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Field Trial and Performance Evaluation of Soybean-Based Bio-Fog Seals for Asphalt Rejuvenation

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Abstract: Cracked and deteriorated asphalt are common problems on our roads, leading to safety concerns and requiring significant resources for rehabilitation and reconstruction. This study investigates bio-fog seals, a promising eco-friendly solution utilizing bio-based rejuvenators. These treatments penetrate aged asphalt, restoring its flexibility and resistance to cracking. We assessed the effectiveness of two bio-fog seal formulations—one containing sub-epoxidized soybean oil (SESO) and the other combining SESO with a biopolymer (BioMag). Applied to real pavement sections, the research evaluated how these bio-seals impacted key performance factors, such as stiffness, permeability, and drying time, and safety factors, including skid resistance and pavement marking visibility. The results indicate the bio-seals did not compromise skid resistance and the reflectivity of the markings, eliminating the need for repainting stripes. Additionally, they successfully reduced pavement stiffness, making the asphalt more flexible and crack-resistant. Remarkably, with rapid setting times, under 30 min, these treatments minimize traffic disruption and do not require a blotter material. Overall, this research demonstrates the potential of bio-fog seals as a sustainable solution for extending pavement lifespan and lowering long-term maintenance costs.

Keywords: biomaterial; fog seal; asphalt; preventive treatment

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1. Introduction

Cracked and deteriorated asphalt are common problems on our roads, leading to safety concerns and requiring significant resources for rehabilitation and reconstruction. This degradation is primarily driven by the complex ageing process of the asphalt binder, which disrupts its chemical composition and ultimately leads to performance deterioration [1–3].

The ageing of asphalt binder is a multifaceted phenomenon that involves chemical and physical transformations. It occurs due to combined effects of high temperatures, exposure to ultraviolet radiation, and oxidation. These factors contribute to the volatilization of lighter components of the binder, disrupting the balance within the colloidal system. This imbalance leads to a stiffer and less ductile binder, which is more susceptible to cracking [4,5].

The condition of pavement declines exponentially over time, as illustrated in Figure 1. Initially, pavements deteriorate at a slower rate, exhibiting only minor cracks and distresses. However, when left unaddressed, these minor distresses escalate rapidly, leading to more extensive damage and requiring costly rehabilitation or reconstruction efforts. To prevent this, early-life treatments can be implemented to slow down the deterioration process and maintain the pavement's good condition for a longer duration (dashed line). As shown in Figure 1, when preventive treatments are applied early and regularly, the pavement condition index (PCI), which is a standardized method for assessing pavement integrity, is maintained as high for longer periods of time [6,7].

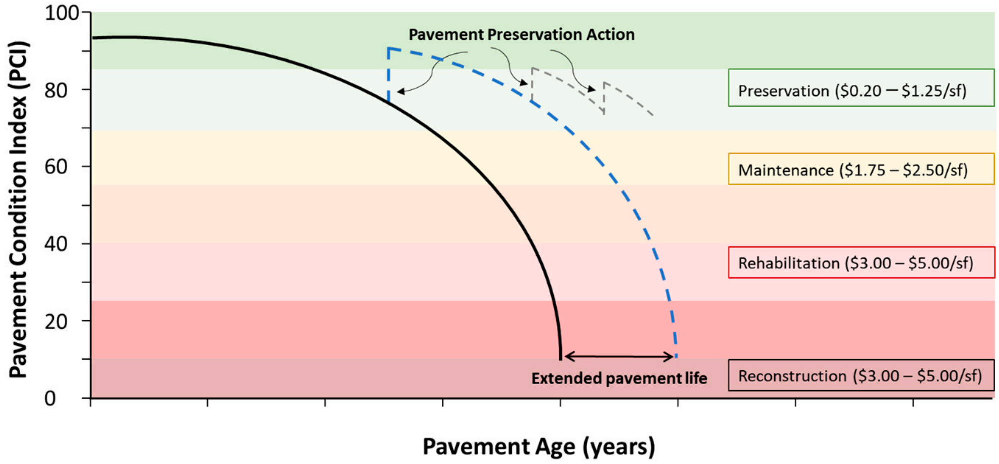

Figure 1. PCI progression over the pavement life. Optimal allocation of dollars obtained by investing in preservation offsetting the need for major interventions, such as rehabilitation and reconstruction.

Based on the study conducted by the Los Angeles County Department of Public Works [8], with the costs of the treatments shown in Figure 1, investing in pavement preservation early on maximizes the return on investment and potentially can save six to ten times the amount spent on future rehabilitation costs, aligning with the saying: 'good roads cost money, but bad roads cost even more.' In addition to cost, a proactive investment in preventive maintenance can also reduce environmental pollution, resource demand, and energy consumption over the life cycle of the pavement [9,10].

To minimize aging effects on the pavement surface, particularly on the top layer, which experiences the most aging, two approaches can be employed: physical and physiological [11]. The physical strategy consists of sealing the pavement and forming a protective barrier that mitigates the penetration of water. A common technique is fog sealing, where a thin layer of diluted asphalt emulsion is applied to the surface of roads in good condition, ideally under 3 years old [12,13], closing interconnected voids, filling small cracks, and preventing moisture damage [14,15]. However, it can initially reduce pavement friction by over 50% [16]. To mitigate this short-term safety concern, loose aggregate (sand) is often applied after fog sealing, improving initial friction. The physiological approach focuses on healing existing damage and restoring the asphalt binder's properties [17].

