

## Short-Term Field Evaluation of Spray-on Rejuvenators for Asphalt Pavement Preservation

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<p>Abstract:</p> <p>Spray-on rejuvenators are pavement preservation treatments intended to mitigate oxidative aging of asphalt binder in the near-surface region of asphalt pavements. Although several highway agencies have evaluated these treatments, reported performance outcomes vary, and the Virginia Department of Transportation (VDOT) has limited documented experience with their use. Prior to this study, VDOT did not have an established specification or standardized evaluation framework for spray-on rejuvenators.</p> <p>This study was conducted to evaluate the feasibility and short-term field performance of spray-on rejuvenators under Virginia conditions and to support the development of guidance for potential future implementation. The scope included a comprehensive review of published literature, agency specifications, and state-of-practice documents, along with field trials conducted in the Lynchburg and Northern Virginia districts. Following completion of the Lynchburg District field trials, a special provision was developed to guide spray-on rejuvenator application practices and was implemented for the Northern Virginia District field trials.</p> <p>The Lynchburg District field trials were performed on two non-residential roadways and included three treated segments and one untreated control segment on each route. Performance monitoring focused on near-surface material response and functional characteristics, including near-surface air void content, near-surface binder rheological properties, surface friction, texture, ride quality, rutting, and pavement condition indices. The Northern Virginia District field trials were conducted on low-speed residential roadways and emphasized documenting application practices, constructability, and short-term near-surface material response, because these sections were treated shortly before the completion of this report.</p> <p>Field observations indicated that spray-on rejuvenators can be applied under Virginia conditions when appropriate surface preparation, application rates, and curing practices are followed. Temporary reductions in friction were observed immediately after application, with recovery trends occurring over time. Changes in surface texture, ride quality, and rutting were generally limited. Near-surface binder testing indicated product-dependent changes in rheological properties, with variable magnitude. The field trials conducted as part of this effort provide an initial foundation for understanding spray-on rejuvenator behavior under Virginia conditions and establish a baseline for continued monitoring and future evaluations.</p> <p>This study recommends that VDOT (1) continue monitoring the existing field trial sections in the Lynchburg and Northern Virginia Districts and (2) consider identifying appropriate pavement categories for spray-on rejuvenator applications and incorporating a broader set of field executions into routine pavement preservation schedules.</p>				



**FINAL REPORT**

**SHORT-TERM FIELD EVALUATION OF SPRAY-ON REJUVENATORS FOR  
ASPHALT PAVEMENT PRESERVATION**

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## ABSTRACT

Spray-on rejuvenators are pavement preservation treatments intended to mitigate oxidative aging of asphalt binder in the near-surface region of asphalt pavements. Although several highway agencies have evaluated these treatments, reported performance outcomes vary, and the Virginia Department of Transportation (VDOT) has limited documented experience with their use. Prior to this study, VDOT did not have an established specification or standardized evaluation framework for spray-on rejuvenators.

This study was conducted to evaluate the feasibility and short-term field performance of spray-on rejuvenators under Virginia conditions and to support the development of guidance for potential future implementation. The scope included a comprehensive review of published literature, agency specifications, and state-of-practice documents, along with field trials conducted in the Lynchburg and Northern Virginia Districts. Following completion of the Lynchburg District field trials, a special provision was developed to guide spray-on rejuvenator application practices and was implemented for the Northern Virginia District field trials.

The Lynchburg District field trials were performed on two non-residential roadways and included three treated segments and one untreated control segment on each route. Performance monitoring focused on near-surface material response and functional characteristics, including near-surface air void content, near-surface binder rheological properties, surface friction, texture, ride quality, rutting, and pavement condition indices. The Northern Virginia District field trials were conducted on low-speed residential roadways and emphasized documenting application practices, constructability, and short-term near-surface material response, because these sections were treated shortly before the completion of this report.

Field observations indicated that spray-on rejuvenators can be applied under Virginia conditions when appropriate surface preparation, application rates, and curing practices are followed. Temporary reductions in friction were observed immediately after application, with recovery trends occurring over time. Changes in surface texture, ride quality, and rutting were generally limited. Near-surface binder testing indicated product-dependent changes in rheological properties, with variable magnitude. The field trials conducted as part of this effort provide an initial foundation for understanding spray-on rejuvenator behavior under Virginia conditions and establish a baseline for continued monitoring and future evaluations.

This study recommends that VDOT (1) continue monitoring the existing field trial sections in the Lynchburg and Northern Virginia Districts and (2) consider identifying appropriate pavement categories for spray-on rejuvenator applications and incorporating a broader set of field executions into routine pavement preservation schedules.

## **FINAL REPORT**

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## **INTRODUCTION**

The Virginia Department of Transportation (VDOT) places a strong emphasis on maintaining the structural and functional condition of its pavement network in a state of good repair. This objective is particularly important as agencies, including VDOT, seek to maximize system performance under constrained funding. Pavement preservation treatments play an important role in achieving this goal by maintaining surface integrity, preserving functional characteristics, and slowing the progression of pavement deterioration, thereby supporting more cost-effective management of pavement assets. In support of these efforts, VDOT routinely evaluates emerging practices and technologies in pavement construction and maintenance to assess their potential applicability in supporting effective pavement management and data-driven decision-making.

In asphalt pavements, oxidative aging of the asphalt binder, particularly in the near-surface region, significantly contributes to surface-related deterioration and increased cracking susceptibility. As binder stiffness increases and ductility decreases over time, pavements become more vulnerable to cracking and durability-related damage. Spray-on rejuvenators have emerged as a potential preservation treatment intended to address these aging-related effects by partially restoring the near-surface binder properties when applied to pavements that remain structurally sound and exhibit early signs of surface aging.

Several highway agencies have investigated the use of spray-on rejuvenators through laboratory studies, field trials, and test track evaluations to better understand treatment behavior, performance expectations, and limitations. These efforts have focused on material characteristics, application practices, short-term functional response, and safety-related considerations such as surface friction. However, the reported findings vary widely, reflecting differences in materials, pavement conditions, application practices, and evaluation approaches.

This study was undertaken in recognition of VDOT's limited experience with spray-on rejuvenators and the absence of an established specification or standardized evaluation framework governing their use on the Virginia roadway network. Aside from a district-level

parking lot treatment with limited documented data, VDOT currently lacks systematic field experience with these treatments.

