Evaluation of RePLAY for Mainline, Shoulders, and Rumbles: Pilot Study in Clinton County

Final Report
January 2022

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Institute for Transportation

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16. Abstract

While asphalt pavement is one of the most common transportation infrastructures in the United States, it requires proper maintenance. Exposure of asphalt binders to air can result in an oxidation process that can result in brittle behavior and distress in an asphalt pavement surface. To mitigate asphalt road deterioration and extend pavement service lives, various preservation strategies can be employed.

Fog seals are a light application of conventional asphalt emulsion on an asphalt-surfaced road to prevent oxidation and reduce water infiltration. In recent years, bio-based products for pavement preservation have attracted considerable attention due to their relatively low cost and environmentally-friendly properties. A proprietary bio-based sealant, RePLAY, has been commercialized and successfully used in many states.

To evaluate RePLAY performance as an alternative fog sealant for preserving asphalt-surfaced roads in Iowa, a 3.3-mile pilot testing section was selected in Clinton County in June 2016 for investigation of both short- and long-term performance by spraying sections with three different applications of RePLAY. A control section without RePLAY application was also set up for comparison purposes.

The set of performance investigations,conducted for five consecutive years (summer 2016 through summer 2021) included visual distress surveys of surface friction, pavement-marking retroreflectivity, laboratory water absorption, air permeability, and depth of penetration. The field results showed that, while a RePLAY application could reduce surface friction and retroreflectivity at early stages, restoration occured after several weeks. A RePLAY-treated section also exhibited a lower growth rate for cracking.

The laboratory results showed that RePLAY is effective in reducing water absorption and air permeability. A life-cycle cost analysis was also conducted, and the findings suggest that RePLAY can be an effective alternative for Iowa asphalt pavement preservation with savings in maintenance costs.

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TABLE OF CONTENTS

ACKNOWLEDGMENTS ... ix
EXECUTIVE SUMMARY ... xi
1. INTRODUCTION ... 1
    Background and Motivation ... 1
    Research Objective ... 2
    Research Approach ... 2
    Report Organization ... 2
2. LITERATURE REVIEW ... 4
    Literature Review of Fog Seals ... 4
    Fog Seals Using Bio-Sealant ... 7
3. REPLAY TEST SECTIONS IN CLINTON COUNTY, IOWA ... 9
    Construction and Experimental Approaches ... 9
    Fog Seal Construction Using RePLAY ... 10
    Field Investigations ... 12
    Specimen Coring ... 14
    Laboratory Testing ... 14
4. FIELD TEST RESULTS AND DISCUSSION ... 17
    Retroreflectivity ... 17
    Friction ... 19
    Distress Survey ... 23
5. LABORATORY TEST RESULTS AND DISCUSSION ... 28
    Water Absorption ... 28
    Air Permeability ... 29
    Depth of Penetration ... 30
6. LIFE-CYCLE COST ANALYSIS ... 32
    LCCA Model ... 32
    Treatment Inputs and Scenarios ... 32
    EUAC Results and Discussion ... 38
7. CONCLUSIONS AND RECOMMENDATIONS ... 42
    Key Findings ... 42
    Recommendations ... 43
REFERENCES ... 45
    Standards from ASTM International, West Conshohocken, PA ... 45
    Author-Date References for All Other In-Text Citations ... 45
APPENDIX: FIELD SURVEY IMAGES ... 49

LIST OF FIGURES

Figure 1. Report organization flowchart 2
Figure 2. Locations of bio-fog seal construction and test sections on CR E-63/Y-32 near Toronto in Clinton County 9
Figure 3. Application equipment for fog seal 10
Figure 4. Appearance of RePLAY-treated pavement surfaces 11
Figure 5. Devices for locked wheel skid resistance tester and British pendulum tester 13
Figure 6. Specimen coring 14
Figure 7. Laboratory air permeability test setup 15
Figure 8. Flashlight for measurements of penetration depth 16
Figure 9. Measured retroreflectivity on (a) sampling location 1 and (b) sampling location 2 18
Figure 10. Results of (a) SN for eastbound, (b) SN for westbound, (c) BPN for eastbound, and (d) BPN for westbound 21
Figure 11. (a) Sealed crack, (b) unsealed crack, and (c) crack caused by coring activities 25
Figure 12. Growth rate of transverse cracking at testing sections: (a) including cracking caused by coring activities and (b) removing cracking caused by coring activity 26
Figure 13. Test results for (a) water absorption and (b) air permeability 29
Figure 14. LED images of specimens from (a) control, (b) TS 1, (c) TS 2, and (d) TS 3 sections 30
Figure 15. UV images of specimens from (a) control, (b) TS 1, (c) TS 2, and (d) TS 3 sections 31
Figure 16. Cases for untreated pavement and RePLAY-treated pavement: (a) one-time treatment in Scenario A and B, (b) repeated treatments in Scenario A and B, (c) one-time treatment in Scenario C and D, and (d) repeated treatments in Scenario C and D 37
Figure 17. EUAC for different scenarios: (a) Scenario A, (b) Scenario B, (c) Scenario C, and (d) Scenario D 41
Figure 18. Field survey on April 13, 2017: (a) control section, (b) treated section No. 1 (0.03 gal/yd^2), (c) treated section No. 2 (0.025 gal/yd^2), and (d) treated section No.3 (0.02 gal/yd^2) 49
Figure 19. Field survey on October 13, 2017: (a) control section, (b) treated section No. 1 (0.03 gal/yd2), (c) treated section No. 2 (0.025 gal/yd2), and (d) treated section No.3 (0.02 gal/yd2) 50
Figure 20. Field survey on March 22, 2018: (a) control section, (b) treated section No. 1 (0.03 gal/yd^2), (c) treated section No. 2 (0.025 gal/yd^2), and (d) treated section No.3 (0.02 gal/yd^2) 50
Figure 21. Field survey on May 11, 2019: (a) control section, (b) treated section No. 1 (0.03 gal/yd^2), (c) treated section No. 2 (0.025 gal/yd^2), and (d) treated section No.3 (0.02 gal/yd^2) 51
Figure 22. Field survey on August 9, 2020: (a) control section, (b) treated section No. 1 (0.03 gal/yd^2), (c) treated section No. 2 (0.025 gal/yd^2), and (d) treated section No.3 (0.02 gal/yd^2) 51
Figure 23. Field survey on August 24, 2021: (a) control section, (b) treated section No. 1 (0.03 gal/yd^2), (c) treated section No. 2 (0.025 gal/yd^2), and (d) treated section No.3 (0.02 gal/yd^2) 52

LIST OF TABLES

Table 1. Summary of state highway agency specifications for fog seals 5
Table 2. Physical and chemical properties of RePLAY 7
Table 3. Benefits and limitations of RePLAY 8
Table 4. Construction information about RePLAY installation 10
Table 5. Average skid number (SN) with standard deviation for the entire site 19
Table 6. Cracking survey at the installation site with 100 ft control section and remaining 14,300 ft section..23
Table 7. Cracking survey at the installation site with the control and remaining sections normalized to 1,000 ft 23
Table 8. Crack growth rate and sealing cost for different cases in Scenario A and B...................34
Table 9. Crack growth rate and sealing cost for different cases in Scenario C and D...................34
Table 10. Various cases utilized in Scenario A and B for LCCA at 5% discount rate..................35
Table 11. Various cases utilized in Scenario C and D at 5% discount rate 35
Table 12. EUAC for different cases and scenarios 39

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EXECUTIVE SUMMARY

Asphalt pavement preservation refers to treatments that extend the remaining service life of asphalt concrete pavements by reducing the damaging effects of pavement surface layer aging and deterioration and helping protect the integrity of the underlying pavement structure. Typical asphalt pavement preservation technologies include fog-seal treatments, thin overlays and crack treatments, slurry seals and micro surfacing, chip seals, Otta seals, cape seals, surface recycling, and others. Among these, widely-used fog seals are the application of liquid asphalt or emulsions to prevent oxidation and seal against water infiltration.

RePLAY, a proprietary fog sealant invented by Sheldon Chesky and designed to enhance performance and longevity of paved surfaces, is composed of 88% bio-based asphalt sealant of which 40% is derived from soybean oil. Claims for its use include its capability for penetrating deeply into the matrix to add new polymers into the mix and reverse oxidation processes below the surface, and also to repair hairline surface cracks.

The objective of this project was to evaluate RePLAY as a proprietary bio-based fog seal material for mainline, shoulders, and rumbles through a pilot study on an asphalt-surfaced county road in Clinton County, Iowa. The fog seal vendor coordinated with Clinton County and the researchers for this investigation.

To evaluate the effectiveness of this bio-based fog sealant product as an alternative application for Iowa asphalt pavement preservation, an approximate 3.3-mile test section was selected in June 2016 as a site for conducting short- and long-term performance evaluation of RePLAY applications applied at three different rates. A control section without RePLAY treatment was also set up for comparison purposes.

A series of performance investigations was conducted over five consecutive years (summer 2016 through summer 2021); the investigations included a visual distress survey of field-measured surface friction, pavement-marking retroreflectivity, laboratory water absorption, and air permeability.

The field results revealed that, after application, both skid resistance and retroreflectivity decreased over the short term but were restored to their original conditions after two weeks and several months, respectively. The British pendulum test indicated that RePLAY could maintain appropriate long-term surface friction after treatment. Laboratory results revealed that the bio-based fog-sealant treatments applied at the highest application rate exhibited the lowest water absorption and air permeability.

The life-cycle cost analysis (LCCA) performed in this study indicated that RePLAY re-applied three times over a 20-year design service life (i.e., Case 3-b) represented a lower equivalent uniform annual cost (EUAC) than the other cases evaluated in this study, and was, therefore, a better strategy than the untreated and other treatment scenarios.

In summary, RePLAY treatment appears to offer an effective surfacing technology for extending the service life of asphalt pavements. It maintains surface friction, controls cracking, reduces moisture penetration into the pavement structure, and reduces both maintenance cost and environmental containment for local low-volume roads.

Based on the assumptions made in this study, RePLAY applications applied at intervals of three to five years are recommended to local county engineers. This study also recommends re-applying RePLAY at the study project site to investigate the benefit of a second RePLAY application. For comparison, treating a section with a traditional petroleum-based fog sealant, such as asphalt emulsion, is also suggested.

1. INTRODUCTION

Background and Motivation

Roadways are one of the most important transportation infrastructures in the United States to meet the basic needs of society. Common pavement types include asphalt and concrete pavements, and both can deteriorate gradually over time due to repeated traffic loading and climatic effects.

Asphalt roads are very susceptible to environmental impacts because the asphalt mixture becomes brittle due to oxidation. To maintain the serviceability of low-volume asphalt pavements and extend their service lives, multiple preservation strategies, including chip seals, slurry seals, crack treatments, overlays, and fog seals, have been employed (Johnson 2000). Each of these approaches can be utilized for different maintenance purposes.

Fog seals are a low-cost maintenance technology that traditionally refers to the light application of petroleum-based asphalt products on the asphalt road surface. The main purpose is to mitigate oxidation, micro-cracking propagation, and water infiltration into the pavement structures. In the past decades, traditional petroleum-based fog sealants, such as asphalt emulsion and coal tar, have been successfully utilized to preserve asphalt pavement surfaces. However, such conventional petroleum-based sealing agents need a long time for curing to allow traffic to open (Kim and Im 2015) and can increase the risk of health issues due to the chemical components, such as polycyclic aromatic hydrocarbons (Ghosh et al. 2016). Moreover, the utilization of fossil energy-based products could contribute to the global energy crisis and more greenhouse gas emissions (IPCC 1996, IPCC 2014, Yang et al. 2018).

Some new sealing products derived from biomass have been attempted for pavement preventive maintenance to overcome the shortcomings of traditional petroleum-based fog sealants. RePLAY is a soy-based product derived from agricultural oil. Its manufacturer, BioSpan Technologies, Inc., claims that RePLAY is capable of mitigating asphalt oxidation, potholing, cracking, and rutting and extending the lifespan of asphalt roadways when applied every three to five years (Shatnawi 2014).

RePLAY has been commercialized and utilized in the US for more than 10 years. States such as Ohio and Missouri have shown the successful use of bio-based fog sealants for their local county road preservation projects (Shatnawi 2014, BioSpan Technologies 2010). Additionally, it was reported that, after treatment, water can quickly shed from the road surface and result in skid resistance being retained at the normal condition. However, the construction experience and performance evaluation were limited and not well documented.

Encouraged by the anecdotal evidence, Iowa Department of Transportation (DOT) staff became interested in using RePLAY as a sustainable alternative to preserve Iowa main lanes, shoulders, and rumble strips.

Research Objective

This study was directed toward evaluating the bio-based product, RePLAY, as a fog sealant on low-volume asphalt pavements in Iowa. In coordination with a vendor in Clinton County, an asphalt-pavement preservation project was initiated, with the proposed task of field evaluation of RePLAY application at the project site. With the goal of evaluating the performance of RePLAY on pavement-marking retroreflectivity, surface friction, laboratory air permeability, water absorption, and depth of penetration, various RePLAY application rates were employed during road construction, and consequent investigations were documented over an approximately five-year period (summer 2016 through summer 2021).

Research Approach

In 2016, an asphalt road in Clinton County was selected for RePLAY application. The field investigation focused on evaluating RePLAY treatment applied at three different rates. Pavement marking retroreflectivity testing, skid-resistance testing, British pendulum testing, and distress surveys were conducted each year through 2021. In situ specimens from testing sections were cored during the first two years for laboratory investigation, and water absorption, air permeability, and depth of penetration measurements were performed. In addition to the field and laboratory investigations, the collective construction costs of the RePLAY-treated sections were documented to support life-cycle cost analysis (LCCA) for RePLAY treatment.

Report Organization

This report is organized into seven sections (see Figure 1).

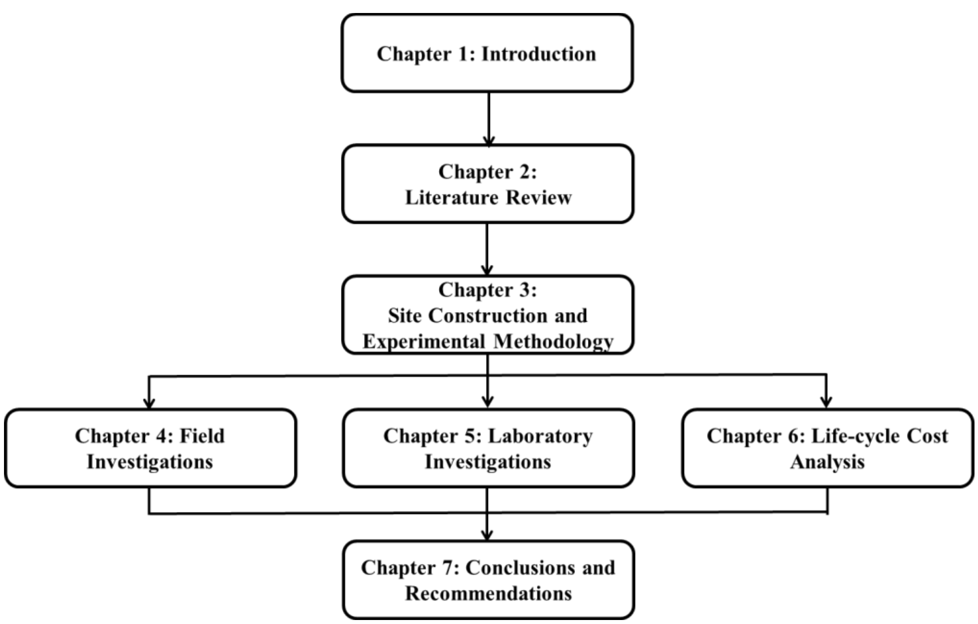

Figure 1. Report organization flowchart

Chapter 1 describes the background, objectives, and research approach of this study. Chapter 2 presents a comprehensive literature review of traditional petroleum-based and nontraditional bio-based fog sealants and includes a summary of construction procedures and experimental methodology. Chapters 4 and 5 discuss testing results from field and laboratory investigations, respectively. Chapter 6 analyzes the life-cycle cost for RePLAY treatment, and Chapter 7 provides a conclusion and summary for this study, as well as recommendations for future studies. This report also includes an Appendix showing site-appearance images for each year.