Rejuvenator seals combine both physical and physiological approaches. They seal the surface and rebalance the asphalt fractions, decreasing its viscosity and stiffness, and counteract aging damage, minimizing the need for extensive rehabilitation [18]. Traditional rejuvenators in fog seals are typically petroleum-based, but the need for sustainable alternatives has led to an increased interest in bio-fog seals [19,20]. These seals utilize bio-based rejuvenators derived from vegetable oils, wood oils, or other organic compounds formulated into emulsions that are sprayed on the pavement.

During application, the bio-rejuvenator emulsion penetrates the asphalt matrix through diffusion, as illustrated in Figure 2a,b. The rejuvenator molecules then soften and reduce the viscosity of the aged binder. This allows the rejuvenated binder to flow through open microcracks, facilitating a self-healing and sealing process under optimal temperatures and sufficient time (Figure 2c,d) [21].

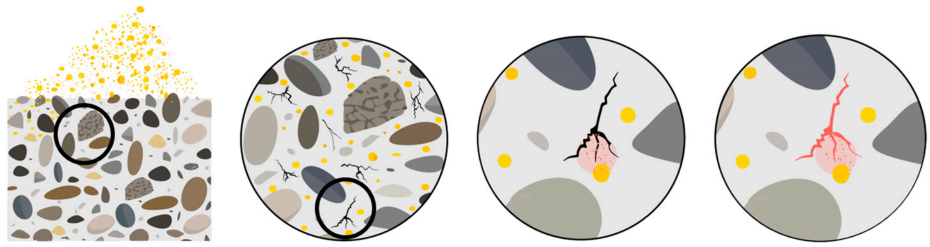

Figure 2. Concept of rejuvenating asphalt mixture, (**a**) bio-fog seal application, (**b**) diffusion of the rejuvenator into the matrix, (**c**) changes in the asphalt binder properties, such as decrease in the viscosity, (**d**) microcrack filling and sealing.

Various bio-based rejuvenator products are currently available in the market. Soybean-derived additives have demonstrated effectiveness as rejuvenators, reducing the stiffness and viscosity of aged and brittle asphalt binders [22]. Iowa State University (ISU) has developed soy-based biotechnologies showing promise in rejuvenating aged asphalt [23,24]. Among them are partially epoxidized soybean oil (SESO) and BioMag. BioMag is a balanced combination of SESO and the biopolymer poly(acrylated epoxidized high oleic soybean oil) (PAEHOSO) in a 50/50 ratio. Beyond the immediate benefits of pavement rejuvenation, these soy-based bio-fog seals offer significant environmental advantages, including carbon capture during production leading to a negative global warming potential, and minimizing the environmental footprint of pavement maintenance [25].

Despite the growing interest in sustainable pavement maintenance solutions, a critical knowledge gap exists regarding the field performance of bio-based rejuvenators. This research aims to bridge this gap by evaluating the effectiveness of soy-based bio-fog seals in restoring pavement properties crucial for longevity without sacrificing safety in real roads.

To examine whether these materials meet the expectation of a fog seal and provide value to the pavement, we will evaluate their impact on pavement stiffness, flexibility, and permeability. Furthermore, a particular focus will be placed on safety, investigating the effect of the treatments on pavement friction, pavement markings, and traffic disruption. By addressing these objectives, this study holds significant value by contributing to developing sustainable preventive maintenance strategies for asphalt pavements. Specifically, we anticipate demonstrating that bio-fog seals are a viable alternative to traditional pavement preservation methods in terms of performance, which can increase the durability and longevity of pavements.

2. Materials and Methods

2.1. Field Testing Sites

This study evaluated the performance of bio-based fog seals (SESO and BioMag) applied to asphalt pavements on three low-volume road sections in Minnesota and was a collaborative effort of MnDOT, Iowa State University (ISU), and the National Road Research Alliance (NRRA).

All test sections were approximately one year old at the time of treatment in July 2021. The sections are located in two sites: MnROAD Test Road, a pavement test track, operated by the Minnesota Department of Transportation Materials and Road Research division, and the local St. Michael County Road (15th Street). The MnROAD test track has two sections, one constructed with 58-28S binder and the other with 58-34H. The St. Michael County Road utilized 58-34H binder grade. All test sections included control sections as well as sections treated with SESO and BioMag (Figure 3).

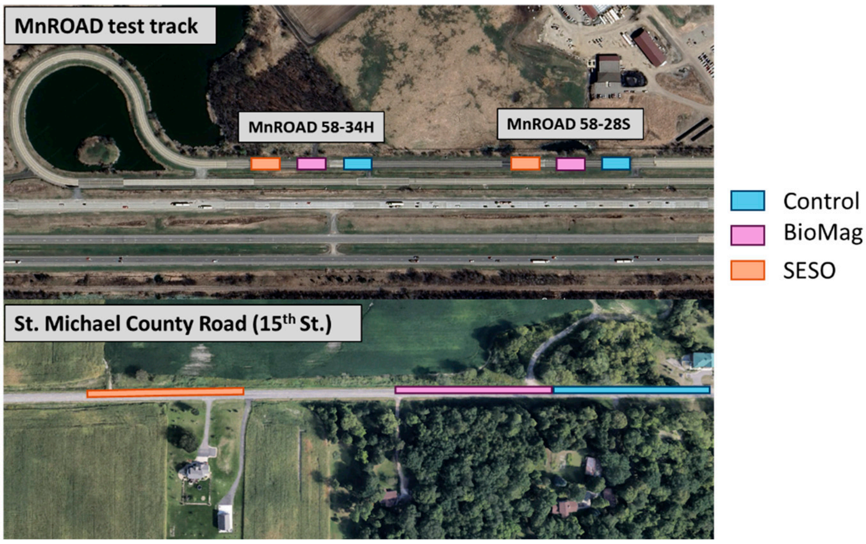

Figure 3. MnROAD and St. Michael test section layout.

