EVALUATION OF BIO-BASED SEAL FOR LOW-VOLUME ROAD PRESERVATION

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Abstract

While asphalt pavement is common in the United States, it is susceptible to oxidation as being exposed to environmental effects, resulting in the surface deterioration. To maintain the performance of a road surface and extend its service life, traditional fog sealers such as asphalt emulsion are used to mitigate micro-cracking, prevent oxidation and reduce water infiltration. Due to the relatively high cost and environmental concerns of petroleum-based sealants, the use of bio-based products as fog sealers has attracted more and more attention. Some new bio-based sealants derived from agricultural oil have been used as fog sealers in many states. To evaluate the effectiveness of a bio-sealant as an alternative to preserve asphalt pavements, a 5.3 km test section was selected for application of a soy-based fog sealant with three different application rates to conduct a two-year investigation of pavement marking retroreflectivity, surface friction, growth rate of cracking, laboratory water absorption, and air permeability. A control section without bio-sealant was also set up for comparison purposes. The field results revealed that, after application, a short-term decrease in retroreflectivity and skid resistance was restored to the original condition after two weeks and several months, respectively. The treated sections also exhibited a better control of growth rate of cracking than that of control section. The laboratory results indicated that the bio-sealant treated specimens applied at the highest application rate exhibited the lowest water absorption and air permeability. Such findings indicate that bio-sealant can be a sustainable preservation alternative for asphalt pavement.

Keywords: fog seal, bio-fog sealant, skid resistance, permeability, absorption, spray rate

1. Introduction

All types of roads, including those with asphalt pavements, steadily deteriorate over time due to repeated mechanical (traffic) and climatic loadings. Pavement preservation consists of applying a suitable treatment on deteriorated roads to maintain good conditions and extend their service lives [1, 2]. Typical preservation approaches for low-volume asphalt pavements include fog seal, crack sealing, slurry seal, chip seal, and overlay, and each can be used for various purposes in preventive maintenance projects. Fog seal is a low-cost application of liquid asphalt or emulsion derived from petroleum or coal tar, sometimes followed by a cover of fine aggregate or sand, to slow down micro-cracking propagation, prevent oxidation, and seal against water infiltration. While such petroleum-based traditional fog sealers have been successfully used to maintain road surfaces for many years, they not only need a long curing time that results in delayed traffic opening [3], but they can also cause health issues from chemical components such as polycyclic aromatic hydrocarbons [4]. Furthermore, the use of fossil fuel-based products increases the risks associated with an energy crisis and environmental contamination [5, 6].

In recent years, a few bio-based fog sealers have been developed as sustainable alternatives to traditional petroleum-based sealers; soy-based fog sealant derived from agricultural oil is one such product. The manufacturers of the bio-sealant claim that it protects asphalt from oxidation, pot-holing, edge rutting, and cracking, and can extend the life of paved asphalt surfaces when applied every 3-5 years [7]. States such as Missouri and Ohio have reported success in using bio-based products for county road preventive maintenance [7, 8]. While the reported observations include quick shedding of water from roadways treated with bio-sealant while retaining the skid resistance of normal pavement, documentation of construction and performance experience is limited.

Based on the successful use of bio-sealant in other states, this study aimed at evaluating a bio-based product as a fog sealant for low-volume asphalt pavements in Iowa. With the intent of checking the effect of such bio-sealant on skid resistance, pavement marking retroreflectivity, water absorption, and permeability, the construction process and consequent field and laboratory investigations based on varied sealant spray rates over a two-year period were documented.

1.1 Literature review of fog seal

Fog seal is a treatment using diluted slow-setting or medium-setting asphalt emulsion without aggregates, applied on a pavement surface by an asphalt distributor [1, 9]. It is used to seal and enrich the pavement surface, seal micro-cracks, prevent raveling and oxidation, and provide shoulder delineation with the least amount of energy consumption [1, 10-13]. Fog seal can be used on low-volume roads, especially for raveling prevention on open-graded friction courses. In current practice, the recommended spray temperature should be between 52°C and 71°C (125°F and 160°F) at a surface temperature of at least 10°C (50°F) and rising. The performance life of fog seal treatment is about one to two years. Because the greatest limitation of fog seal treatment is its reduction of pavement friction after spraying, it is not recommended to use fog seal on heavy-traffic roads. The prices of fog seal vary with the type of emulsion, the binder application rate, and the size of the project, and is usually about US $0.60 per square meter (US $0.50 per square yard) [14].

Chip seal is a common pavement preservation practice in civil engineering. Because the major concern of chip seal is aggregate loss, several efforts have been made to characterize the aggregate retention. Miller et al. [15] conducted bitumen bond strength test for chip seal specimens and evaluated the bonding behavior between asphalt emulsion and aggregate. Liu et al. [16] analyzed macrostructure of aggregate-asphalt interface by using a 2-D finite element model, indicating temperature and horizontal load could influence shear strain in chip seal significantly. Some literature has reported that fog seal has been applied as a top surface on chip seal because fog seal could possibly be used to reduce the potential for the aggregate loss, improve aggregate retention, and extend pavement service life [3]. Polymer-modified emulsions (PMEs) are recommended over unmodified emulsion since PMEs can not only improve emulsion bond strength, shorten curing rates, decrease temperature susceptibility, and increase emulsion adhesion, but also provide better aggregate retention and bleeding performance [11, 17, 18].

While fog-seal treatments are widely used throughout the world, there is a lack of documentation comparing fog-seal applications in state specifications in different states in terms of materials, equipment, application instructions, and opening to traffic. The details of applying fog seal have been documented on the basis of state highway agency standard specifications. The most important criteria for preparing and applying fog seal onsite based on six state highway agency specifications in the US are summarized in Table 1.

Suggested quality assurance/quality control (QA/QC) tests to be employed in the laboratory or in the field for estimating performance of fog seals include Vialet test, indirect tension test, evaporation test, bitumen bond strength test, rolling ball test, damping test, aggregate loss test, bleeding analysis, third-scale model mobile load simulator test, the British pendulum test, and use of a three-dimensional (3-D) laser scanner [12, 17, 18]. The six state highway agency specifications on fog seal application all suggest a slow-setting asphalt emulsion, the most often used being CSS-1 or SS-1 at a dilution rate of 1:1 and an application rate between 0.09 to 0.9 L/m^2 (0.02 to 0.2 gal/yd^2). All six states use a bituminous distributor for fog-seal application equipment with roadway condition requirements of dry and clean surfaces with either the pavement temperature or the air temperature above 10°C (50°F) and rising.

To assess the effectiveness of fog seal treatments, Prapaitrakul et al. [19] measured the stiffness of recovered pavement binder and compared treated and untreated binders through a paired t-test analysis. Test specimens were cored from selected pavement sites with both treated and untreated sections. The core samples were trimmed and sliced into three 0.64 cm (¼ in.) thick layers. Asphalt binder composed of a blend of fog seal material and the original in situ pavement binder was extracted and recovered from each core layer so that a flowing measurement could effectively determine the presence of the fog seal materials at a certain layer depth. A gel permeation chromatography (GPC) was used to measure the molecular size distribution of asphalt materials, and overall test results indicated that the fog seal penetrated mostly into the top layer at 0.64 cm (¼ in.) thickness and could, therefore, affect only the top layer properties. According to the statistical analysis, only EB44 coal tar-type had a statistically significant effect on the binder rheology, by stiffening only the top layer of the binder [19].

Im and Kim [17] reported a study using fog seal as a potentially cost-effective method to enhancing aggregate retention and investigating the curing and adhesive properties of fog seal for a determination of traffic opening times in the field. The emulsions that were selected in that study were CSS-1h, CQS-1h, and modified PME-A and PME-B, and performance tests were conducted on chip seal texture using CRS-2L emulsion with EARs (emulsion application rates) of 1.132 L/m^2 (0.25 gal/yd^2) and 5.4 kg/m^2 (10 lb/yd^2) of lightweight aggregate in comparison with different emulsion types. The results showed that all four types of emulsions exhibited a short curing time once placed with low EARs at a high temperature. PME-A and PME-B exhibited shorter curing time than unmodified CSS-1h and CQS-1h. Rolling-ball test results showed that the curing rate of PME-B was faster than that of the other emulsions. While PMEs can be cured within one hour, the unmodified emulsions required more than 1.25 hours. Aggregate loss test results indicated that the PMEs samples experienced less than 5% aggregate loss while the unmodified emulsions experienced a 15% aggregate loss. The samples with PME-B exhibited the best aggregate retention performance [17].

