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Bio-Material Maintenance Treatments

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16. Abstract (Limit: 250 words) Asphalt pavements deteriorate from temperature cycling, moisture, oxidation, and loading-related distresses. Pavement preservation is critical in maintaining the functional and structural integrity of roads and extending pavement life. Surface treatments can prevent or restore the aging effects by rejuvenating and/or sealing the pavement's surface, limiting further damage, and restoring its flexibility. This collaborative study of MnDOT, the National Road Research Alliance (NRRA), and Iowa State University investigates the efficacy of fog seal/bio-fog seal topical treatments based on soy-derived rejuvenators, epoxidized soybean oil (SESO), and BioMAG, which contains SESO and the biopolymer poly(acrylated epoxidized high oleic soybean oil) (PAEHOSO). Each topical treatment is applied at three locations in different asphalt binder grades to provide a comprehensive approach to their impacts on the dry time, reflectivity, friction, and permeability of the pavement course. It is observed that the bio-fog seal treatments improve the skid resistance of the pavement, do not affect the reflectivity of pavement markings, and are able to restore the stiffness of the asphalt mixtures. Additionally, the fog seals show fast setting and curing and allows the road to be open to traffic in less than 30 minutes.		
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Bio-Material Maintenance Treatments

Final Report

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Table of Contents

List of Figures

List of Tables

Executive Summary

As asphalt pavement oxidizes and ages, it becomes brittle, increasing the potential to fatigue or for thermal cracking to occur, which can lead to the deterioration of pavement surfaces and infrastructure over time. To increase the longevity of the roadway, extend the pavement service life, and delay major rehabilitation, maintaining good pavement condition, pavement preservation treatments are applied in the pavement. One of these treatments is fog seals, which consist of spraying a thin layer of emulsion onto the pavement to slow or in some cases reverse the damage caused by oxidative aging. Asphalt emulsions are the most common material used in fog seals and the formulation may include a rejuvenator to lower its viscosity and possibly even rejuvenate the surface of the existing aged pavement.

Two soy-derived surface treatments, epoxidized soybean oil (SESO), and BioMAG, which contains SESO and the biopolymer poly(acrylated epoxidized high oleic soybean oil) (PAEHOSO), were formulated into bio-fog seals and applied on 3 pavement sections. In this project, the performance of these water-based emulsions was evaluated, regarding their dry time, pavement skid resistance, permeability, stiffness, and pavement marking reflectivity.

The field and laboratory tests showed that the pavements treated with the bio-fog seal exhibited an improvement in the skid resistance, the reflectivity of pavement markings was not affected on the St. Michael's test sections, and the treatments were able to restore the stiffness of the asphalt mixtures. Additionally, the fog seals showed a fast setting and curing and allowed the road to be open to traffic in less than 30 minutes.

Chapter 1: Introduction

Aging pavement infrastructure and the deterioration of pavement surfaces over time remain an ongoing challenge in meeting roadway user expectations. The oxidative aging causes the embrittlement of the asphalt binder in the pavement, which increases the potential to fatigue or for thermal cracking to occur (Alamdary et al., 2019 and Wang et al., 2019).

Preventive pavement preservation treatments that are applied in sound structured condition pavements, can extend the pavement functional service life and reduce future maintenance costs (Uzarowski et al., 2009). One of these treatments are fog seals, which consist of spraying a thin layer of emulsion onto the pavement to slow or in some cases reverse the damage caused by oxidative aging. Asphalt emulsions are the most common material used in fog seals and in their formulation usually a rejuvenator is used to lower its viscosity and possibly even rejuvenate the surface of the existing aged pavement (Cheng et al., 2015).

A variety of bio-sealant products are available on the market and can be used to seal, and in some cases, rejuvenate the in-place asphalt. Soybean derived additives have been found to be effective rejuvenators, reducing the stiffness of aged and brittle asphalt binders. Iowa State University developed soy-based biotechnologies that show promise in rejuvenating aged asphalts and can be developed into a biobased rejuvenating emulsion fog seal. The unique feature of this rejuvenator is that multiple stress creep recovery tests are not negatively affected by the addition of the soy-based rejuvenator (Cochran et al., 2021).

Two soy-derived surface treatments, epoxidized soybean oil (SESO), and BioMAG, which contains SESO and the biopolymer poly(acrylated epoxidized high oleic soybean oil) (PAEHOSO), were formulated into bio-fog seals and applied on 3 pavement test sections for evaluation. The proposed research consisted of evaluating the performance of these bio-fog seals, regarding their dry time, pavement skid resistance, permeability, stiffness, and pavement marking reflectivity.

The benefits of this research are improved flexibility, sealing, and preservation of roadways while developing new domestic markets for soybean products. Increased longevity of the roadway delays major rehabilitation and provides improved pavement condition in the interim. Preservation of pavements helps keep roads in better condition longer, which leads to reduced pavement life-cycle cost.

Chapter 2: Literature Review

2.1 Background

As pavements age over time, they become increasingly prone to climate and traffic related distresses. As asphalt components react in the presence of oxygen and aging occurs, the percent of heavy fractions in the binder increase leading to an increase in asphalt stiffness. This has led to the development of treatments intended to 'turn back time' on the asphalt pavement, and in the late 1950's, the first asphalt rejuvenators were developed to help counter asphalt aging (Brown and Johnson, 1976). Since then, rejuvenators under several proprietary names have been developed to combat aging in asphalt pavements. Rejuvenator application is not without problems because their application can reduce pavement friction and lead to increased safety issues. This has led to several states limiting rejuvenators for use for certain applications and a realization that the application rate must balance both rejuvenating effectiveness and friction values (G. King and H. King, 2008). Ideally, a rejuvenator would also be formulated to avoid unnecessary delays to re-opening the road to traffic, such as curing quickly.