2.2. Bio-Fog Seal Formulation

The bio-fog seals used in this study were formulated from two soybean-based additives: SESO and BioMag. SESO, derived from partially epoxidized soybean oil, which contains triglyceride molecules and plays a key role in asphalt rejuvenation. The epoxy rings formed chemically during processing react with asphalt molecules, addressing asphaltene aggregation, a consequence of aging, and restabilizing the structure [26,27]. Additionally, SESO modifies asphaltene molecules, enhancing binder solubility and flexibility and ultimately reducing the stiffness of aged binders [28]. BioMag, a 50/50 blend of SESO and the thermoplastic biopolymer poly(acrylated epoxidized high oleic soybean oil) (PAEHOSO), further enhances performance. The SESO component acts as a solvent, while PAEHOSO is synthesized through RAFT polymerization [29].

The bio-fog seals were formulated as water-based and fast-setting emulsions, 100% derived from soybean oil with 0% residual bitumen. Their composition includes 30% solids, 2% surfactant, and 1% emulsion aid, resulting in a stable and highly penetrating product. The viscosity is set below 20 cP at 35 °C, and the density is approximately 0.97 g/cm^3. The surfactant emulsifies the rejuvenator and polymer components into micron-sized droplets within the water, while also reducing surface tension to facilitate rapid penetration into the pavement.

2.3. Application

The emulsions were sprayed at a rate of 0.09 L/m^2 using a distributor truck, as illustrated in Figure 4. This application rate was chosen based on experience and pavement permeability considerations.

To control the application rate and ensure consistent application, the fog seal application rate was verified in the field. This involved placing three geotextile fabric samples with known mass and dimensions on the pavement surface before fog seal application. These samples were randomly distributed across the test area. The geotextiles were collected following the fog seal application, and the mass of the fog seal adhering to each sample was measured. The average mass of the fog seal collected on the three samples was then used to calculate the actual field application rate.

Figure 4. Application truck.

2.4. Experimental Plan

The experimental plan, as illustrated in Figure 5, involved a comprehensive assessment of the pavement characteristics before and after the bio-fog seal application.

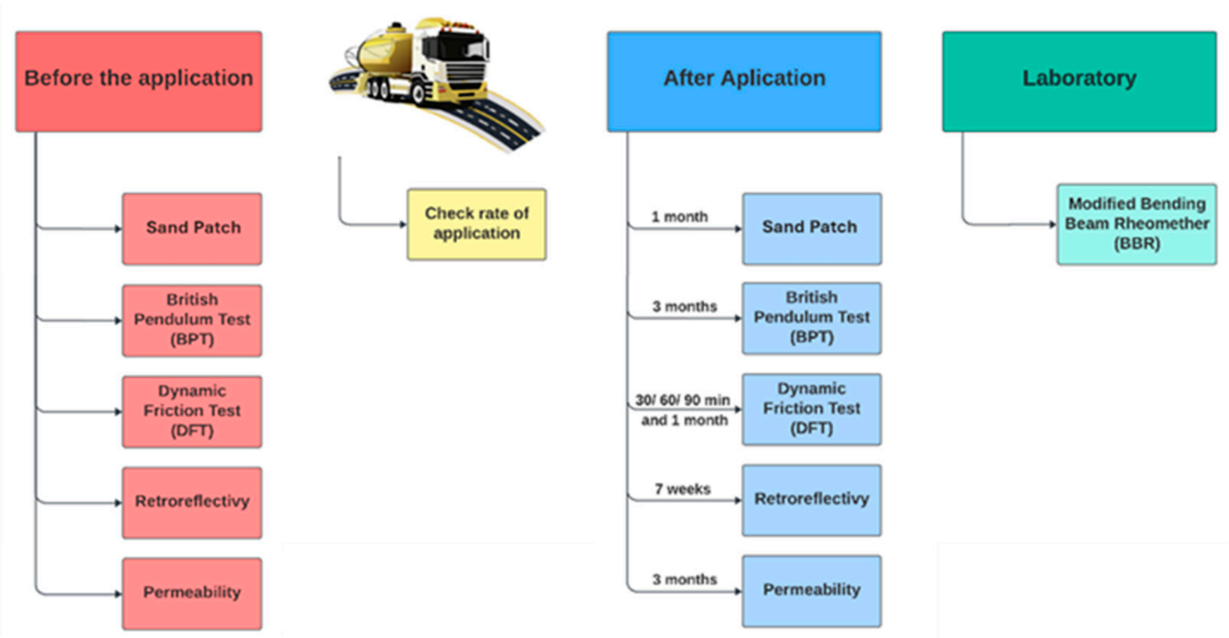

Figure 5. Experimental Plan.

2.4.1. Pavement Friction

Pavement surface texture plays a critical role in maintaining friction between the tire and the road surface, which affects vehicle stopping distance and stability. Two primary factors influencing pavement texture are macrotexture and microtexture. Macrotexture (Figure 6a), with irregularities with wavelength ranging from 0.5 to 50 mm, is assessed through measurements of texture depth or profile depth and is crucial for preventing hydroplaning at high speeds. Microtexture (Figure 6b), on the other hand, refers to the roughness of the aggregate particles and is essential for providing skid resistance at lower speeds. To assess the influence of the fog seals on the pavement's skid resistance, the Sand Patch Volumetric Method, British Pendulum Test (BPT), and Dynamic Friction Test (DFT) were used.