2. LITERATURE REVIEW

Literature Review of Fog Seals

Fog sealing is a road surface treatment that uses an asphalt distributor to apply diluted slow-setting or medium-setting asphalt emulsion containing no aggregates to a pavement surface (Johnson 2000, Estakhri and Agarwal 1991). The application of fog seals not only seals and enriches the asphalt road surface, seals micro-cracking, and mitigates aging and raveling, but also consumes the least amount of energy to delineate the shoulder (Johnson 2000, Chehovits and Galehouse 2010, Jahren et al. 2007, Janisch and Gaillard 1998). Fog sealing is primarily used to protect low-volume asphalt roads from the raveling issues on open-graded hot-mixed asphalt (HMA).

The current practice of fog sealing requires the spray temperature to be controlled between 125°F and 160°F, and the pavement surface temperature should be above 50°F. Generally, fog sealing is not recommended for roads with heavy traffic loads, because, after spraying fog seals, surface friction can significantly decrease and cause safety issues.

The cost of fog sealing depends on the type of emulsion, the spray rate, and project scale in the field and is usually about \$0.40/yd^2 (Savemyroad 2021a). Typically, the benefit of a fog seal can last one or two years.

Some studies have reported using a fog seal applied as a top surface on a chip seal (Kim and Im 2015). Because the significant concern associated with using chip seals is aggregate loss, fog seals have been suggested to reduce the potential for aggregate loss, improve aggregate retention, and extend pavement service life.

Miller et al. (2010) tested the bond strength of the asphalt binder in chip seal specimens and investigated the behavior of bonding between aggregate particles and asphalt emulsion. Liu et al. (2018) developed a two-dimensional (2D) finite element model to analyze the macrostructure of the interface of the asphalt mixture, reporting that the horizontal load and temperature significantly influenced the shear strain in chip seal specimens.

Some studies recommend using polymer-modified emulsions (PMEs) over unmodified emulsions to strengthen the bonding between bitumen and aggregate (Jahren et al. 2007, Im and Kim 2013, Lawson et al. 2007). These studies also report that the PMEs could improve aggregate retention and emulsion adhesion and mitigate periods of curing, temperature susceptibility, and bleeding issues.

Fog seals have been widely used to preserve roads throughout the US for many years. The specifications applied by different states regarding the asphalt type, spray rate, distributor, heating temperature, and period of traffic control vary a lot and lack comparison documentation. State highway agency standard specifications have documented the details of fog seal application, and Table 1 summarizes the six most essential state criteria concerning on-site fog seal installation in the US.

Table 1. Summary of state highway agency specifications for fog seals

State	Ref.	Material: Emulsion Grade	Material: AE/W ratio	Material: Application Rate, gal/yd^2	Equipment	Application Instructions
IA	Iowa DOT (2012)	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 wet surface; do not apply when either the pavement temperature or the air temperature is below 60°F
CA	Caltrans (2010)	Slow-setting asphalt emulsion	1:1	0.02 to 0.06	Bituminous distributor	Do not start fog seal when precipitation has been forecasted during the application and curing period; do not apply when either the pavement or the air temperature is below 40°F
MO	MoDOT (2018)	SS-1, SS-1h, CSS-1, or CSS-1h	given by engineer	0.20	Bituminous distributor	Sand dams may be necessary to prevent the emulsion from being applied outside of designated areas; asphalt emulsion shall not be placed on a damp surface, and the surface shall be free of objectionable material prior to sealing
OR	ODOT (2018)	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	TxDOT (2014)	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	WSDOT (2018)	CSS-1, CSS-1h	1:1	0.10 to 0.18	Bituminous distributor	–

AE/W ratio, or dilution rate, indicates asphalt emulsion-water ratio; – indicates not specified

All six states recommend using the cationic slow-setting (CSS-1) or slow setting (SS-1) asphalt emulsion for the fog seal treatment, and a dry and clean surface should be created before installing the fog seal. The typical application rates vary from 0.02 to 0.2 gal/yd^2 at a dilution rate of 1:1. The bitumen distributor is commonly used to heat and spray the asphalt sealant using the specific rate on the project site. The pavement surface temperature or air temperature should be higher than 50°F to receive the fog seal.

Several quality assurance/quality control (QA/QC) tests have been suggested to estimate the performance of fog sealants, including sweep tests, binder bond strength tests, bleeding tests, evaporation analysis, damping tests, surface friction tests, indirection tension tests, Vialet tests, third-scale model mobile load simulator tests, and scanning analysis with a three-dimensional (3D) laser system (Im and Kim 2013, Janisch and Gaillard 1998, Wood et al. 2006, Lawson et al. 2007).

Prapaitrakul et al. (2010) conducted a comprehensive study to assess fog seal treatment performance. The researchers took core specimens from the selected pavement sites at both untreated and fog seal treated sections and then trimmed and sliced them into three 1/4 in. thick plates. The in situ specimens, which were composed of both the original bitumen and fog sealant, were prepared to extract the asphalt binder. The extracted mixed bitumen samples were used for the flowing test to measure the presence of the fog sealant and determine the depth of penetration. In addition to that, the gel permeation chromatograph test was carried out to determine the molecular size distribution of the asphalt materials and the stiffness measured for the recovered pavement binders.

According to the laboratory testing results, the fog sealant was mainly retained at the top 1/4 in. layer and influenced the properties of the top layer. The paired t-test examined the significant effect of the fog sealant on the pavement binder rheology, indicating that only the EB44 coal type could significantly stiffen the top layer only.

A study by Im and Kim (2013) evaluated the curing behavior of fog seals and how they affect traffic opening time. The researchers tested multiple emulsions, including CSS-1h and a cationic quick setting emulsion (CQS-1h), modified PME-A and PME-B on chip seal specimens containing a CRS-2L emulsion, and lightweight aggregate with the application rates of 0.25 gal/yd^2 and 10 lb/yd^2. The test results revealed that all four types of binders could shorten the curing time with the low emulsion application rates (EARs) and high temperature, and two PMEs could cure faster than CSS-1h and CQS-1h. PME-B achieved the fastest curing rate in the rolling-ball test among four emulsions, showing that PMEs could be cured within one hour and the unmodified CSS-1h and CQS-1h required longer than 1.25 hours.

This study also investigated the effect of fog seals on retaining aggregates. The aggregate loss testing showed that PME B could have less than 5% aggregate loss while the unmodified CSS-1h and CQS-1h could exhibit more than 15% aggregate loss. This study concluded that fog seal treatments could be a potentially cost-effective way to improve aggregate retention and shorten curing time by choosing the appropriate emulsion.

Fog Seals Using Bio-Sealant

Bio-based sealants have attracted more attention in recent years due to their relatively low cost and environmentally friendly properties such as non-toxicity and renewability. The soy-based agricultural oil, RePLAY, is one such product that has been successfully used in other states. RePLAY contains at least 88% bio-components with 40% derived from soybean oil, it is a black oil, and it has a slight citrus odor. Table 2 presents both the physical and chemical properties of this bio-based sealant and shows that RePLAY has a pH in the range of 5 to 6 with a similar flowability to water.

Table 2. Physical and chemical properties of RePLAY

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

Source: Shatnawi 2014

RePLAY contains different polymers such as styrene-butadiene-styrene (SBS) and styrene-butadiene-butadiene-styrene (SBBS) that are widely known to enhance the flexibility of asphalt pavement in cold weather.

RePLAY is a pavement preservation sealant purported to maintain the surface condition of the asphalt roadway when applied every three to five years by protecting pavement against water infiltration and maintaining long-term surface friction (Shatnawi 2014). RePLAY application is also claimed to supply the polymers into the asphalt binder and to strengthen the stabilization of the asphalt matrix. Therefore, it can prolong the service life of the asphalt pavement as it makes the pavement more resilient and less brittle due to the reverse of the oxidation process and penetration of the surface layers of the pavement. Typically, the penetration can achieve about 0.75 to 1.25 in. rapidly and fill voids to resist moisture infiltration and freez-thaw damages.

The standard application rates of RePLAY range from 0.01 to 0.02 gal/yd^2, which are lower than those for petroleum-based fog sealants (see previous Table 1) due to its good followability.

Some efforts have been made to validate the performance of RePLAY. Ghosh et al. (2016) reported that RePLAY could soften the control binder, but it had no significant impacts on bending creep and strength. Johnson (2018) conducted both laboratory and field testing to evaluate different fog sealants, including RePLAY. The documented test results indicated the nontraditional and bio-based fog sealants like RePLAY could cause a temporary reduction in surface friction and pavement marking retroreflectivity. Nahvi et al. (2021) concluded that RePLAY was cost-effective to extend the service life of the pavement up to seven years.

As a product with a competitive price, RePLAY can reduce the need for traditional asphalt emulsion in pavement perseveration by prolonging road lifespan. Moreover, it can be a sustainable alternative that is bio-based, non-toxic, and carbon negative. Additionally, it is easy to spray and apply since it does not require a heating process or a long curing time like conventional petroleum-based asphalt sealers. The pavement receiving the treatment can also be opened to traffic rapidly, and typically after about 30 minutes. However, this bio-based fog sealant also has some limitations, such as cannot repair alligator cracking. Table 3 summarizes the benefits and limitations of applying RePLAY.

Table 3. Benefits and limitations of RePLAY

Benefits of using RePLAY	Limitations of using RePLAY
• Three to five additional years of service life • Reduces oxidation • Penetrates deep into asphalt • Adding polymers to the asphalt cement • Seals hairline cracks • Helps maintain skid resistance • Reduces moisture penetration • Reduces potholing and edge rutting • Does not affect line stripping • Is not removed by snowplowing • No heating, carbon negative • Reduces life-cycle costs	• If a road is in good shape, bio-sealant should be applied every four to five years. It should be applied every two to three years if it is in fair shape, as long as the road is not raveling. If the road has alligator cracking, the 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 40°F. It should never be used in wet or freezing conditions

Sources: Shatnawi 2014, BioSpan Inc. 2010

3. REPLAY TEST SECTIONS IN CLINTON COUNTY, IOWA

Construction and Experimental Approaches

To evaluate the performance of RePLAY, a 3.3-mile long section of asphalt pavement on County Road (CR) E-63/Y-32 northeast of Toronto in Clinton County, Iowa, was selected for RePLAY installation (see Figure 2).

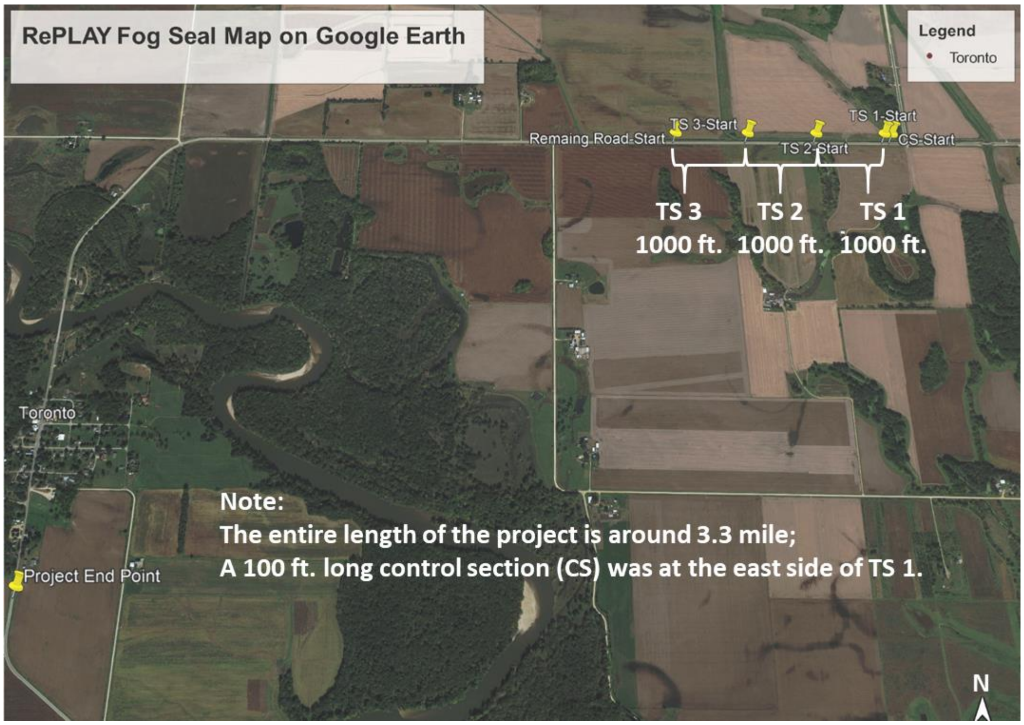

Image © Google Earth

Figure 2. Locations of bio-fog seal construction and test sections on CR E-63/Y-32 near Toronto in Clinton County

The existing surface layer was paved in 2011, and it was a 3 in. HMA overlay on a 3.5 in. cold-in-place recycling layer; an additional 0.5-mile long section through Toronto had a 2 in. HMA overlay. This roadway includes two lanes, and each lane is 10 ft wide with a 3 ft aggregate shoulder.

The annual average daily traffic (AADT) of this site was less than 400 vehicles per day (vpd), which is considered a low-volume road. As shown in Table 4, the entire project site for RePLAY installation was divided into five sections, including four treated sections and the one untreated section.

Table 4. Construction information about RePLAY installation

Section	Length, ft	Spray rate, gal/yd^2
Control section (CS)	100	0
Treated section No. 1 (TS 1)	1,000	0.03
Treated section No. 2 (TS 2)	1,000	0.025
Treated section No. 3 (TS 3)	1,000	0.02
Remaining section (RS)	14,324	0.02

Three different spray rates, 0.02, 0.025, and 0.03 gal/yd^2, were selected to investigate the effects of the application rate on the performance of the road surfaces.

Fog Seal Construction Using RePLAY

The installation of the bio-based fog seal using RePLAY on CR E-63/Y-32 near Toronto started on June 29, 2016, and the pavement surface was thoroughly swept and cleaned before application. The weather was clear and dry with an ambient temperature varying between 59ºF and 79ºF. The spraying equipment is shown in Figure 3, illustrating the truck equipped with an oil tank (Figure 3a) connected to an automatic spray bar with nozzles (Figure 3b).

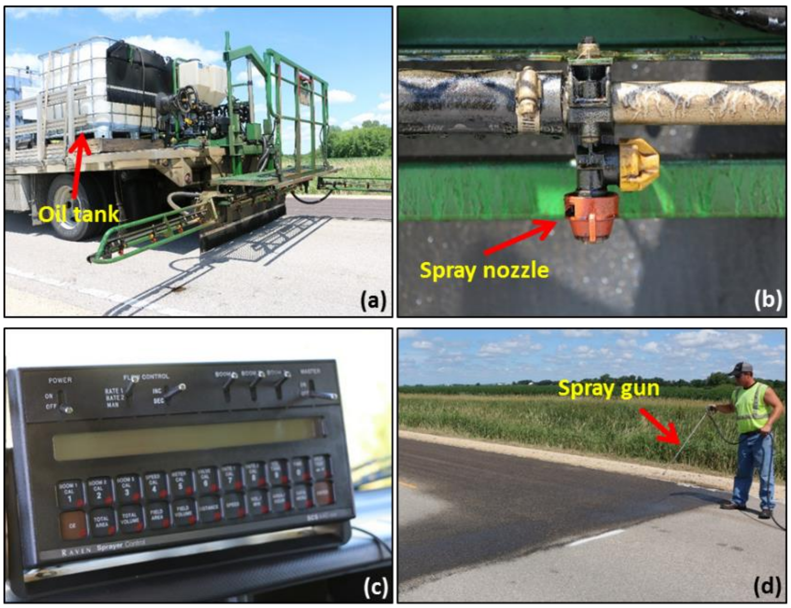

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Figure 3. Application equipment for fog seal

The spray machine had a control system to adjust the spray rate (Figure 3c). The spray bar was adjustable to fit different lane widths, and the evenly spaced nozzles could cover each of the 10 ft lanes for this project.

The contractor began applying the fog seal at about 10 a.m., and the driving speed of the sprayer ranged from 5 mph to 10 mph. After machine spraying, a spray gun was utilized to spray the edge areas that the spray truck could not cover (Figure 3d). The entire spraying system did not include a heating system given there is no heating for a bio-based agricultural oil like RePLAY.