There are two main purposes for applying fog seals. The first type of application is a treatment to enhance stone retention or reduce raveling on the surface of a roadway. The second application type is a penetrating seal formulated to infiltrate into the pavement to fill cracks/voids and rejuvenate the asphalt (Estakhri and Agarwal, 1991) The different application purposes require different considerations for emulsion formulation.

The emulsion setting characteristics for fog seals formulated to address raveling are typically faster setting while the penetrating seals are designed to set more slowly to allow for penetration and filling of small voids (Estakhri and Agarwal, 1991). Both applications will fill voids to some extent; however, the penetrating fog seal is designed to penetrate the pavement's surface and requires a slower-setting chemistry to allow the emulsion to maintain fluidity while it seals cracks and fills small voids.

The success of a fog seal relies on selecting the correct emulsion type and application rate. Fog seals applied on top of chip seals or a raveling pavement can use a rapid setting emulsion, while fog seals that need to penetrate and seal thin, hairline cracks on the pavement surface need emulsions with considerably lower viscosity and higher wetting potential., Slow and rapid setting emulsions have high emulsifier contents which result in small particle sizes and hence low viscosity. This makes them ideal for use in penetrating fog seals (James, 2006). Fog seal emulsions are often diluted to further reduce viscosity. Another important factor to consider for fog seal treatments is the application rate, which depends on the surface characteristics of the asphalt pavement (Zhang et al., 2019). A high application rate may allow for more crack sealing properties but could lead to reduced friction, while a lower application rate may not achieve desired results. Application rates of fog seals depend on the type of surface to be sealed as well as the amount of residual asphalt desired (Qureshi et al., 2013). Application rates as low as 0.01gal/yd2 for low absorption surfaces to as high as 0.59 gal/yd2 for high absorption surfaces is suggested by AEMA (Kim and Im, 2012). Minnesota typically applies fog seals at an application rate of 0.06 gal/yd2 to 0.12 gal/yd2 (Wood et al., 2006).

Rejuvenators are generally oil-based applications that penetrate the pavement surface and soften the aged asphalt by restoring the balance of asphaltenes and maltenes in the asphalt binder (Boyer, 2000). Rejuvenators need to have a low viscosity to penetrate and disperse through the asphalt, while maintaining a uniform consistency (Epps et al 1980). It must be noted that rejuvenating agents are different from softening agents, which do not restore the asphaltene/maltene ratio of the asphalt, but rather lower the viscosity of the binder (Karlsson and Isacsson, 2006; Moghaddam and Baaj, 2016).

The need for cost effective and environmentally sustainable pavements has lead to an increased interest in bio-based asphalt rejuvenators and pavement preservation. A typical asphalt rejuvenator contains the lighter and highly aromatic fractions of crude oil, and several studies indicate that these compounds can be successfully synthesized from natural and sustainable materials. Some rejuvenators also include recycled waste materials (Karlsson and Isacsson, 2006; Moghaddam and Baaj, 2016).

2.2 Rejuvenators for Asphalt Pavement Applications

With the focus shifting from using virgin materials in asphalt pavements to recycling aggregate and using more sustainable materials and methods for pavement construction and rehabilitation, bio-based materials are growing in popularity as a sustainable additive in asphalt mixes. The addition of both biomass-based additives, petroleum-based additives, and recycled oil-based additives has been researched over the years (Qu et al., 2018; Cooper Jr et al., 2017). Biomass may be in the form of animal waste, wood and cooking oil wastes and corn or soy based materials (Podolsky et al., 2016; Chen at al., 2017) and finds use in warm mix technology as well as recycling existing pavement materials and binder modification. Recycling existing asphalt pavement materials is a sustainable alternative to using virgin aggregate in pavement construction, however the stiff aged binder present in RAP (recycled asphalt pavement) limits the amount of RAP that can be incorporated into HMA. Adding rejuvenating agents can increase the amount of recycled material that can be added into an asphalt mix design while maintaining performance specifications (Silva et al., 2012) Rejuvenating emulsions may also be diluted sufficiently and used as rejuvenating fog seals. These emulsions contain oils that reduce the viscosity of existing asphalt binder and can seal voids that in turn prevent further binder oxidization (Prapaitrakul et al., 2005). This section will look at the role of bio-based rejuvenating materials used in HMA and asphalt emulsions in greater depth.