## **PURPOSE AND SCOPE**

The purpose of this study was to evaluate the feasibility and short-term effectiveness of spray-on rejuvenators as a pavement preservation treatment for surface asphalt mixtures under Virginia conditions. The study was initiated to address VDOT's limited experience with these treatments and the lack of a standardized framework to guide their evaluation and application. The primary focus was on assessing whether spray-on rejuvenators can meaningfully alleviate near-surface binder aging characteristics.

The scope of work included a comprehensive review of the published literature, agency guidance, and existing specifications related to spray-on rejuvenators to establish the current state of knowledge and practice. Two sets of field trials were conducted, one in the Lynchburg District in 2023 and one in the Northern Virginia (NoVA) District in 2025, to document construction practices and short-term field response following application. Non-residential routes in the Lynchburg District and residential routes in the NoVA District were selected to evaluate application practices under representative operating conditions. Multiple spray-on rejuvenator products were applied during the field trials, and untreated control sections were included in the Lynchburg District to support comparative evaluation.

Field performance monitoring focused on near-surface material response, specifically binder rheological properties, for both districts. For the Lynchburg District field trials, additional performance indicators were evaluated, including near-surface air void characteristics, surface friction and texture, ride quality, rutting, and pavement condition survey indices. For the NoVA District field trials, the emphasis was on documenting application practices, because the trials were conducted shortly before the preparation of this report. Together, these activities were used to inform interpretation of short-term field response, support development and refinement of draft specification considerations, and guide future long-term monitoring efforts or additional trials.

## **METHODS**

### **Literature Review**

A targeted literature review was conducted to document the current state of knowledge and practice on spray-on rejuvenators. The review included peer-reviewed journal articles, national and state agency research reports, technical guidance documents, specifications, and synthesis publications related to spray-on rejuvenators. The literature review encompassed both fundamental research and applied studies addressing various aspects of spray-on rejuvenators, such as material characteristics, rejuvenation mechanisms, penetration depth, performance expectations, and life-cycle implications. Particular emphasis was given on field performance

studies, agency specifications, and state-of-practice documents to ensure that the synthesis reflected practical implementation considerations alongside laboratory findings.

### **Field Trials**

The study included field trials conducted on two routes in the Lynchburg District and four routes in the NoVA District.

#### **Lynchburg District Field Trials**

Two routes in the Lynchburg District, Routes 640 and 750, were identified for field evaluation. Candidate pavements were selected based on condition and age criteria established through an initial review of the literature and consultation with product suppliers. Selection criteria included pavements in generally excellent condition, defined as having a critical condition index (CCI) of approximately 90% or greater and an age of less than 6 years at the time of treatment. CCI is calculated as the lower of the Load-Related Distress Rating (LDR) and Non-Load-Related Distress Rating (NDR), and in general, pavement sections with CCI values greater than 90 are considered as “excellent” condition.

Both routes are two-lane, undivided roadways consisting of one lane in each direction. The pavements were overlaid in 2018 and were therefore approximately 5 years old at the time of spray-on rejuvenator application in September 2023. The nominal maximum aggregate size of the surface mixture was 9.5 mm for Route 640 and 19 mm for Route 750.

Each route was divided into four adjacent segments, including one untreated control segment (C) and three treated segments (P1, P2, and P3). Each treated segment per route received a different spray-on rejuvenator product. The evaluated products included two bio-based rejuvenators and one bio-petroleum-based rejuvenator. Applications were performed in the northbound direction on segments approximately 1,850 feet in length, with transition zones of approximately 50 feet provided between adjacent segments to minimize potential interactions between products.

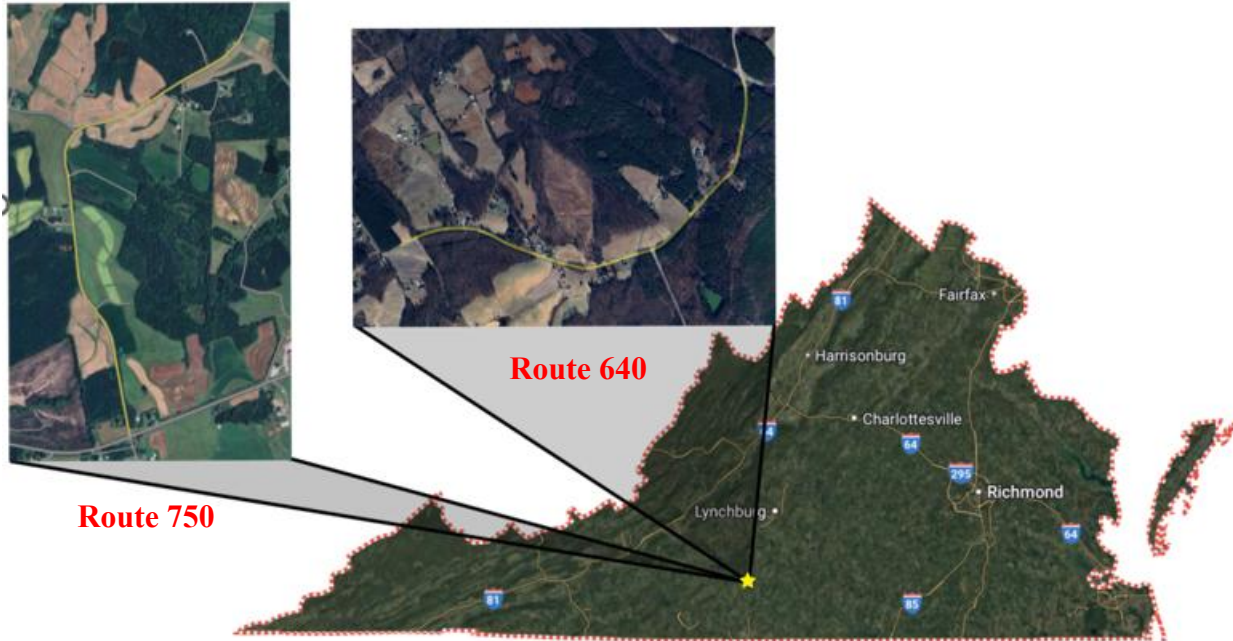
Contractors were requested to apply their respective materials in accordance with manufacturer-recommended best practices. They were responsible for determining appropriate application rates for their products, avoiding application over pavement markings, and implementing necessary measures to address potential surface slipperiness concerns during and immediately following application.