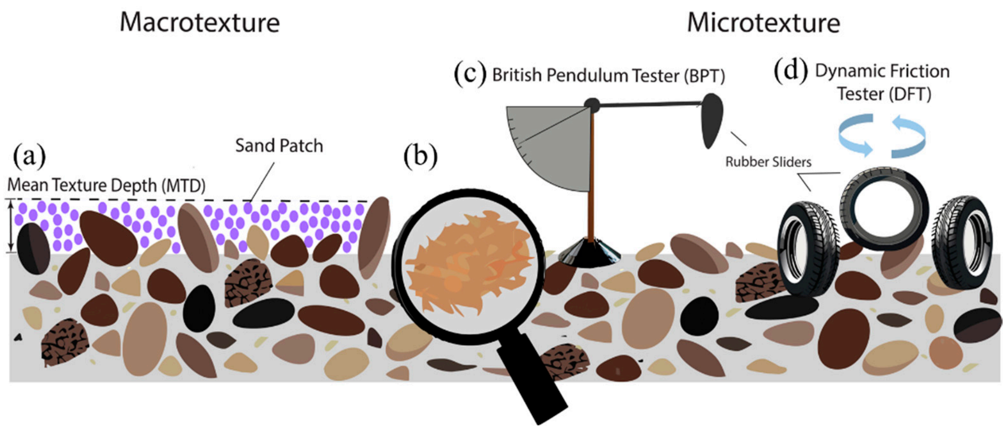

Figure 6. Pavement texture: (**a**) Macrotexture: the texture of the asphalt mixture surface measured by Sand Patch test, and (**b**) Microtexture: the texture of the aggregate measured by (**c**) British Pendulum Tester (BPT) and (**d**) Dynamic Friction Tester (DFT).

The Sand Patch Volumetric Method assesses macrotexture by measuring the mean texture depth (MTD) (Figure 6a). The test was conducted following the ASTM E965 [30], spreading a known volume of sand on the pavement surface. The sand fills the voids, and the area of the resulting circular patch is measured. MTD reflects the average depth below the surface peaks.

The British Pendulum Test (BPT) is a dynamic pendulum impact-type test that simulates the contact between a tire and the pavement surface using a rubber slider (Figure 6c). The test measures the energy loss when the slider impacts the pavement, which is indicative of the surface's frictional properties and an indirect evaluation of skid resistance. The results are expressed as the British Pendulum Number (BPN), in which a higher number signifies greater skid resistance. This test is conducted following ASTM E303 [31], and it requires a minimum BPN of 55 for high-traffic roads, like motorways, trunk roads, class 1 roads, and heavily trafficked urban areas (over 2000 vehicles per day) [32].

The Dynamic Friction Tester (DFT) measures surface friction using a horizontally spinning disk with three spring-loaded rubber sliders, according to ASTM E1911 [33] (Figure 6d). The tester applies a controlled load and rotates the disk at varying speeds. The decrease in the disk's speed upon contact with the pavement reflects the friction between the sliders and the surface, thus allowing an indirect evaluation of microtexture. In this study, DFT was conducted before and after one month of treatment on the middle lane and outer wheel path under wet conditions. Additionally, in the St. Michael section, DFT was used to assess the immediate change in friction at 30-min, 60-min, and 90-min intervals following fog seal application.

It is important to note that DFT provides valuable information about pavement microtexture; however, it is not typically used as the sole criterion for pavement friction by Departments of Transportation (DOTs). In this study, due to its strong correlation with Skid Number at 40 mph (65 km/h) with Ribbed Tire (SN40R) [34], a minimum DFT threshold of 0.35 at 40 mph (DFT40) was chosen based on recommendations for skid resistance intervention on motorways [35].

2.4.2. Retroreflectivity

This study investigated the effect of a bio-rejuvenator application on the retroreflectivity of pavement markings, such as traffic stripes. Retroreflectivity describes a material's ability to return light back to its original source and was measured before and after a 7-week period following the bio-rejuvenator treatment. A retroreflectometer, specifically the LTL-X, was used to quantify this property, following ASTM E1710 [36] procedures. Research suggests that longitudinal markings of roadways with speed limits exceeding 55 km/h should maintain a minimum level of retroreflectivity of 50 mcd/m^2/lx under dry conditions to ensure clear visibility of pavement markings at night and during wet weather [37].

2.4.3. Permeability

The falling head permeability test with the National Center for Asphalt Technology (NCAT) Permeameter is a valuable tool for assessing pavement drainage characteristics. In this study, it was employed to evaluate whether the sprayed rejuvenator effectively sealed the pavement surface. The test works by sealing the permeameter to the pavement, filling it with water, and monitoring the water level decrease over time. The rate of decrease reflects the pavement's permeability; higher values indicate better drainage and potentially less effective sealing by the rejuvenator. This method follows the guidelines established by the NCAT [38]. To ensure accurate results, the permeability test was conducted at multiple locations on the pavement surface to account for potential variations in permeability across the area.

2.4.4. Stiffness and Relaxation

To assess the impact of bio-rejuvenators on the low-temperature performance of the top layer of the asphalt pavement, a modified Bending Beam Rheometer (BBR) was conducted. This test was chosen for its ability to target the surface of the pavement, the critical zone most affected by bio-rejuvenators and susceptible to cracking. This creep compliance test, typically used for asphalt binders, was adapted to accommodate testing of asphalt mixture beams obtained from the field. Cores extracted from the MnROAD test sections after 7 weeks of the applied treatment were sliced into thin beams, with the top quarter-inch representing the estimated penetration depth of the rejuvenator treatment and tested at the Iowa State University laboratories.