2.3 Bio-based Materials for Rejuvenating Aged Asphalt

A review of literature reveals multiple studies into the potential rejuvenating properties of several bio-materials, as well as bio-based asphalt alternatives. Plant-based additives like soybean and palm oil, as well as engine oil residue are similar in chemical composition to asphalt binders and hence can be used as additives to asphalt, as well as binder alternatives (Abd El-latief, 2018). These materials are commonly produced by pyrolysis which involves a high heat transfer rate to the biomass and a short vapor residence time, causing the biomass to decompose. A variety of proprietary materials currently exist with rejuvenating and softening properties that can be applied to asphalt mixes. Treatments like RePlay and Biorestor are bio-based fog seal treatments that have been applied to pavement sections (Ghosh et al., 2016). Podolsky et. al. (2016a), studied the effects of isosorbide distillation bottoms on the rutting and stripping performance of hot mix and warm mix asphalt using the MSCR test and the Hamburg wheel tracking test to determine the rutting resistance of the binder and mix, respectively. The authors also noted a decrease in mixing and compaction temperatures with all bio additives (Podolsky et al., 2016b). Isosorbide distillation bottoms is a common byproduct from corn oil synthesis. The effects of antioxidants like lignin on the performance of asphalt binders have also been studied. In one study, co-products containing lignin from a wet mill ethanol plant were combined with asphalt binders and their effect on binder performance was observed (McCready and Williams, 2008). The study noted stiffening of the binder with increased addition of the lignin-based product, enhancing the high temperature properties of the binder. While some negative effects were noted on the low temperature performance of the binder, these were observed to be small in comparison to the overall increase in the working temperature range of the binder. Waste cooking oil is another material that has elicited increased interest as an additive to asphalt binder. Vegetable oils in general are rich in unsaturated fatty acids which are similar to light oil components in asphalt. These vegetable oils include soybean oil and corn oil, and added in the right dosage can be as effective as conventional rejuvenating agents in softening aged asphalt (Ji et al., 2017). The properties of a bio asphalt containing 33% waste cooking oil were studied by Sun et.al., (Sun et al., 2017) who noted that the bio-based binder exhibited similar performance to SBS modified asphalt and superior performance to PEN 70 base asphalt for high and low temperature performance. Another study on waste cooking oil (WCO) noted that the quality of the WCO added to asphalt affects binder performance. The quality of WCO was determined with an acid test, with a high acid value potentially causing degradation in rheological performance. However, transesterification of WCO with alkaline catalysts reduces high fatty acid contents, allowing it to be used as a modifier in asphalt binder (Azahar et al., 2016). Asphalt emulsions can prove advantageous as a rejuvenator since they can be formulated to set at varying rates and contain a variety of rejuvenating additives, polymer modifiers, vulcanizing agents, and surface tension reducing agents (Takamura, 2005). The critical components in a rejuvenating asphalt emulsion are lower molecular weight maltene and aromatic fractions. The amount of rejuvenating agent added to the emulsion can be increased according to the amount of maltenes present in the asphalt binder that is emulsified and the degree of oxidation of the pavement surface (Morris and Shealey, 2014). A search of literature reveals limited knowledge on the effect of rejuvenating agents on the stability of asphalt emulsions. However, most rejuvenators are essentially composed of the light fractions of asphalt, e.g. aromatics and resins, or compounds of similar nature. Studies on the effect of these fractions on the stability of asphalt emulsions do exist. While the heavier fractions of asphalt (asphaltenes and waxes) decrease asphalt emulsion stability, aromatics and resins facilitate emulsion formation and enhance stability (Al-Sabagh et al., 1997). Therefore, it is possible that rejuvenating agents can aid in the stability of an asphalt emulsion. Table 1 summarizes various examples of bio-based asphalt additives from literature.

Table 1 Summary of bio-based asphalt additives

Bio-based additive	Purpose of addition	Effect on binder	Citation
Isosorbide distillation bottoms (IDB) derived from corn oil	Warm mix additive	Decreases mixing and compaction temperature	Podolsky et al., 2016b
Lignin derived from bioethanol production	Bio-asphalt	Increases working temperature of binder. Anti-oxidizing properties.	McCready and Williams, 2008
Waste cooking oil	Bio-asphalt	Enhanced high temperature performance similar to SBS modified asphalt	Ji et al., 2017, Azahar et al., 2016, Sun et al., 2017
Bio oil generated from sawdust	Rejuvenating agent	Improved cracking resistance. High degree of restoration of aged asphalts	Zhang et al., 2019
Soybean derived bio oil	Rejuvenating agent	Significant drop the binder's critical high and low temperature. Sustained performance in RTFO and PAV aged samples	Elkashef et al., 2017
Castor oil residue	Rejuvenating agent	Enhance asphalt binder serviceability temperature range. Effects of the rejuvenator performance vary with temperature	Zeng et al., 2018
Palm oil	Rejuvenating agent/binder replacement	Suitable for use in hot mix asphalt and hot in place recycling	Nigen-Chaidron and Porot, 2010

2.4 Quantifying the Effects of Rejuvenators on Asphalt Pavements: Performance Testing

In order for a rejuvenating treatment to be deemed successful, it needs to penetrate into the asphalt pavement, seal up existing cracks to prevent further oxidation and prove economically beneficial while not delaying the opening of the road to traffic or reducing the friction of the pavement surface. Rejuvenating materials are often tested by studying their effect on softening of aged asphalt binder. Measuring the rejuvenated binder's rheological properties by penetration tests and using dynamic shear and bending beam rheometers allows researchers to understand and quantify the effects of a rejuvenating agent on asphalt binder (Shen and Ohne, 2002). Performance grades of the aged and rejuvenated binders are compared to that of the aged binders without rejuvenating agents, with an expected drop in high temperature and low temperature asphalt performance grades expected. This can lead to an adverse effect on the rutting resistance, but may still be favorable if the gain in low temperature behavior is higher than the loss in high temperature grade (Zeng et al., 2018). According to Brownridge (2010), the effectiveness of a rejuvenator can be measured by extracting and recovering the aged asphalt binder from samples treated with rejuvenating agents as well as control samples, and comparing their viscosities. Usually, the extraction of the asphalt binder is limited to the top ½ inch.

Field testing of rejuvenating emulsions and fog seals is an important aspect of quantifying how a treatment performs in real world conditions. Friction reduction is one of the biggest drawbacks of fog seals, with the Indiana DOT reporting a 50% reduction in friction values immediately after fog seal application. The friction values of the sections tested eventually returned to their original values after a period of 18 months (Li et al., 2012). A number of tests exist to measure the friction values of a pavement surface, some of them include the locked wheel tester, British pendulum skid resistance tester, surface texture tester and the dynamic friction tester (Kebede, 2016).