During the application of the bio-based fog seal, the traffic for both lanes of the project site was controlled by county secondary road department personnel, and one lane was applying the RePLAY while the other lane was open to traffic. When the application of the bio-based fog seal on the first lane was completed, it was immediately opened to traffic. Then, the second lane was controlled to continue the installation of RePLAY.

Figure 4 illustrates the appearance of the roadway with both the untreated lane and the RePLAY-treated lane on the day of spraying.

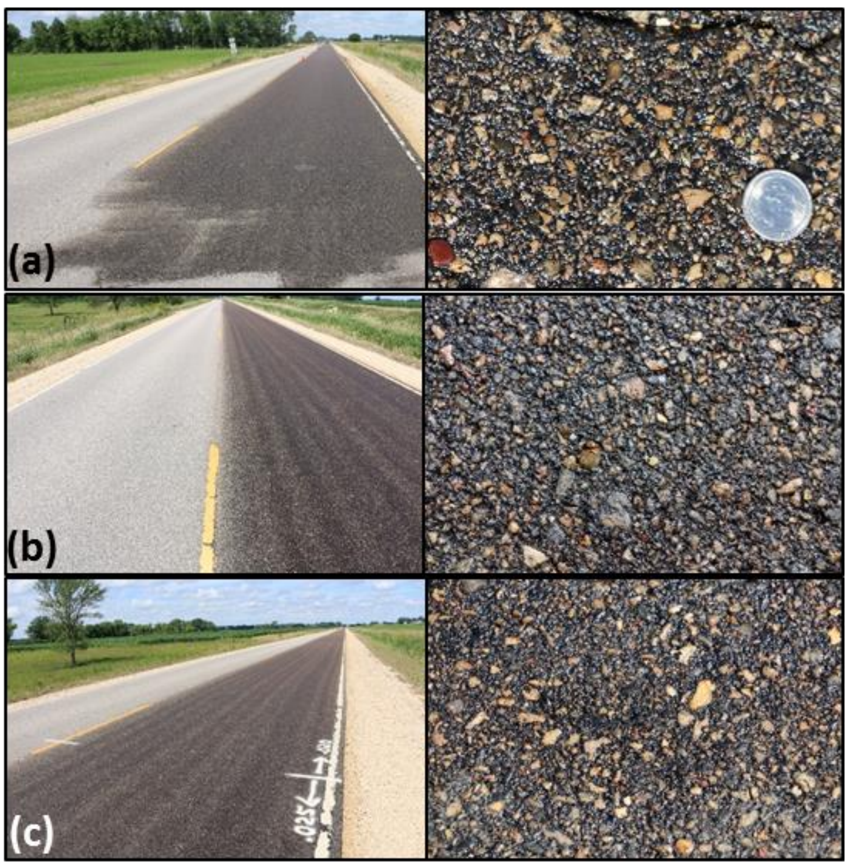

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Figure 4. Appearance of RePLAY-treated pavement surfaces

By contrast, the lane treated with RePLAY presented a darker color than the lane without any treatment. This darker color in the appearance of treated sections faded after a couple of days. Figure 4 also shows the visible and clear pavement strip markings after spraying the bio-based fog sealer, indicating that the visibility of the strip markings was not significantly reduced. As a matter of fact, the field observation showed that the pavement strip markings became brighter and more visible due to the increased contrast in the darkened appearance of the road surface.

Figure 4 also shows the close-up images of the treated surface. No free oil was observed standing on the surface due to the good flowability and absorbability on the pavement surface. This characteristic made the road surface absorb RePLAY rapidly and allowed opening the treated section to traffic in less than 30 minutes, also indicating the great advantage over conventional petroleum-based fog sealants that need a longer curling time for reopening (Kim and Im 2015).

Overall, the documented installation process for RePLAY showed that it is a simple seal technology to apply in the field. Its advantages to conventional petroleum-based fog sealants, such as no heating energy needed and less traffic control time, help make it a potentially cost-effective preservation method to prolong asphalt pavement lifespans.

Field Investigations

In this study, several field investigations were undertaken to evaluate the performance of the project site before and after the application of RePLAY. The research team conducted two activities during each field visit, including distress surveys and British pendulum testing. Skid resistance measurements and retroreflectivity tests were completed by the Iowa DOT due to the availability of the instruments. The field images for each visit are included in the Appendix.

The distress conditions, retroreflectivity, skid numbers (SNs), and British pendulum numbers (BPNs) for both the untreated and RePLAY-treated sections were documented up to the fifth year (summer of 2021). The distress surveys present visual evidence about pavement performance and can help in the decision-making process for pavement preservation. The cracking type and length were recorded for comparison purposes. The retroreflectivity of pavement strip markings is an essential indicator of driving safety because the markings on the surface can immediately provide guidance information to drivers (Austin and Schultz 2009).

Retroreflectivity gives a certain amount of illuminance to the selected object and measures reflected illuminance from the same object. The difference in illuminance between the given and reflected is defined as the retroreflectivity in units of $mcd/ft^2/lux$ (i.e., millicandela per square foot per lux). In this study, two spots of pavement marking strips for each section were investigated before and after applying RePLAY by following Iowa DOT Specification Materials instructional memorandum (I.M.) 386 (Iowa DOT 2016).

Skid resistance is a safe-driving-related performance indicator for pavements. It is a measure of the friction force to prevent the tire from sliding along the road surface. The standard testing instrument for this test is a trailer equipped with a locked wheel skid tester system, as shown in Figure 5.

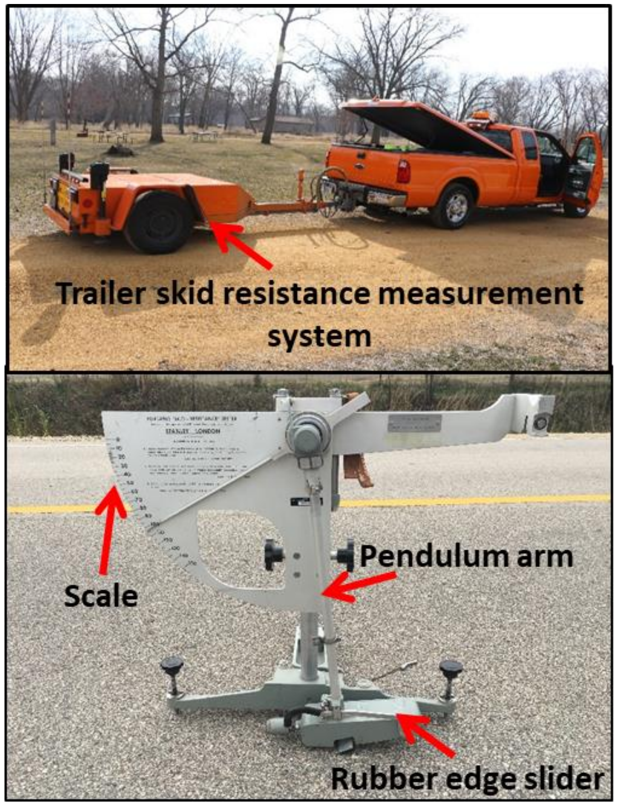

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Figure 5. Devices for locked wheel skid resistance tester and British pendulum tester

A truck is utilized to connect with the trailer testing system and collect the discontinuous spot data along the road with a driving speed of 40 mph in accordance with ASTM E274. As an automatic data collection system, a skid resistance tester can conveniently and efficiently survey the road over long distances. However, it is challenging for such a dynamic tester to recollect the skid resistance data at the exact location.

This study collected skid resistance for all five sections, including an untreated section, three treated sections, and the remaining treated section before and after the installation of RePLAY. Both westbound and eastbound lanes were measured to plot the data points along the road distance to show SN variation for all sections.

Like the skid resistance measurement, the British pendulum test is another standard test used to measure surface friction under laboratory and field conditions. As shown in Figure 5, a British pendulum tester is a static tester consisting of a body dial, a pendulum arm, and a standard rubber slider. The testing procedures are in accordance with ASTM E303, requiring the swing of the pendulum arm and allowing the rubber slider to propel over the test surface. The contact between the slider and the surface generates friction, which gets converted to the BPN on the scale.

Although both the skid resistance test and British pendulum test intend to measure the friction of pavement surface, the British pendulum test can be repeated to monitor the change of the BPN value at the same data point over time.

This study performed a British pendulum test on the control section and three RePLAY-treated sections (while the remaining section was excluded) and only after RePLAY application. In each section, two data points on the right wheel path were selected, and one was from the westbound lane with the other on the eastbound lane. The selected points were 10 ft away from the beginning of each section. Four repetitions were conducted for each measurement.

Specimen Coring

To investigate laboratory-based performance, in situ HMA specimens from both the control section and three treated sections were cored at a 6 in. depth using an electric core driller. As of July 2021, two field coring activities had been conducted at the project site. As shown in Figure 6, during the first coring activity, which was completed on May 8, 2017, two cores were taken from each section from each lane, excluding the treated remaining area; a total of 16 cores were collected.

Figure 6. Specimen coring

A second coring activity involving the same number of cores was conducted on April 11, 2018.

Laboratory Testing

After coring, all in situ specimens were sealed in zip-lock bags and transported to the Iowa State University laboratory where the HMA specimens were first sawed into 2 in. thick specimens, and then oven-dried at 125°F until constant mass was achieved. Based on the experimental plan, two cores were used to measure water absorption and the other two were used to measure air permeability.

By following ASTM D2726, the saturated surface-dry weight (SSD), weight during immersion, and dry weight of the prepared HMA specimens were determined to calculate water absorption. Water absorption is a standard laboratory test for compacted asphalt mixtures to determine the percentage of moisture absorbed during soaking in a water tube. It is expressed as the percentage on a volume basis for the whole specimen. Generally, a greater capability to absorb water indicates a higher void ratio and permeability in the asphalt mix, associating the mix to more aging behavior and pavement deterioration.

Permeability is immediately related to the void in the asphalt mixture, and low permeability is expected to improve the asphalt pavement durability. While many methodologies have been developed to measure the permeability of asphalt specimens, for this study, an air chamber device, as shown in Figure 7, was used to measure the air permeability of the specimens.

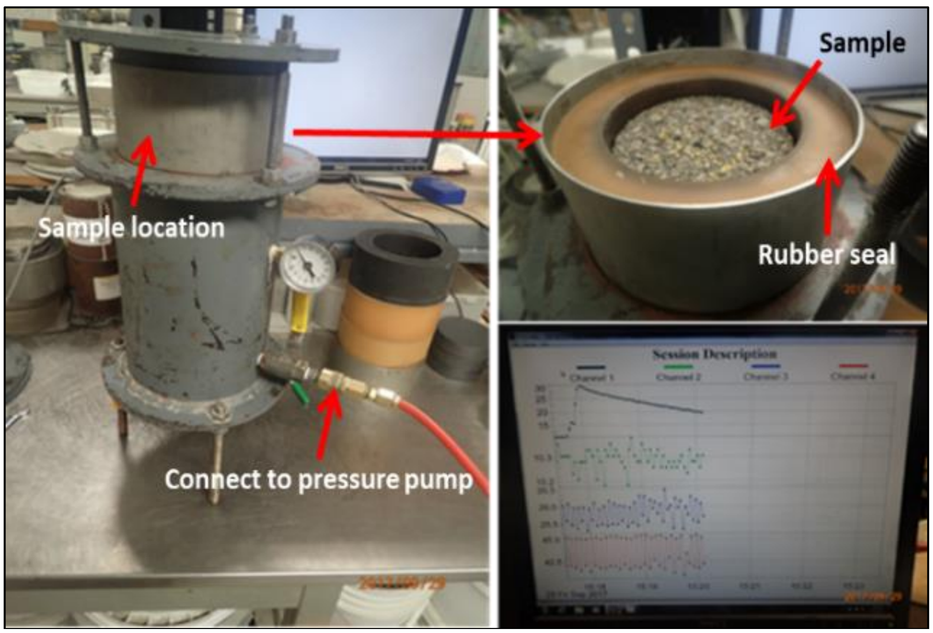

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Figure 7. Laboratory air permeability test setup

This device was originally designed and developed by the University of Innsbruck in Austria (Paulini 2010). The research team made some modifications to the device to serve the specific research needs under laboratory conditions.

As shown in Figure 7, the device consisted of a steel chamber and a rigid collar with a rubber ring inside of it. Each prepared specimen needs to be inserted into the rubber ring and fixed on top of the chamber, and then its upper surface is open to the atmosphere. An air gun was inserted at the bottom of this chamber to supply the airflow to pressurize the chamber. The inlet valve is kept open at the initial testing stage until the pressure reaches 21.75 psi; then, the outlet valve closes to start the measurement. The chamber has a pressure gauge connected to the computer to output the real-time plot of the falling pressure-time curve. After testing, all data obtained was plotted as $\ln(P_0/P_t)$ versus time t, where P_0 was the initial pressure and P_t was the pressure at time t.

The following Equation 1 was used to calculate the air permeability of a specimen:

$$k = 3.28 \times \frac{\omega V g d z}{R A \varphi}, \quad \textbf{(1)}$$

Where, k is the coefficient of air permeability (ft/s); ω is the molecular mass of air (1.02 oz/mol); V is the volume of air under pressure (ft^3); g is the acceleration due to gravity (32.2 ft/s^2); A is the cross-sectional area of the specimen (ft^2); d is the average specimen thickness (ft); φ is the temperature (K); z is the slope of the $\ln(P_0/P_t)$ versus t line; and R is the universal gas constant, 8.3145 J/K-mol.

This study investigated the penetration depth of RePLAY after application on the pavement surface. As shown in Figure 8, two types of flashlights and a yellow glass and camera with yellow filter were used to take the images for RePLAY-treated cores.

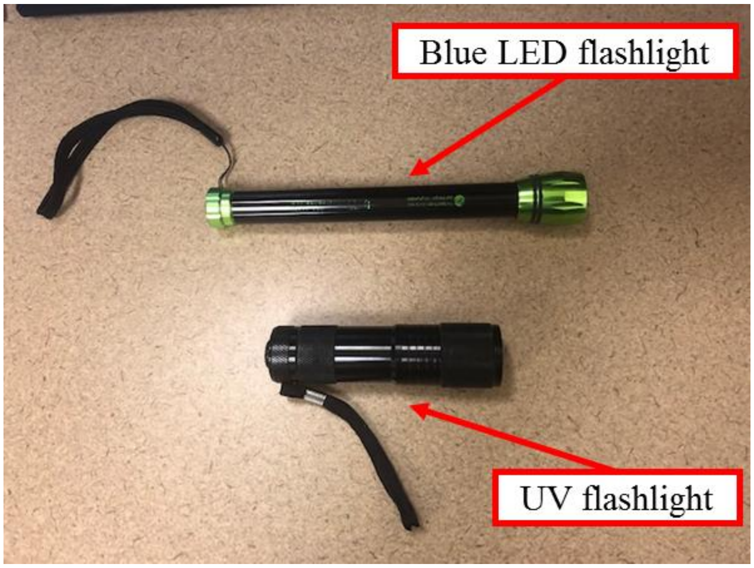


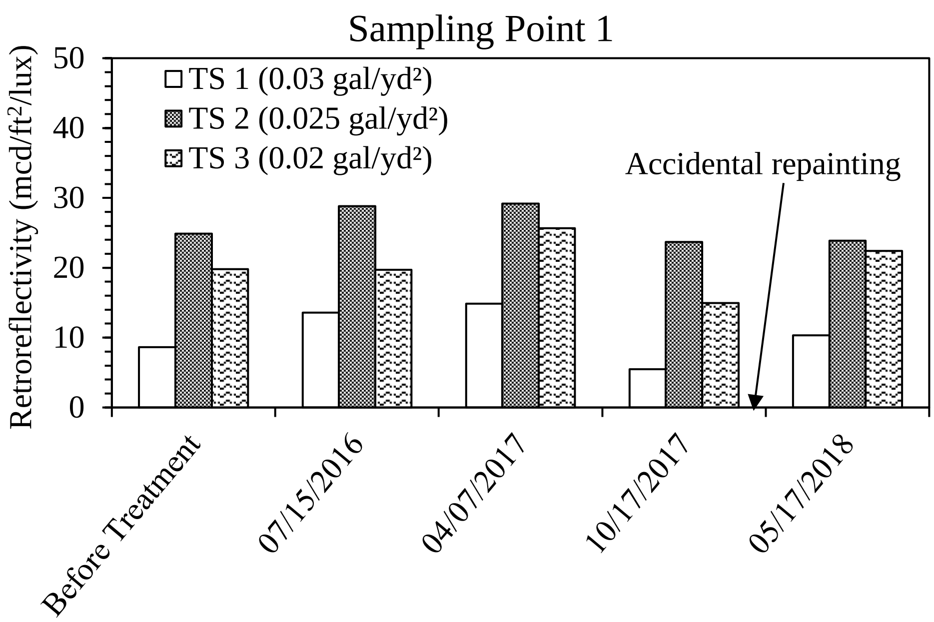
Figure 8. Flashlight for measurements of penetration depth

Based on the reports from BioSpan Technologies (2010), RePLAY materials and asphalt mixtures should have different colors under the blue light-emitting diode (LED) and ultraviolet (UV) lights. In this study, cores collected from the RePLAY application site were split to observe the penetration depth.