Table 1 summarizes key site characteristics for the Lynchburg District field trials, and Figure 1 presents a location map of the evaluated sections.

**Table 1. Site Characteristics for the Lynchburg District Spray-on Rejuvenator for Field Trials**

County	Route Name	Mile Post		Speed Limit	ADT	Application Order North Bound			
		From	To			P1	P2	P3	C
Pittsylvania	640	19.06	20.66	45	685	P1	P2	P3	C
Pittsylvania	750	9.07	10.59	45	1197	C	P1	P2	P3

ADT = average daily traffic. C denotes the untreated control segment; P1–P3 denote segments receiving spray-on rejuvenator application.



**Figure 1. Map Showing the Location of Spray-on Rejuvenator Field Trial Sections on Routes 640 and 750**

### Northern Virginia District Field Trials

The NoVA District field trials were initiated to evaluate the feasibility of applying spray-on rejuvenators on low-speed, low-volume residential roadways. The effort was motivated by prior district experience with a spray-on rejuvenator applied to a parking lot facility, which remained in satisfactory condition several years after treatment, as the following sections of this report will discuss. Based on this experience, district leadership expressed interest in exploring whether similar treatments could be applied to residential pavements under controlled conditions.

From an operational perspective, the NoVA District sought to evaluate spray-on rejuvenators as a potential alternative preservation option for residential routes where traditional surface treatments may present constructability or public acceptance challenges. Treatments such as slurry seals and microsurfacing, although effective for surface preservation, can increase surface texture and temporary roughness that may generate public complaints in residential settings. In contrast, spray-on rejuvenators offer a surface treatment approach that maintains the visual and tactile characteristics of asphalt pavement.

Four residential routes were selected for field evaluation: Walney Park Drive, Leighfield Valley Drive, Point Pleasant Drive, and Star Flower Drive. All routes are low-speed residential streets (posted speed limit of 25 mph) consisting of two to three unmarked travel lanes with curb



Four different spray-on rejuvenator products were evaluated as part of the NoVA District field trials. Walney Park Drive and Leighfield Valley Drive were each treated with a single product (Products A and B, respectively). Point Pleasant Drive and Star Flower Drive were each treated with two different products. From an aerial perspective, the inside lanes of both routes received Product C, and the outside lanes received Product D. Table 3 summarizes the product types and application locations.

**Table 3. Product Placement for the Northern Virginia District Spray-on Rejuvenator for Field Trials**

<b>Product<sup>a</sup></b>	<b>Product Type</b>	<b>Application Location</b>
A	Bio-Based Rejuvenator	Walney Park Drive
B	Bio-Based Rejuvenator	Leighfield Valley Drive
C	Bio-Polymer-Based Rejuvenator	Inside Lane of Point Pleasant Drive and Inside Lane of Star Flower Drive
D	Bio-Polymer-Based Rejuvenator	Outside Lane of Point Pleasant Drive and Outside Lane of Star Flower Drive

<sup>a</sup> The four products evaluated (A–D) are distinct, proprietary formulations. Although Products A and B are categorized as bio-based rejuvenators and Products C and D are categorized as bio-polymer-based rejuvenators, each product has a unique formulation and chemical composition specific to the manufacturer.

A special provision was developed for the spray-on rejuvenator treatments conducted in the NoVA District and was further refined based on field experience gained during the NoVA applications. The final version is in Appendix A. The special provision took into consideration the specifications of other existing government agencies and non-governmental organizations for the application of spray-on rejuvenators across varying climates to best produce a document applicable to VDOT. Contractors were requested to apply their respective materials in accordance with the special provision.

### **Documentation of Existing Pavement Condition and Application Process**

Prior to spray-on rejuvenator applications, walk-through inspections were conducted on all field trial sections to document existing pavement conditions and identify visible surface distresses. Observations focused on the presence of cracking, raveling, surface irregularities, and other apparent distress features. Representative photographs were collected to support documentation of pre-application conditions.

Application activities were documented throughout construction to capture surface preparation, the equipment used, material placement procedures, and field observations during and shortly after application. Environmental conditions were recorded at the time of application.

Post-application walk-through inspections were conducted to document curing behavior, surface appearance, and any observable material tracking, runoff, or irregularities. Photographs were collected to document surface appearance immediately following application and during subsequent site visits.

## Laboratory and Field Data Collection

### Near-Surface Air Void Content

Near-surface air void contents were evaluated only for the Lynchburg District field trials. Pavement cores were collected on the day of application after curing was achieved. Core locations were randomly stratified along both the longitudinal and transverse directions within each segment. Cores from the untreated control segments were collected concurrently to ensure comparable sampling conditions. Each core was trimmed to obtain the top approximately 9.5 mm of material, representing the near-surface region zone most likely influenced by spray-on rejuvenator application. Air void content was determined in accordance with AASHTO T 269, Standard Method of Test for Percent Air Voids in Compacted Dense and Open Asphalt Mixtures (AASHTO, 2014).

### Near-Surface Binder Rheological Testing

Near-surface binder properties were evaluated for the Lynchburg and NoVA Districts field trials using asphalt binder extracted and recovered from the top approximately 9.5 mm of field cores. Testing was conducted to characterize binder stiffness and viscoelastic response following spray-on rejuvenator application. The complex shear modulus ( $|G^*|$ ) was used as an indicator of binder stiffness, and phase angle ( $\delta$ ) was reported to describe elastic-viscous behavior.

Extraction of asphalt binder from collected specimens was performed in accordance with AASHTO T 164, Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA), Method A, using n-propyl bromide as the solvent (AASHTO, 2014). Following extraction, the asphalt binder was recovered from the solvent using the rotary evaporator recovery procedure specified in AASHTO T 319, Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures (AASHTO, 2015). Recovered binders were subsequently tested using a dynamic shear rheometer at 60°C and 10 rad/s to determine  $|G^*|$  and  $\delta$ .

### Friction Characteristics

Surface friction was evaluated only for the Lynchburg District field trials. Friction testing was not conducted for the NoVA District trials because of posted speed limitations on the evaluated routes (approximately 25 mph) and the requirement for the locked-wheel skid tester to operate at higher test speeds. Pavement friction was measured using VDOT's locked-wheel skid tester equipped with a smooth tire in accordance with Virginia Test Method (VTM) 122 (VDOT, 2007). Testing was performed under controlled water application at a test speed of 40 mph. Corrected skid numbers at 40 mph (SN40) were used to assess changes in surface friction before and after spray-on rejuvenator application.

