Joule/m²)
4000
3500
3000
2500
2000
1500
1000
500
0
2,748.1
1,482.2
1,098.5
2,373.0
1,427.7
1,429.7
1,101.2
1,105.7
1,023.1
1,288.5
1,192.9
1,009.8
Control
7SA + 7.5SBS
14SA + 7.5SBS
14SA + 10SBS
Mix Type

**(b)**


Test Temperature = 0°C
Short Terms Aging
Long Term Aging
Extended Long Term Aging
Fracture Toughness (MPa.m^0.5)
70
60
50
40
30
20
10
0
40.4
48.1
40.5
31.3
29.5
24.3
12.6
16.6
16.7
16.0
20.1
18.7
Control
7SA + 7.5SBS
14SA + 7.5SBS
14SA + 10SBS
Mix Type

**(c)**

**DCT Results**

Furthermore, the fracture energy values obtained using the DCT testing are presented in Figure 12 for all tested mixtures at the three aging levels (i.e., short-, long-, and extended-long term aging). The results in Figure 12 show that using a modification dosage of 7% SA and 7.5% SBS (i.e., 7.5-SBS-7-SA mix) resulted in the highest fracture energy value compared to other tested mixtures, indicating that it has the highest cracking resistance. When comparing the fracture energy values for the 7.5-SBS-14-SA and 10-SBS-14-SA mixes, it can be seen that increasing the SBS dosage (i.e., 7.5 to 10%) reduced the fracture energy of asphalt mixtures indicating that incorporating higher SBS dosage had a negative impact on the cracking resistance of asphalt mixtures.

The impact of aging was also evaluated by comparing the fracture energy values of all mixtures tested at long- and extended-long term aging levels. As shown in Figure 12, the 7.5-SBS-7-SA and 7.5-SBS-14-SA mixes showed similar fracture energy (within≈64.3 Joule/$m^2$) in long- and extended-long-term aging levels. This finding suggests that increasing the SA dosage in asphalt binder from 7% to 14% did not improve the cracking resistance of asphalt mixtures. The finding also suggests that using a 7.5% dosage of SBS polymer led to the best improvement compared to a higher SBS dosage (i.e., 10%).

Following the similar trend found in the literature review, increasing the SBS dosage to 10% had a negative impact on the low-temperature cracking performance. This finding suggests that there is an optimum modification dosage to produce a cracking resistant asphalt mix and increasing the modification beyond the optimum will not necessarily improve the performance of asphalt mixtures. It can also be observed from

Figure 12 that increasing the aging level from short to long and extended-long term aging increased the fracture energy value for the 7.5-SBS-14-SA mix. This increment might be referred to the increase of the mixture's strength, and thereby, crack's initiation required a higher tensile load.

Overall, it can be concluded based on the DCT results that the use of SBS and corn oil SA improved the cracking resistance of asphalt mixtures; however, increasing the modification dosages (i.e., to 7.5-SBS-14-SA or 10-SBS-14-SA) have a negative impact on the cracking resistance. Among the tested mixes, the mix with 7.5% of SBS and 7% of corn oil SA led to the best improvement in short-, long-, and extended-long term aging levels.

In order to validate the DCT results obtained in this study, the ASTM D7313-13 recommended to report CMOD versus Time Regression, as illustrated in Figure 13. The validity of DCT test is examined by plotting the CMOD versus time and fitting a line through the data to determine its slope and intercept. The slope value of the linear regression between the data points is the key factor in determining whether the test is valid or no, and it should be within a range of $0.017 \pm 0.00034$ mm/s. As illustrated in Figure 13, all tested samples fall within the specified range, indicating the validity of DCT test for all samples tested in this study.