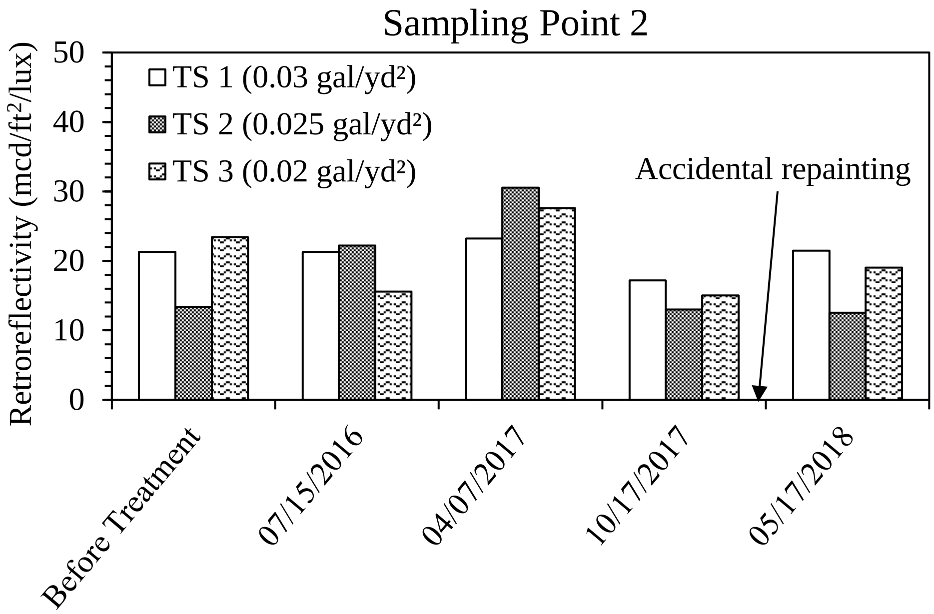
4. FIELD TEST RESULTS AND DISCUSSION

Retroreflectivity

The lane markers at the project site were durable paint pavement markings. The measurements of retroreflectivity included two spots at white lines. However, due to the accidental repainting activities on lines in the fall 2017, the measurements became incomparable after 2017. Consequently, the measurements were stopped after 2018. Figure 9 depicts the retroreflectivity of the pavement edge marking on both the treated and untreated sections at the project site before and after installation of RePLAY, indicating that the retroreflectivity of the edge line was restored within two weeks (July 15, 2016) after the application date of RePLAY (June 29, 2016).



(a)



(b)

Figure 9. Measured retroreflectivity on (a) sampling location 1 and (b) sampling location 2

The results also show that, at the TS 1 and TS 2 sections, the retroreflectivity at either sampling point did not reduce. But at the T3 section with the lowest application rate of 0.02 gal/yd^2, the second sampling point exhibited a reduction of 84 mcd/ft^2/lux in terms of retroreflectivity.

The essence of the retroreflectivity of these lane markers is the embedded glass beads in the painting materials. The beads render the illuminance from the headlights of vehicles to make the surface markings retroreflective. Hence, a surface treatment like a fog seal could reduce the retroreflective of the glass beads due to the covered and blocked retroreflective illuminance (Johnson 2018). Since the documented retroreflectivity at the treated sections before and two weeks after installation of this bio-based fog seal did not exhibit a significant difference, it indicated that the pavement surface had absorbed RePLAY.

Traffic wear, rain washing, and wind blowing also can contribute to the abrasion of remaining oil retained on the surface. The study conducted by Johnson (2018) presented the reduction in retroreflectivity of lane markers after spraying different fog sealants, including RePLAY products. Truck passes were implemented to observe the recovery of retroreflectivity, reporting that the RePLAY-treated section could recover its retroreflectivity after 1,600 truck passes. Subsequent measurements in 2017 and 2018 were performed in addition to 2016. The results of measurements in 2018 showed that the retroreflectivity was randomly changed after repainting. In summary, the negative impacts of RePLAY on the retroreflectivity of pavement markings were not observed two weeks after application. The potential reduction in retroreflectivity in the short-term due to the spraying of RePLAY could be fully recovered within two weeks.

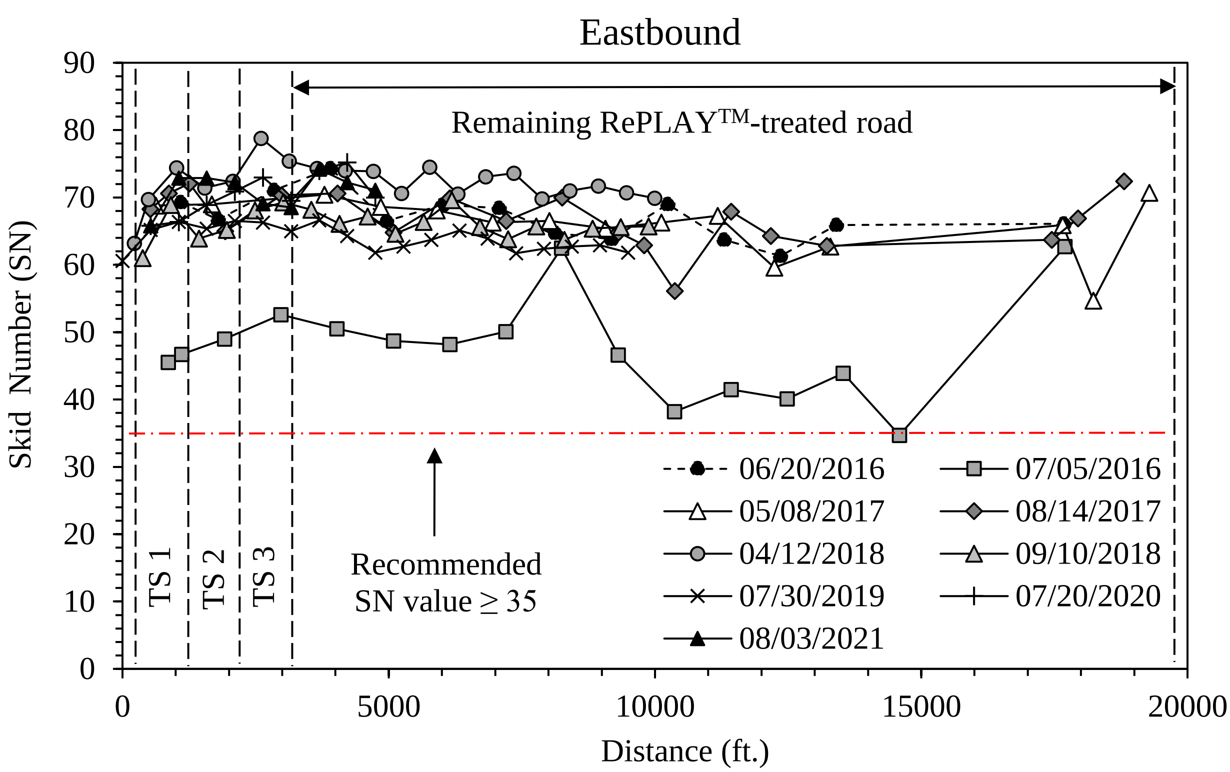
Friction

Skid Resistance

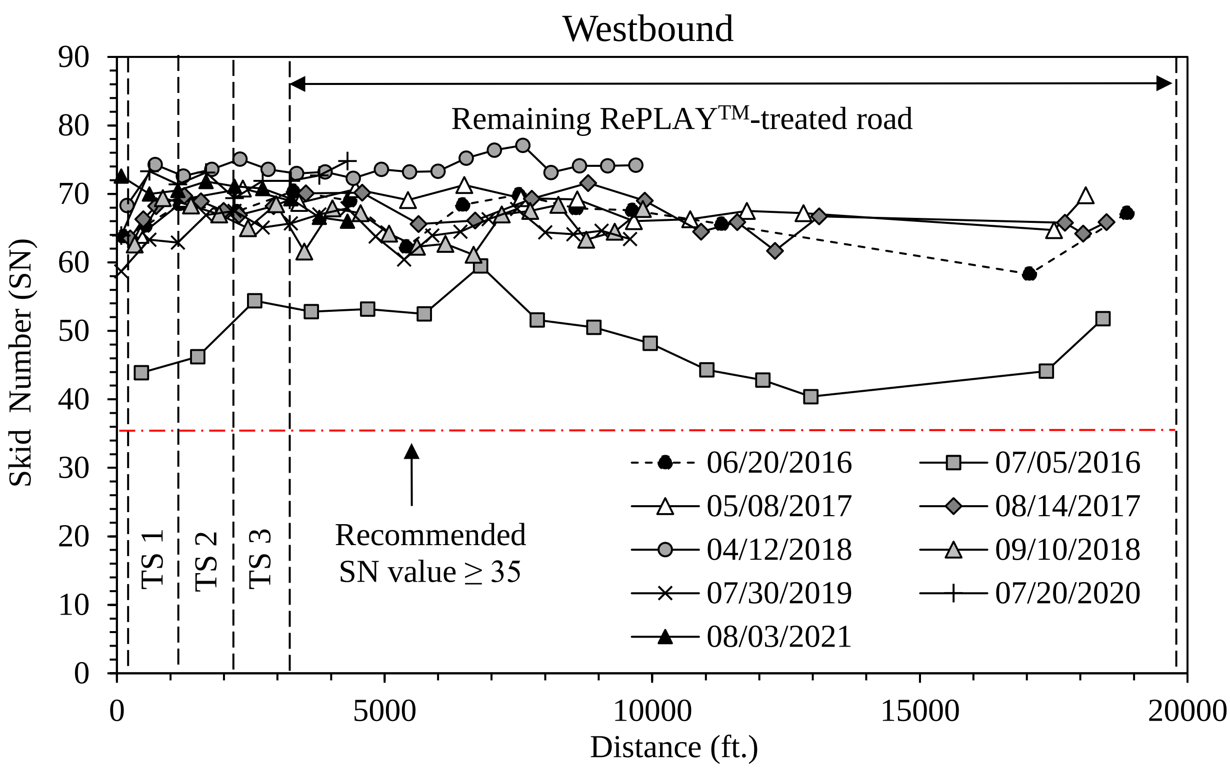
The effects of the RePLAY treatment on pavement surface friction are shown in Table 5 and Figure 10, which consist of the locked-wheel skid resistance test results (Figure 10a and Figure 10b) and British pendulum test results (Figure 10c and Figure 10d).

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

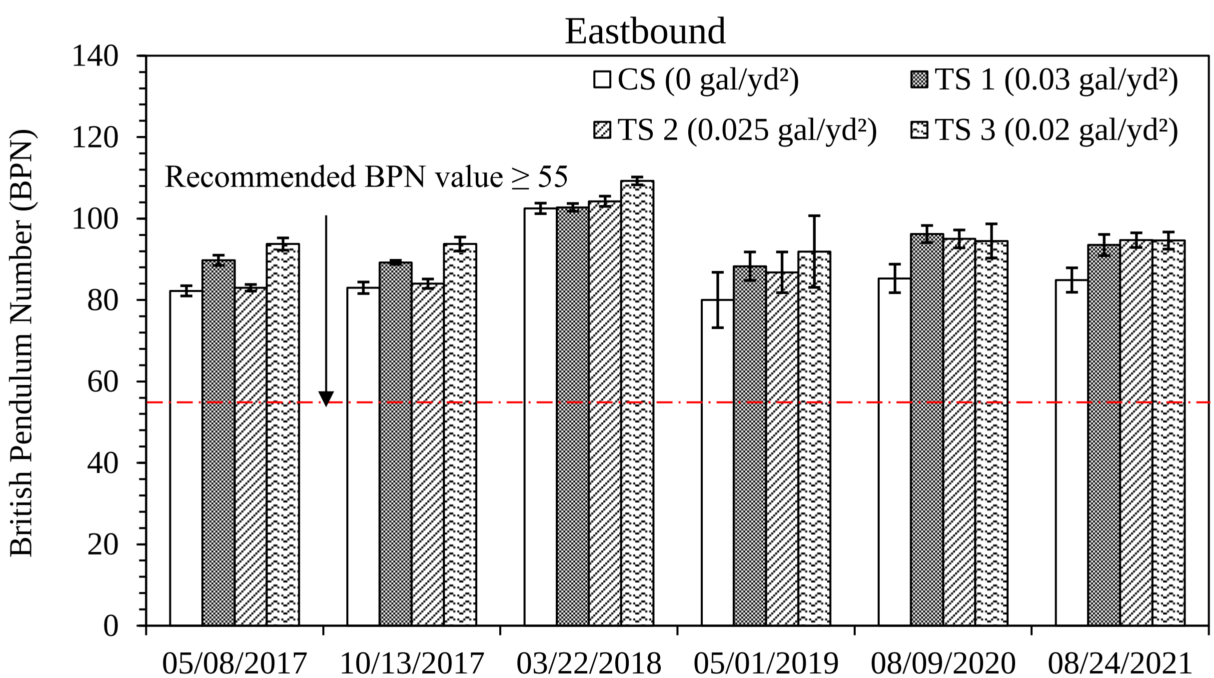
Measurement Date	SN of Eastbound	SN of Westbound
6/20/2016 (before application)	67.1 ± 3.2	66.9 ± 3.3
7/5/2016	47.6 ± 7.3	49.7 ± 5.2
5/8/2017	66.0 ± 4.1	68.5 ± 2.0
8/14/2017	66.8 ± 4.0	67.3 ± 2.4
4/12/2018	72.1 ± 3.0	74.0 ± 1.3
9/10/2018	66.0 ± 2.1	65.5 ± 2.5
7/30/2019	63.9 ± 1.8	65.1 ± 1.9
7/20/2020	70.4 ± 3.0	72.2 ± 1.5
8/3/2021	71.0 ± 2.5	69.4 ± 2.1



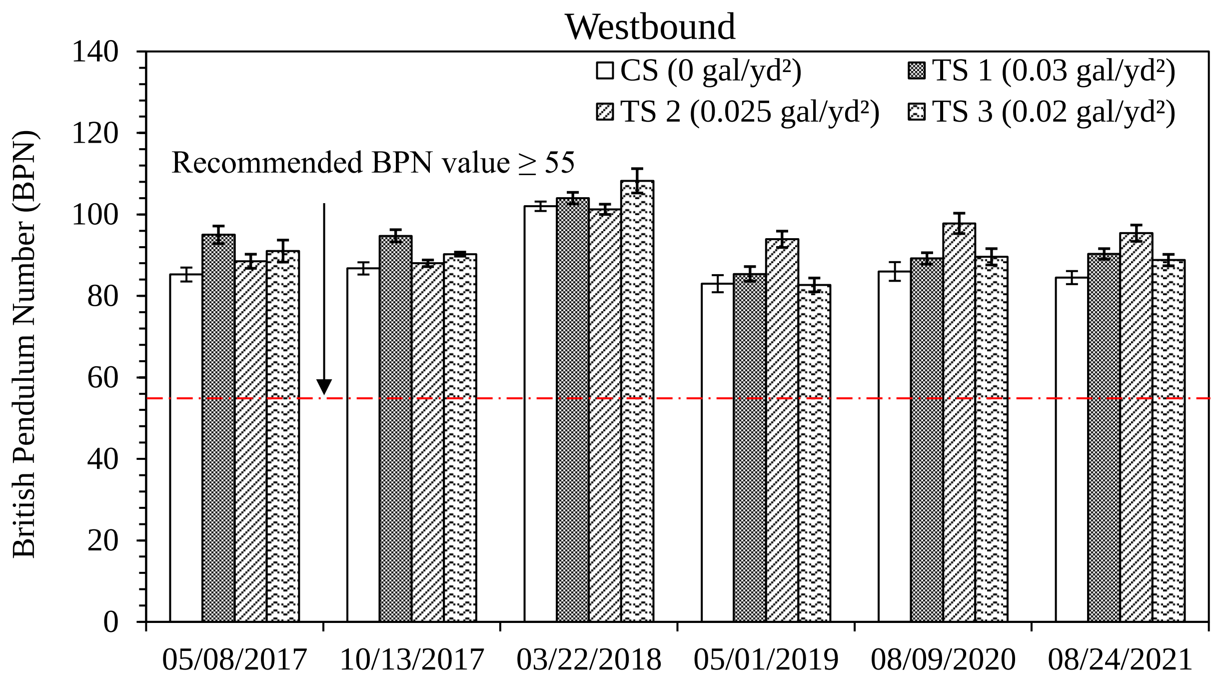
(a)


Westbound
Remaining RePLAY™-treated road
Skid Number (SN)
Distance (ft.)
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
07/20/2020
08/03/2021
0
10
20
30
40
50
60
70
80
90
0
5000
10000
15000
20000

(b)


Eastbound
British Pendulum Number (BPN)
CS (0 gal/yd²)
TS 1 (0.03 gal/yd²)
TS 2 (0.025 gal/yd²)
TS 3 (0.02 gal/yd²)
Recommended BPN value ≥ 55
0
20
40
60
80
100
120
140
05/08/2017
10/13/2017
03/22/2018
05/01/2019
08/09/2020
08/24/2021

(c)



(d)

Figure 10. Results of (a) SN for eastbound, (b) SN for westbound, (c) BPN for eastbound, and (d) BPN for westbound

The measurements were conducted at the wheel paths in both the eastbound and westbound lanes. The effects of skid resistance in both the eastbound lane and the westbound lane depict the significant reduction in SN on July 5, 2016. The average SN of the project road prior to the application of RePLAY was 67 and, then, had decreased to 49 within the first week after treatment. However, the follow-up measurements conducted in May 2017 showed that the SN was restored to 67, almost the same as the original SN.