The BBR testing configuration adopted in this study follows the modifications described by Velasquez et al. [39] and Ghosh et al. [40]. This modified configuration utilizes a three-point bending setup where a constant load is applied to the mid-point of the asphalt mixture beam at two critical low temperatures: −24 °C and −12 °C. These temperatures represent conditions that can lead to pavement distress through low-temperature cracking. The resulting deflection of the beam under this constant load is measured and is correlated with two key properties that influence the asphalt mixture's behavior at low temperatures. The first property, stiffness, reflects the mixture's resistance to deformation under load. Lower stiffness is generally desirable as it helps mitigate thermal cracking caused by pavement contraction during cold weather. The second property, known as the m-value, represents the rate of change in stiffness over time. A higher m-value indicates a greater ability of the asphalt mixture to relax stresses that accumulate during cold periods. This stress relaxation capability helps reduce the risk of low-temperature cracking, ultimately enhancing the pavement's resistance to damage from severe winter conditions.

3. Results

3.1. Application

The bio-fog seal application process proved to be efficient and practical. The emulsion cured quickly and did not require post-application blotting due to achieving sufficient friction. No tracking was observed. From the application point of view, it showcased advantages over the traditional asphalt emulsion fog seals and some other bio-fog seals, as it was a one-pass process, and there was no need for preheating. Visual inspection indicated an improved surface appearance with a darker color (Figure 7a). The treated sections exhibited visible texture, suggesting good potential for friction (Figure 7b).

(a) (b)

Figure 7. Pavement before and after the bio-rejuvenator application: (**a**) surface appearance and (**b**) texture.

3.2. Pavement Friction

Our analysis of the sand patch test results (Figure 8) using a one-way ANOVA with Tukey's post-hoc test (α = 0.05) revealed no statistically significant difference in MTD between pre- and post-treatment. Additionally, the test did not detect a significant difference between measurements taken in the middle of the lane (MDL) and the outer wheel path (OWP) within each section. However, it is important to note that the test can be sensitive to location-specific factors, as evidenced by the differences observed in the "before" treatment measurements across sections in the same test section.

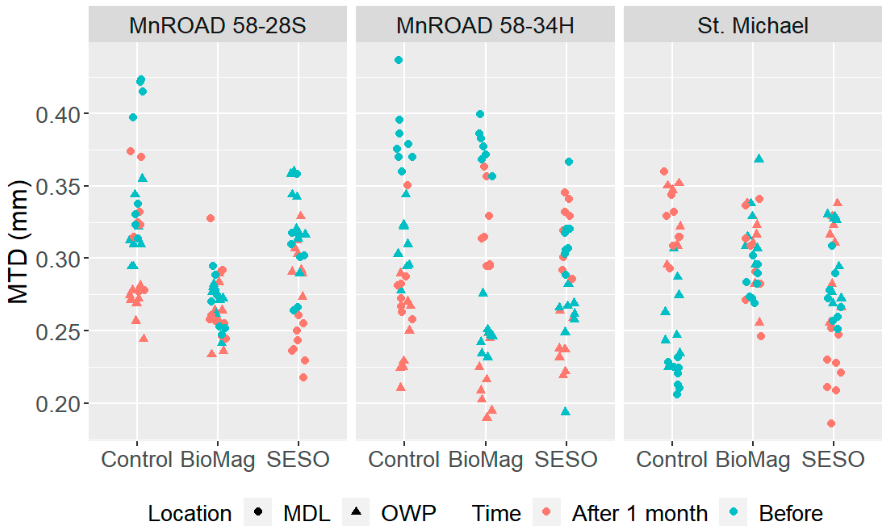

Figure 8. Macrotexture evaluation of the treated and untreated sections with Sand Patch test.

In Figure 9, the BPN results demonstrate that all MnROAD test sections, regardless of treatment, and location (MDL, OWP), exceeded the minimum requirement of 55 for heavily trafficked urban roads. Statistical analysis using a *t*-test and Tukey's HSD test confirmed no significant difference ($p > 0.05$) in BPN between control and treated sections. This suggests successful penetration of the bio-fog seal into the pavement matrix, avoiding completely coating the aggregates that could negatively affect microtexture and friction.

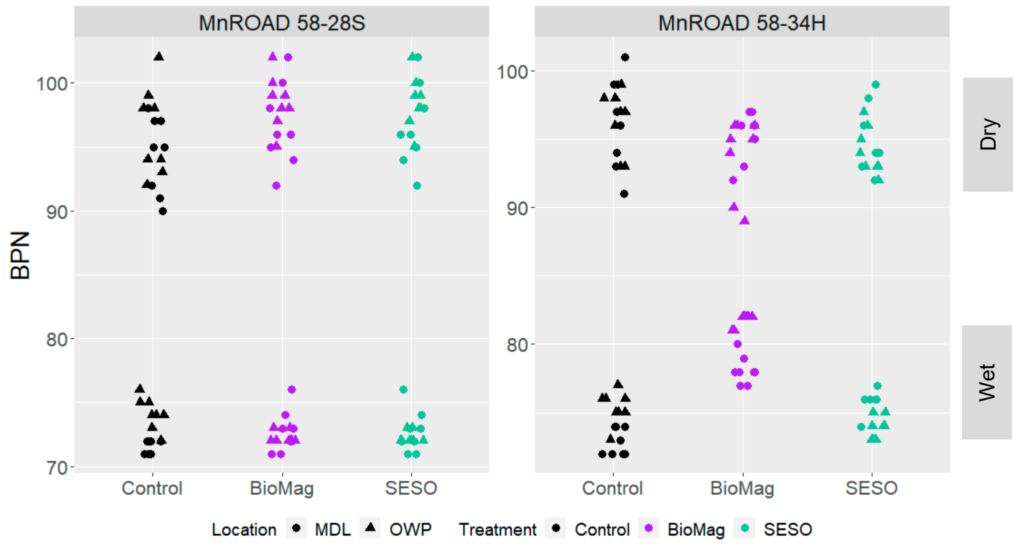

Figure 9. BPN of MnROAD test sections.