Studies by the University of Minnesota and the Minnesota DOT investigated the effect of bio-based sealants on the mechanical properties of asphalt mixes and how they impacted pavement performance (Ghosh and Marasteanu, 2016). This involved testing treated and untreated binder samples for rheological properties using a DSR and BBR, while also collecting treated as well as control field cores. Thin beams were cut from these field cores in order to test the effects of the sealants on mix properties of HMA. The study found that oil-based sealants had a significantly higher softening effect on the asphalt binder when compared to the water-based sealants. Testing HMA mixes showed different trends between field cores and laboratory prepared samples, with significant differences between the performance of water-based and oil-based sealants. Lastly, there was no significant effect of the sealants on the low temperature properties of the asphalt binder. Other trials by the Minnesota DOT involved using a bio-oil-based preservation agent intended to prevent the ingress of water into the pavement (Olson, 2011). The bio-based additive was able to increase the rate of water runoff from the pavement surface and had an application cost equal to that of a chip seal. It was also noted that the additive did not become hot and sticky during hot weather periods. This contradicts a study conducted by Medina and Clouser (2009) for the Pennsylvania DOT on the effects of the same soy-based derivative to reduce water and air infiltration into pavement layers, as well as its claims to reduce raveling, rutting, and cracking without compromising on pavement durability and skid resistance. They found no significant reduction in water permeability between the control and treated sections, and further noted a drop in friction values of the pavement. However, it needs to be noted that the Minnesota DOT's selection of projects was more specifically targeted to old and cracked pavements that were already suffering from high permeability issues, highlighting the need for correct project selection. The Minnesota DOT applied bio-based pavement rejuvenators on shoulder sections with application rates of 0.015 to 0.10 gal/yd2 and were shown to provide various levels of waterproofing and reduced thermal cracking than the control section (Johnson, 2018). There was also no significant reduction in high and low temperature performance when compared to the control section. Another study by the Minnesota DOT focused on material performance in cold climates and evaluated binders treated with a bio-sealer as well as untreated control samples. Both oil based and water based sealants were used, and results showed that the oil based sealants both softened the control binder as well as increased its rutting, fatigue and low temperature cracking resistance (Ghosh, 2017). Further studies on the waterproofing abilities of bio-sealants on longitudinal joints in asphalt pavements were studied by Huang and Shu (2010) for the Tennessee Department of Transportation using permeability tests, indirect tensile strength testing and X-ray CT. The sections used application rates of 0.03 and 0.08 gal/yd2 for two different treatment applications. Results showed that the bio sealants reduced water absorption in the test sections.

Overall, these studies show there is great potential for expanding research in the areas of formulating bio-materials for use in asphalt emulsions to preserve and rejuvenate asphalt pavements.

Chapter 3: Materials

3.1 Materials

The materials used in this study come from a field project conducted by MnDOT, ISU and National Road Research Alliance (NRRA) research bio-fog seals at two sections of Mn/ROAD Test Road and on a section of a county road in St. Michael, Minnesota. The treatments were performed on July 20-21st, 2021.

The SESO and BioMag topical treatments were applied on the three test sections. At the Mn/ROAD Test Road two binder grades were used, 58H-34 (Group A) and 58S-28 (Group B), as shown in Figure 1. On the St. Michael County Road (15th Street) the treatments were applied on a 58H-34 binder grade (Figure 2).

Figure 1 Aerial image of the Mn/ROAD test track where the topical treatments SESO (red/white thick stripes) and BioMAG (blue/white thin stripes) were applied for testing.

Figure 2 Aerial image of the St. Michael County Road (15th St.) where the topical treatments SESO (red/white thick stripes) and BioMAG (blue/white thin stripes) were applied for testing.

The test sections were investigated in-field and four cores from each location and treatment were collected and evaluated through laboratory tests.

3.1.1 Bio-based Rejuvenated Fog Seal

Two bio-based fog seals were formulated using SESO and Bio-Mag as sealants and rejuvenators. The fog seals were lab formulated to restore the flexibility of an existing asphalt pavement at a low-cost. The lab formulation was based on the estimated binder stiffness at the time of application and considered the depth of the emulsion penetration into the pavement system to achieve at least ¾-inch of emulsion penetration and achieving a cure time of less than 2 hours. These bio-based fog seals are water-based and fast setting emulsion. Their formulation was 30% solids containing 2% surfactant and 1% emulsion aid and therefore 70% water.

3.2 Methods

3.2.1 Application Procedure and Rate

The soybean-based SESO and BioMAG fog seal design application rate was 0.02 gal/yd^2. The mixtures were premixed prior to application to ensure uniformity for application and sprayed on the pavement by a distributor truck, as shown in Figure 3.

Figure 3 Bio fog seal application

The application rate in the field was calculated based on the area that the bio fog seal was applied and the difference in the weight of the seal tank. The fog seal application rates are shown in Table 2.

Table 2 Fog seal application rates

Test Section	Application rate (gal/yd^2)
Mn/ROAD 58S-28 SESO	0.016
Mn/ROAD 58S-28 BioMag	0.018
Mn/ROAD 58H-34 SESO	0.015
Mn/ROAD 58H-34 BioMag	0.020
St. Michael 58H-34 SESO	0.016
St. Michael 58H-34 BioMag	0.018

3.2.2 Field Investigation Methods

3.2.2.1 Dynamic Friction Testing (DFT)

The Dynamic Friction Testing (DFT) measures surface friction as function of a horizontal spinning disk with three spring-loaded rubber sliders. The speed of the disk, when in contact with a surface, will decrease due to friction between sliders and surface friction. The friction is calculated as a function of sliding speed. This test was performed, in accordance with ASTM E1911-19, inside and outside the wheel path at speeds ranging from 0 to 80kph, before the seal application, and after 30 minute, 60 minutes, 90 minutes and 1 month. Jayawickrama et al. (1996) defined that a friction coefficient of 0.35 at 20 kph is the minimum acceptable for heavy traffic roads.

3.2.2.2 British Pendulum Test

The British Pendulum test uses a dynamic pendulum impact-type with a rubber slider and was performed following ASTM E303-18. The energy loss between the slider and the test surface determines frictional properties and skid resistance of a surface evaluated as British Pendulum Number (BPN). A minimum of 6 data points were collected for each value and a dry and wet measurement were taken for each section. The wet section had an initial 5-6 spray applications of water and was re-wetted prior to each measurement.