Many studies have suggested that the application of a fog sealant could fill the surface texture of the pavement, resulting in reduced skid resistance (Lu and Steven 2006, Cheng et al. 2015, Abaza et al. 2017). However, the reduced SN could be restored within a few months because the sealants were worn away from continuous tire wearing (Prapaitrakul et al. 2005, Johnson 2018).

The measurements at the initial stage observed the considerable reduction in SN on the RePLAY-treated sections, and the higher the application rate, the lower the skid resistance. This is a reasonable finding that agreed with the observations from previous studies.

While the RePLAY treatments on the project site led to the reduced SN at the early stage, the values were all acceptable and above the recommended threshold limit of 35 (Wambold 1998). Within the 11 months after spraying, all four RePLAY-treated sections showed the restoration in skid resistance. Considering the reduction of 14 in the average SN, a minimum SN of 50 for the roadway is required before spraying RePLAY to avoid the safe driving issue of an SN less than 35.

British Pendulum Test

Figure 10c and d present the results of the British pendulum tests between untreated sections and RePLAY-treated sections. The average BPN with the standard deviation were compared, illustrating that the higher frictions were consistently observed in the treated sections for both the eastbound and westbound lanes. All BPNs, including those for the control section, were above the recommended BPN of 55 (Wambold 1998). In fact, since the BPN measurements were not initially scoped in this study, the results before the bio-based fog seal were not documented.

The first British pendulum test was conducted on May 8, 2017, almost 11 months after spraying. At this stage, the friction of the treated sections had been restored, and the researchers were unable to evaluate the early reduction in BPN due to the fog seal application. The latest measurements of BPN were performed on August 24, 2021, and the results showed that the BPNs at the RePLAY-treated sections were still higher than that of the control section, although the differences were not significant. These findings indicate that the bio-based sealing agent, RePLAY, could maintain the required surface friction of the pavement.

Friction Results Summary

The field results due to the surface friction from both the British pendulum tests and skid resistance tests indicated that the spraying of RePLAY could reduce the surface friction of pavement in the first few weeks. However, it would be restored within a year.

Prapaitrakul et al. (2005) indicated that the friction of newly constructed asphalt pavement could keep increasing during the first two years due to the loss of binder. Then, the reduction in friction was observed due to the polished aggregate. They also claimed that the friction in fall and winter were typically higher than that of spring and summer (Ahammed and Tighe 2010, Zhang et al. 2019, Zhang et al. 2018, Kaya et al. 2019).

In this study, the highest SNs and BPNs were measured on April 12, 2018, indicating that the project site was currently identified in the stage of reduced friction due to the polished aggregate. The latest measurements in the summer of 2021 showed that the surface friction was maintained after the RePLAY treatments. In conclusion, while the application of RePLAY at the rate up to 0.03 gal/yd^2 on the pavement surface could lead to a reasonable reduction in surface friction in terms of SN and BPN in the early stage, the native effects could be reversed and restored after several months.

Distress Survey

This study evaluated crack resistance annually by conducting a manual distress survey. Cracking records collected from the field before and after spraying are listed in Table 6, and cracking images are included in the Appendix.

Table 6. Cracking survey at the installation site with 100 ft control section and remaining 14,300 ft section

Section	Survey Date						
	6/29/2016 (before application)	4/13/2017	10/13/2017	3/22/2018	5/11/2019	8/9/2020	8/24/2021
CS	No distress	No distress	No distress	No distress	2T (1T)	3T (1T)	4T (1T)
TS 1	2T	2T	2T	3T (1T)	20T (4T)	21T (4T)	22T (4T)
TS 2	2T	2T	2T	3T (2T)	8T (4T)	12T (6T)	12T (6T)
TS 3	No distress	No distress	No distress	No distress	9T (2T)	9T (2T)	9T (2T)
RS	45T –	45T 2L	46T 2L	47T 2L	95T 2L	99T 3L	101T 3L

T: transverse cracking, L: longitudinal cracking
The number not in the parentheses is the total amount of cracking
The number in the parentheses is the amount of cracking caused by the coring activities

Table 7 also shows the results of the cracking surveys, but it normalizes the length of the control and remaining sections to 1,000 ft for comparsion purposes.

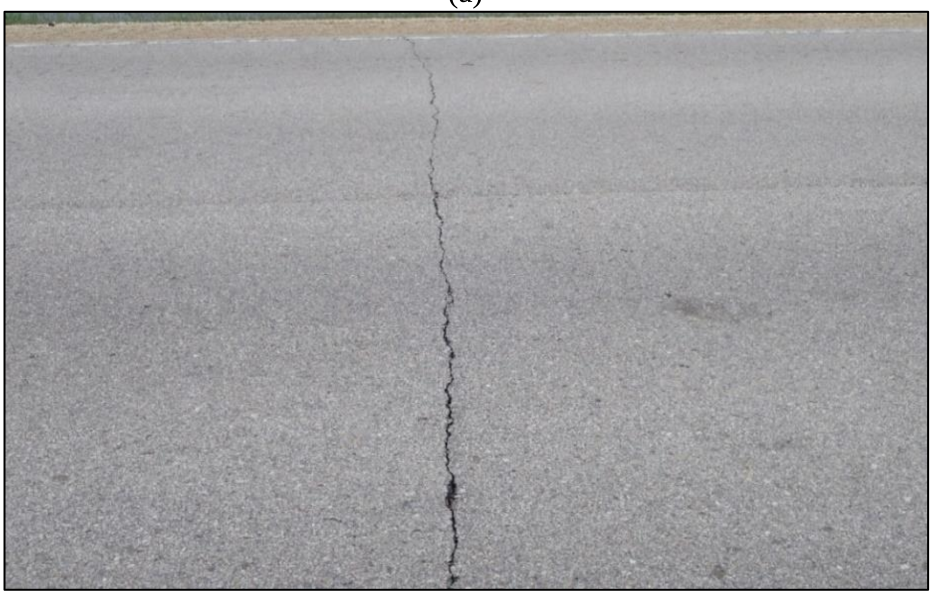
Table 7. Cracking survey at the installation site with the control and remaining sections normalized to 1,000 ft

Section	Survey Date						
	6/29/2016 (before application)	4/13/2017	10/13/2017	3/22/2018	5/11/2019	8/9/2020	8/24/2021
CS	No distress	No distress	No distress	No distress	20T (10T)	30T (10T)	40T (10T)
TS 1	2T	2T	2T	3T (1T)	20T (4T)	21T (4T)	22T (4T)
TS 2	2T	2T	2T	3T (2T)	8T (4T)	12T (6T)	12T (6T)
TS 3	No distress	No distress	No distress	No distress	9T (2T)	9T (2T)	9T (2T)
RS	4T	4T 1L	4T 1L	4T 1L	7T 1L	7T 1L	7T 1L

T: transverse cracking, L: longitudinal cracking
The number not in the parentheses is the total amount of cracking
The number in the parentheses is the amount of cracking caused by the coring activities

The actual length of the control section was only 100 ft. At the Clinton County project site, only longitudinal and transverse cracking types were observed. In fact, transverse cracking, which is an environment-related issue (i.e., low temperature), was the primary cracking type in this area. Figure 11a and Figure 11b depict sealed and unsealed transverse cracking, respectively, for the treated sections.

(a)



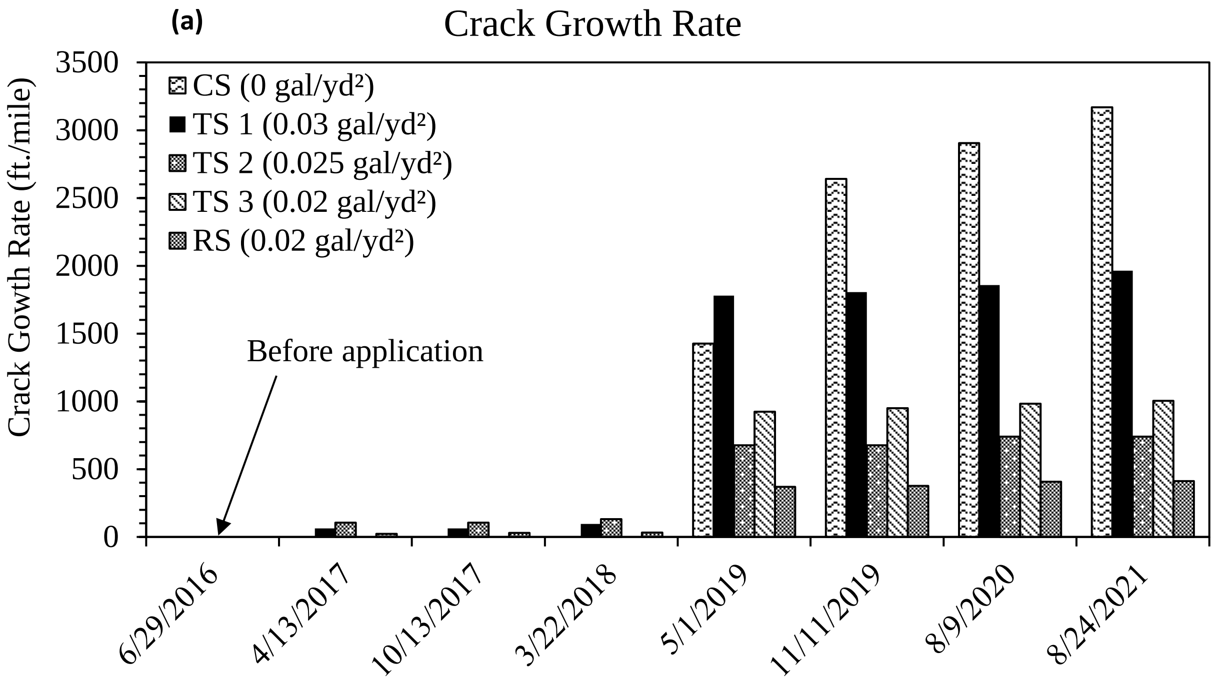
(b)

(c)

Figure 11. (a) Sealed crack, (b) unsealed crack, and (c) crack caused by coring activities

As shown in Figure 11c, some coring locations exhibited cracking over time. The coring activities created the weak spots in the pavement. In 2016, before RePLAY installation, all cracking was unsealed, while after installation, cracking was sealed through 2017. As shown in the previous Table 6, cracking records show that about 80 new cracking occurrences were identified in 2019, almost three years after application.

The crack growth rate results depicted in Figure 12a and Figure 12b show that sections treated at the lowest application rate exhibited the lowest crack growth rate, while the control section had the highest crack rate according to the latest survey in 2021.



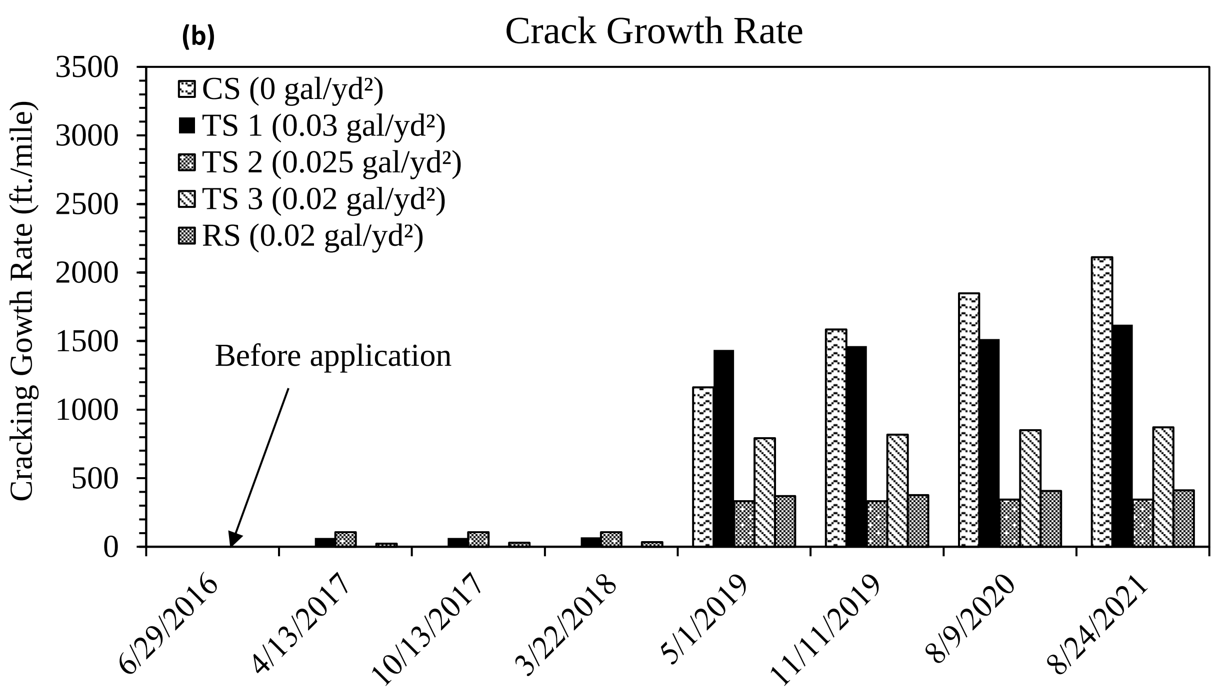


Figure 12. Growth rate of transverse cracking at testing sections: (a) including cracking caused by coring activities and (b) removing cracking caused by coring activity

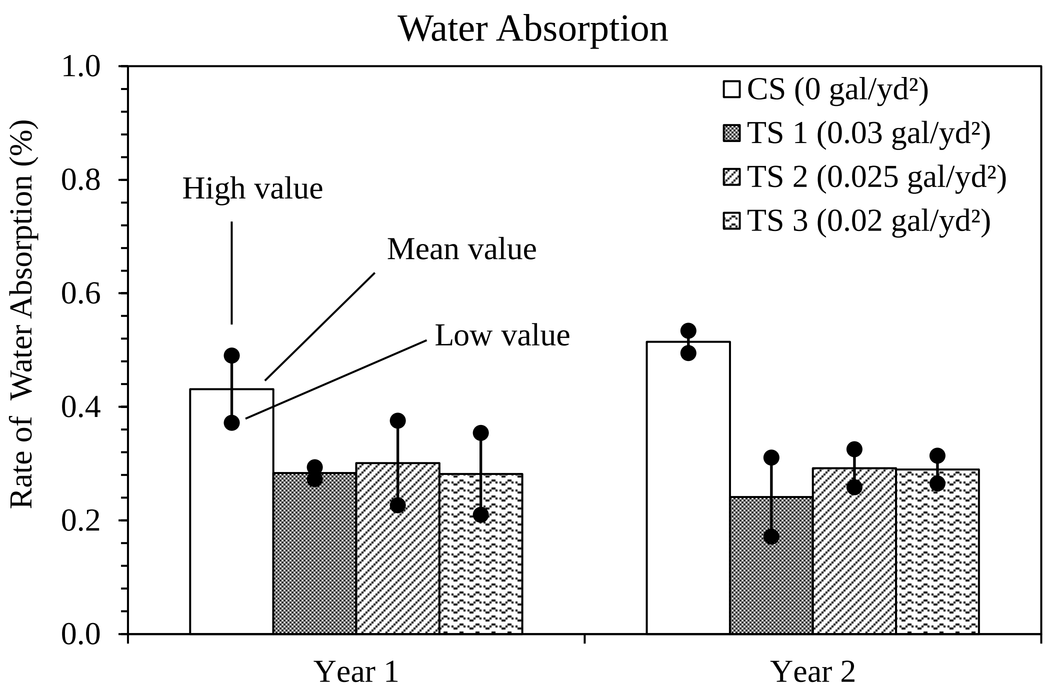
In Figure 12b, the cracking caused by the coring activity was removed, resulting in the lower crack growth rates for all sections. The lower transverse cracking in the RePLAY-treated sections was due to oxidation process reversal. While investigations by Ghosh et al. (2016) and

Johnson (2018) indicated that a bio-fog sealant could soften the asphalt binder and reduce the distress, Johnson (2018) reported that a RePLAY-treated section exhibited a higher crack growth rate than an untreated section. In summary, RePLAY applied at the lowest rate of 0.02 gal/yd^2 was most effective in slowing surface deterioration, and that a benefit could be maintained for at least five years.