Friction measurements were collected before application, immediately following application, and during subsequent monitoring periods to document friction recovery trends. Readings were obtained at approximately 0.1-mile intervals along the full length of each test

section. Each reported SN40 value represents the average of all point measurements collected during a single test event. All friction values were corrected in accordance with VTM 122.

### **Surface Texture Characteristics**

Surface macrotexture was evaluated only for the Lynchburg District field trials. Surface texture testing was not conducted for the NoVA District trials because of operational constraints associated with the selected residential routes. Surface macrotexture was quantified using mean profile depth (MPD) in accordance with ASTM E1845, Standard Practice for Calculating Paving Macrotexture Mean Profile Depth (ASTM International, 2015). MPD measurements were collected using a VDOT high-speed inertial pavement profiler equipped with laser sensors, consistent with applicable VDOT profiling procedures.

Surface texture data were collected before spray-on rejuvenator application, immediately following application, and during subsequent monitoring periods to evaluate short-term and longer-term (approximately 1 year) changes in macrotexture. MPD measurements were obtained along the length of each test section at nominal intervals of approximately 0.01 mile, and segment-level MPD values were calculated by averaging measurements within the defined segment limits.

### **Ride Quality**

Ride quality was evaluated only for the Lynchburg District field trials. Ride quality measurements were not conducted for the NoVA District trials because of operational constraints associated with the selected residential routes. Ride quality was quantified using the International Roughness Index (IRI) in accordance with VTM 106 (VDOT, 2001). IRI data were collected using a VDOT high-speed inertial pavement profiler equipped with laser sensors in accordance with applicable VDOT profiling procedures.

IRI measurements were collected before spray-on rejuvenator application, immediately following application, and during subsequent monitoring periods to evaluate short-term and longer-term (approximately 1 year) changes in pavement smoothness. Measurements were obtained continuously along the length of each test section, and segment-level IRI values were calculated by averaging data within the defined segment limits.

### **Rutting Performance**

Rutting performance was evaluated only for the Lynchburg District field trials. Rut depth measurements were not conducted for the NoVA District trials because of operational constraints associated with the selected residential routes. A third-party vendor collected rut depth data using a high-speed inertial pavement profiling system equipped with a five-laser transverse scanning configuration. Measurements were performed in accordance with applicable VDOT profiling procedures and the vendor's standard data collection protocols.

Rut depth measurements were obtained approximately 1 week prior to spray-on rejuvenator application and again 1 day following application. Data were collected continuously

along the length of each test section, and segment-level rut depth values were calculated by averaging measurements within the defined segment limits.

## **Pavement Condition Surveys**

Pavement condition was evaluated only for the Lynchburg District field trials using NDR and LDR indices obtained from the VDOT pavement management system. Pavement condition data were not available for the NoVA District trials at the time of this study because those sections were treated recently and had not yet been incorporated into the routine condition survey cycle.

For Routes 640 and 750, baseline condition data corresponding to the 2018 asphalt overlays were obtained from VDOT pavement management records. Spray-on rejuvenators were applied in 2023, and post-application condition surveys were conducted approximately 78 days following application and again in 2024, approximately 1 year after application. Condition index values were summarized at the segment level for each treated section (P1–P3) and the untreated control section (C). The NDR index reflects distress types primarily associated with surface aging and environmental effects, whereas the LDR index reflects distress types influenced by traffic loading and structural condition.

# **RESULTS AND DISCUSSION**

## **Literature Review**

### **Role of Spray-on Rejuvenators**

Spray-on rejuvenators, also referred to as rejuvenating seals or rejuvenating fog seals, are preventive pavement preservation treatments primarily intended to address aging-related deterioration of asphalt binder in the near-surface region of asphalt pavements. In addition to their primary function of partially restoring aged surface binder properties, it has been documented that these treatments can seal fine surface discontinuities, reduce surface permeability and raveling, and improve surface appearance. However, the extent of these benefits is highly dependent on product formulation, pavement condition, surface texture, and application practices (Blanchette et al., 2020; Brown, 1988; Brownridge, 2010; California Department of Transportation [Caltrans], 2010; Islam et al., 2025; Kebede, 2016; King and King, 2008; Moraes et al., 2025; Rushing and Falls, 2010; Shoenberger, 2003; Taghavi et al., 2022).

Oxidative aging of asphalt binder occurs most rapidly near the pavement surface because of exposure to oxygen, solar radiation, and temperature cycling. This process increases binder stiffness and brittleness and has been linked to the development of surface-initiated distresses such as raveling and cracking (Button, 1996; Estakhri and Agarwal, 1991). Spray-on rejuvenators are typically applied as low-viscosity materials intended to penetrate the upper portion of the asphalt pavement, where oxidative aging progresses most rapidly, with the objective of partially restoring binder properties. As a result, their intended role is limited to mitigating surface distress mechanisms associated with binder embrittlement rather than

addressing deeper structural deficiencies (Blanchette et al., 2020; National Center for Asphalt Technology [NCAT], 2021). Accordingly, spray-on rejuvenators are not intended as corrective or structural treatments and are generally considered appropriate only for pavements that are structurally sound and exhibit early indications of surface aging (Blanchette et al., 2020; Caltrans, 2010; Estakhri and Agarwal, 1991; Federal Highway Administration, 2006; NCAT, 2024). The literature consistently emphasizes that these treatments are most effective when applied prior to the development of well-defined surface distress and should not be expected to restore pavements with advanced cracking or underlying structural problems (Blanchette et al., 2020; Caltrans, 2010; NCAT, 2021).