1.2 Fog seal using bio-sealant

The soy-based bio-sealant used in this study is a black liquid with a non-descript slightly citrus odor, with the physical and chemical properties presented in Table 2. This product has a viscosity of 5 to 20 seconds at room temperature, similar to the flowability of water. It is 88% bio-based, with 40% obtained from soybean oil. By making use of agricultural and recycled materials, this bio-sealant is a non-toxic and environmentally friendly alternative to petroleum-based sealing agents. It contains some polymers, including SBS (styrene-butadiene-styrene) and SBBS (styrene-butadiene-butadiene-styrene), common admixtures in traditional asphalt emulsion used to improve pavement flexibility under colder conditions.

The soy-based sealant is a pavement preservation agent that claims to prolong asphalt pavement surface life when applied every 3-5 years to protect pavement against water damage and to maintain skid resistance after a long term [7]. It also claims that can stabilize the asphalt binder and strengthens the asphalt matrix. As a result, application of bio-sealant prolongs the lifespan of asphalt roadways as it penetrates and fills voids near the surface, protects against water penetration, minimizes freeze/thaw damage, and makes the asphalt more resilient. The typical spray rate of bio-sealant can vary from 0.045 to 0.091 L/m^2 (0.01 to 0.02 gal/yd^2), which is lower than for the rate of traditional fog sealant (Table 1). The relatively low rate of bio-sealant is due to its good followability. When applied to an asphalt surface, the patented solution reverses the oxidation process, on average penetrating 1.9 to 3.2 cm (0.75 to 1.25 in.) deep into the asphalt in a matter of minutes. Bio-sealant can not only reduce the need to use petroleum-based products in pavement maintenance but can also reduce the need for using bitumen in the manufacturing of new asphalt by causing the road surface to last longer. Bio-sealant is a competitively priced, environmentally benign alternative to traditional petroleum-based asphalt sealers. The application of bio-sealant is cost-comparable to other asphalt seal coat treatments, but it is the only solution that is bio-based, non-toxic, and carbon negative. It is also easier to apply and extends the life of asphalt pavements. Moreover, the application of bio-sealant does not need the heating process, and the road can open the traffic after only 30 minutes which is much faster than for conventional fog sealant. Table 3 summarizes the benefits and limitations of applying the bio-based fog seal.

2. Construction and Experimental Approaches

The sites selected for bio-sealant installation were located near Toronto in Clinton County, IA, including a 4,506-m (2.8-mile) section road in E63/Y32 with a 7.6 cm (3 in.) hot mix asphalt (HMA) overlay on a 8.9 cm (3.5 in.) cold-in-place recycling (CIR) layer and a 805-m (0.5-mile) long section through the City of Toronto with a 5.1 cm (2 in.) HMA overlay (Figure 1). It was a two-lane low-volume road with annual average daily traffic (AADT) of less than 400 vehicles. Each lane was 3.05 m (10 ft.) wide with a 0.91-m (3-ft.) wide sand-paved shoulder on each side. Based on previous construction information, the HMA overlay was replaced in 2011. The test sections at the installation site were divided into five sub-sections and shown in Table 4. These three spray rates which are different from the typical rates were selected to investigate the effects of high rate on the pavement surface.

2.1 Fog seal construction using bio-fog sealant

The application of fog seal using bio-sealant in Clinton County, IA began on June 29, 2016, during dry and clear weather with an ambient temperature ranging from 15 to 26ºC (59 to 79ºF). Before application, all road surfaces were swept and cleaned, and the boundary marking lines for each section were painted. Figure 2a shows a vehicle equipped with an automatic bio-sealant spray machine equipped with a system for controlling the application rate. The adjustable spray bar with evenly-spaced nozzles was set to totally treat a width of 3.05 m (10 ft). During application, the vehicle speed typically ranged from 8 to 16 km/h (5 to 10 mph). In addition to the automatic spraying system, a spray gun was also used for some edge areas where nozzles of the automatic spraying system could not reach. Since this bio-based agent needs no heating before spraying, the sprayer was not equipped with a heating system. During the spraying, county secondary road department personnel controlled traffic in both lanes of the road, allowing only one lane to be open for traffic while spraying was occurring in the other lane. After bio-sealant application to the first lane, it was immediately opened to traffic, with the second lane then closed for subsequent spraying work.

For purposes of comparison, Figure 3 provides images of both a bio-sealant treated lane and an untreated lane on the day of construction. While the bio-sealant treated lane exhibited a darker color than the untreated lane, this difference in appearance disappeared after a few days. During construction, the pavement marking (centerline and edge line) was applied along with the bio-sealant materials, but no obvious reduction in visibility of the marking was observed. In fact, the darkened pavement appearance could possibly make the pavement marking more visible due to increased contrast. As shown in Figure 3, the bio-sealant treated section did not exhibit free liquid standing on its surfaces, indicating that the bio-sealant could be quickly absorbed by the pavement surface due to its natural properties. Based upon this characteristic, a bio-sealant treated road can be opened to traffic within 30 minutes after application, somewhat more rapidly than when applying traditional fog sealers [3]. In summary, the documented construction process showed that the application of bio-sealant is easy to perform, does not require extra energy for heating of the sealant, and the treated road section can be opened to traffic quickly. From these perspectives, it is a cost-effective technology.

2.2 Field investigations

To document the performance of bio-sealant treated roads, several field visits were conducted to measure retroreflectivity, skid number (SN), British pendulum number (BPN) and growth rate of cracking for the bio-sealant installation site within the first three years after application. Pavement marking on a road can provide guidance and helpful information to drivers, and a road's retroreflectivity plays an important role in safe driving [26]. Retroreflectivity is a measure of the amount of light returned back from an illuminated object for a given amount of illuminance. In this study, a Roadvista Stripemaster 2 Touch D35229 retroreflectometer (Figure 4) was used to measure the retroreflectivity of two selected spots at the white edge line on each test section before and after bio-sealant installation in accordance with Materials I.M. 386 [27], with measurement units of mcd/m^2/lux (i.e. millicandela per square meter per lux, how much light will be reflected at a given illuminance). To evaluate the performance of bio-based sealant, a distress survey was conducted before and after installation.

Skid resistance is an important field measurement for evaluating the force developed when a tire prevented from rotating slides along a pavement surface. Figure 4a shows a locked wheel skid tester consisting of a truck and a special trailer used for skid resistance measurement. This locked wheel test requires driving the vehicle at a speed of 64 km/h (40 mph) to collect discontinuous data points during measurement in accordance with ASTM E274 [28]. Because it provides automatic data collection during driving, and this test is an efficient test for a long road, it is difficult to perform repeated measurements at the same point. In this study, skid resistance of treated sections, including sections remaining before and after installation of bio-sealant, was measured for both eastbound and westbound lanes and the collected data points plotted provide an overview of SN levels for all sections.

The British pendulum test is a common test for surface friction measurement both in the laboratory and in the field. As shown in Figure 4a, the tester consists of a pendulum arm with a standard rubber slider. In accordance with ASTM E303 [29], the measurement requires swinging the arm to propel the slider edge over a test surface to obtain BPN on the scale. Although the British pendulum test has a similar purpose to that of the locked wheel skid measurement, it can perform repeated measurements at specific points in each test section. This study performed British pendulum measurement after bio-sealant installation for the control section and three treated sections (the remaining section after TS 3 was not included), and two points were tested in each section, including one in the eastbound lane and another in the westbound lane. Each selected point was located in the right wheel path 3.05 m (10 ft) from the section beginning, and each point measurement was repeated four times.

In addition to the measurements of retroreflectivity and friction, the cracking survey at each section was performed as well. The growth rate of cracking was documented in this study to evaluate the performance of bio-sealant in terms of cracking control.

2.3 Specimen coring

To perform the laboratory testing for HMA specimens, sixteen cores with 10.16 cm (4 in.) diameter were taken through electric core drill from the bio-sealant treated sections (the remaining section after TS 3 was not included) and control section in the site every year. Each section had four cores, and two of them from the eastbound lane and the other two from the westbound lane. As of November 2018, there have been two specimen coring activities completed. The first on May 8, 2017, and the second on April 11, 2018. For both activity dates, core samples were taken and all HMA specimens were brought to the laboratory and sawed into 5.08 cm (2 in.) thickness, and then were oven-dried at 52°C (125°F) to obtain the constant mass. Since four cores were taken from each section, the experiments planned to use the one from the eastbound lane and another one from the westbound lane for permeability measurements, and the other two were used for water absorption measurements.