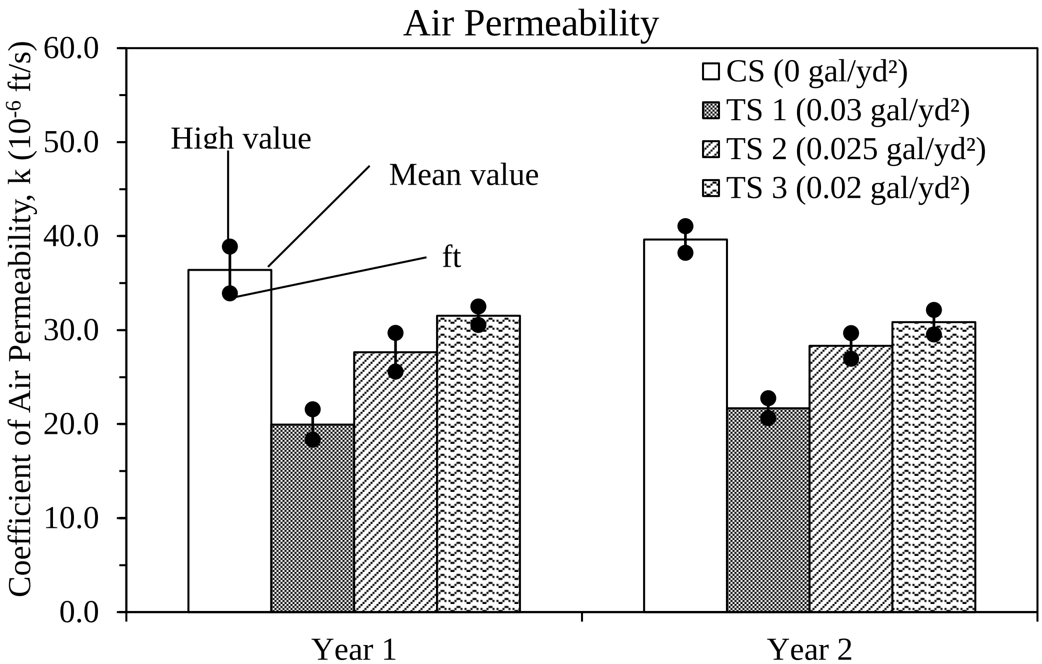
5. LABORATORY TEST RESULTS AND DISCUSSION

Water Absorption

The water absorption results for core specimens collected in 2017 (Year 1) and 2018 (Year 2) are shown in Figure 13a.



(a)



(b)

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Figure 13. Test results for (a) water absorption and (b) air permeability

The Year 1 specimens with RePLAY treatment displayed lower water absorption than that of the untreated specimens. Both cores from TS 1 exhibited similar results, but cores from TS 2 and TS 3 had one specimen that showed similar absorption to the one specimen from the untreated section. For the cores taken from 2018, the follow-up water absorption testing that was conducted revealed that the TS 1 specimens presented the lowest water absorption capacity. However, the TS 2 and TS 3 specimens exhibited slightly higher water absorption than that of the TS 1 specimens, while still significantly lower than that of the control specimens.

In general, the specimens with the highest application rate of RePLAY were associated with the lowest water absorption, and the untreated specimens showed the most elevated values. The results indicated that the bio-based sealant, RePLAY, could fill voids in the asphalt matrix to decrease the water absorption due to its excellent flowability. The benefits of void-filling could reduce air and moisture and improve oxidation and water penetration resistance in the asphalt pavement. The results indicated that the reduction in the RePLAY application rate could increase water absorption.

Air Permeability

The results from the air permeability tests are presented in Figure 13b and reflect that the RePLAY-treated specimens had a lower permeability than the untreated specimens. Johnson (2018) also reported that RePLAY could benefit the permeability of asphalt specimens. Both sets of core specimens from 2017 and 2018 showed similar trends in that the increase in the application rate of the sealant could result in a reduction in permeability.

The researchers were satisfied that the void-filling ability of RePLAY can maintain these effects for at least two years. Moreover, the conclusions from water absorption and air permeability results were similar, revealing that the higher spray rate could lead to decreased voids by preventing air and moisture in the pavement structure. Given that excessive water in the pavement system could damage the base course and subgrade soils, resulting in structural deterioration (Yang et al. 2018), lower water absorption and permeability are desired properties to resist environmental damage from oxidation and freeze-thaw cycles that are due to seasonal temperature and moisture variations.

Depth of Penetration

After the air-permeability tests, the core specimens were sawed to observe their internal conditions using a blue LED flashlight and a UV flashlight and determine the depth of RePLAY penetration (see Figure 14 and Figure 15).

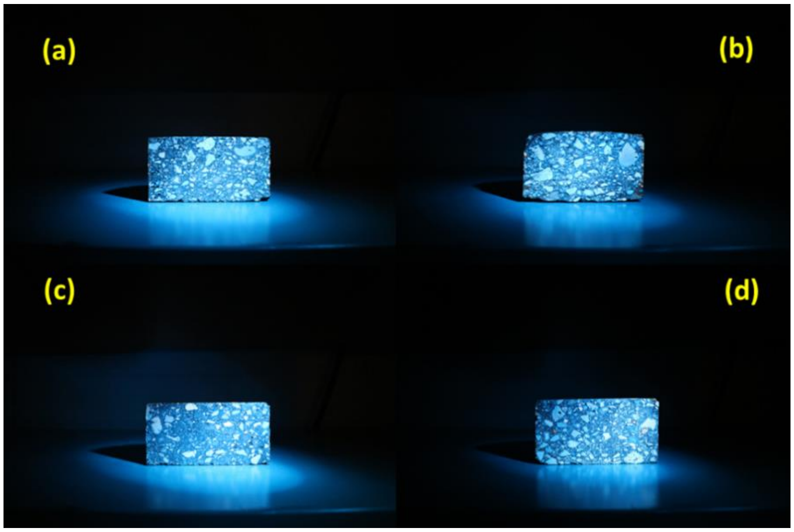


Figure 14. LED images of specimens from (a) control, (b) TS 1, (c) TS 2, and (d) TS 3 sections

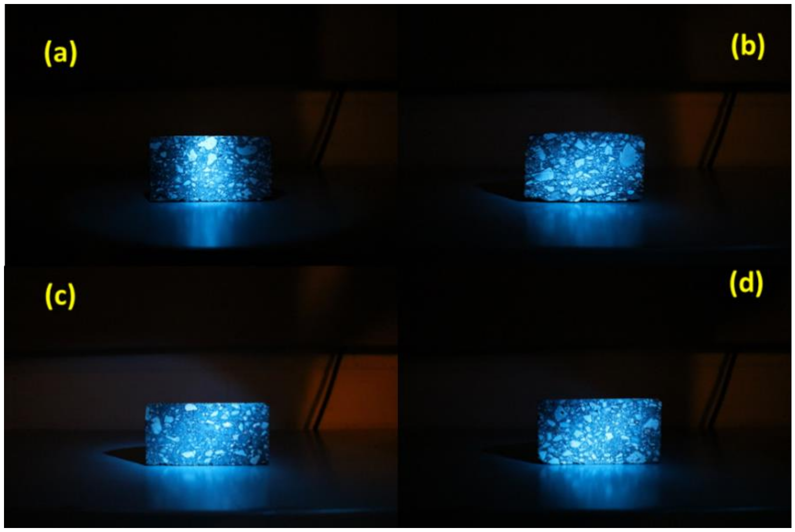


Figure 15. UV images of specimens from (a) control, (b) TS 1, (c) TS 2, and (d) TS 3 sections

No clear penetration of RePLAY material was observed under either the blue LED or UV lights. RePLAY materials in the specimens were probably evaporated or absorbed by the aggregate, resulting in a visualization challenge. In support of this conclusion, Ghosh et al. (2016) and Johnson (2018) performed Fourier transform infrared (FTIR) absorption spectroscopy evaluations for RePLAY-treated specimens and detected no trace of sealant, and the researchers hypothesized that the RePLAY had evaporated or had been absorbed by the aggregate.

6. LIFE-CYCLE COST ANALYSIS

LCCA Model

The selection of appropriate strategies to preserve pavement should consider the effectiveness and financial viability of a sealant; LCCA is a tool for performing economic analysis of different preservation methods, assisting the engineering decision-making process by considering cost-effectiveness (FHWA 2002, Pittenger et al. 2011).

The most typical way to evaluate cost-effectiveness is the net present value (NPV) method, which uses the analysis period as its critical input (Pittenger et al. 2011). NPV calculation determines the current total value by considering cash inflows and outflows of a future stream, and Equation 2 shows how NPV is calculated (FHWA 2002).

$$NPV = F \times 1/\left(1+i\right)^{n}, \tag{2}$$

Where, F is future value ($); i is the discount rate (%), and n is the analysis period (year).

While the NPV model has become a standard method for judging the cost of various options, the comparison is unfair when different analysis periods are selected (Pittenger et al. 2011). The equivalent uniform annual cost (EUAC) method is an approach for evaluating options with varying years of service. It avoids the challenges of analysis periods by converting all items to an annual cost. The calculation of EUAC is show in Equation 3.

$$EUAC = \sum P \times \left[\left(i\left(1+i\right)^{n} \div \left(1+i\right)^{n} - 1\right)\right], \tag{3}$$

Where, P is the present value ($); i is the discount rate (%), and n is the analysis period (year).

In this study, application of RePLAY was expected to extend pavement service life and result in different analysis periods. With respect to the available modeling and inputs in LCCA, the EUAC model was utilized to evaluate the annual cost of using RePLAY as an alternative fog-seal method.

Treatment Inputs and Scenarios

LCCA is sensitive to inputs such as treatment cost and service life. In this study, the 2016 contract document from the Clinton County engineer reflected a total construction cost of RePLAY for the project site of $81,568.50, including labor, equipment, and material costs. The entire project site was 3.3-miles long and 20-ft wide, corresponding to a RePLAY unit installation cost of $\$2.12/yd^2$, which was nearly the same as the cost of $\$2.22/yd^2$ reported in Minnesota by Johnson (2018).

The pavement service life of CR E-63/Y-32 was assumed to be 20 years without any RePLAY treatment, and the extended service life after RePLAY treatment was calculated based on the crack growth rates shown in the previous Figure 12.

This calculation assumes that, once the total cracking length in the treated site increases to the level of untreated pavement at the end of the service life (20 years), the road will fail to serve and require reconstruction of a new asphalt surface or rehabilitation of the existing pavement. A Minnesota study (Nahvi et al. 2021) estimated the construction cost of a 6 in. bituminous and a 6 in. aggregate to be about $\$35/yd^2$, and, for this study, $\$40/yd^2$ was estimated for reconstruction cost, including removing the existing pavement surface and paving with new asphalt materials.

For the rehabilitation case, this study assumed using cold-in-place recycling for existing surface reclamation. The estimated cost was $\$25/yd^2$ based on the information provided by the Clinton County engineer, Todd Kinney. Given the coring activity caused some cracking, it could affect the crack growth rate and result in a different service life using the LCCA model. Therefore, this study created four different scenarios by considering the causes of cracking and options at the end of the pavement service life, as follows:

- Scenario A is one that reconstructs a new surface after the service life and counts all cracking, including the coring-related cracking
- Scenario B is a rehabilitation scenario instead of reconstruction that also counts all cracking, including the coring-related cracking
- Scenario C is a reconstruction scenario, but the coring-related cracking is eliminated for estimating the crack growth rate
- Scenario D is a rehabilitation scenario, but the coring-related cracking is eliminated for estimating the crack growth rate

Given the elimination of coring-related cracking influenced the total crack length etimations, total cracking lengths of untreated cases at a 20 year-service life with coring-related cracking (Scenario A and B) and without coring-related cracking (Scenario C and D) were estimated as about 9,500 ft and about 6,300 ft, respectively, to estimate the extended service life for treated cases.

As another vital input, this study also considered the effective period of RePLAY treatment. The effective period in this study was defined as the period over which RePLAY can preserve the pavement surface.

Shatnawi (2014) indicated that the effective period of RePLAY varied between three and five years. In this study, the treated sections were assumed to deteriorate similarly to the untreated section and to have the same crack growth rate as with no re-application at the end of the effective period. In addition to RePLAY application and reconstruction, the cracks would require repair and sealing every year, and the typical cost of crack sealing is estimated to be $1/ft. (Savemyroad 2021b).

To analyze the cost-effectiveness of RePLAY during the life cycle of the pavement, cases with various inputs were evaluated, and Table 8 and Table 9 show the seven cases in each scenario assessed in this study.

Table 8. Crack growth rate and sealing cost for different cases in Scenario A and B

Cases	Treatment Scenario	Estimated Effective Period for One Treatment (year)	Yearly Crack Growth Rate during Effective Period (ft/mile/year)	Yearly Cost of Crack Sealing during Effective Period	
				$/mile	$/yd^2
Untreated Case	No	N/A	634	634	0.055
Case 1-a	One time	3	343	343	0.029
Case 1-b	Re-apply	3	343	343	0.029
Case 2-a	One time	4	258	258	0.022
Case 2-b	Re-apply	4	258	258	0.022
Case 3-a	One time	5	206	206	0.018
Case 3-b	Re-apply	5	206	206	0.018

Table 9. Crack growth rate and sealing cost for different cases in Scenario C and D

Cases	Treatment Scenario	Estimated Effective Period for One Treatment (year)	Yearly Crack Growth Rate during Effective Period (ft/mile/year)	Yearly Cost of Crack Sealing during Effective Period	
				$/mile	$/yd^2
Untreated Case	No	N/A	422	422	0.037
Case 1-a	One time	3	271	271	0.024
Case 1-b	Re-apply	3	271	271	0.024
Case 2-a	One time	4	203	203	0.018
Case 2-b	Re-apply	4	203	203	0.018
Case 3-a	One time	5	162	162	0.014
Case 3-b	Re-apply	5	162	162	0.014

The untreated case is the 20-year design service life asphalt pavement case without RePLAY treatment. Cases 1a and 1b, 2a and 2b, and 3a and 3b are the cases reflecting RePLAY treatment with effective periods of three, four, and five years, respectively. Subcase "a" was designed for one-time treatment only, while subcase "b" would re-apply RePLAY at the end of each effective period until the 20 service years of the untreated case had elapsed.