## **Material Characteristics and Rejuvenation Mechanisms**

Spray-on rejuvenators encompass a wide range of formulations, including petroleum-derived products, bio-based oils, and blended systems. These formulations may incorporate low-viscosity carrier components, emulsified binders, or polymers to facilitate application and promote interaction with the pavement surface (Lin et al., 2013; Moraes et al., 2025; Taghavi et al., 2022; Vaddy et al., 2025). As a result, spray-on rejuvenators can vary substantially in chemical composition, viscosity, volatility, and curing behavior, all which influence how they interact with aged asphalt binder in the near-surface region of asphalt pavements (Blanchette et al., 2020; Islam et al., 2025; Lin et al., 2013; Moraes et al., 2025). When evaluating the asphalt binder properties, rejuvenation is generally described as a partial restoration of rheological properties through reductions in stiffness and improvements in stress relaxation behavior (Blanchette et al., 2020; Estakhri and Agarwal, 1991; Islam et al., 2025; Lin et al., 2013; Moraes et al., 2025). Laboratory studies have demonstrated that rejuvenators can modify the properties of aged binders when sufficient interaction occurs between the applied material and the existing asphalt binder. These changes are commonly reflected in reductions in complex shear modulus and improvements in creep or relaxation behavior at low or intermediate temperatures, although the magnitude of these effects depends on material formulation, dosage, and the degree of binder-rejuvenator interaction achieved (Ghosh et al., 2018; Islam et al., 2025; Lin et al., 2013; Moraes et al., 2025; Vaddy et al., 2025).

## **Penetration Depth and Depth of Influence**

Penetration depth strongly governs the extent to which rejuvenation mechanisms are achieved under field conditions. Laboratory and field investigations consistently indicate that spray-on rejuvenators penetrate only a limited distance below the pavement surface, with measurable effects largely confined to the near-surface zone of the asphalt layer. Reported depths of influence vary considerably, typically ranging from approximately 6 to 20 mm, with average values commonly reported near 9 to 10 mm (Blanchette et al., 2020; Brown, 1988; Button, 1996; Chiu and Lee, 2006; Estakhri and Agarwal, 1991; Ghosh et al., 2018; Islam et al., 2025; Kebede, 2016; King and King, 2008; Lee et al., 2013; Lin et al., 2014; Moraes et al., 2025; Rushing and Falls, 2010; Taghavi et al., 2022).

From a practical standpoint, penetration depth should not be viewed as an intrinsic or fixed property of a rejuvenator product. Instead, it represents a field-dependent outcome that pavement conditions and application practices strongly influence. Factors shown to affect

penetration include surface texture and condition, mixture air-void structure and permeability, pavement age, binder film thickness, rejuvenator formulation, application rate, and curing behavior (Button, 1996; Estakhri and Agarwal, 1991; Ghosh et al., 2018; King and King, 2008; Lee et al., 2013; Taghavi et al., 2022). Field and laboratory studies also indicate that increasing the application rate does not necessarily result in deeper penetration but may instead increase the likelihood of surface residue, delayed curing, tracking, and short-term reductions in surface friction (Ghosh et al., 2018; Taghavi et al., 2022). Because penetration is inherently limited, the effective role of spray-on rejuvenators is best understood as a localized modification of near-surface material properties rather than a uniform change throughout the asphalt concrete layer. This distinction helps explain why these treatments are most effective on pavements exhibiting early-stage surface aging and relatively open near-surface structure, and why measurable effects diminish rapidly with depth below the pavement surface (Blanchette et al., 2020; Button, 1996; Lee et al., 2013).

### **Pavement Selection and Application Timing**

The effectiveness of spray-on rejuvenators is strongly dependent on both the selection of appropriate candidate pavements and the application timing within the pavement life cycle. As discussed previously, these treatments are most effective when applied to pavements that are structurally sound and exhibit early indications of surface aging, rather than advanced distress. Accordingly, spray-on rejuvenators should be applied before surface deterioration becomes well developed, because their ability to interact with aged binder and slow surface-related degradation diminishes once cracking, raveling, or permeability-related damage is established (Blanchette et al., 2020).

Several agencies have established pavement screening criteria to support appropriate candidate selection (Blanchette et al., 2020). For example, the Federal Aviation Administration's (FAA) Item P-632, Asphalt Pavement Rejuvenation, specifies that treatment performance is contingent on pavement condition at the time of application and recommends a corrected pavement condition index of 70 or greater, determined in accordance with ASTM D5340 (ASTM International, 2024), as a typical threshold for candidate pavements. The specification further indicates that pavements should be free of structural or load-associated distresses, or include provisions to correct such deficiencies, and should primarily exhibit low to moderate environmentally driven surface distress (FAA, 2018).

In addition to condition-based indicators, several studies have emphasized the importance of surface air void content in supporting effective rejuvenator absorption and near-surface interaction. Field and laboratory investigations have reported that pavements with surface air void contents of approximately 7 to 8% or greater tend to exhibit a more favorable response to spray-on rejuvenator applications, because higher interconnected void structure facilitates material penetration and reduces the likelihood of surface pooling or runoff (Brown, 1988; Estakhri and Agarwal, 1991; King and King, 2008; Prapaitrakul et al., 2005; Shoenberger, 2003). Although air void content is not typically specified as a formal criterion, these findings suggest that mixture density and surface permeability characteristics should be considered as part of the candidate pavement screening.

Additional agency practices link pavement selection to traffic and safety considerations. As Blanchette et al. (2020) summarized, Maryland's screening criteria for rejuvenator application (Type B-2) include traffic levels up to approximately 25,000 average daily traffic, a minimum skid number greater than 40, and additional condition indicators such as a structural condition index greater than 75 and an IRI between 0 and 100. These criteria reflect the common practice of limiting rejuvenator applications to pavements that retain adequate structural capacity and baseline friction. Pavements exhibiting low existing skid resistance, macrotexture, air void content, and permeability, extensive cracking, loss of surface integrity, or underlying structural deficiencies are generally considered unsuitable candidates for spray-on rejuvenator application (Blanchette et al., 2020; Brown, 1988; Chiu and Lee, 2006; Estakhri and Agarwal, 1991; Kebede, 2016; King and King, 2008; Prapaitrakul et al., 2005; Shoenberger, 2003; Yang et al., 2023). This unsuitable condition reinforces the preventive nature of these treatments and highlights the need to screen out pavements where safety, surface integrity, or structural concerns are expected to dominate performance.

Application timing recommendations are most commonly presented in terms of pavement condition and functional performance rather than in terms of a fixed number of years in service. Preservation guidance distinguishes between pavements experiencing early oxidative aging and those where surface aging may be more pronounced, but the structural capacity remains adequate (Blanchette et al., 2020; Estakhri and Agarwal, 1991; King and King, 2008). Some agency guidance also includes minimum pavement age considerations as a proxy for ensuring that sufficient surface aging has occurred prior to treatment. For example, the Caltrans Maintenance Technical Advisory Guide indicates that rejuvenating seals are generally intended for pavements that have been in service for 2 years or more, reflecting the expectation that measurable surface oxidation has developed by that time. Such age-based guidance is intended to supplement, rather than replace, condition-based pavement screening (Caltrans, 2010).