As expected, skid resistance was higher in dry compared to wet conditions. Interestingly, BioMag-treated sections displayed an increase in wet skid resistance compared to control sections. This phenomenon might be attributed to the biopolymer component within BioMag, which could enhance surface tackiness in wet conditions, thereby increasing friction.

In contrast to the BPN findings, DFT measurements conducted one month after application (Figure 10) revealed a significant difference at 95% confidence level in skid resistance between treated and untreated sections in the two MnROADs. Specifically, the DFT results showed lower friction coefficients for both BioMag- and SESO-treated sections compared to the control sections, despite all sections exceeding the minimum required friction coefficient of 0.35 (red line) for safe driving conditions. This reduction in friction highlights the need to consider both the age and existing friction characteristics of the pavement in the decision-making process for application of bio-fog seal treatments.

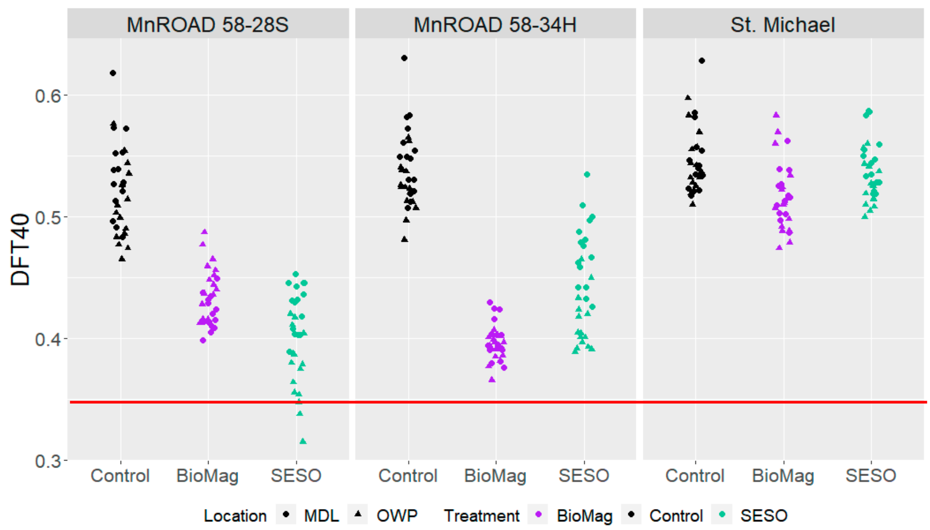

Figure 10. Friction coefficient from DFT at 40 mph (65 km/h).

Agreeing with the sand patch and BPN results, the location within the lane, MDL or OWP, did not appear to affect the results, as the measurements showed a consistent pattern across both placements.

However, the St. Michael section did not exhibit a substantial difference in friction coefficient between treated and untreated sections. A possible explanation for this could be attributed to the higher traffic volume in this section, which might accelerate the wear-off process of the seal from the pavement surface and, in so doing, reducing the differential impact observed in friction.

In the St. Michael test section, the changes in friction were monitored over time, as demonstrated in Figure 11. The data indicate that, while the friction of treated sections was statistically significantly lower ($p < 0.05$) compared to the control section (pink region) throughout the monitoring period, all sections maintained friction coefficients exceeding the minimum threshold of 0.35 (red line). This indicates that opening the road to traffic 30 min after application would be safe, causing minimal disturbance, and there is no need for a blotter material to increase friction.

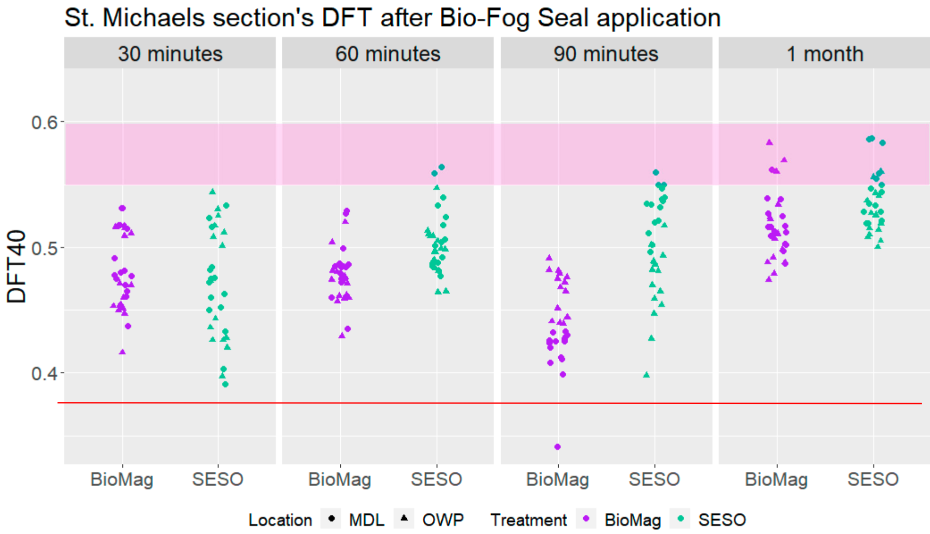

Figure 11. Bio-rejuvenator treatment dry time in St. Michael test section.