2.4 Laboratory testing

Water absorption is a measure of the percentage of water on a volume basis absorbed by a specimen during immersion. For asphalt mixture, capability for water absorption is an important indicator about the presence of voids. In general, high water absorption in bituminous pavements is associated with many voids and permeability, resulting in more oxidation and pavement structural damages. In this study, dry weight, weight in water, and saturated surface-dry weight (SSD) of specimens were measured to calculate water absorption, following ASTM D2726 [30].

Permeability is an important property of HMA for evaluating asphalt pavement durability. To measure the permeability of HMA, this study used the air chamber device shown in Figure 4b, originally developed by the University of Innsbruck in Austria [31] and modified at Iowa State University (ISU) in the United States; it was used on specimens under laboratory conditions. A specimen core was inserted into a compressible collar within a rigid sleeve, then was fixed in the steel chamber. The upper surface of the specimen was open to the atmosphere, and its underside was connected to an inlet through which an air gun inserted air to pressurize the chamber. Once the pressure had been loaded to 150 kPa (21.75 psi), the outlet was closed, and the measurement initiated. The pressure gauge could record falling pressure in the chamber and output the pressure-time relationship to the computer. After data had been obtained, it was plotted as $\ln(P_0/P_t)$ versus t, with P_0 as the initial pressure and Pt the pressure at time t. Equation 1 was then used to calculate the coefficient of permeability k (m/s) for each sample.

$$k = \frac{\omega V g d z}{R A \varphi}, \qquad \text{Eq. (1)}$$

where, ω – molecular mass of air (28.97 g/mol (1.02 oz/mol)), V – volume of air under pressure (m^3), g – acceleration due to gravity (9.81 m/s^2 (32.2 ft/s^2)), A – cross-sectional area of specimen (m^2), d – average specimen thickness (m), φ – temperature (k), z – slope of the $\ln(P_0/P_t)$ vs t line.

3. Results and Discussion

3.1 Retroreflectivity

Retroreflectivtiy of pavemenent marking is a significant factor with respect to the safety driving. The results for retroreflectivity of white edge lines on all treated sections are shown in Figure 5, depicting the retroreflectivity recovered about two weeks (July 15, 2016) after the date of bio-fog sealant application on June 29, 2016. The centerline durable markings results were not documented because of accidental repainting that occurred in fall, 2017. In this study, TS 1 and TS 2 exhibited no decrease in retroreflectivity at either sampling point two weeks after construction, but the lowest spray rate of 0.091 L/m^2 (0.020 gal/yd^2), used in TS 3 application, resulted in a reduction of 84 $mcd/m^2/lux$ (84 $mcd/ft^2/ft\text{-}cd$) at the second sampling point. The lane markers are rendered retroreflective through their inclusion of painting materials that contain special glass beads, and fog seal might possibly cause a reduction in retroreflectivity by covering the beads and blocking the light retroreflection [32].

In this study, the retroreflectivity values at the test site before bio-sealant application and two weeks after that application did not significantly differ, suggesting that the bio-sealant had been abraded from tire wear and environmental effects (rain and wind) within this two-week interval. Johnson [32] reported a decrease in retroreflectivity of pavement markings after applying different fog sealers, including some bio-based products, and he also reported observing retroreflectivity recovery for bio-based fog-sealed pavement markings after 1,600 truck passes. In addition to the pavement marking tests in 2016, subsequent retroreflectivity measurements in 2017 and 2018 exhibited random changes resulting from of traffic and environmental effects. Based on current measurements, there was no evidence indicating that bio-sealant would have long-term negative impacts on pavement-marking retroreflectivity, and potential short-term reduction in retroreflectivity due to the application of bio-fog seal could be restored within two weeks.

3.2 Skid resistance test

The results due to friction from locked-wheel tests and British pendulum tests are shown in Table 5 and Figure 6. For measurements of skid numbers, both the eastbound lane (Figure 6a) and the westbound lane (Figure 6b) exhibited significant decreases in skid resistance within the first week after application. The original average SN of the entire road without bio-sealant was 67 (Table 5). One week after application, the average SN had dropped to 49 (Table 5). After several months (between July 2016 and May 2017), the skid resistance was restored to its original condition of 66 (Table 5). Decreased surface friction because of the use of fog sealants has been reported in several studies [33-35], suggesting that filling in the pavement surface texture by fog sealant was the primary reason reducing the skid resistance. With continuous tire wear, the fog sealants were worn away from the surface, resulting in restoration in friction [36].

In this study, a higher spray rate led to a reasonably large reduction in skid resistance at the initial stage, which agree with the previous study finding. However, all SN measurements after bio-sealant treatments are still above the recommended SN value of 35 [37]. After 11 months, all treated sections returned to the original SN level. In consideration of the average SN dropped from 63 to 49, that the minimum SN value prior to application of bio-fog seal must be 50 to avoid the dropped SN is below 35.

3.3 British pendulum test

As shown in Figure 6c and d, the British pendulum test results were compared in terms of BPN using standard deviations (Std) between the control section and the other three bio-sealant treated sections. The measurements before application of bio-sealant were not conducted because BPN was not in the original research scope. For both eastbound and westbound lanes, the treated sections presented higher BPN values than the control section, although the differences were slight and all measured numbers were significantly higher than the recommended BPN of 55 [37]. Since the first measurement of BPN was performed about 11 months after the bio-sealant application (May 8, 2017), the results did not exhibit a reduced BPN at the early stage as did the reduced SN on July 5, 2017 (Figure 6a & Figure 6b). The presented BPN values from the first measurement indicated the restoration of friction. Figure 6c and d also indicate that the latest measurement on May 1, 2019, bio-sealant -treated section produced higher BPN values than those from control section, indicating the surface friction was maintained by bio-fog sealant.

The combined results from locked wheel tests and British pendulum tests indicated that the application of bio-sealant could lead to a reduction in surface friction at an early stage, although after several months the friction could be restored. In a newly constructed HMA pavement system, the friction typically increases during the first two years due to the loss of asphalt binder, then decreases due to polished aggregates [36]. In this study, reduced friction was observed in the measurements of July 5, 2017, 11 months after application, and the highest friction was exhibited on March 22, 2018, (Figure 6c and d) and April 12, 2018, (Figure 6a and b), with another reduction detected on September 10, 2018, (Figure 6a and b). In consideration of the typically higher skid resistance in cold seasons due to the temperature and moisture [36, 38-42], the site was identified currently to be in a stage of decreased friction, and the latest measurements on May 1, 2019 and July 30, 2019 exhibited the maintained skid resistance due to the application of bio-sealant.

In summary, while pavements treated with bio-sealant at rates up to 0.136 L/m^2 (0.03 gal/yd^2) displayed an acceptable short-term decrease in skid resistance, they resumed and maintained their previous skid performance after several months.

3.4 Distress survey

The distress survey results before and after installation are shown in Table 6. At the installation site, both transverse cracking and longitudinal cracking were recorded, and no other cracking types were observed. All cracks before application of bio-sealant were unsealed, and then were sealed by asphalt binder a few months after application of bio-sealant. The results show that about three years after installation of bio-sealant (May 1, 2019), 87 new cracking at the entire site was observed. Figure 7 shows the growth rate of cracking for each section. For CS, TS 1, TS 2, TS 3 and RS, their cracking growth rates showed 270, 337, 128, 175 and 70 m/km (1426, 1779, 676, 924 and 369 ft./mile) about 3 years after installation of bio-sealant (May 1, 2019), respectively. It indicates that bio-sealant could mitigate the growth rate of cracking about three years after installation of bio-sealant but such beneficial effect of bio-sealant could not continue after then.

3.5 Laboratory water absorption

Figure 8a shows water absorption for cores taken in 2017 and 2018. For the cores taken in 2017, the specimens from the treated sections displayed absorption smaller than that of the control section specimen. The specimens in TS 1 in 2017 and 2018 associated with the highest spray rate of bio-sealant displayed the lowest water absorption of 0.28% and 0.24%, respectively. Follow-up testing to the specimen taken in the second year continued to reveal lower water absorption capability for all bio-sealant treated specimens, indicating that the studied bio-sealant can decrease water absorption of pavement cores for at least two years. As mentioned, bio-sealant has good flowability that results in satisfactory void-filling ability in HMA concrete, reducing the likelihood of asphalt binder directly contacting air or moisture. The testing results revealed that the increase in spray rate decreased absorption.