The FAA specification further differentiates acceptance expectations based on pavement age, with separate binder-property change requirements specified for pavements less than 3 years old and more than 3 years old. This distinction implies that agencies anticipate different levels of response depending on the degree of surface binder aging at the time of treatment (FAA, 2018).

Life cycle-based assessments further suggest that the greatest preservation benefit from spray-on rejuvenators is realized when treatments are applied early enough to delay the onset of surface-related deterioration, rather than attempting to mitigate advanced aging or cracking (Yang et al., 2023). Consistent with these findings, the literature indicates that appropriate pavement selection combined with timely application is critical to achieving meaningful preservation benefits from spray-on rejuvenators. Collectively published guidance supports treating candidate selection and timing as the primary determinants of whether spray-on rejuvenators provide measurable benefit, with application to pavements outside the intended preservation window frequently associated with limited performance and elevated safety risk.

## **Application Methods and Field Practices**

### *Surface Preparation and Pre-Application Considerations*

Effective application of spray-on rejuvenators requires appropriate surface preparation and pre-application verification to promote uniform distribution, facilitate interaction with the pavement surface, and minimize short-term performance or safety concerns. Proper surface preparation is consistently identified as a prerequisite for achieving intended preservation benefits (Blanchette et al., 2020; Button, 1996; FAA, 2018). Most guidance emphasizes that pavement surfaces should be clean and free of loose debris, dust, vegetation, and standing water prior to application. The presence of surface contaminants can inhibit contact between the rejuvenator and the pavement, leading to non-uniform coverage, reduced penetration, and inconsistent field response (Blanchette et al., 2020; Button, 1996). Consequently, sweeping or equivalent surface cleaning operations are commonly recommended immediately before treatment.

Coordination with pavement repair and crack-sealing activities is essential in planning spray-on rejuvenator applications. Because these treatments are not intended to correct structural deficiencies or advanced surface distress, repairs addressing significant cracking, patching needs, or structural deficiencies should, whenever feasible, be completed prior to rejuvenator application. Such repairs should be allowed sufficient time to stabilize and cure so that the treated surface reflects typical in-service pavement conditions rather than newly placed repair materials (Blanchette et al., 2020; Florida Pavement Preservation Council [FPPC], 2016). For example, an industry standard recommends that any crack repair or surface preparation activities be completed in advance of treatment and allowed a minimum curing period of 4 weeks prior to rejuvenator application, unless otherwise directed by the manufacturer (Collaborative Aggregates, 2021). This waiting period is intended to ensure adequate curing of repair materials and to minimize potential interference with rejuvenator penetration and absorption.

In situations when completing repairs in advance is impractical, repair or crack-sealing activities may be performed after rejuvenator application, provided that the applied material has adequately penetrated and cured. Although specific waiting periods are not uniformly prescribed, material curing behavior, surface condition, and safety considerations typically govern sequencing decisions (Blanchette et al., 2020; FAA, 2018).

Surface moisture and temperature at the time of application also play a critical role in treatment success. Agency guidance consistently emphasizes that spray-on rejuvenators should be applied only to dry pavement surfaces and when ambient and pavement temperatures meet minimum requirements specified by the product manufacturer or agency specification (Caltrans, 2010; FAA, 2018). Moisture present on the surface or within near-surface voids can interfere with material distribution, penetration, and curing, increasing the likelihood of tracking and non-uniform performance. Minimum temperature requirements are commonly imposed to promote adequate curing and acceptable early-life behavior. Although thresholds vary by product and agency, minimum ambient and pavement temperatures of 50 to 60°F (10–16°C) are frequently cited, with application generally restricted to dry conditions and stable or rising temperatures (Blanchette et al., 2020; Caltrans, 2010; FAA, 2018).

Pre-application inspections are widely recommended to confirm that candidate pavements meet condition requirements and to identify localized areas where treatment may be inappropriate or require adjustment. These inspections typically include visual assessment of surface distress, verification of surface cleanliness and dryness, and confirmation that pavement condition indicators remain within acceptable ranges for rejuvenator application (Blanchette et al., 2020). Such checks reinforce the preventive nature of spray-on rejuvenators and help reduce the risk of unintended performance or safety concerns following application. Collectively, the literature indicates that surface preparation and pre-application verification are foundational controls for achieving uniform coverage and minimizing short-term safety concerns.

### *Application Rate Determination and Control*

Application rate is one of the most essential variables governing spray-on rejuvenator performance and field constructability, because it directly influences (1) the quantity of material available to interact with the near-surface binder and void structure, (2) the potential for runoff or surface residue, and (3) early-life safety concerns related to tracking or temporary friction reduction. Accordingly, application rate is treated as a field-controlled variable that must be established and verified under project-specific conditions rather than assumed to be a fixed product property (Blanchette et al., 2020; FAA, 2018).

Application rates are commonly expressed as gallons per square yard (gal/yd<sup>2</sup>) or equivalent metric units and may be specified in terms of concentrate, diluted product, or residual asphalt content. For example, FPPC specification 335 requires blending the rejuvenating agent with water at a specified ratio prior to application and applying the material at a target rate of 0.04 to 0.10 gal/yd<sup>2</sup>, subject to engineer approval following field evaluation (FPPC, 2016). In contrast, FAA Item P-632 emphasizes the determination of a project-specific rate through control sections established with a qualified manufacturer's representative present and approved prior to full production (FAA, 2018). Synthesis studies further demonstrate that published application rates span a broad range. Blanchette et al. (2020), for example, summarize rates reported from NCAT test track screening and Missouri Department of Transportation field projects ranging from approximately 0.015 to 0.10 gal/yd<sup>2</sup>, depending on product type and dilution method, with some products requiring blotter material in field practice. Such variability in application rates reinforces the need for project-level calibration and underscores that a rate suitable for one pavement surface may be inappropriate for another.