**Figure 12**

*The DCT Test Results (Fracture Energy)*

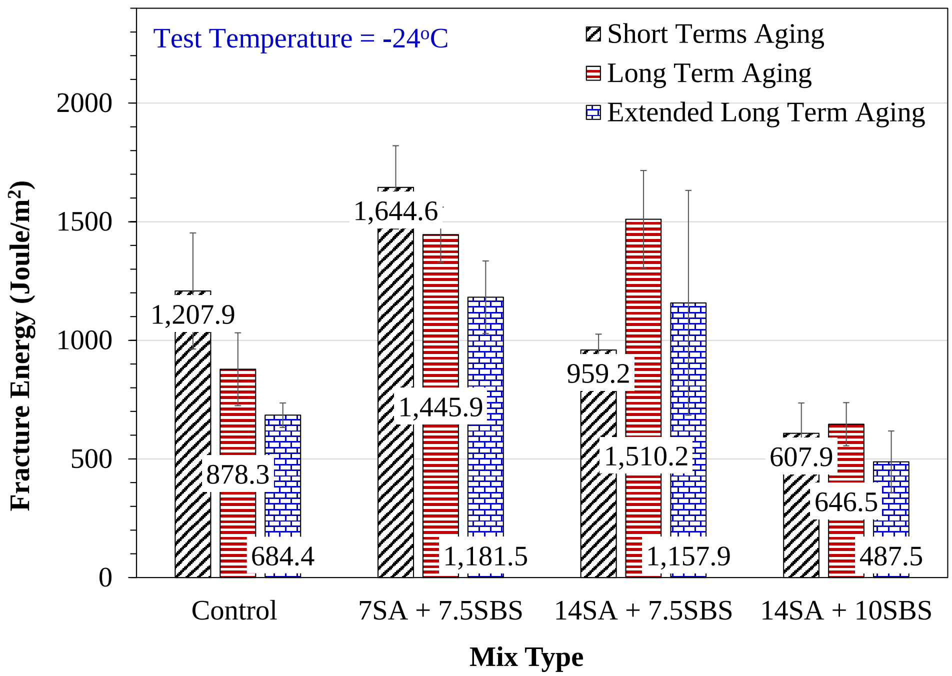
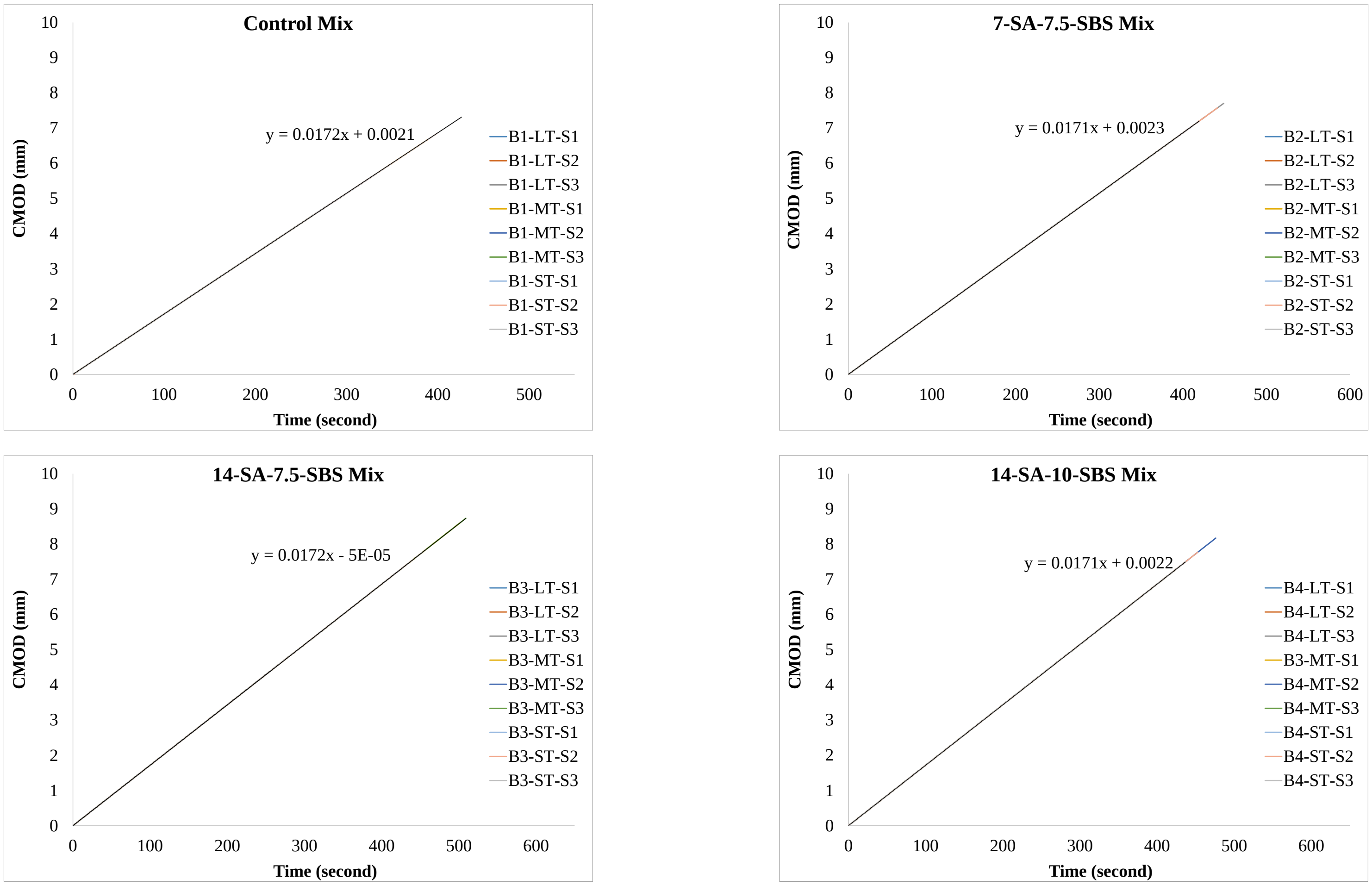


**Figure 13**

*DCT Test Validation: CMOD vs. Time Regression (R-squared, all = 1)*



**Statistical Analysis using Analysis of Variance (ANOVA)**

Statistical analyses were conducted in this study to compare the laboratory performance of modified asphalt mixtures compared to the baseline (control) mix. In particular, the Analysis of Variance (ANOVA) as well as a Tukey's Honestly Significant Difference (HSD) post-hoc analysis were performed in this study at a 95% confidence level (i.e., p-value <= 0.05 for a significant impact). The statistical analysis methods used in this study allow to investigate the statistical impact of SBS and corn oil SA on the performance of asphalt mixtures. This investigation was performed by considering the control mix as the baseline mix and the comparison was conducted between the baseline and each modified mix produced in this study.

The results of the statistical analysis for the durability and rutting performance of modified asphalt mixtures compared to the control mix are presented in Table 5. As shown in Table 5, the ANOVA test was conducted on the Cantabro Loss values to evaluate the durability of asphalt mixtures, while the cycles to failure and Rut Depth values were analyzed to evaluate the rutting resistance as was observed using the FN and the HWTD tests, respectively. The results in Table 5 indicate that there is a significant impact between each of the durability and rutting performance tests with p-values less than 0.05. Although the ANOVA test indicated a significant impact between control and HPMA mixtures, the HSD post-hoc analysis allows for a direct comparison between the baseline mix and all other HPMA mixtures. The post-hoc analysis shows that the enhancement in durability for all modified mixtures in this study was statistically significant (i.e., p-values are less than 0.05). These finding shows that incorporating SBS and SA into asphalt mixtures at the three tested dosage rates statistically have a significant improvement on the durability performance compared to that observed for the control mix.