3.6 Laboratory air permeability

The results from air permeability tests shown in Figure 8b reflect lower permeability in bio-sealant -treated sections compared to that in specimens from the control section, indicating the increase in spray rate associated with the decrease in air permeability. The thickest/highest rate of application resulted in the lowest air permeability of 6.1 and 6.6 10^{-6} m/s (20.0 and 21.7 10^{-6} ft./s) for specimens taken both from the first year (2017) and the second year (2018), respectively, reflecting the greater void-filling in bio-sealant -treated specimens. The results from permeability tests exhibited trends similar to those obtained from the water absorption tests. From the perspective of pavement preservation, lower permeability is desirable since it can prevent water infiltration into pavement structures and thereby minimize damage caused by seasonal variations such as freeze-thaw cycles.

4. Conclusion

Although traditional petroleum-based fog sealers have been successfully used for many years, alternative non-traditional fog sealers such as bio-sealant, derived from agricultural matter, with potentially greater cost-effectiveness and environmental-friendliness, have not yet been sufficiently investigated. In this study, current practice in the use of fog seal was reviewed and summarized, and the bio-based fog sealer bio-sealant, derived from agricultural oil, was applied to a selected asphalt pavement section at various spray rates over a two-year evaluation interval. Detailed construction procedures were documented, and the key findings and recommendations from both field investigations and laboratory tests can be summarized as follows:

- While pavement marking retroreflectivity decreased immediately after fog seal application using bio-sealant, it was restored to its pre-application level two weeks after application.

- Pavement distress surveys showed that bio-sealant was able to mitigate cracking growth on the asphalt pavement over a certain period of time, about three years after application of sealant in this study.
- While a short-term decrease in friction was observed after bio-sealant application, frictional requirements were met throughout and had returned to their original levels within 11 months after application.
- The minimum SN value of a road surface prior to application of bio-fog seal must be 50.
- Laboratory results indicate that specimens treated at a higher bio-sealant spray rate are associated with lower water absorption and permeability.
- If permeability is a critical issue in some roads, the highest bio-sealant spray rate of 0.136 L/m^2 (0.030 gal/yd^2) is most practically applicable based on field and laboratory performance test results. The middle level of 0.113 L/m^2 (0.025 gal/yd^2) is also acceptable based on financial considerations.
- It was difficult to determine depth of penetration of bio-sealant material either under LED or UV lighting.
- While use of bio-sealant without an associated heating process is rapid and cost-effective and only a 30-minute delay is required before re-opening to traffic, the associated reduction in surface friction could be a concern to roads having low skid numbers before application.
- Three-year evaluation results indicated that bio-sealant could seal voids in the pavement, and while the negative impacts on retroreflectivity and friction could be restored within several months after installation of bio-sealant, further investigation during ensuing years would be required to ensure longevity of such beneficial effects.
- The performance and behavior in terms of variations in skid resistance and surface friction of bio-sealant treated sections are recommended to be monitored continuously.
- A benefit-cost analysis is recommended to evaluate cost-effectiveness of the treatment method based on performance evaluation results and benefit-cost analysis results.

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Table 1. Summary of state highway agency specifications on fog seal.

State	Reference	Material			Equipment	Application Instruction
		Emulsion Grade	Dilution Rate (AE/W ratio)	Application Rate, gal/yd^2		
IA	IA-DOT (*17*)	CSS-1,SS-1	1:4	0.12	Bituminous distributor	One-half of the roadway with an overlap of about 4 in. at the middle; do not place on a damp or wet surface; do not apply when either the pavement temperature or the air temperature is below 60°F
CA	Caltrans (*18*)	slow-setting asphalt emulsion	1:1	0.02 to 0.06	Bituminous distributor	Do not start fog seal when precipitation is been forecasted during the application and curing period; do not apply when either the pavement temperature or the air temperature is below 40°F
MO	MO-DOT (*19*)	SS-1, SS-1h, CSS-1, or CSS-1h	given by engineer	0.20	Bituminous distributor	Sand dams may be necessary to prevent emulsion from being applied outside of designated areas; asphalt emulsion shall not be placed on a damp or wet surface, and the surface shall be free of objectionable material prior to sealing
OR	OR-DOT (*20*)	CSS-1, CSS-1h, HFRS-P1	≥1:1	0.10 to 0.15	Bituminous distributor, hauling vehicles	Apply emulsified asphalt to only one designated traffic lane at a time; do not place fog seal when the air temperature is below 60°F
TX	TX-DOT (*21*)	SS-1, SS-1h, CSS-1, CSS-1h	–	–	Bituminous distributor	Apply the mixture when the air temperature is at or above 60°F or above 50°F and rising
WA	WA-DOT (*22*)	CSS-1, CSS-1h	1:1	0.10 to 0.18	Bituminous distributor	–

Note: AE/W Ratio indicates asphalt emulsion-water ratio; – indicates not specified. 1 gal/yd^2 = 4.53 l/m^2; 1 in. = 2.54 cm; (1°F − 32) × 5/9 = -17.22°C.

Table 2. Physical and chemical properties of bio-fog sealant (*7*).

Property	Value/Description
pH range	5.0–6.0
Specific gravity	0.87-0.88
Saybolt viscosity	5-20 seconds at 25°C (77°F)
Boiling point	154-166°C (310-330°F)
Solubility in water	Immiscible
Residue by distillation	12% min and 18% max

Table 3. Benefits and limitations of using bio-sealant for fog seal (*7*, *8*).

Benefits of using bio-sealant	Limitations of using bio-sealant
• Resistance to deterioration o 3-5 additional years of service life. o Reduces oxidation. o Penetrates deep into asphalt. o Adding polymers to the asphalt cement. • Improvements to surface o Seals hairline cracks. o Helps maintain skid resistance. o Reduces moisture penetration. o Reduces potholing and edge rutting. • Financial considerations o Does not affect line stripping. o Is not removed by snowplowing. o No heating, carbon negative. o Reduces lifecycle costs.	• If a road is in good shape, bio-sealant should be applied every four to five years. If it is in fair shape, it should be applied every two to three years, as long as the road is not ravelling. If the road has alligator cracking, bio-sealant cannot repair the damage and should not be used. • Applying bio-sealant calls for dry conditions and a dry road with temperatures above 40ºF. Bio-sealant should never be applied in wet or freezing conditions.

Table 4. Construction information about bio-sealant installation.

Section	Length, m (ft.)	Spray rate, L/m^2 (gal/yd^2)
Control section (CS)	31 (100)	0 (0)
Treated section No. 1 (TS 1)	305 (1,000)	0.136 (0.03)
Treated section No. 2 (TS 2)	305 (1,000)	0.113 (0.025)
Treated section No. 3 (TS 3)	305 (1,000)	0.091 (0.02)
Remaining section (RS)	4,366 (14,324)	0.091 (0.02)

Table 5. Average skid number (SN) with standard deviation at the entire site.

Measurement Date	SN of Eastbound	SN of Westbound
06/20/2016 (before application)	67.1 ± 3.2	66.9 ± 3.3
07/05/2016	47.6 ± 7.3	49.7 ± 5.2
05/08/2017	66.0 ± 4.1	68.5 ± 2.0
08/14/2017	66.8 ± 4.0	67.3 ± 2.4
04/12/2018	72.1 ± 3.0	74.0 ± 1.3
09/10/2018	66.0 ± 2.1	65.5 ± 2.5
07/30/2019	63.9 ± 1.8	65.1 ± 1.9

Table 6. Amount of cracking at the installation site.

Section	Survey Date				
	6/29/2016 (before application)	4/13/2017	10/13/2017	3/22/2018	5/1/2019
CS	No distress	No distress	No distress	No distress	2 T-cracking
TS 1	2 T-cracking	2 T-cracking	2 T-cracking	3 T-cracking	20 T-cracking
TS 2	2 T-cracking	2 T-cracking	2 T-cracking	3 T-cracking	8 T-cracking
TS 3	No distress	No distress	No distress	No distress	9 T-racking
RS	45 T-cracking	45 T-cracking, 2 L-cracking	46 T-cracking, 2 L-cracking	47 T-cracking, 2 L-cracking	95 T-cracking, 2 L-cracking

Note: T-cracking is transverse cracking, L-cracking is longitudinal cracking.