A more evident reduction in the treated sections was observed around 90 min after application. This decrease in friction for the treated sections compared to the control might be due to the breakdown of the emulsion in the bio-fog seal, resulting in the evaporation of water and leaving behind oil residues. These residues make the pavement surface slicker, consequently reducing its skid resistance.

3.3. Retroreflecticity

The analysis of pavement marking reflectivity in Figure 12 shows a decrease post-application of bio-fog seal across all sections and treatment combinations. Despite this reduction, all sections maintained reflectivity levels exceeding the minimum threshold of 50 mcd/m^2·lx required for nighttime visibility (red line). This finding suggests that bio-fog seal treatments do not compromise pavement marking functionality in the short term, eliminating the immediate need for repainting after application. Additionally, with traffic, the reflectivity might increase as the fog seal wears out.

However, the observed average reduction in reflectivity at around 40% highlights the importance of assessing the initial pavement marking reflectivity before applying bio-fog seals. Pavement markings with lower initial reflectivity might require repainting of the pavement horizontal markings.

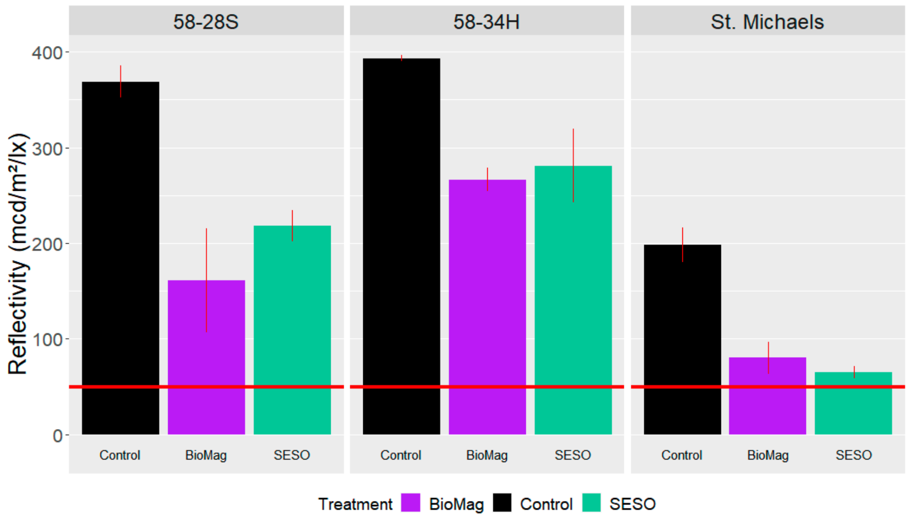

Figure 12. Horizontal pavement markings' reflectivity before and after treatment.

3.4. Permeability

In terms of permeability, a decreasing trend was noted after the bio-fog seal treatment in the MnROAD 58-28S section, as illustrated in Figure 13. This finding aligns with expectations, as bio-fog seals are intended to fill cracks and voids, thus reducing permeability. However, it is important to acknowledge limitations in the test's sensitivity to location-specific factors, as evidenced by the differences among all sections' measurements before the treatment.

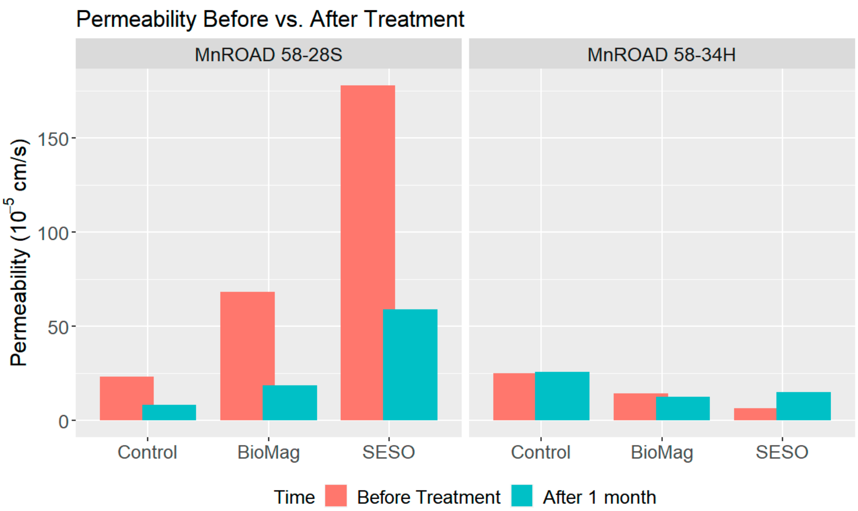

Figure 13. Field coefficient of permeability.

The observed decrease in permeability in the 58-28S control section, despite no treatment being applied, could be attributed to external factors, like rainfall prior to testing, which can influence results. By factoring out the baseline change in the control section, the results suggest that SESO and BioMag treatments are likely to have reduced permeability in the MnROAD 58-28S section. In contrast, the MnROAD 58-34H section did not show a statistically significant difference in permeability between 'before' and 'after' treatments across all sections.