In terms of evaluating the rutting performance of asphalt mixtures, the ANOVA and post-hoc analysis for HPMA compared to control mix are also shown in Table 5. As illustrated in Table 5, the ANOVA analysis shows that HPMA mixtures have a significant impact on the FN (number of cycles to failure) and the Rut Depth values compared to the control mix. In particular, the post-hoc analysis shows a statistically significant improvement of rutting performance for the 7.5-SBS-7-SA mix as was evaluated based on both FN and Rut Depth values. Unlike the FN values, the Rut Depth value obtained for the 10-SBS-14-SA mix shows a statistically significant improvement in its rutting resistance with a p-value of 0.003. From a statistical perspective, the post-hoc analysis of the FN and Rut Depth illustrates that the enhancement in rutting resistance is attributed to the presence of SBS polymer in asphalt mixtures, while adding SA into asphalt mixtures increases the rutting susceptibility of asphalt mixtures. This can be observed by comparing the p-values for modified mixes when the SA increased from 7% to 14% (i.e., 7.5-SBS-7-SA and 7.5-SBS-14-SA). In summary, the results in Table 5 show that incorporating 7.5% of SBS along with 7% of corn-oil SA (i.e., 7.5-SBS-7-SA mix) has significant improvement on the durability and rutting performance of asphalt mixtures.

**Table 5**

*Analysis of Variance (ANOVA) on Durability and Rutting Resistance for HPMA Mixtures Compared to Control Mixtures*

| **Durability and Rutting Performance of HPMA** | | | | | |
|---|---|---|---|---|---|
| **Analysis of Variance (ANOVA)** | | | | | |
| *p-value (Cantabro)* | | *p-value (FN Cycles)* | | *p-value (Rut Depth)* | |
| *0.000** | | *0.001** | | *0.000** | |
| **Tukey's HSD Post-Hoc Analysis ST** | | | | | |
| Control Mix vs. 7.5-SBS-7-SA Mix | Sig. | Control Mix vs. 7.5-SBS-14-SA Mix | Sig. | Control Mix vs. 10-SBS-14-SA Mix | Sig. |
| *Cantabro Loss* | *0.009** | *Cantabro Loss* | *0.004** | *Cantabro Loss* | *0.000** |
| *FN Cycles* | *0.001** | *FN Cycles* | *0.993* | *FN Cycles* | *0.755* |
| *Rut Depth* | *0.000** | *Rut Depth* | *0.132* | *Rut Depth* | *0.003** |

*Represents statistically significant condition at 95% confidence level.

The ANOVA and post-hoc analyses were also conducted on the cracking performance tests (i.e., DCT, SCB, and IDEAL-CT tests) at the three aging levels (i.e., short, long, and extended long-term aging levels). The results in Table 6 illustrates that the ANOVA and post-hoc results on the fracture energy values obtained using the DCT test for the HPMA mixes. The fracture energy, as was discussed above, gives insight on the cracking propagation resistance of asphalt mixtures, while higher fracture energy represents higher cracking resistance of the asphalt mix. The ANOVA analysis results in

Table 6 show a significant impact of HPMA mixtures on the fracture energy values obtained using the DCT test. As shown in Table 6, ANOVA analysis shows significance of the fracture energy values for HPMA mixtures compared to the control mix at the three aging levels. More importantly, when comparing the fracture energy values of the 7.5-SBS-7-SA mix with the baseline mix, the post-hoc results show a significance improvement in cracking performance (i.e., lower p-value) at the long-and extended long-term aging levels although it does not show any significance at the short-term aging level. This finding indicates that incorporating 7.5% SBS and 7% SA into asphalt mixtures significantly improves their cracking resistance compared to control mixtures throughout their service life (i.e., at the long and extended long term aging levels).

The ANOVA and post-hoc analysis results for the SCB and IDEAL-CT tests are shown in Table 7. As shown in Table 7, when comparing the SCB FI values, the ANOVA and post-hoc results show that all HPMA mixtures tested in the study statistically have a significant improvement on the FI compared to the baseline mix at the three aging levels. The FI is an indicator on the crack's related damage and the improvement in FI value means that the impact of cracks to induce damage in asphalt pavements less (higher resistance to damage). Statistically, this finding illustrates the significant improvement of incorporating SBS and SA into asphalt mixtures in mitigating the damage occurs due to cracking in asphalt pavements at all aging levels (throughout their service life). The fracture energy results obtained from the SCB test were also analyzed using the ANOVA and post-hoc statistical tools. As shown in Table 7, all HPMA mixtures show significant difference in the fracture energy results obtained using the SCB test. However, the post-hoc results of the SCB fracture energy for the 7.5-SBS-

7-SA mix at extended long-term aging level is the only value that shows the significant improvement. Although the other two HPMA mixtures (i.e., 7.5-SBS-14-SA and 10-SBS-14-SA) show a statistically significant difference compared to control mix, but this was a negative significance which means that the use high content of softening agent in asphalt mixtures (i.e., 14%) reduced the cracking resistance of the asphalt mixtures.

In terms of analyzing the IDEAL-CT testing results, the ANOVA and post-hoc analyses methods were performed on two parameters including the CT-Index and the ITS parameters as shown in Table 7. The ANOVA results in Table 7 show a significant difference in the CT-Index values obtained at short and long-term aging levels. The results show that adding SBS and SA in asphalt mixtures improves its cracking resistance at intermediate temperature in their early service life. However, as the HPMA mixtures aged more, their resistance to intermediate cracking becomes closer to that obtained for the control mix and their improvement becomes statistically insignificant. With regards to the ITS analysis results, the results in Table 7 show that all HPMA mixtures tested in this study showed a significant difference of ITS values compared to the control mix for long and extended long term aging levels. The ITS values at short term level had a significant difference for two mix types: 7.5-SBS-14-SA and 10-SBS-14-SA compared to the baseline mix. This finding illustrates the ability of HPMA mixtures in softening the asphalt mix (significant decrement of ITS values compared to the control mix). The significant decrement in ITS values is attributed to the presence of softening agent in HPMA mixtures. Although ITS is not a good parameter to examine the cracking resistance of asphalt mixtures, but it is a good candidate in this study to understand the impact of adding softening agent to asphalt mixtures. Furthermore, when comparing the

7.5-SBS-7-SA and 7.5-SBS-14-SA mixes, it can be seen that lower p-values were obtained for the mix with 14% SA compared to the control mix. This further highlights that the decrement of ITS values is mainly attributed to the presence of softening agent in HPMA mixtures which reduce the impact of aging on asphalt mixtures by reducing its stiffness compared to the control mix.