Figures

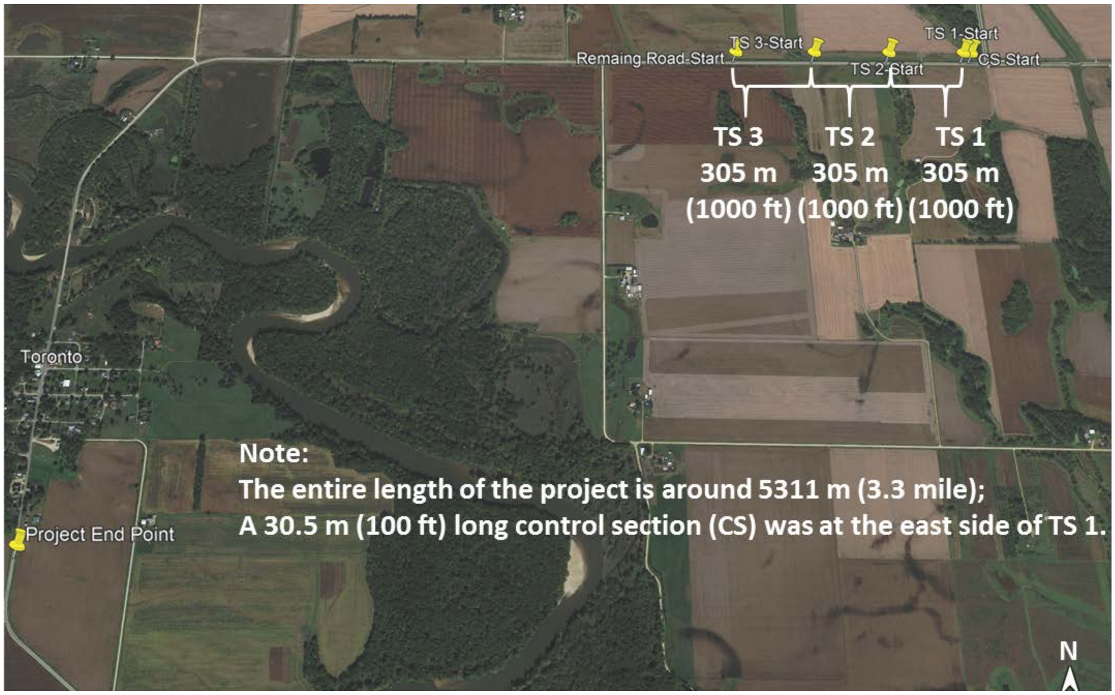


Figure 1. Location of the bio-fog seal construction and test sections in 2016.

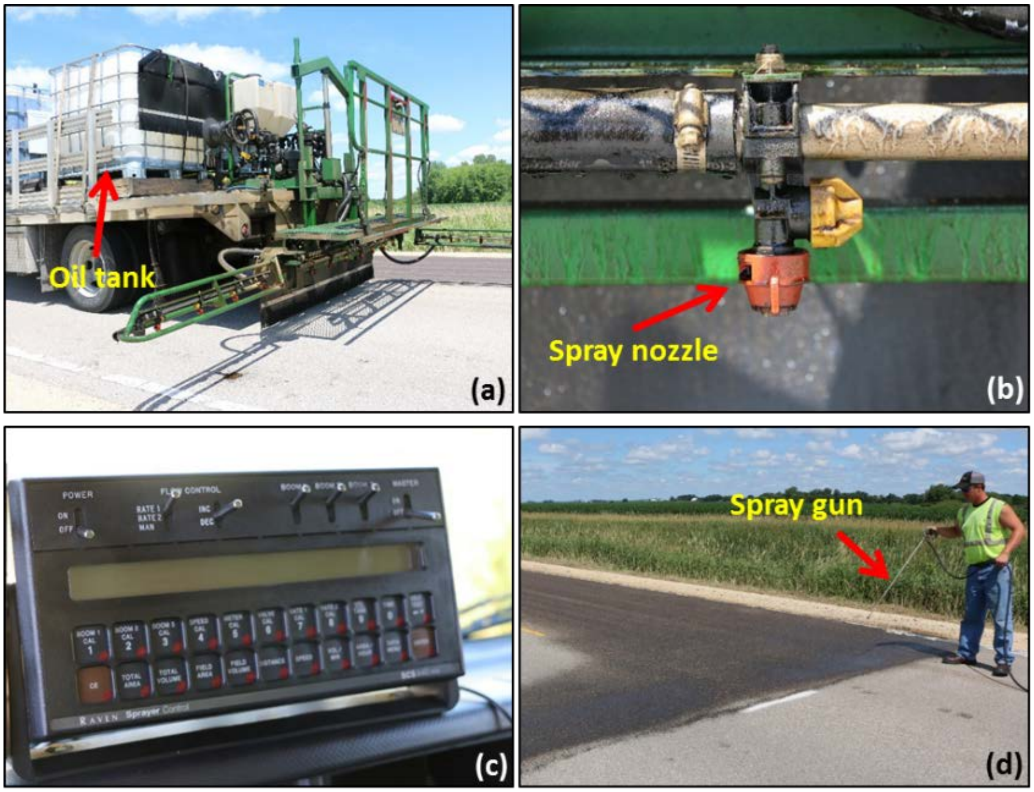


Figure 2. Construction equipment for fog seal.