The crack growth rates derived from the previous Figure 12 were converted to a yearly basis and associated with a crack sealing cost of $1/ft. In total, 28 cases for four scenarios were evaluated, as documented in this chapter.

Table 10 and Table 11 show the inputs for each case and scenario, where a discount rate of 5% was used.

Table 10. Various cases utilized in Scenario A and B for LCCA at 5% discount rate

Cases	Treatment Times	Total Effective Period (year)	Service Life (year)	Extended Service Life (year)
Untreated Case	0	0	20.0	0
Case 1-a	1	3	21.4	1.4
Case 1-b	5	15	26.9	6.9
Case 2-a	1	4	22.4	2.4
Case 2-b	4	16	29.5	9.5
Case 3-a	1	5	23.4	3.4
Case 3-b	3	15	30.1	10.1

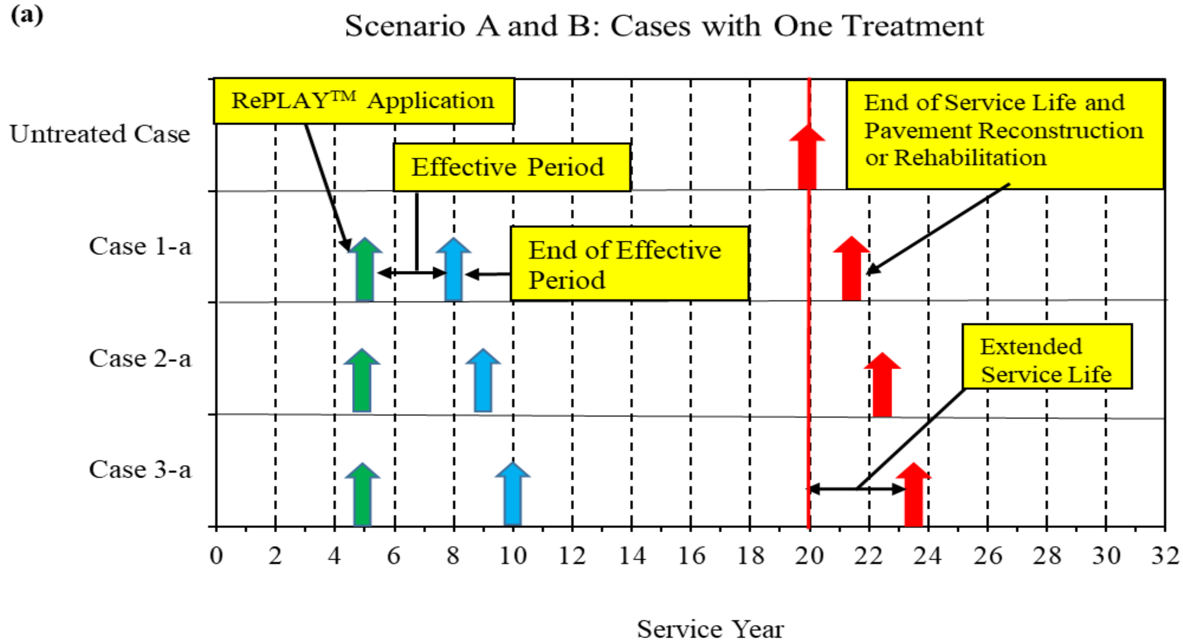
Table 11. Various cases utilized in Scenario C and D at 5% discount rate

Cases	Treatment Times	Total Effective Period (year)	Service Life (year)	Extended Service Life (year)
Untreated Case	0	0	20.0	0.0
Case 1-a	1	3	21.1	1.1
Case 1-b	5	15	25.4	5.4
Case 2-a	1	4	22.1	2.1
Case 2-b	4	16	28.3	8.3
Case 3-a	1	5	23.1	3.1
Case 3-b	3	15	29.2	9.2

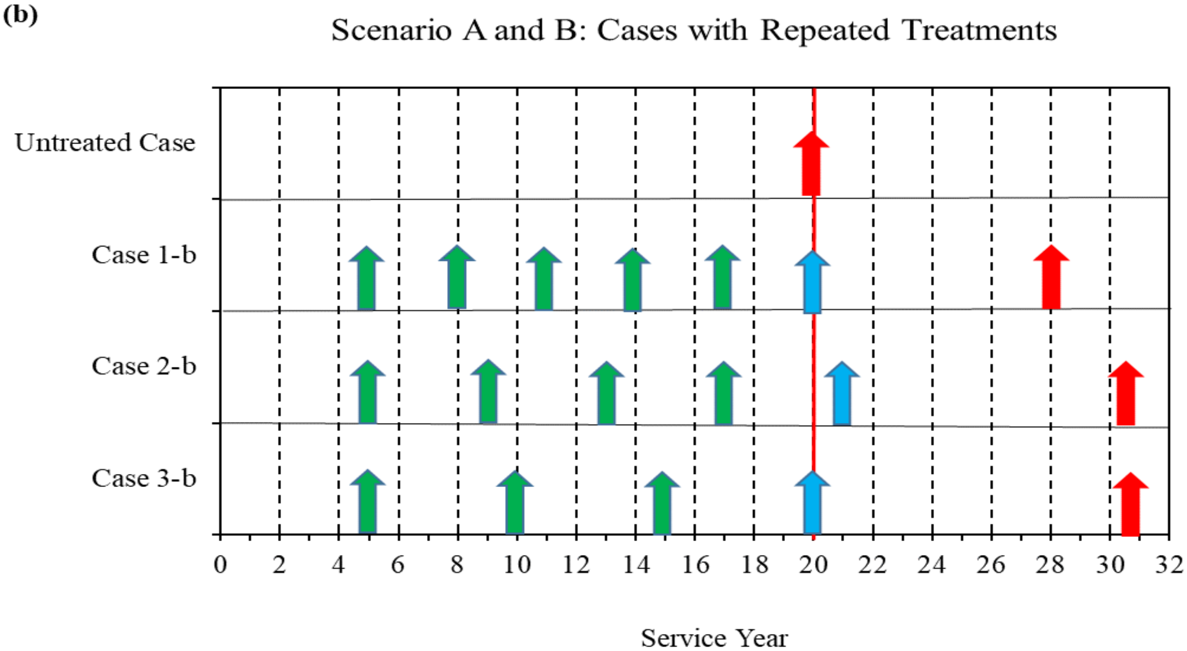
The extended service life was calculated based on the yearly crack growth rates shown in the previous Table 8 and Table 9, with the result that Case 3-b had the most extended service life for all scenarios. The treatment times depended on the effective period for each case, and the shorter effective period in the re-application scenario required more treatments.

The project site in Clinton County was initially constructed in 2011, and five years later, in 2016, it received the RePLAY application and crack sealing. To simulate the actual construction and preservation schedules, all cases with treatment were assumed to start with the first RePLAY treatment and crack sealing in the fifth year. Figure 16 provides a diagram for each case and scenario and indicates the different applications and reconstruction or rehabilitation schedules.

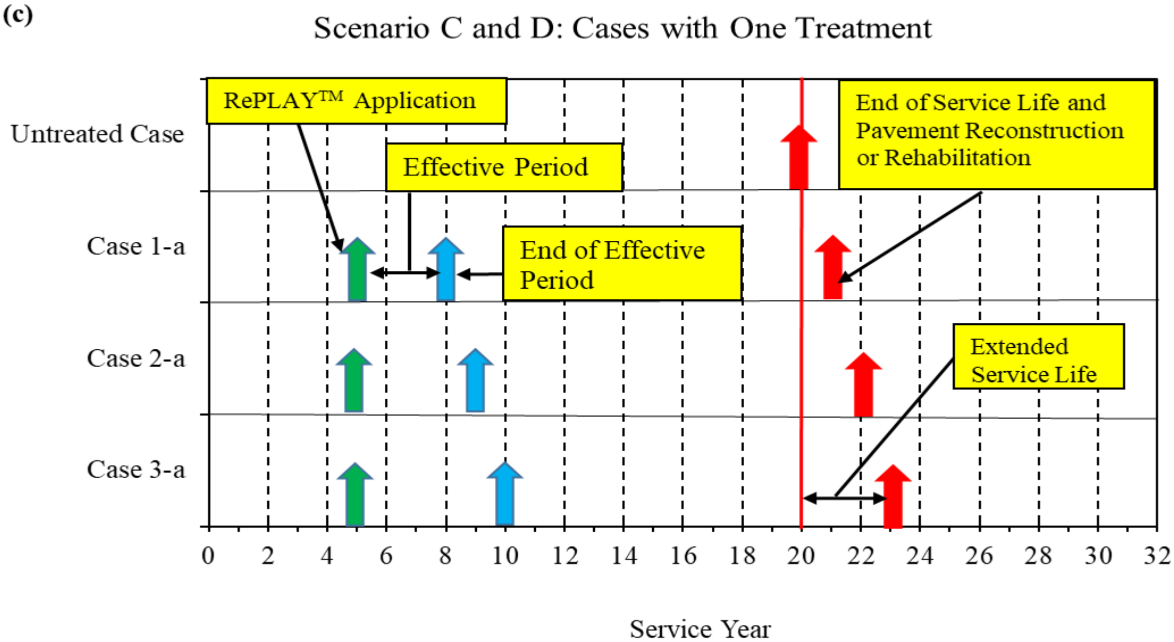
(a)


Scenario A and B: Cases with One Treatment
Untreated Case
Case 1-a
Case 2-a
Case 3-a
RePLAYTM Application
Effective Period
End of Effective Period
End of Service Life and Pavement Reconstruction or Rehabilitation
Extended Service Life
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Service Year

(b)


Scenario A and B: Cases with Repeated Treatments
Untreated Case
Case 1-b
Case 2-b
Case 3-b
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Service Year

(c)



(d)

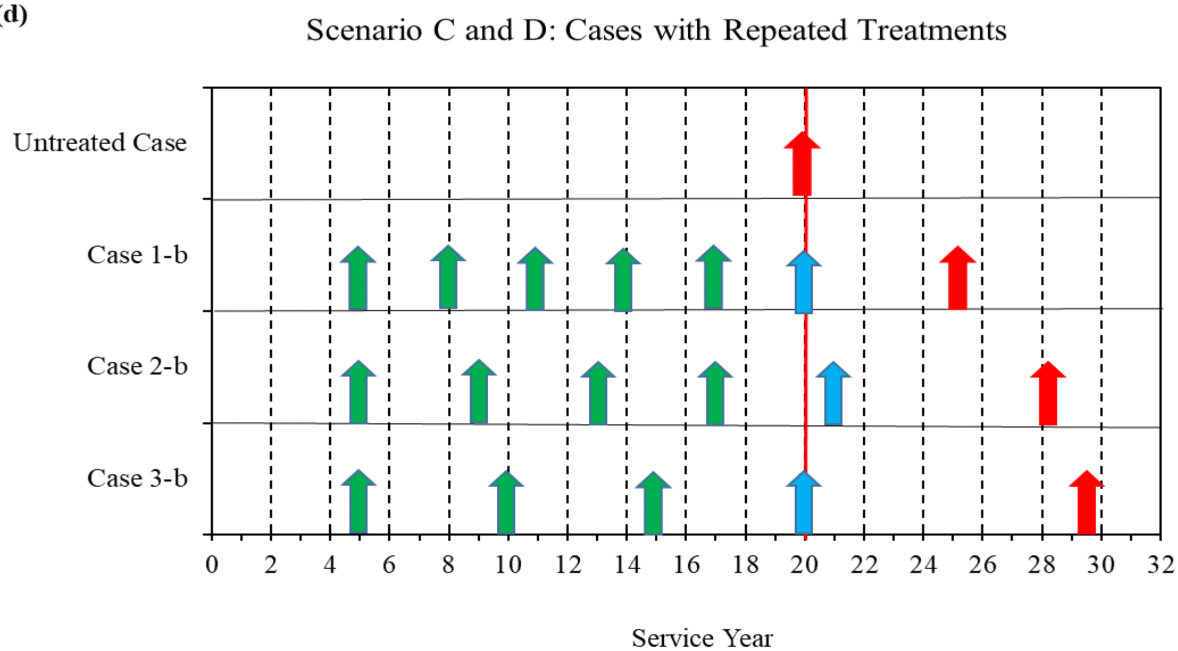


Figure 16. Cases for untreated pavement and RePLAY-treated pavement: (a) one-time treatment in Scenario A and B, (b) repeated treatments in Scenario A and B, (c) one-time treatment in Scenario C and D, and (d) repeated treatments in Scenario C and D

The EUAC calculations relied on the cash flow indicated in Figure 16, and, to perform the calculations using the EUAC model, reasonable assumptions and estimations based on the performance of the project site in Clinton County were used. All inputs, including the assumed values, can be summarized as follows:

- Four scenarios were assessed, and each scenario had seven cases, including an untreated case, three one-time application cases, and three re-application cases.

- The analysis period for each case was the estimated service life value shown in the previous Table 8 and Table 9.

- The pavement was assumed to experience three action activities during the analysis period: RePLAY application, reconstruction or rehabilitation, and crack sealing.

- In the untreated case, the pavement would experience reconstruction or rehabilitation and crack sealing only.

- The unit costs of reconstruction and rehabilitation used were $40/yd^2 and $25/yd^2, respectively.

- The RePLAY installation cost used was $2.12/yd^2. The estimated costs of crack sealing for the different cases are shown in the previous Table 8 and and Table 9.

- It was assumed that no cracking occured at the site within the first five years. Crack sealing was intended to represent an annual cost from the fifth year to the end of the pavement service life.

- The first RePLAY application occured in Year 5.

- Three, four, and five effective years were associated with five, four, and three treatments for the re-application cases, respectively.

- The discount rate used was 5%.

Given these inputs, with some of them derived from the assumptions, the results and conclusions could differ with changed inputs.

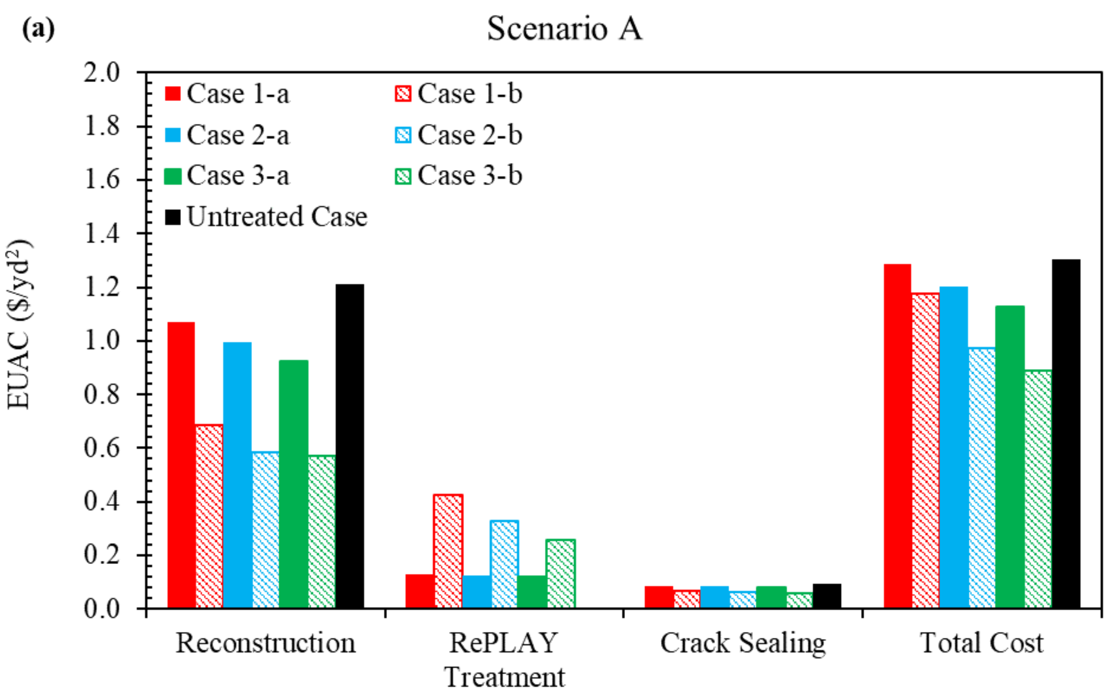
EUAC Results and Discussion

Table 12 and Figure 17 show the results of the EUAC analysis for the four different scenarios.