**Table 6**

*The ANOVA Results on DCT Test for the HPMA Mixtures*

| **Fracture Energy obtained from the DCT test.** | | | | | |
|---|---|---|---|---|---|
| **Analysis of Variance (ANOVA)** | | | | | |
| *p-value (ST)* | | *p-value (LT)* | | *p-value (ELT)* | |
| *0.000** | | *0.000** | | *0.025** | |
| **Tukey's HSD Post-Hoc Analysis ST** | | | | | |
| Control Mix vs. 7.5-SBS-7-SA | Sig. | Control Mix vs. 7.5-SBS-14-SA | Sig. | Control Mix vs. 10-SBS-14-SA | Sig. |
| *ST* | *0.066* | *ST* | *0.165* | *ST* | *0.020** |
| *LT* | *0.007** | *LT* | *0.013** | *LT* | *0.088* |
| *ELT* | *0.006** | *ELT* | *0.16* | *ELT* | *0.072* |

*Represents statistically significant condition at 95% confidence level.

*ST: Short Term Aging Level, LT: Long Term Aging Level, and ELT: Extended Long Term Aging Level*

**Table 7**

*The ANOVA Analysis on the SCB, IDEAL-CT and ITS Cracking Performance Tests for the HPMA Mixtures*

| **SCB Test (FI)** | | | | | | **SCB Test (Fracture Energy)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Analysis of Variance (ANOVA)** | | | | | | | | | | | |
| *p-value (ST)* | | *p-value (LT)* | | *p-value (ELT)* | | *p-value (ST)* | | *p-value (LT)* | | *p-value (ELT)* | |
| *0.000** | | *0.000** | | *0.000** | | *0.000** | | *0.008** | | *0.001** | |
| **Tukey's HSD Post-Hoc Analysis ST** | | | | | | | | | | | |
| Control Mix vs. 7.5-SBS-7-SA | Sig. | Control Mix vs. 7.5-SBS-14-SA | Sig. | Control Mix vs. 10-SBS-14-SA | Sig. | Control Mix vs. 7.5-SBS-7-SA | Sig. | Control Mix vs. 7.5-SBS-14-SA | Sig. | Control Mix vs. 10-SBS-14-SA | Sig. |
| *ST* | *0.000** | *ST* | *0.000** | *ST* | *0.000** | *ST* | *0.296* | *ST* | *0.007** | *ST* | *0.006** |
| *LT* | *0.000** | *LT* | *0.000** | *LT* | *0.000** | *LT* | *0.640* | *LT* | *0.014** | *LT* | *0.077* |
| *ELT* | *0.000** | *ELT* | *0.000** | *ELT* | *0.002** | *ELT* | *0.015** | *ELT* | *0.352* | *ELT* | *0.218* |

| IDEAL-CT Test (CT-Index) | | | | | | IDEAL-CT Test (ITS Value) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Analysis of Variance (ANOVA)** | | | | | | | | | | | |
| *p-value (ST)* | | *p-value (LT)* | | *p-value (ELT)* | | *p-value (ST)* | | *p-value (LT)* | | *p-value (ELT)* | |
| *0.000** | | *0.000** | | *0.511* | | *0.000** | | *0.003** | | *0.000** | |
| **Tukey's HSD Post-Hoc Analysis ST** | | | | | | | | | | | |
| Control Mix vs. 7.5-SBS-7-SA | Sig. | Control Mix vs. 7.5-SBS-14-SA | Sig. | Control Mix vs. 10-SBS-14-SA | Sig. | Control Mix vs. 7.5-SBS-7-SA | Sig. | Control Mix vs. 7.5-SBS-14-SA | Sig. | Control Mix vs. 10-SBS-14-SA | Sig. |
| *ST* | *0.000** | *ST* | *0.349* | *ST* | *0.000** | *ST* | *0.061* | *ST* | *0.000** | *ST* | *0.001** |
| *LT* | *0.011** | *LT* | *0.000** | *LT* | *0.003** | *LT* | *0.086* | *LT* | *0.024** | *LT* | *0.014** |
| *ELT* | *0.384* | *ELT* | *0.173* | *ELT* | *0.724* | *ELT* | *0.004** | *ELT* | *0.000** | *ELT* | *0.001** |

**Represents statistically significant condition at 95% confidence level.*

*ST: Short Term Aging Level, LT: Long Term Aging Level, and ELT: Extended Long Term Aging Level*

**Impact of Aging on HPMA Mixtures**

In order to investigate the impact of aging a loose mix asphalt on their cracking resistance, the ANOVA and post-hoc analyses tools were utilized at 95% confidence level. The sensitivity of asphalt mixtures to aging was assessed by determining the statistical difference for a specific parameter (e.g., fracture energy, ITS, CT-Index, and others) of long- and extended long-term aged asphalt mixtures compared to that obtained for the same mix type at the short-term aging level. The results of this analysis are illustrated in Table 8 and Table 9. The statistical significance gives insight that the mix is more sensitive to aging, in other words, its properties significantly changed with aging. With the same concept, a mix type without a significant difference represents that the mix is more resistant to aging (its properties did not change significantly with aging).