3.2.2.3 Sand Patch Test

The sand patch test is employed to measure the pavement macrotexture. Based on the diameter of the circle formed spreading a known volume of sand over a clean pavement surface the mean texture depth can be calculated. The procedure for performing the sand patch test can be found in ASTM E965-15.

3.2.2.4 Retroreflective Pavement Marking Test

The retroreflectivity properties of horizontal pavement marking materials, such traffic stripes, were measured before and after the application of the bio-fog seal to investigate if there was a significant loss in reflectivity of pavement markings, using a portable retroreflectometer. The test was performed in the field before the treatment and after 7 weeks, using LTL-X Retroreflectometer and following ASTM E1710-18 procedure. According to Pike and Barrette (2020), the minimum performance for in-place wet-reflective markings is 50 mcd/m2.l to be adequately visible in wet-night conditions which is above the 35 mcd/m^2/lux identified in the qualitative rating portion of the study. Pike and Barrette (2020) referenced a Virginia Tech Transportation Institute study (Gibbons et al, 2004; Gibbons et al., 2005) that showed the detection distance of pavement markings under wet retroreflectivity is less than that under dry retroreflectivity of the same value (e.g., 500 mcd/m^2/lux).

3.2.2.5 Permeability

The permeability of asphalt mixtures was measured based on the Florida Test Method FM 5-565. The test determines the water conductivity through the rate of flow of water through a saturated specimen using a falling head permeability apparatus. The coefficient of permeability of the asphalt sample is then determined based on Darcy's law.

3.2.3 Laboratory Test Methods

3.2.3.1 Bending Beam Rheometer (BBR)

Bending Beam Rheometer test consists of a low-temperatre creep test, in which a constant load is aplied on an asphalt beam in a three-point bending configuration. The deflection of the beam relates to the stiffness and relaxation properties of asphalt binders. Asphalt mixture beams were prepared from the field cores. The practice of the method is described in AASHTO T 313-19.

Chapter 4: Field Investigation and Laboratory Testing Results

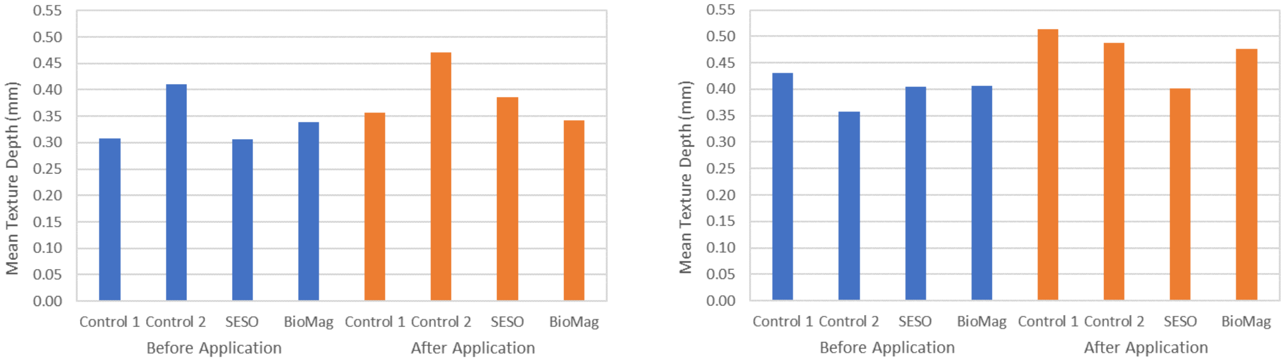
4.1 Field Investigation Results

The bio-fog seals were applied in three test sections. A visual inspection showed that there was an improvement on the surface appearance, sealing of minor cracks and surface voids, as shown in Figure 4.

Figure 4 Pavement before (left) and after (right) the bio fog seal application

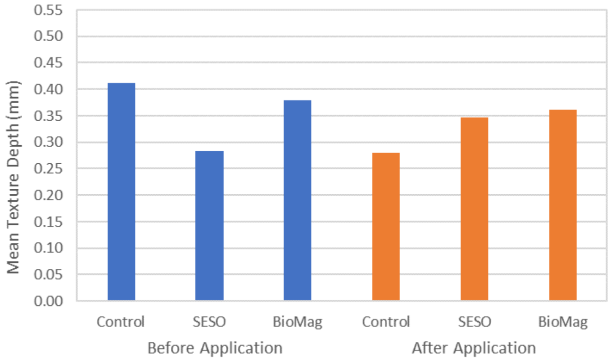
4.1.1 Friction

The sand patch results are shown in Figure 5. There is a substantial difference between Control sections 1 and 2 and between the measurements done before and after the other sections were treated, showing that this test is very sensitive to the location as testing was done in different locations. In the three test sections, the bio-fog seal treatment did not affect or improved the mean texture depth of the pavement.



(a) Mn/ROAD 58S-28, Inside Wheel Path

(b) Mn/ROAD 58H-34, Inside Wheel Path



(c) St. Michael, Inside Wheel Path

Figure 5 Sand patch results

The BPN of the Mn/ROAD tests sections are shown in Figure 6. The skid resistance in most of the cases was not significantly affected by the application of the fog seal, showing that the friction of the pavement was maintained. The BioMag fog seal pavement in the outer wheel path track in the wet condition outperformed the track with no treatment for both Mn/ROAD sections.