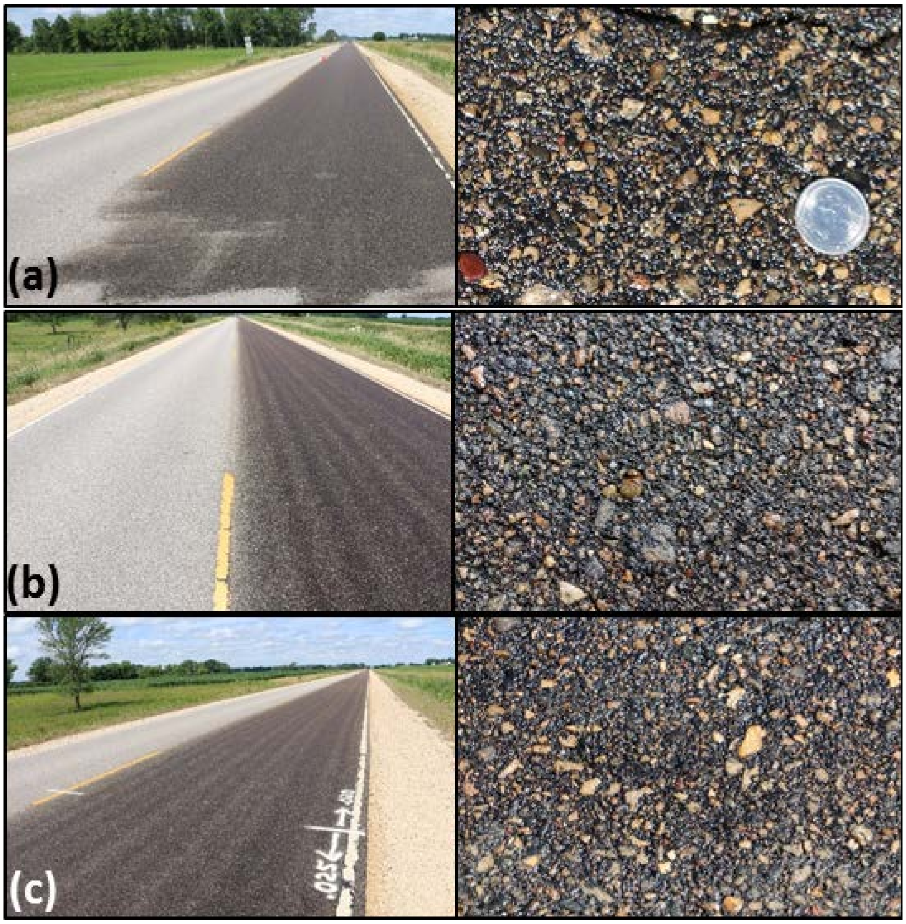
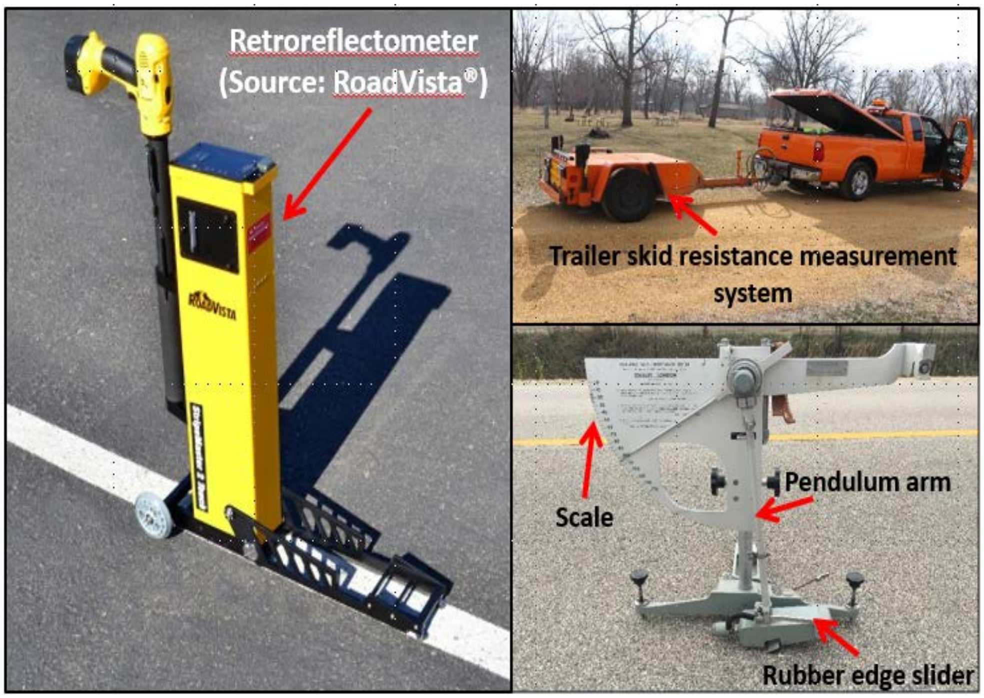
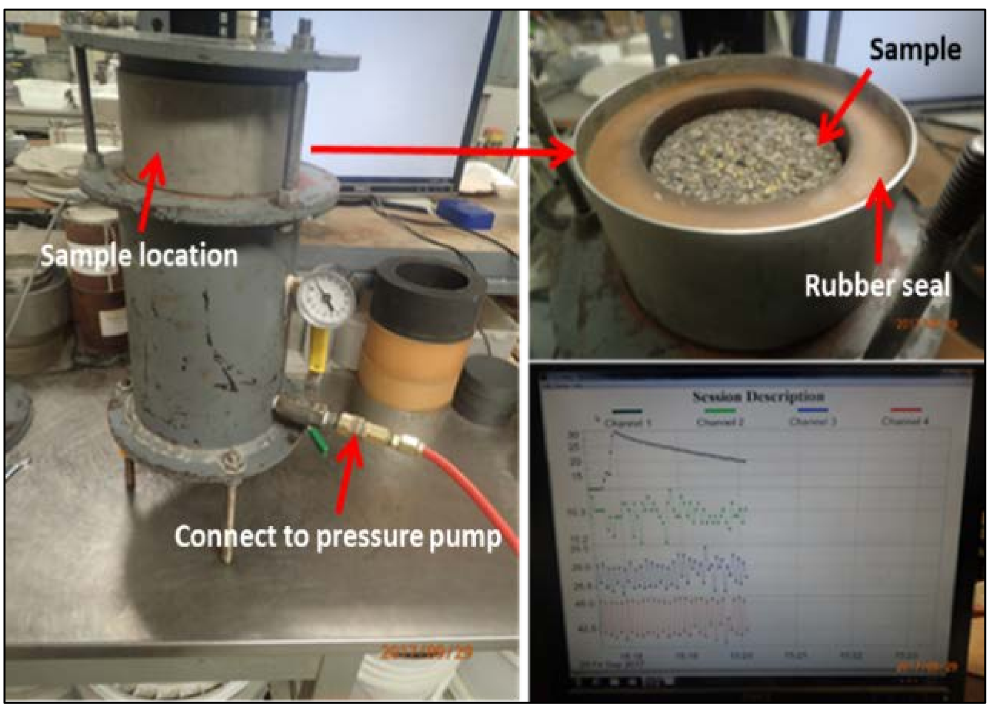


Figure 3. Appearance of bio-sealant treated pavement surfaces.



(a)



(b)

Figure 4. Images of devices of (a) retroreflectometer, locked wheel skid resistance tester, and British pendulum tester; (b) laboratory air permeability tester.