The DCT fracture energy differences with aging are presented in Table 8. As shown in this table, the ANOVA analysis shows that the control and the 7.5-SBS-7-SA mix had a significant difference in their cracking resistance at extreme low temperature with aging ($p$-values $< 0.05$). The post-hoc analysis for the same mixtures shows that for both mixtures the change of their cracking resistance increased with aging and it was a significant difference when comparing the fracture energy values obtained at ST aging level with those obtained at ELT aging level. This finding highlights that although using a modification dosage of 7.5% of SBS and 7% of SA improved the significantly the DCT fracture energy at long- and extended long-term aging levels compared to the control mix, the modification dosage did not improve their aging resistance. On the other hand, when comparing the mixtures those were modified with 14% SA (i.e., 7.5-SBS-14-SA and 10-SBS-14-SA), the ANOVA results show that their cracking resistance did not change significantly with aging (p-value > 0.05). This highlights that adding 14% of corn-oil SA improved statistically the aging resistance of asphalt mixtures. It is noted here that for all mixtures the sigmoid value for each mix is always 1.000 because of comparing the results of each aging level with the short-term aging level (comparing the same results together gives a value of 100% similar).

**Table 8**

*DCT Fracture Energy Statistical Difference*

<table>
<tr><th colspan="8">DCT Fracture Energy</th></tr>
<tr><th colspan="8">Analysis of Variance (ANOVA)</th></tr>
<tr><td colspan="2">p-value (Control)</td><td colspan="2">p-value (7.5-SBS-7-SA)</td><td colspan="2">p-value (7.5-SBS-14-SA)</td><td colspan="2">p-value (10-SBS-14-SA)</td></tr>
<tr><td colspan="2">0.025*</td><td colspan="2">0.026*</td><td colspan="2">0.155</td><td colspan="2">0.299</td></tr>
<tr><th colspan="8">Tukey's HSD Post-Hoc Analysis ST</th></tr>
<tr><td>Control</td><td>Sig.</td><td>7.5-SBS-7-SA</td><td>Sig.</td><td>7.5-SBS-14-SA</td><td>Sig.</td><td>10-SBS-14-SA</td><td>Sig.</td></tr>
<tr><td>ST</td><td>1.000</td><td>ST</td><td>1.000</td><td>ST</td><td>1.000</td><td>ST</td><td>1.000</td></tr>
<tr><td>MT</td><td>0.119</td><td>MT</td><td>0.177</td><td>MT</td><td>0.012*</td><td>MT</td><td>0.692</td></tr>
<tr><td>LT</td><td>0.022*</td><td>LT</td><td>0.026*</td><td>LT</td><td>0.512</td><td>LT</td><td>0.318</td></tr>
</table>

**Represents statistically significant condition at 95% confidence level.*

*ST: Short Term Aging Level, LT: Long Term Aging Level, and ELT: Extended Long Term Aging Level*

The impact of aging on the cracking resistance of HPMA mixtures at low and intermediate temperatures (i.e., 0 and 13°C) was investigated by determining the change in the SCB and IDEAL-CT cracking resistance indicators with aging. Similar to the DCT fracture energy analysis, the ANOVA and post-hoc analyses methods were utilized to assess the impact of aging on HPMA mixtures' cracking resistance as illustrated in Table 9.

The impact of aging on the cracking resistance of HPMA mixtures at low temperature (i.e., at 0°C) can be determined by analyzing the SCB testing results as shown in Table 9. The ANOVA and post-hoc results in Table 9 show a significance difference in the SCB FI for all mixtures with aging regardless the aging protocol (i.e., LT or ELT). As illustrated in Table 9, subjecting loose asphalt mix to aging significantly impacted their FI values. This indicates that cracking-related damage resistance of asphalt mixtures is sensitive to aging. In addition to that, the significant difference in FI values with aging indicates its ability to capture the impact of loose asphalt mix aging on asphalt mixtures. The SCB fracture energy results are also shown in Table 9. As presented in this table and similar to the DCT fracture energy trend, the ANOVA analysis results show that increasing the softening agent dosage into asphalt mixtures (i.e., 14%) improved significantly their cracking resistance at low temperature with aging. This improvement is mainly attributed to the presence of softening agent in asphalt mixtures as can be seen when comparing the p-value for the 7.5-SBS-7-SA and 7.5-SBS-14-SA mixtures that is 0.000 and 0.733, respectively, while higher p-value means less aging susceptibility. This finding further highlights the ability of softening agents to reduce the aging impact on the cracking resistance of asphalt mixtures (similar fracture energy results with aging).

The aging impact on intermediate-temperature cracking resistance of HPMA mixtures can be assessed using the IDEAL-CT testing results (i.e., CT-Index and ITS). The ANOVA and post-hoc results of those parameters are illustrated in Table 9. The ANOVA analysis results for the CT-Index and ITS values shows that adding SBS and/or softening agent was not able to reduce the aging sensitivity ($p$-value $< 0.05$) of asphalt mixtures at intermediate temperature (i.e., 13°C). This finding highlights that softening agents are not able to improve the cracking susceptibility of asphalt mixtures at intermediate temperature.

**Table 9**

*Statistical Difference of SCB and IDEAL-CT Parameters with Aging*

| SCB Flexibility Index | | | | | | | |
|---|---|---|---|---|---|---|---|
| Analysis of Variance (ANOVA) | | | | | | | |
| *p-value (Control)* | | *p-value (7.5-SBS-7-SA)* | | *p-value (7.5-SBS-14-SA)* | | *p-value (10-SBS-14-SA)* | |
| *0.000** | | *0.000** | | *0.000** | | *0.000** | |
| Tukey's HSD Post-Hoc Analysis ST | | | | | | | |
| Control | Sig. | *7.5-SBS-7-SA* | Sig. | *7.5-SBS-14-SA* | Sig. | *10-SBS-14-SA* | Sig. |
| *ST* | *1.000* | *ST* | *1.000* | *ST* | *1.000* | *ST* | *1.000* |
| *LT* | *0.001** | *LT* | *0.000** | *LT* | *0.000** | *LT* | *0.000** |
| *ELT* | *0.000** | *ELT* | *0.000** | *ELT* | *0.000** | *ELT* | *0.001** |