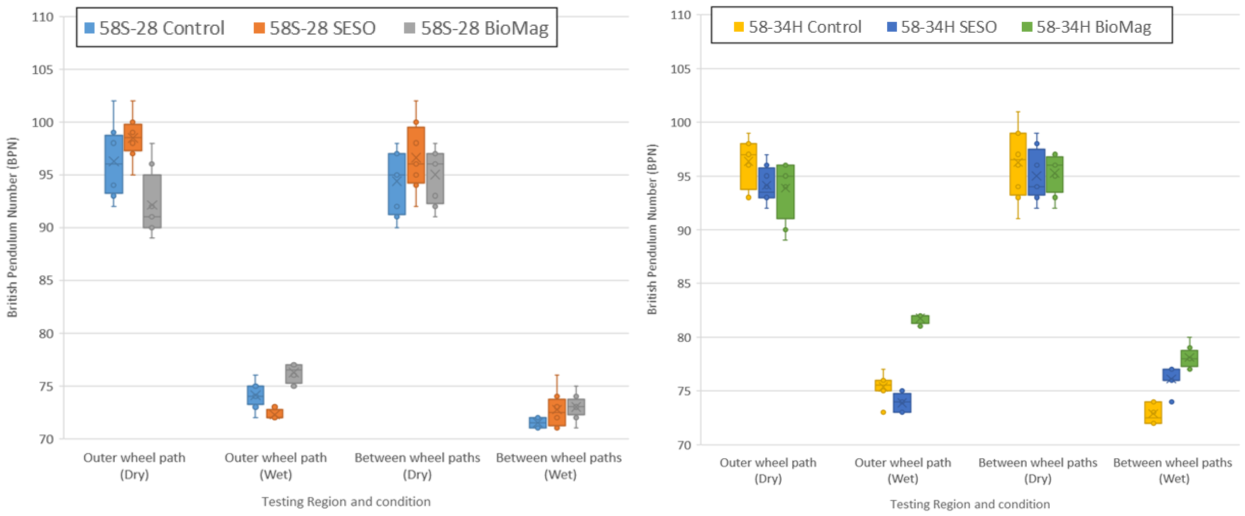
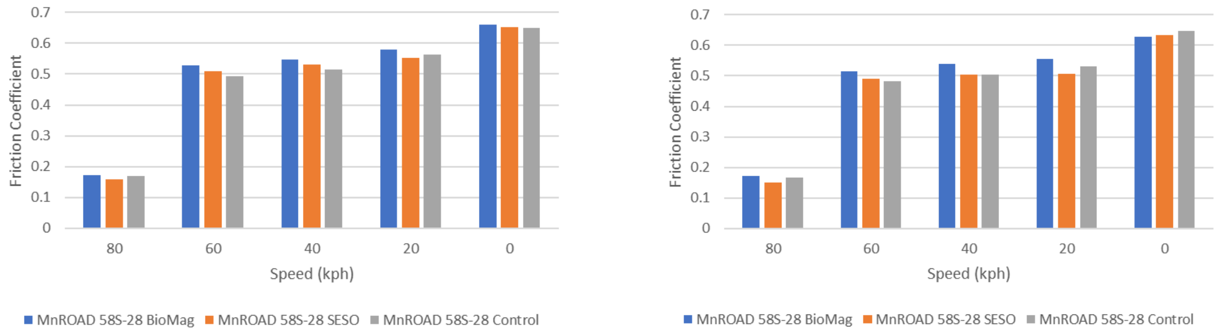


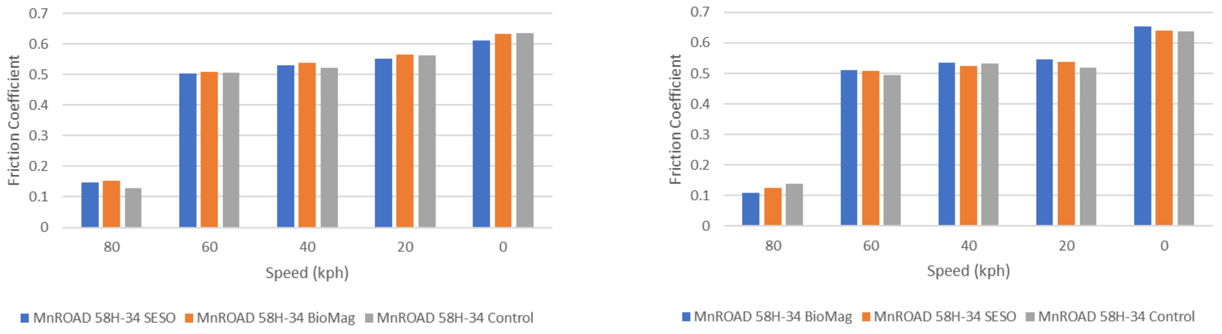
Figure 6 BPN of Mn/ROAD test sections

Figure 7 shows the results of DFT for the three test sections. Comparing the friction coefficient before and after the application of the bio-treatment. The friction did not significantly change or was improved, and for all the test sections at 20kph the friction coefficients were greater than 0.35, the minimum safe level.



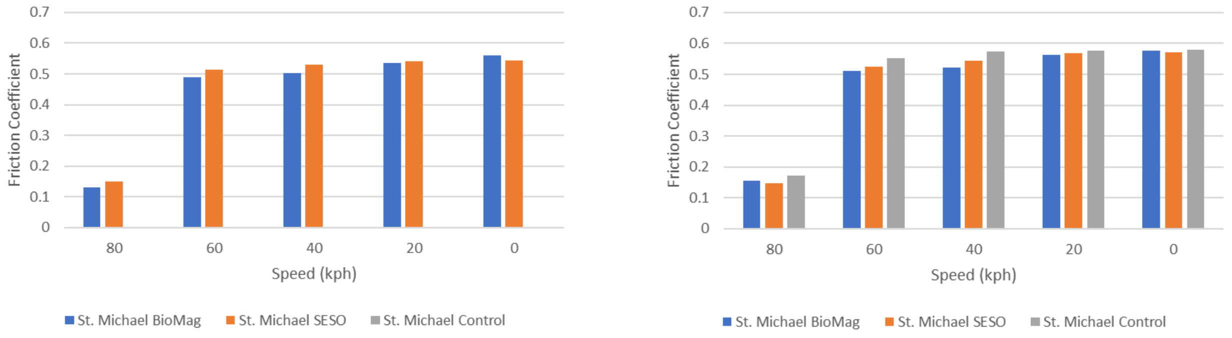
(a) Mn/ROAD 58S-28, Pre-Application

(b) Mn/ROAD 58S-28, 1-Month Post-Application



(c) Mn/ROAD 58H-34, Pre-Application

(d) Mn/ROAD 58H-34, 1-Month Post-Application



(e) St. Michael, Pre-Application

(f) St. Michael, 1-Month Post-Application

Figure 7 DFT results

Figure 8 shows the friction coefficient before the application of the surface treatment on the St. Michael test section pavement and after. Since the friction coefficient of the control and the treated sections are not substantially different, it shows that the bio fog seals were placed and cured within 30 minutes for opening to traffic.