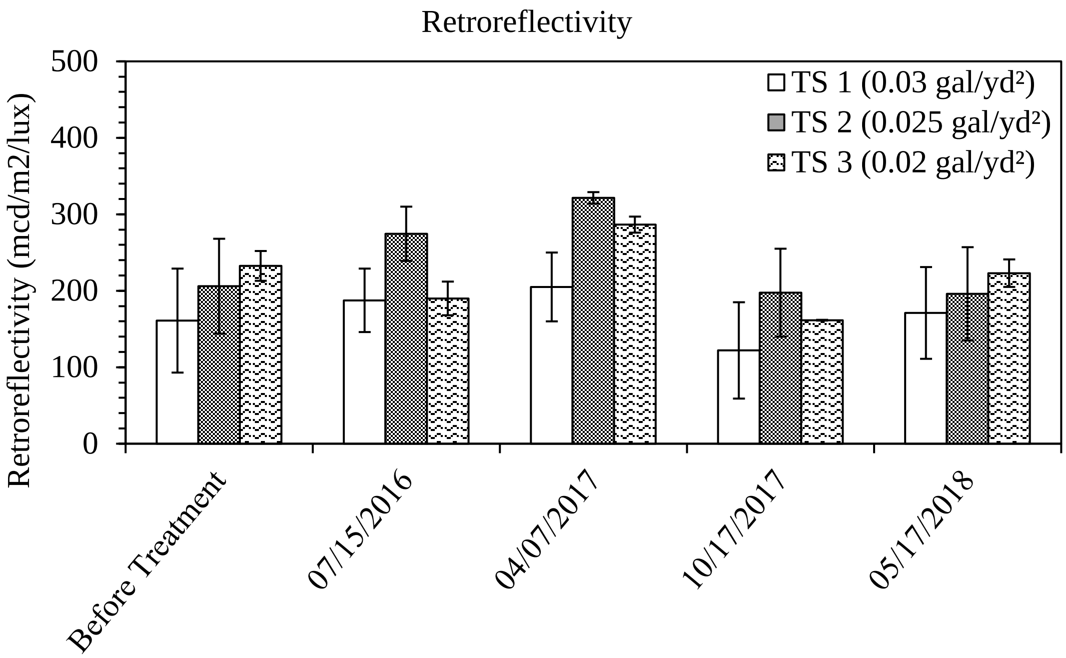
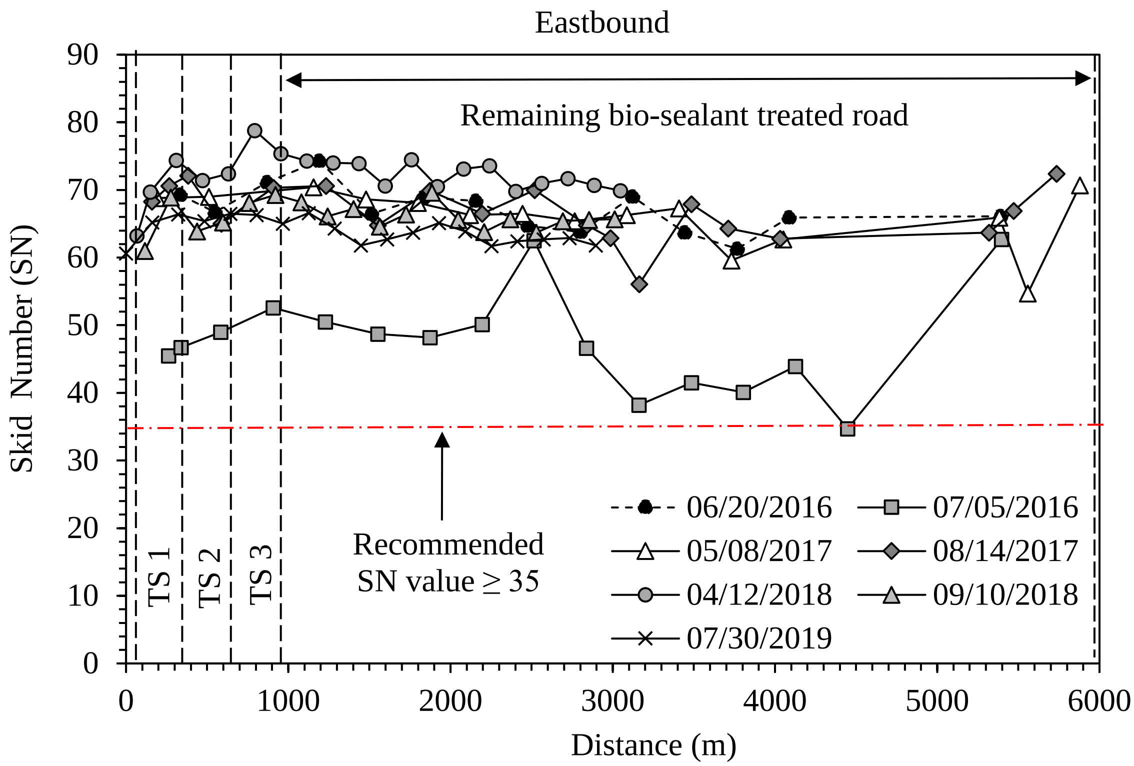
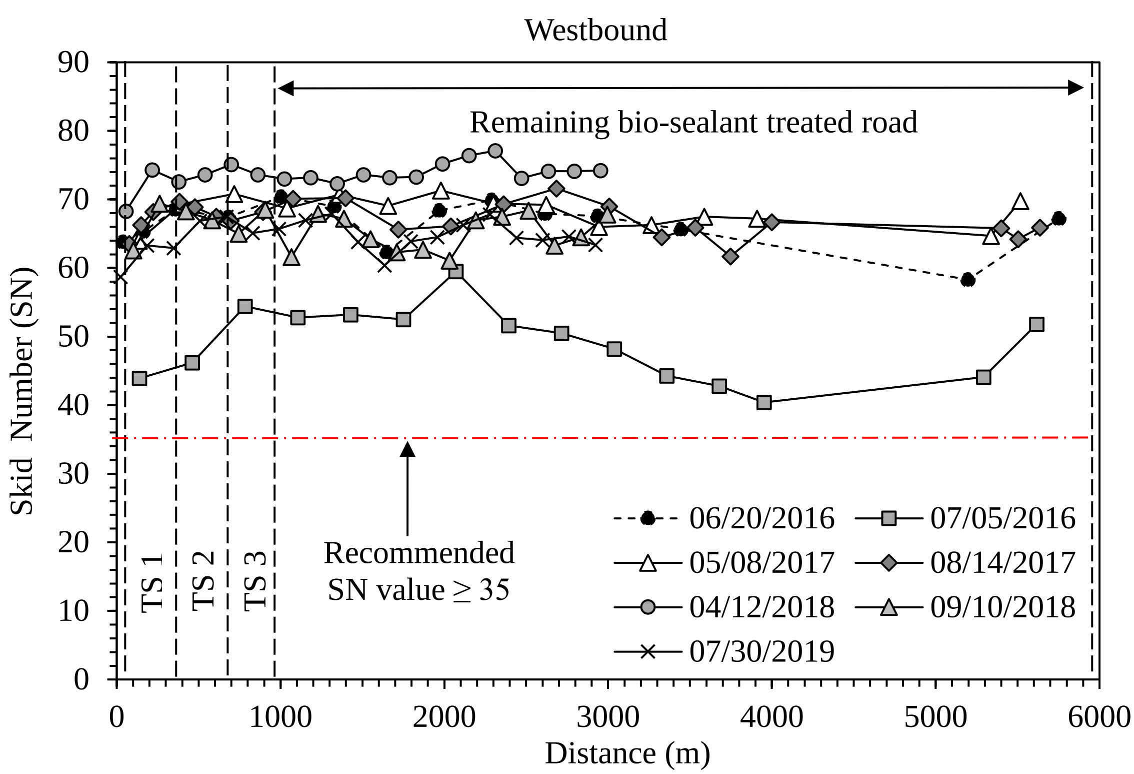
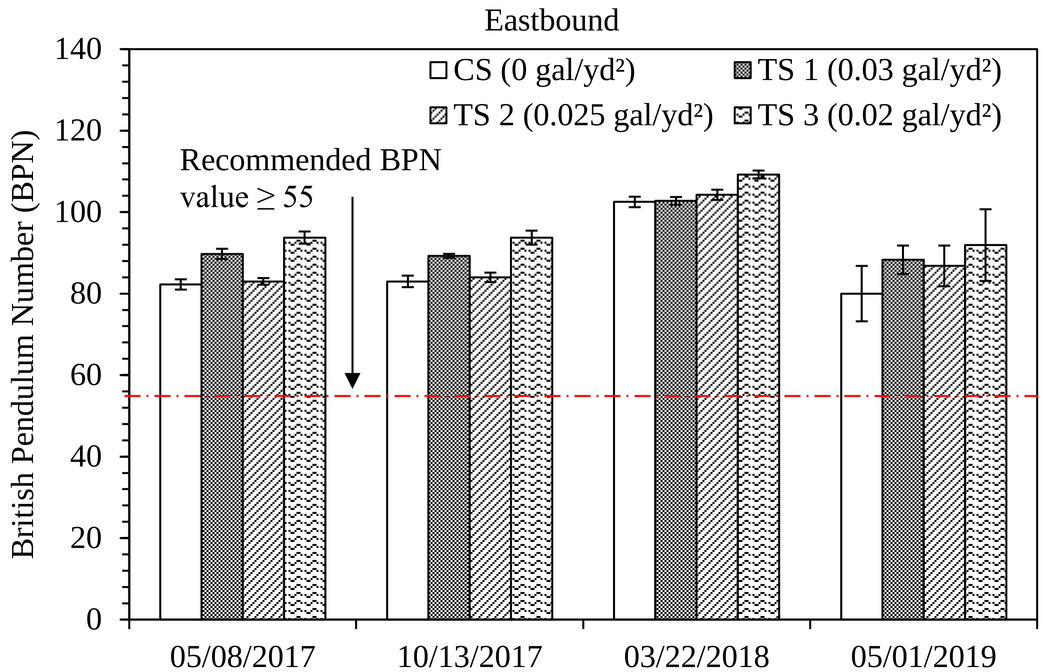


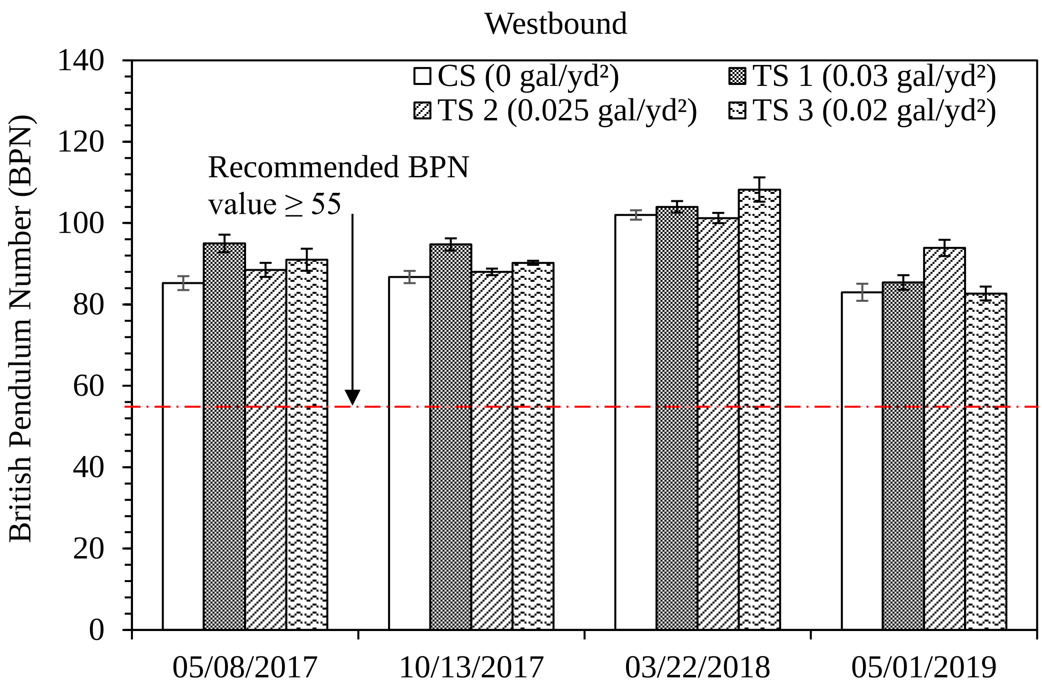
Figure 5. Results of retroreflectivity of pavement markings at the test sections.