| SCB Fracture Energy | | | | | | | |
|---|---|---|---|---|---|---|---|
| Analysis of Variance (ANOVA) | | | | | | | |
| *p-value (Control)* | | *p-value (7.5-SBS-7-SA)* | | *p-value (7.5-SBS-14-SA)* | | *p-value (10-SBS-14-SA)* | |
| *0.002** | | *0.000** | | *0.733* | | *0.199* | |
| Tukey's HSD Post-Hoc Analysis ST | | | | | | | |
| Control | Sig. | *7.5-SBS-7-SA* | Sig. | *7.5-SBS-14-SA* | Sig. | *10-SBS-14-SA* | Sig. |
| *ST* | *1.000* | *ST* | *1.000* | *ST* | *1.000* | *ST* | *1.000* |
| *LT* | *0.018** | *LT* | *0.000** | *LT* | *0.715* | *LT* | *0.602* |
| *ELT* | *0.007** | *ELT* | *0.001** | *ELT* | *0.533* | *ELT* | *0.125* |

| CT-Index | | | | | | | | ITS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Analysis of Variance (ANOVA)** | | | | | | | | **Analysis of Variance (ANOVA)** | | | | | | | |
| *p-value (Control)* | | *p-value (7.5-SBS-7-SA)* | | *p-value (7.5-SBS-14-SA)* | | *p-value (10-SBS-14-SA)* | | *p-value (Control)* | | *p-value (7.5-SBS-7-SA)* | | *p-value (7.5-SBS-14-SA)* | | *p-value (10-SBS-14-SA)* | |
| *0.000** | | *0.000** | | *0.003** | | *0.000** | | *0.000** | | *0.000** | | *0.000** | | *0.010** | |
| **Tukey's HSD Post-Hoc Analysis ST** | | | | | | | | **Tukey's HSD Post-Hoc Analysis ST** | | | | | | | |
| Control | Sig. | *7.5-SBS-7-SA* | Sig. | *7.5-SBS-14-SA* | Sig. | *10-SBS-14-SA* | Sig. | Control | Sig. | *7.5-SBS-7-SA* | Sig. | *7.5-SBS-14-SA* | Sig. | *10-SBS-14-SA* | Sig. |
| *ST* | *1.000* | *ST* | *1.000* | *ST* | *1.000* | *ST* | *1.000* | *ST* | *1.000* | *ST* | *1.000* | *ST* | *1.000* | *ST* | *1.000* |
| *LT* | *0.498* | *LT* | *0.000** | *LT* | *0.013** | *LT* | *0.000** | *LT* | *0.018** | *LT* | *0.003** | *LT* | *0.008** | *LT* | *0.006** |
| *ELT* | *0.000** | *ELT* | *0.000** | *ELT* | *0.013** | *ELT* | *0.000** | *ELT* | *0.000** | *ELT* | *0.001** | *ELT* | *0.000** | *ELT* | *0.073* |

**Represents statistically significant condition at 95% confidence level.*

*ST: Short Term Aging Level, LT: Long Term Aging Level, and ELT: Extended Long Term Aging Level*

**Assessing the Ability of Cracking Tests to Capture the Benefits of HPMA Mixtures**

Several performance tests (i.e., IDEAL-CT, SCB, and DCT tests) that were conducted in this study to evaluate the cracking resistance of asphalt mixtures to determine various levels of improvements of HPMA mixtures. The different performance tests varied in their testing mechanism, sample preparation, and testing temperature. Therefore, it is valuable to assess the ability of a particular cracking tests to capture the benefits of using HPMA mixtures with softening agent. This section contains a summary on sample preparation, testing procedure, and testing temperature of each performance test. Afterwards, a discussion on the ability of each test to capture the benefits of HPMA mixtures with softening agent is provided.

As was discussed before, three cracking performance tests were conducted in the study to evaluate the cracking resistance of HPMA mixtures with softening agent. Table 10 provides a summary of these tests including the testing temperature, specimen's dimensions, and testing time. As illustrated in Table 10, the testing time fluctuated between two hours up to four days for each mix type. In particular, the specimens tested using the IDEAL-CT test do not require a preparation prior to testing such as that for SCB and DCT tests. The SCB samples are prepared by cutting a specimen in half and then notched at the center of each sample. On the other hand, the DCT samples are prepared by coring two holes in asphalt specimen followed by notching the sample at the center and finally cutting a flat surface that is perpendicular to the notch.

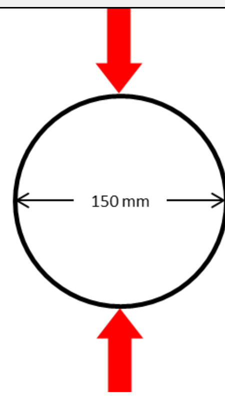
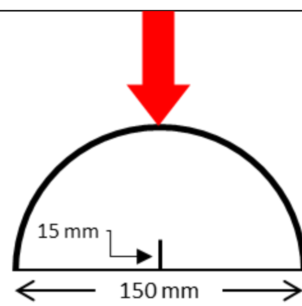
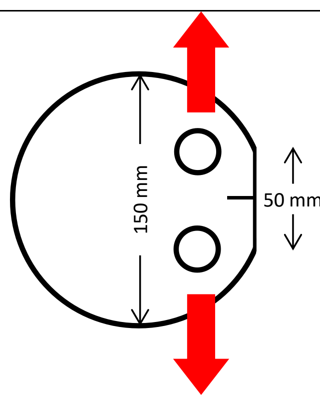
The previously illustrated testing and statistical results (Table 6) showed that DCT Fracture Energy values obtained for the 7.5-SBS-7-SA mix were significantly higher (better cracking resistance) than the control mix at long and extended long-term aging levels. The SCB FI values for all HPMA mixtures were significantly higher than the control mix. In addition to that, the CT-Index values obtained from the IDEAL-CT test showed significant improvement statistically compared to the control mix at short- and long- term aging levels.  However, the results at extended long term aging level were similar compared to the control mix. In contrast, the ITS results showed that control mix outperformed all HPMA mixes in this study at all aging levels (short, long, and extended long-term levels).