3.5. Stiffness and Relaxation

The results in Figure 14 show the influence of bio-fog rejuvenators on asphalt mixture stiffness and relaxation behavior in the MnROAD 58 test sections. Compared to the control section, the BioMAG treatment in the MnROAD 58-28S section resulted in a statistically significant decrease in mixture stiffness, and the SESO showed an increase in relaxation, as indicated by Tukey's HSD mean comparison at a 95% confidence level. On the other hand, no notable difference was observed with the 58-34H treatment, likely due to the binder's lower stiffness compared to -28S.

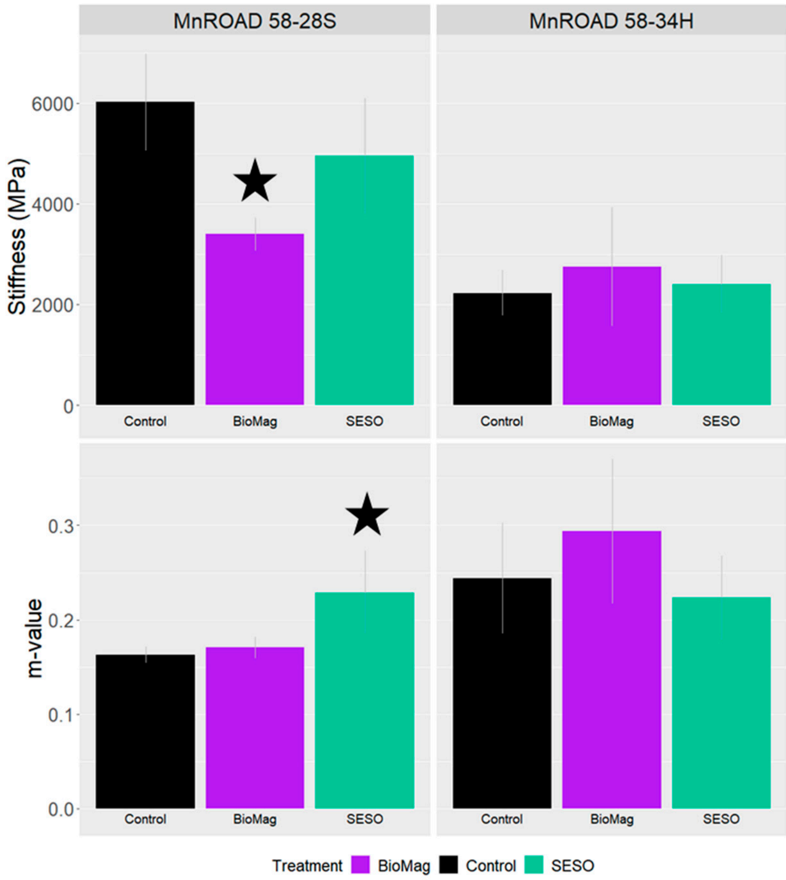

Figure 14. Stiffness and relaxation properties of the MnROAD asphalt samples. ★ Statistically different.

As asphalt binders age, their stress relaxation capabilities at low temperatures decrease, and stiffness increases. Therefore, the observed decrease in stiffness with BioMAG and the increase in m-value with SESO suggest potential improvements in the anti-cracking properties of the mixtures in the MnROAD 58-28S section. These findings are promising as they indicate that bio-fog seals might act beyond simple sealing and contribute to the rejuvenation of the binder's rheological properties, potentially enhancing overall pavement performance.

Despite the potential of bio-fog seals to enhance binder performance, their observed impact was less than expected. This might indicate that an increase in the application rate of bio-fog seals may yield more substantial enhancement.

4. Conclusions and Recommendations

This field study investigated the effectiveness of soy-based bio-fog seals (SESO and BioMag) as a sustainable pavement maintenance strategy. The following conclusions were summarized:

- The one-pass, no-heat application process offers significant advantages over traditional methods, which allows rapid drying and minimal traffic disruption.
- The bio-fog seals effectively reduced pavement permeability, potentially enhancing long-term durability by sealing cracks and preventing water infiltration.

- Pavement marking reflectivity remained acceptable, eliminating the need for immediate restriping.
- The soybean-based treatments showed promise for improving anti-cracking properties.

However, limitations require further investigation:

- The study focused on samples collected after a short period (less than 2 months).
- Bio-fog seals caused a slight decrease in pavement friction and marking reflectivity. Careful selection of roads for application is necessary, potentially excluding older pavements with low initial friction.
- The lack of understanding regarding bio-fog seal diffusion leads to application rates based on experience. Optimizing these rates could lead to more substantial pavement rejuvenation.

To unlock the full potential of bio-fog seals, future research should address several key areas. Understanding the diffusion process within the pavement is crucial for developing more precise application rates. Additionally, long-term performance evaluation is necessary to assess the durability of these effects. Furthermore, incorporating advanced testing methods, like Fourier-Transform Infrared Spectroscopy (FTIR) analysis of extracted asphalt binder, can reveal changes in chemical composition due to the rejuvenation process and aging rates. Finally, a life cycle assessment will comprehensively evaluate the environmental impact of bio-fog seals compared to traditional methods.

By addressing these limitations and expanding the knowledge base, bio-fog seals have the potential to become a widespread and sustainable solution for pavement maintenance, extending pavement life, reducing long-term costs, and promoting environmentally friendly practices.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: Author Maxwell Staver was employed by Ashland, and Irvin Pinto was employed by Mott Mac-Donald. The remaining authors declare no competing interests. Authors Nacu Hernandez, Eric Cochran, and R. Christopher Williams are inventors on U.S. Patent No. 9,932,435 related to biorejuvenators, owned by Iowa State University Research Foundation (ISURF). The authors assert that these affiliations and the patent do not influence the data presented in this manuscript.

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