From a field control standpoint, agencies commonly require verification of application rate through distributor calibration and documentation. FAA Item P-632 references ASTM D2995 for estimating application rate and residual application rate, consistent with broader practices aimed at confirming distributor output and uniformity prior to production application (ASTM International, 2014; FAA, 2018). FPPC 335 similarly emphasizes uniform coverage and provides guidance intended to minimize streaking and ensure consistent placement (FPPC, 2016). In practice, rate control is typically demonstrated through a combination of distributor calibration, verification of applied volume over a known area, comparison of measured and target yields, and field observation of surface response. Acceptance of control sections is commonly based on achieving uniform surface wetting without excessive runoff, ponding, or residue (FAA, 2018; FPPC, 2016).

As stated previously, the literature cautions that higher application rates do not necessarily result in improved rejuvenation outcomes and may increase construction and early-life performance risks. Excessive application has been associated with surface residue, delayed curing, tracking, and the need for mitigation measures such as blotter material (Ghosh et al., 2018; Taghavi et al., 2022). FAA Item P-632 explicitly provides remedial options for sanding when skid resistance is a concern during curing, illustrating the operational linkage between rate selection, curing behavior, and early-life friction response (FAA, 2018). Collectively, these findings indicate that application rate should be treated as a controlled field variable and determined through project-specific test sections to balance rejuvenation effectiveness with constructability and short-term safety considerations.

### *Spray Equipment, Materials Handling, and Placement*

Proper spray equipment configuration, materials handling, and placement practices are essential for achieving uniform application and acceptable early-life performance. Because spray-on rejuvenators are applied at relatively low rates and rely on near-surface interaction, small deviations in spray pattern, nozzle setup, or material handling can result in streaking, non-uniform coverage, or localized over- or under-application (Blanchette et al., 2020; Button, 1996). Agency guidance frequently requires the use of calibrated bituminous distributors capable of delivering a uniform spray pattern across the full treatment width. Specifications commonly emphasize proper spray bar height, nozzle spacing, and nozzle angle to promote even transverse distribution and minimize striping (FAA, 2018; FPPC, 2016). Uniformity is particularly important for rejuvenators because localized excess material can exacerbate curing delays and short-term friction loss.

Distributor setup and verification are critical components of quality control. Improper overlap between spray passes or inconsistent nozzle operation can lead to visible streaking and variable surface response, potentially requiring corrective action (Blanchette et al., 2020). As a result, test strips or control sections are commonly required not only to establish the application rate but also to verify the spray pattern and placement quality prior to full production (FAA, 2018).

Material handling practices are also important, particularly for products delivered as concentrates requiring onsite dilution or blending. FPPC 335 specifies dilution procedures and emphasizes adherence to manufacturer recommendations to ensure consistency throughout application (FPPC, 2016). Inadequate mixing or agitation can result in material separation, variable viscosity, and inconsistent performance. Additional handling considerations include maintaining material temperatures within recommended limits to ensure pumpability and sprayability. Although rejuvenators are typically applied at lower temperatures than hot asphalt binders, excessive cooling or prolonged storage in distributor tanks may alter viscosity and adversely affect spray uniformity (Blanchette et al., 2020).

Placement practices must also address overspray control and protection of pavement appurtenances. Agency specifications commonly require shielding of pavement markings, raised pavement markers, lighting fixtures, and signage prior to application. FAA Item P-632 explicitly

mandates protection of retroreflective markings and requires corrective action if contamination occurs (FAA, 2018).

Field studies further demonstrate that spray-on rejuvenators can reduce pavement marking retro reflectivity when applied directly over striping (Islam et al., 2025; Rodrigues et al., 2024; Yang et al., 2023). For example, evaluations from MnROAD, a pavement test track, reported immediate reductions exceeding 30% for several products, with reductions of 40 to 60% observed in some cases. Recovery was found to depend primarily on traffic exposure rather than time alone (Islam et al., 2025). These findings reinforce the importance of masking markings where practicable or planning restriping and reapplication of markings following treatment.

Overall, placement practices emphasize achieving continuous, uniform coverage without runoff, ponding, or excessive surface residue. Agencies typically require steady distributor speeds and avoidance of abrupt operational changes that could disrupt uniformity (FAA, 2018). Field observation remains a critical component of placement control, with inspectors evaluating visual indicators such as surface wetting, absence of streaking, and consistency of appearance. When non-uniformity is observed, corrective actions may include adjusting spray bar configuration, distributor speed, or overlap patterns (Blanchette et al., 2020).

#### *Curing Behavior and Return-to-Traffic Considerations*

Curing behavior is a critical aspect of spray-on rejuvenator performance because it governs short-term safety and return-to-traffic timing. Unlike aggregate-based surface treatments, rejuvenators cure through a combination of absorption into the pavement surface, evaporation of carrier components, and viscosity changes over time. Therefore, material formulation, application rate, pavement surface characteristics, and environmental conditions strongly influence curing behavior (Blanchette et al., 2020; Button, 1996).

Agency and industry guidance consistently emphasize that traffic should not be permitted on treated surfaces until curing is adequate and surface tackiness has dissipated (FAA, 2018; FPPC, 2016). Incomplete curing can lead to material pickup, tracking, localized residue, and temporary reductions in surface friction, all which present short-term safety concerns (Ghosh et al., 2018; Taghavi et al., 2022). Curing requirements are typically expressed in qualitative or performance-based terms rather than fixed time intervals. Specifications commonly require that the surface be dry to the touch, free of tracking, and capable of supporting traffic without material displacement prior to reopening (FAA, 2018; FPPC, 2016). Reported curing times vary widely, ranging from less than 1 hour under warm, dry conditions and low application rates to several hours or longer under less favorable environmental conditions (Blanchette et al., 2020). Environmental factors also strongly influence curing behavior. Higher pavement temperatures, low humidity, and moderate wind speeds generally promote faster curing, whereas cool temperatures, high humidity, shading, or damp surfaces can significantly delay curing (Blanchette et al., 2020; Button, 1996). Consequently, agencies commonly restrict applications to favorable weather windows and require suspending work when curing cannot be reliably achieved within an acceptable timeframe (Caltrans, 2010; FAA, 2018).

The literature and agency specifications typically include mitigation measures to address curing-related issues when they arise (Blanchette et al., 2020; FAA, 2018, Islam et al., 2025; Kebede, 2016; King and King, 2008; Moraes et al., 2025). FAA Item P-632 allows the application of fine sand or approved blotter materials to restore surface friction if slipperiness is observed during curing (FAA, 2018). Although such measures can facilitate earlier reopening, the literature cautions that reliance on blotter material should be minimized through proper rate selection, uniform placement, and appropriate environmental conditions, because excessive use may reduce effective binder-rejuvenator interaction (Blanchette et al., 2020).