The results obtained from the IDEAL-CT test was not sufficient to assess the impact of HPMA mixtures with softening agent, especially, because the statistical analysis did not show any improvement at extended long-term aging level.

On the other hand, the SCB testing results did show that cracking related damage of all HPMA mixtures with softening agent was significantly lower. The mix that showed higher FI values had the best improvement in the cracking resistance, and it was consistent with the DCT fracture energy values, especially when compared to the control mix at long and extended long term aging level. However, this was not the case for other HPMA mixtures (i.e., 7.5-SBS-14-SA and 10-SBS-14-SA) those had a significant FI improvement but similar DCT fracture energy values compared to the control mix. Consequently, it is recommended based on the testing results and the subsequent statistical analysis to utilize the DCT test to evaluate the performance of HPMA mixtures with softening agent due to its ability to capture the benefit of using this type of binders in asphalt mixtures. In addition to that, the DCT test is able to investigate the cracking resistance at an extreme low temperature which gives insights of the cracking resistance in a harsh cold environment.

**Table 10**

*Summary of Cracking Performance Tests Utilized in the Study*

| Laboratory Test | Testing Temperature | Specimen Dimensions | Testing Time (per mix type) * |
|---|---|---|---|
| **IDEAL-CT** | 13°C |  | 2 Hours |
| **SCB Test** | 0°C |  | 1-2 Days |
| **DCT Test** | -24°C |  | 3-4 Days |

*Approximate preparation and conditioning time after compaction.

## Chapter 5

## Summary, Conclusion, and Recommendations

### Summary of Findings and Conclusions

The goal of this study was to evaluate the impact of HPMA binders containing a softening agent on the performance of asphalt mixtures. The study carried an investigation on the rutting susceptibility, cracking resistance, and durability of asphalt mixtures. The study also included an evaluation of the effect of loose mix aging conditions on the performance of HPMA mixtures. One baseline (control) asphalt binder (PG 52-34), SBS polymer modifier, and corn-oil SA were used to produce four asphalt mixtures. These mixes included: a control prepared using the PG 52-34 binder, a modified mix produced using PG 52-34 blended with 7.5% SBS and 7% corn oil SA (7.5-SBS-7-SA), a modified mix prepared using PG 52-34 blended with 7.5% SBS and 14% SA (7.5-SBS-14-SA), and a modified mix prepared using PG 52-34 blended with 10% SBS and 14% SA (10-SBS-14-SA). The rutting susceptibility of all mixtures produced in this study was evaluated using the HWTD and FN tests, their resistance to cracking was assessed using the IDEAL-CT, SCB, and DCT tests, the change in their viscoelastic properties was evaluated using the DCM test, and the durability (or resistance to breakdown) of asphalt mixes was examined using the Cantabro Durability test. The impact of loose mix aging on cracking resistance of the mixes was evaluated by subjecting these mixes to short-, long-, and extended-long-term aging levels before compaction. The study also carried out statistical analysis to signify the difference in testing results for the tested asphalt mixtures. The ANOVA and HSD post-hoc analysis methods were conducted to investigate the statistical difference between control mix and the modified mixtures at a 95% confidence level.

Based on the laboratory experimental results and the subsequent statistical analyses, the following findings are summarized:

- The HPMA mixes showed lower Cantabro Loss of 40% to 60% compared to the control mix.
- Increasing the SBS dosage from 7.5% to 10% decreased the Cantabro Loss by 34% to 40% of its value for both mixes those were modified with 7.5% SBS.
- Statistical analysis showed that the durability improvement of HPMA mixes was significant compared to the unmodified mixture;
- Based on the obtained |E*| values, increasing the SA dosage from 7% to 14% led to increase the cracking resistance and rutting susceptibility of asphalt mixtures, while increasing the SBS dosage from 7.5% to 10% improved the cracking and rutting resistance of asphalt mixtures;
- The 7.5-SBS-7-SA mix outperformed the control mix in mitigating cracking at low temperature and all mixes (HPMA and control) in rutting resistance;
- The FN results show that all HPMA mixes have a higher FN values compared to unmodified mix (130% to 830% of the FN values obtained for the control mix). However, increasing the SA content from 7% to 14% reduced the FN value by 85% of its value for the mix with 7% SA. Increasing the SBS dosage from 7.5% to 10% increased the rutting resistance by 246% of its value at 10% SBS. Statistically, the mix with 7.5-SBS-7-SA showed a significant improvement in FN number (rutting resistance) compared to the control mix;
- The HWTD rutting performance showed that all modifiers had lower rut depth values ranging from 20% to 60% than that obtained for the control mix. In

addition, increasing the SA dosage from 7% to 14% led the mix to fail quickly without reaching the maximum number of cycles (i.e., 13,680 cycles out of 20,000 cycles) with a 9.8mm rut depth. However, increasing the SBS content from 7.5% to 10% allowed the mix to reach the maximum number to cycles with 5.6mm rut depth. The mix with 7.5-SBS-7-SA furthermore reached the maximum number of cycles with 4.1mm rut depth.