Eastbound
Remaining bio-sealant treated road
Skid Number (SN)
TS 1
TS 2
TS 3
Recommended SN value ≥ 35
06/20/2016
07/05/2016
05/08/2017
08/14/2017
04/12/2018
09/10/2018
07/30/2019
Distance (m)
(a)


Westbound
Remaining bio-sealant treated road
Skid Number (SN)
TS 1
TS 2
TS 3
Recommended SN value ≥ 35
06/20/2016
07/05/2016
05/08/2017
08/14/2017
04/12/2018
09/10/2018
07/30/2019
Distance (m)
(b)



(c)



(d)

Figure 6. Results of (a) SN of eastbound, (b) SN of westbound, (c) BPN of eastbound and (d) BPN of westbound.

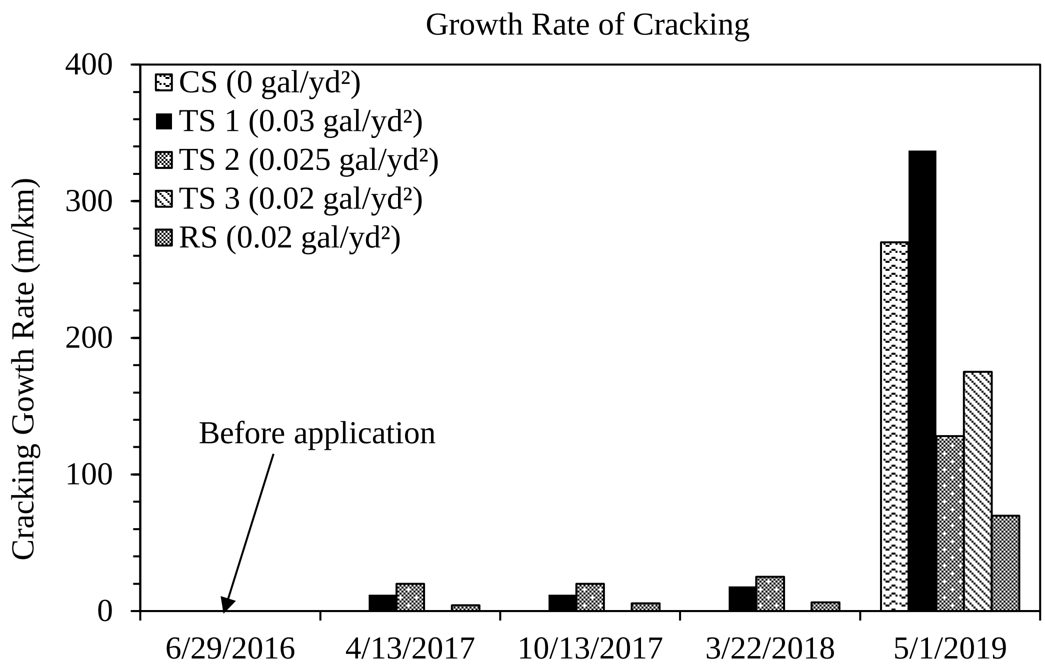
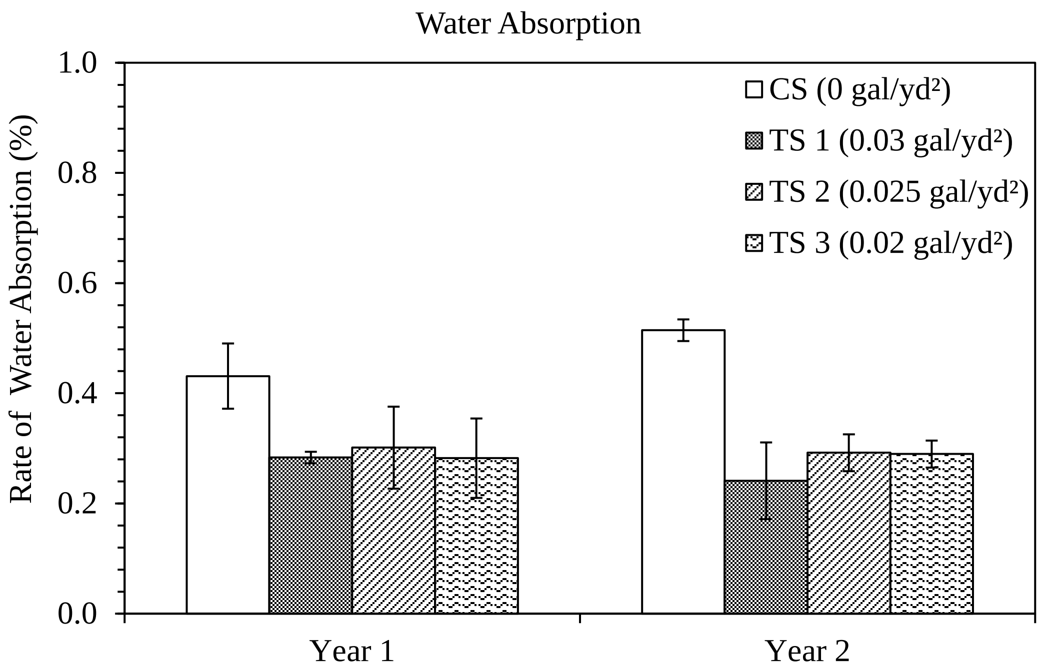
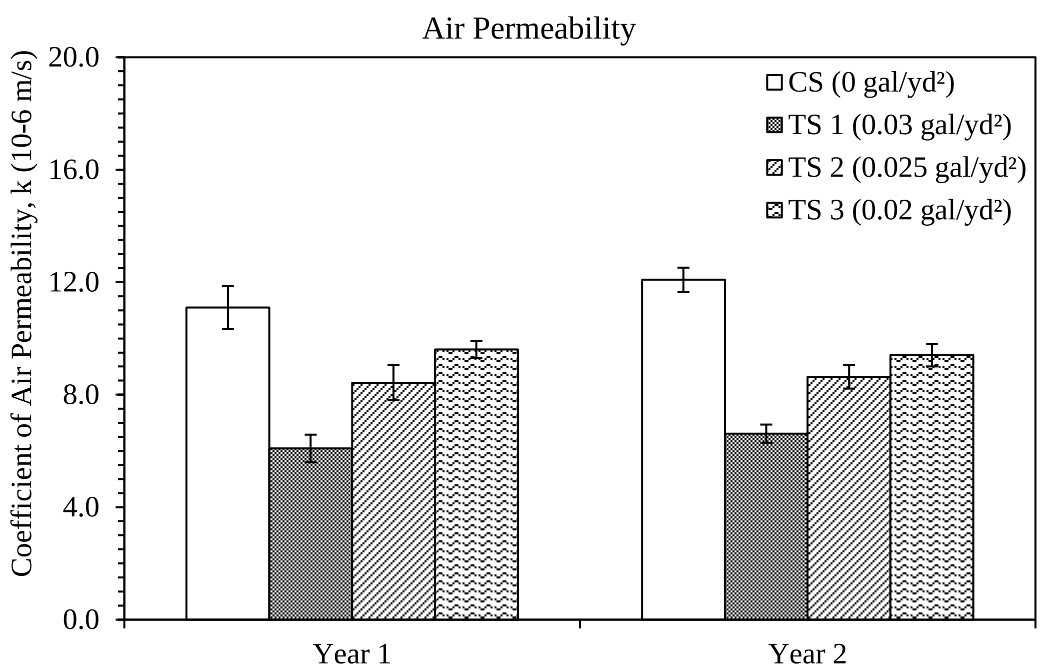


Figure 7. Growth rate of transverse cracking at testing sections.



(a)



(b)

Figure 8. Test results of (a) water absorption and (b) air permeability.