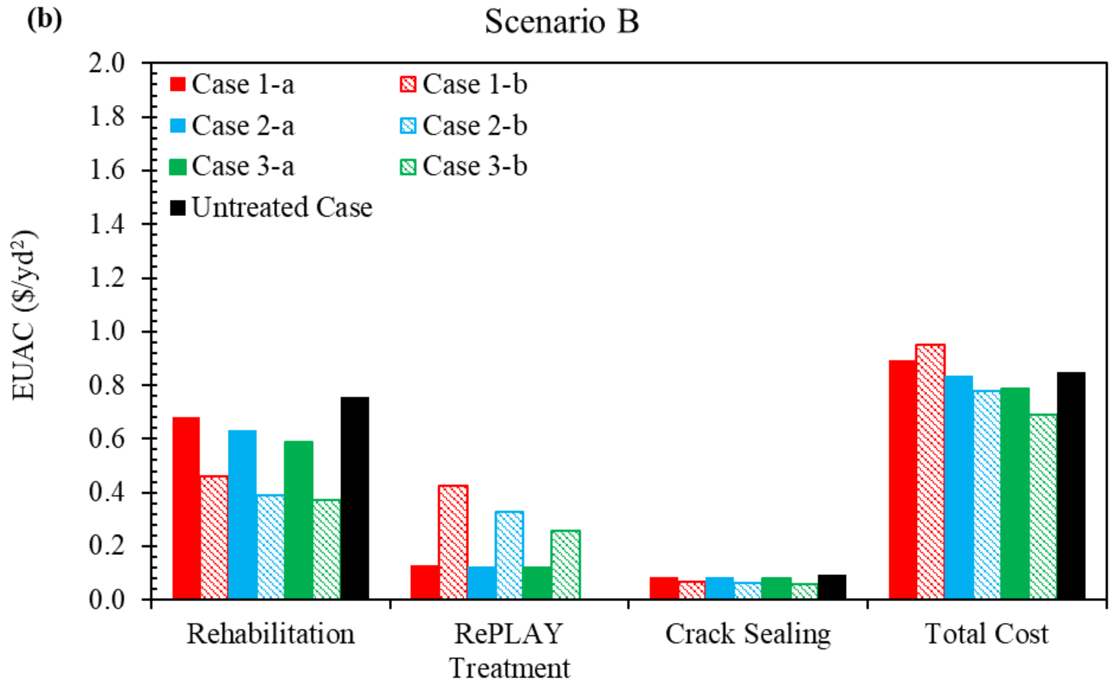
Table 12. EUAC for different cases and scenarios

Cases	Total EUAC ($/yd²)			
	Scenario A	Scenario B	Scenario C	Scenario D
Untreated Case	1.30	0.85	1.26	0.81
Case 1-a	1.28	0.89	1.29	0.88
Case 1-b	1.18	0.95	1.31	1.00
Case 2-a	1.20	0.84	1.21	0.82
Case 2-b	0.97	0.78	1.05	0.80
Case 3-a	1.13	0.79	1.13	0.77
Case 3-b	0.89	0.69	0.93	0.70

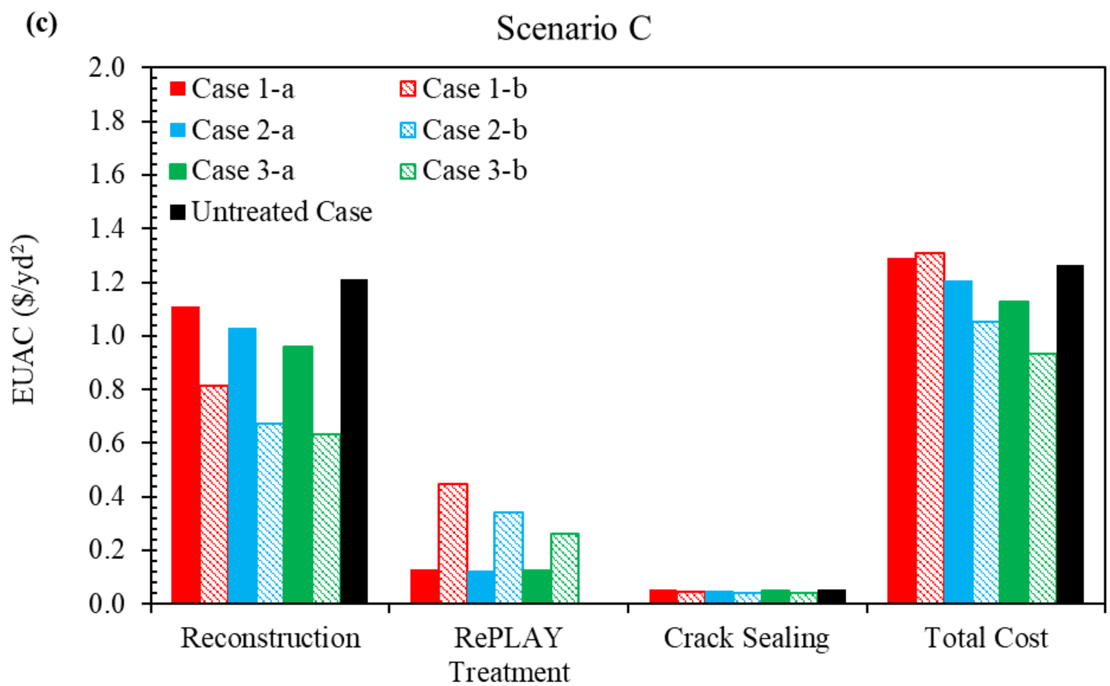
(a)



(b)


Scenario B
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
EUAC ($/yd^2)
Case 1-a
Case 1-b
Case 2-a
Case 2-b
Case 3-a
Case 3-b
Untreated Case
Rehabilitation
RePLAY Treatment
Crack Sealing
Total Cost

(c)


Scenario C
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
EUAC ($/yd^2)
Case 1-a
Case 1-b
Case 2-a
Case 2-b
Case 3-a
Case 3-b
Untreated Case
Reconstruction
RePLAY Treatment
Crack Sealing
Total Cost

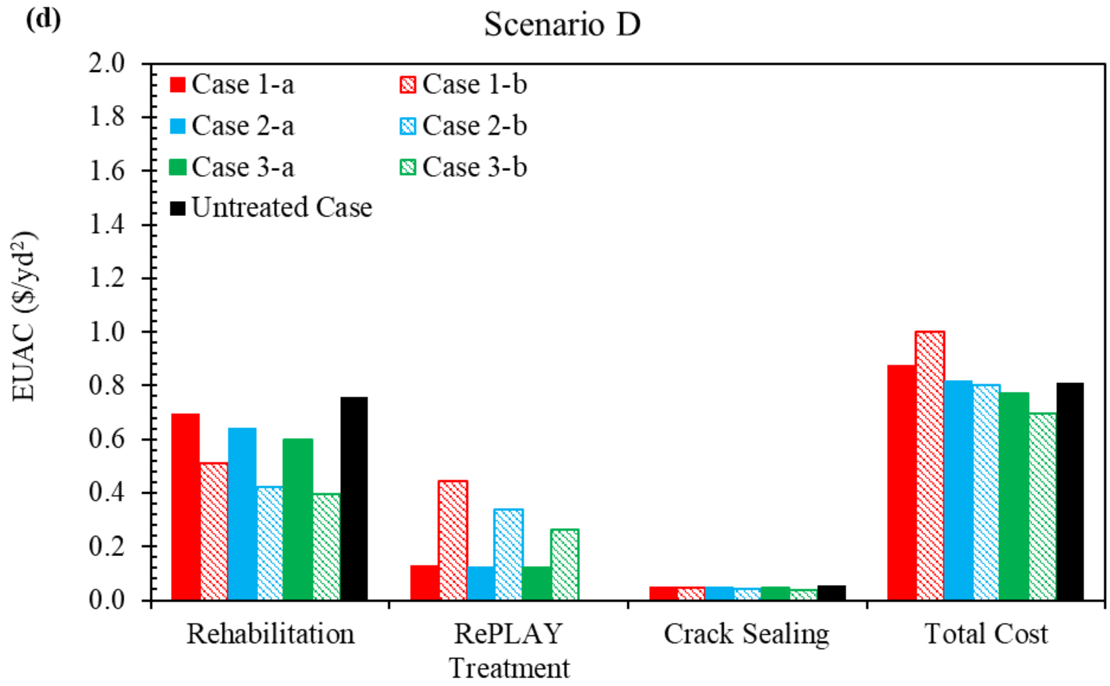


Figure 17. EUAC for different scenarios: (a) Scenario A, (b) Scenario B, (c) Scenario C, and (d) Scenario D

Among these cases, the untreated cases in Scenario A and Scenario C (the reconstruction scenarios) had the higher EUAC of about \$1.30/yd^2, while Case 3-b with three RePLAY treatments in Scenario B and Scenario D (the rehabilitation scenarios) showed the lower value of about \$0.70/yd^2 and the most extended lifespan of about 30 years.

These results indicate RePLAY application could extend the additional pavement service life up to 10 years and reduce the equivalent annual maintenance cost up to about 30%. Rehabilitation with lower unit cost could reduce the EUAC for both the treated and untreated cases.

Nahvi et al. (2021) used a similar analysis approach to evaluate the economic viability of RePLAY-treated sites constructed in Minnesota, reporting that RePLAY could reduce the EUAC and extend the pavement service life up to seven years. The Minnesota study recommended three treatments in a design service life. By comparison, the one-time application cases are worse than the reapplication cases from the perspective of EUAC, and all for RePLAY-treated Case 2 and Case 3 are better than the untreated case due to the decreased total EUAC. In Scenario B, C, and D, Case 1 had the higher EUAC than the untreated cases.

7. CONCLUSIONS AND RECOMMENDATIONS

Key Findings

As a common type of fog sealer, while petroleum-based asphalt emulsions have been successfully used to preserve asphalt roads for many years, environmental issues associated with bitumen products drive engineers to seek a sustainable alternative. The bio-based fog sealant, RePLAY, is a proprietary nontraditional agricultural oil, derived from soybeans. While it has been claimed to be a potentially cost-effective and environmentally friendly product for preserving roads, its benefits have not been well documented or evaluated.

In this study, existing fog sealing practices and specifications were reviewed and summarized. A 3.3-mile HMA roadway was selected to install the RePLAY product at three rates over a five-year evaluation period. The construction procedure was documented in detail, and the primary results from the laboratory and field investigations and LCCA can be summarized as follows:

- Field distress investigations indicated that the RePLAY-treated sections exhibited lower crack growth rates than the untreated section. The lowest application rate of 0.02 gal/yd^2 resulted in better control of crack growth rates than the other application rates evaluated in this study.

- While the skid resistance of the investigated site decreased immediately after the application of the bio-based fog seal, the original friction value was restored within 11 months after spraying.

- While the RePLAY application could cause reduced retroreflectivity of pavement strip markings, the original retroreflectivity was restored within two weeks after RePLAY application.

- Laboratory investigations indicated that an increase in the application rates of RePLAY resulted in reduced water absorption and air permeability in the tested specimens.

- For pavements with critical permeability issues, the highest spray rate of 0.03 gal/yd^2 was found to reduce permeability based on the field and laboratory investigations. For a limited budget, lower rates of 0.025 and 0.02 gal/yd^2 are also acceptable.

- The RePLAY material depth of penetration under either LED or UV lighting was was difficult to determine.

- Based on the assumptions utilized in this study, the results of the LCCA in this study indicates that RePLAY treatment can reduce the EUAC by extending the service life of the pavement.

- RePLAY application is a non-heated, safe, and rapid process after which traffic can be reopened 30 minutes after spraying, although reduced friction could be a potential concern when opening traffic. It is recommended that caution signs be placed along roadsides.

- The five-year investigations of the RePLAY-treated sections indicated that RePLAY can be used as an effective alternative fog sealant for asphalt pavement preservation in Iowa.

Recommendations

Based on the detailed construction documentation, field investigations, laboratory testing, and LCCA, the following recommendations for evaluation of bio-based fog sealants as an effective alternative for Iowa asphalt pavement preservation were developed:

- The local agency should perform a quality control test on the sprayer to ensure a correct application rate.

- For safety considerations, the skid number of untreated pavement should be greater than 50 before receiving the RePLAY treatment.

- While after installing RePLAY, the treated lanes can be opened to traffic immediately, caution signs concerning speed control should be placed before treated sections.

- Continuous monitoring of surface friction is needed until it is restored to a proper level.

- RePLAY should not be applied to pavements with a wet or freezing surface.

- Based on the assumptions utilized in this study, RePLAY re-application is recommended every three to five years.

- Recommended RePLAY application rates can vary from 0.02 to 0.03 gal/yd^2. For a road without serious permeability issues, 0.02 gal/yd^2 is recommended due to the better cracking control provided than with other application rates evaluated in this study.

- The local agency should consider the potential reduction in retroreflectivity immediately after RePLAY application.

- A site previously treated with RePLAY could receive a fog seal treatment using emulsified asphalt.

Although this study exhibited the benefits of RePLAY as an alternative fog sealant for pavement maintenance purposes, some potential advantages or limitations have not been clearly identified. A follow-up investigation (i.e., Phase II study) is recommended, focusing on the following items:

- Re-application of RePLAY at the same project site utilized in this study to continue monitoring its performance. While the effective period may have expired, a follow-up evaluation can help in quantifying the benefits of the re-application.

- Validation of the recommended re-application scenario identified in this study by re-applying RePLAY.

- More accurate measurement of reduction of surface friction and retroreflectivity immediately after RePLAY application. Given traffic might be opened directly after treatment, the critical conditions should be evaluated for safety considerations.

- A follow-up study including the construction of a site treated with a traditional petroleum-based fog sealant, such as asphalt emulsion, for comparison purposes. Comparing traditional petroleum-based and nontraditional bio-based sealing agents or rejuvenators with respect to the laboratory and field performance and the economic analysis could provide more comprehensive views for engineers seeking to develop a maintenance strategy.

- Evaluation of other proprietary fog sealers or rejuvenators such as Biorestor and Reclamite, and identification of their recommended application rates for Iowa pavement systems.

- Evaluation of the performance of proprietary fog sealers or rejuvenators on lightly-surfaced roads, such as those constructed with Otta seals, cape seals, chip seals, etc.

- Evaluation of the effects of proprietary fog sealers or rejuvenators on the international roughness index (IRI) and the pavement condition index (PCI).

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APPENDIX: FIELD SURVEY IMAGES

Figure 18. Field survey on April 13, 2017: (a) control section, (b) treated section No. 1 (0.03 gal/yd²), (c) treated section No. 2 (0.025 gal/yd²), and (d) treated section No.3 (0.02 gal/yd²)

Figure 19. Field survey on October 13, 2017: (a) control section, (b) treated section No. 1 (0.03 gal/yd2), (c) treated section No. 2 (0.025 gal/yd2), and (d) treated section No.3 (0.02 gal/yd2)

Figure 20. Field survey on March 22, 2018: (a) control section, (b) treated section No. 1 (0.03 gal/yd^2), (c) treated section No. 2 (0.025 gal/yd^2), and (d) treated section No.3 (0.02 gal/yd^2)

Figure 21. Field survey on May 11, 2019: (a) control section, (b) treated section No. 1 (0.03 gal/yd^2), (c) treated section No. 2 (0.025 gal/yd^2), and (d) treated section No.3 (0.02 gal/yd^2)

Figure 22. Field survey on August 9, 2020: (a) control section, (b) treated section No. 1 (0.03 gal/yd^2), (c) treated section No. 2 (0.025 gal/yd^2), and (d) treated section No.3 (0.02 gal/yd^2)

Figure 23. Field survey on August 24, 2021: (a) control section, (b) treated section No. 1 (0.03 gal/yd^2), (c) treated section No. 2 (0.025 gal/yd^2), and (d) treated section No.3 (0.02 gal/yd^2)

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