- The ITS values showed that HPMA have lower ITS values compared to control mix at all aging levels (43% to 83% of that determined for the control mix);
- The CT-Index values for the HPMA at short-term aging level were higher than those obtained for the control mix, however, as mixes reached the extended long term aging level, the CT-Index values for HPMA mixes were statistically similar to the control mix;
- The SCB test showed that HPMA mixes showed a significant improvement in FI values, by two, three, and five times at short, long, and extended long term aging levels, respectively, compared to the control mix.
- SCB fracture energy for the modified mixes were statistically similar or lower than those obtained for the control mixture at short term level.
- SCB fracture energy for the mix with 7.5-SBS-7-SA showed a statistical significant in improving the cracking resistance compared to control mix at extended long-term aging level, and;
- Fracture energy of asphalt mixtures at extreme low temperature obtained using the DCT test showed that 7.5-SBS-7-SA mix had 1.35, 1.65, 1.73 times the fracture energy that obtained for the control mix at short, long, and extended long-

term aging levels, respectively. The improvement of the 7.5-SBS-7-SA was statistically significant compared to the control mix at long and extended long terms aging levels. It was also shown that adding more SA dosage (i.e., 7% to 14%) improved the cracking resistance of asphalt mixtures at long-term aging level only, while adding more SBS improved the cracking performance at short-term aging level only.

- Assessing the impact of aging on the cracking resistance of HPMA mixtures using ANOVA and post-hoc statistical tools showed that DCT and SCB fracture energy values for mixtures modified with 14% softening agent had similar values statistically regardless the aging level (p-value > 0.05). It also showed that increasing the softening agent dosage (i.e., from 7% to 14%) resulted in a mix with similar fracture energy values at long- and extended long-term aging levels compared to that obtained at short term aging level.

The findings as were observed from the testing results and the statistical analysis led to the following conclusions:

- The use of SBS modifier and corn oil SA increased the durability (or resistance to breakdown) of asphalt mixtures. This improvement is mainly attributed to the SBS polymer;
- The DCM testing results show that the use of balanced modification (i.e., 7.5-SBS-7-SA) resulted in better rutting and cracking resistant mixtures compared to the control mixture. However, adding more softening agent resulted in more cracking resistance and rutting susceptibility compared to other mixtures;
- Modifying asphalt binders using a combination of SBS and corn oil SA enhanced

the rutting resistance of asphalt mixtures. This was because the control mix had higher rut depth values and lower FN values than the modified mixes at all modifier dosages considered in this study. This improvement in rutting performance for is mainly attributed to SBS polymer modifier;

- The 7.5-SBS-7-SA mix had the lowest measured rut depth values and highest FN values among all the mixes.
- The IDEAL-CT ITS values suggests that HPMA mixes had lower cracking initiation resistance than the control mix at intermediate temperature.
- The CT-Index values show that at short term aging level, SBS and corn oil modified asphalt mixtures have better cracking resistance than the control mix at intermediate temperature.
- The FI results obtained using the SCB test shows that using a combination of SBS polymer and bio-based SA in HPMA mixtures improved their crack-damage resistance (higher FI values) significantly, while 7.5-SBS-7-SA mix had the best improvement at long term aging;
- Based on the SCB fracture energy values for the 7.5-SBS-7-SA and control mixes, modifying asphalt binder with 7.5% SBS and 7% of SA statistically improved the extended long term aging cracking resistance at low temperature;
- Adding SBS and corn oil SA at higher dosages did not improve the low-temperature cracking of the modified asphalt mixtures in comparison to the control mix.
- Based on the DCT fracture energy results and the statistical analysis, the use of 7.5-SBS-7-SA in asphalt mixture showed the best improvement at long and extended-

long term aging levels ($p$-values $< 0.05$) in mitigating the extreme low-temperature cracking compared to the control mix.

- The statistical analyses used to investigate the aging impact on HPMA mixtures showed that incorporating 14% of softening agent in asphalt mixtures was able to reduce the aging sensitivity of asphalt mixtures at low and extreme-low temperatures (i.e., 0 and -24°C, respectively).
- Investigating the performance of HPMA mixtures with softening agent was better predicted using the DCT test due to its ability to capture the benefits of using HPMA mixtures with softening agent, especially, at extreme low temperatures.

This research was initiated to investigate the hypothesis that using SBS polymer and corn oil SA to modify asphalt mixtures can improve their rutting and cracking performance, and to evaluate the hypothesis that constructing HPMA is an effective approach to extend the service life of asphalt mixtures at field. Based on the performance testing results, the consequent statistical analysis, and the observed conclusions, the research hypothesis of this study is approved.

**Recommendations**

This study focused on the laboratory performance evaluation of the HPMA mixtures containing softening agents. Based on the findings from this study, the following is recommended when using HPMA binder with softening agent in asphalt mixtures:

- The use of HPMA mixes is recommended to improve the durability, rutting, and cracking performance of asphalt mixtures.
- Increasing the modification dosage (i.e., 10% SBS and 14% SA) did not improve the cracking and rutting performance of asphalt mixes.

- A modification dosage rate of 7.5% SBS and 7% SA is recommended to achieve a significant improvement in durability, rutting, and cracking resistance compared to unmodified mix.

Though this study evaluated the laboratory performance of asphalt mixtures modified by SBS and corn oil SA, this study was limited to one binder type, two modifiers, and three modification dosage rates. Therefore, there is a need to further investigation in order to:

- Assessing the impact of different modification techniques on the performance and effectiveness of HPMA mixtures with softening agent;
- Determine the expected performance of HPMA with softening agent to quantify the benefits of modifying asphalt binder;
- Study the influence of aggregate gradation, binder type, and softening agent type on the performance and the volumetric properties of asphalt mixtures;
- A thorough investigation of the polymer modification additives to investigate the impact of different dosages rates on the performance of asphalt mixtures to determine the optimum content of SBS polymer and SA;
- The chemical changes in asphalt mixtures and binders due to modification and aging should be investigated to understand the impact of aging on HPMA mixtures containing softening agent;
- The rehabilitating and recycling the HPMA mixes with softening agent needs to be investigated further by understanding the failure's mechanism of HPMA mixes more deeply; and,

- Last but not least, to evaluate the environmental impact of the modification process of asphalt binder as well as the use of SBS with softening agent.

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