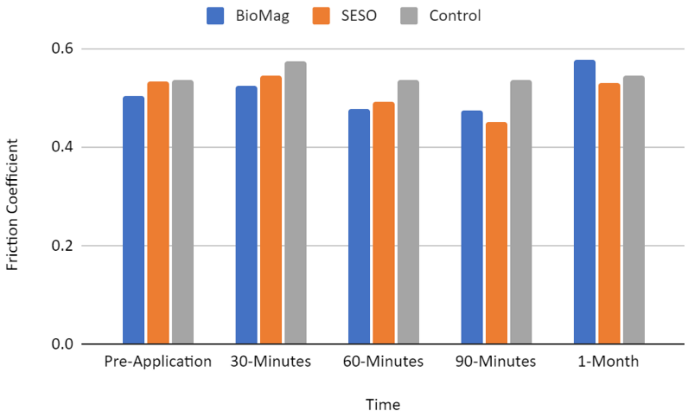


Figure 8 Bio-fog seal dry time in St. Michael test section

4.1.2 Reflectivity

The effect of the fog seals in the horizontal pavement markings reflectivity are shown in Figure 9. In the St. Michael section, all pavement markings had decreased reflectivity, but were above minimum value of f 50 mcd/m2 l. In Mn/ROAD sections the bio-fog seals improved the reflectivity of the horizontal markings.

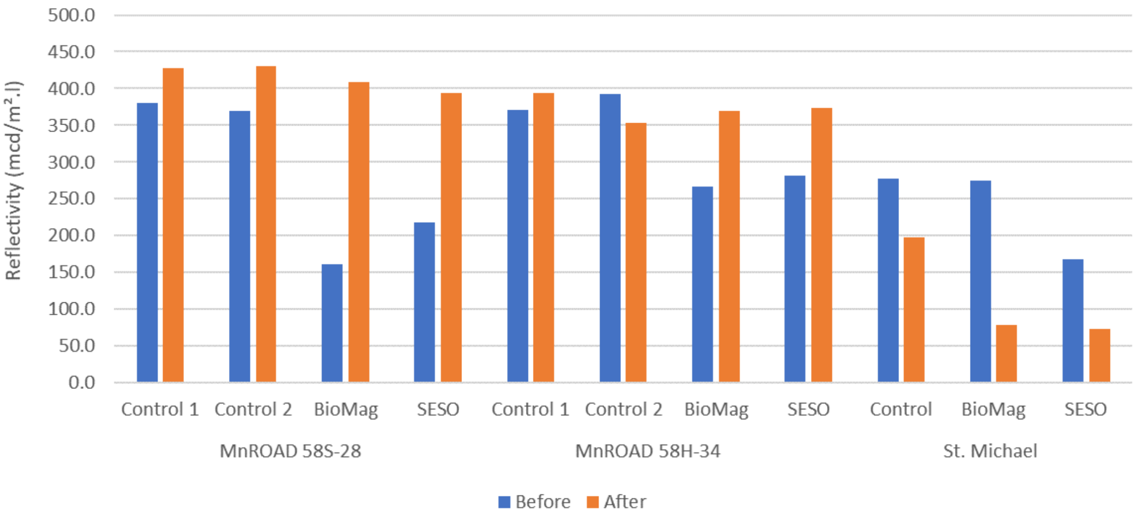
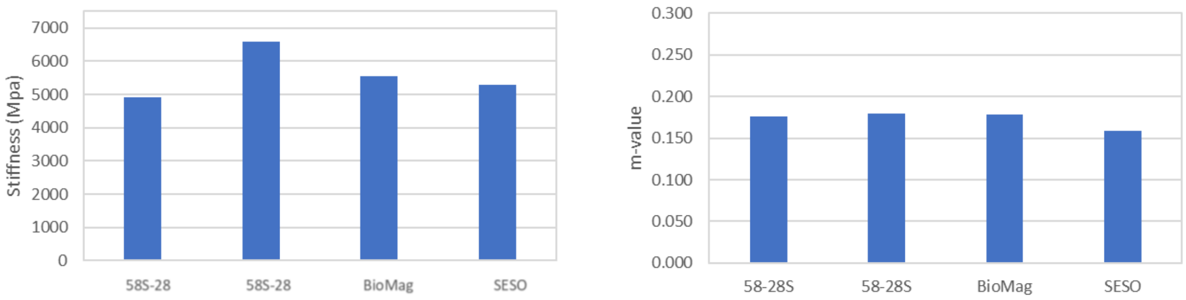


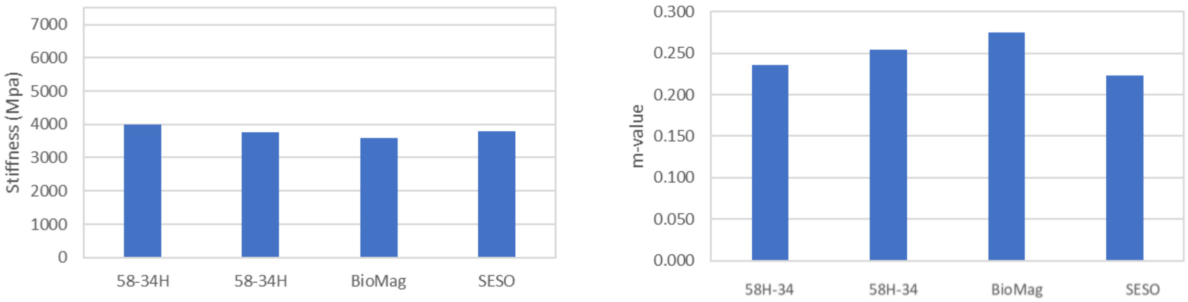
Figure 9 Horizontal pavement markings reflectivity before and after treatment

4.1.3 Stiffness and Relaxation Properties

Figure 10 shows the stiffness and m-value, that correlates with the asphalt relaxation properties, of the cores from Mn/ROAD test sections. The stiffness of the mixture on average decreased with both treatments. The asphalt mixtures treated with BioMag showed a slight increase in the m-value. Generally, a lower stiffness and a higher m-value are associated with better anti-cracking properties of a mixture. These minor changes of the properties in the results can indicate that the bio-based fog seals, is not only acting as a sealant, but also as a rejuvenator.



(a) Mn/ROAD 58S-28



(b) Mn/ROAD 58H-34

Figure 10 Stiffness (left) and m-value (right) results

4.1.4 Permeability

Figure 11 shows the coefficient of permeability measured in the field and it showed a tendency of decreasing permeability after the surface treatment. The SESO fog seal decreased this coefficient in the sections tested. Based on the control sections, the Mn/ROAD 58S-28 BioMag is apparently an outlier, but the BioMag treatment did reduce the permeability. In the 58H-34 section, after the BioMag treatment the permeability increased. An impermeable pavement would have a value of 0 for the coefficient of permeability.

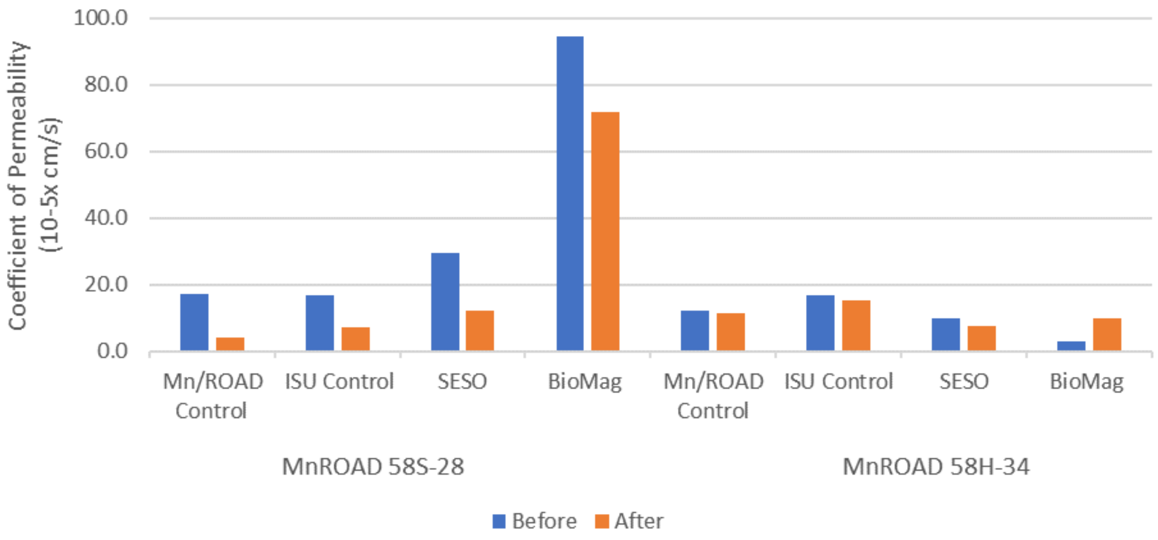


Figure 11 Field coefficient of permeability (10^{-5} cm/s)

Chapter 5: Conclusions and Recommendation

5.1 Conclusions

From this study, the following can be concluded:

1. The test tracks treated with bio-fog seals maintained the skid resistance of the pavement compared to testing prior to treatment.
2. The bio fog seals were placed and cured within 30 minutes for opening to traffic.
3. The reflectivity of the horizontal pavement markings was not affected and even improved in the Mn/ROAD test tracks from the treatments. However, in the St. Michael test section, the reflectivity decreased.
4. After the application of the SESO and BioMag fog seals, the stiffness of the asphalt mixture decreased. For the BioMag treated samples, there was also an increase in the m-value, showing an improvement in the relaxation properties of the binder. Those results showed that the bio-based fog seals were not only acting as sealants but also as rejuvenators in the pavement.
5. The permeability results showed a tendency toward decreasing permeability after the surface treatment. BioMag fog seal sealed the 58S-28 pavement, and the SESO fog seal, did not affect the permeability of the 58H-34 pavement.

Generally, it can be concluded that the use of bio fog seals as a maintenance treatment can help to postpone the need of resurfacing or applying a new overlay. The treatments improved the skid resistance of the pavements, didn't affect the reflectivity of the pavement markings, and restored the stiffness of the asphalt mixture. Additionally, it had a fast setting, opening the road to traffic within 30 minutes of the fog seal application.

5.2 Recommendation

SESO rejuvenator treatment would benefit from an increase in the application rates that were 0.015 to 0.016 gal/yd^2 to the targeted rate of 0.020 gal/yd^2.

5.3 Potential Benefits

The potential benefits of this research are:

1. Improve flexibility and preservation of roadways while developing new domestic markets for bio-based products.
2. Increase longevity of the roadway delays major rehabilitation and provides improved pavement condition in the interim. Preservation of pavements helps keep roads in better condition longer, which leads to reduced pavement life-cycle cost.

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