Although short-term reductions in surface friction following application have been documented, agencies generally do not specify numeric friction thresholds for return-to-traffic decisions. Instead, reopening is typically based on field observation of surface condition, including tackiness, tracking, visual uniformity, and overall safety, with mitigation applied as needed (Blanchette et al., 2020; FAA, 2018; FPPC, 2016). Friction measurements reported in research studies are generally used to characterize short-term response and recovery trends rather than to control construction-phase decisions. Overall, the literature and agency and industry guidance indicate that a combination of material properties, application practices, and environmental conditions govern curing behavior and return-to-traffic timing for spray-on rejuvenators. Therefore, successful implementation requires conservative decision-making, close field monitoring, and adherence to specification requirements to balance preservation objectives with short-term safety and constructability concerns.

### **Performance Evaluation Metrics**

Because spray-on rejuvenators are surface-focused pavement preservation treatments, their effectiveness is typically evaluated using near-surface material properties and functional performance indicators, rather than traditional structural response measures. The literature consistently emphasizes that evaluation metrics and sampling protocols must be aligned with the limited depth of influence associated with these treatments to avoid misinterpretation of results (Blanchette et al., 2020; Brownridge, 2010; Button, 1996; Estakhri and Agarwal, 1991; Islam et al., 2025; King and King, 2008; Moraes et al., 2025). At the material level, evaluation commonly focuses on changes in near-surface binder rheological properties. Metrics reported in the literature and referenced in agency specifications include complex shear modulus, phase angle, creep stiffness, and relaxation behavior at low and intermediate temperatures, which are used to assess short-term changes in stiffness and viscoelastic response following application (Ghosh et al., 2018; Islam et al., 2025; Lin et al., 2013; Moraes et al., 2025; Vaddy et al., 2025). These metrics are intended to determine whether interaction between the applied rejuvenator and the aged binder has occurred in the near-surface region.

Several agencies define quantified binder-level performance thresholds as part of acceptance or verification procedures. Under FPPC 335, verification of rejuvenator effectiveness is based on chemical and rheological analysis of binder extracted from the upper 3/8 inch of pavement, with testing conducted on paired untreated and treated cores obtained approximately 15 to 30 days following application (FPPC, 2016). The specification requires that the recovered binder exhibits a minimum viscosity reduction of 25% for pavements 2 years old or less and a minimum reduction of 40% for pavements more than 2 years old. These thresholds are intended

to confirm both penetration and incorporation of the rejuvenating agent into the aged binder, rather than simple surface coating effects.

Similar quantified performance expectations are defined in FAA Item P-632 (FAA, 2018), which is frequently cited as a governing standard in the literature for spray-on rejuvenators. In this framework, acceptance testing is also based on rheological properties of binder recovered from the upper 3/8 inch of pavement, with cores typically extracted 30 to 45 days after application. For pavements 3 years old or less, a minimum 25% decrease in complex shear modulus or viscosity at 60°C is specified, and pavements more than 3 years old are required to demonstrate a minimum 40% reduction. Phase angle at 60°C is reported as a supplemental indicator to support the interpretation of changes in viscoelastic behavior.

At the pavement level, evaluation typically relies on functional indicators, including surface texture, friction response, visual condition surveys, and observations of surface residue or tracking. With respect to friction, agency specifications recognize that spray-on rejuvenators may temporarily influence surface friction immediately following application. FAA Item P-632 guidance recommends that friction testing be conducted within approximately 24 to 96 hours after application to verify that it is recovering toward pretreatment levels (FAA, 2018). The expectation is not an immediate improvement in friction, but rather that friction values demonstrate an increasing trend toward the original pavement condition.

## **Field Performance**

Field evaluations of spray-on rejuvenators consistently demonstrate that the same near-surface mechanisms identified in laboratory investigations govern their performance, with observable effects largely confined to surface condition, friction, texture, and aging-related distress progression. Across a wide range of climatic conditions, pavement types, traffic levels, and product formulations, field studies indicate that spray-on rejuvenators can influence short-term surface behavior, although the magnitude, persistence, and practical significance of these effects vary substantially.

Shoenberger (2003) investigated multiple proprietary rejuvenators, rejuvenator and sealers, and seal coat materials applied to dense-graded asphalt airfield pavements in both hot, humid Florida and cold, humid New Jersey environments. Monitoring conducted for more than 1 year showed that several rejuvenator products reduced near-surface binder stiffness, as reflected by increased penetration values and reduced viscosity of recovered asphalt relative to untreated controls. Visual inspections suggested temporary improvements in surface appearance and reductions in oxidation- and raveling-related distresses. However, the limited monitoring duration constrained the ability to quantify long-term deterioration trends. Skid resistance measurements consistently indicated short-term reductions following application, particularly for treatments placed without aggregate, although friction generally improved with trafficking and aging. Surface texture response was limited and inconsistent, with most treatments preserving existing macrotexture rather than producing measurable enhancement. Overall, the study suggested that spray-on rejuvenators may provide short-term preservation benefits on structurally sound pavements, while highlighting friction-related safety as a critical implementation consideration.

King and King (2008) documented multi-year evaluations of fog seals and spray-on rejuvenators across diverse climatic regions and pavement surface types, including dense-graded mixtures, asphalt rubber surfaces, open-graded friction courses, and chip seals. Monitoring periods extended up to 6 years at select sites. Field observations indicated that when applied to pavements in good condition and with sufficient surface permeability, rejuvenators and fog seals were effective in reducing surface oxidation and limiting moisture intrusion, with continued water repellency and reduced cracking observed for up to 4 years in some cases. However, consistent with earlier findings, friction testing revealed immediate reductions following treatment. Although friction typically recovered over time, particularly when sand was applied and traffic exposure increased, the study emphasized that friction loss remained the primary constraint for dense-graded surfaces. More consistent performance benefits were observed on open-graded mixtures, chip seals, and shoulders, where macrotexture was higher and friction sensitivity was reduced.

Large-scale agency pilot programs have provided additional insight into both performance and safety considerations associated with spray-applied rejuvenators. Cheng et al. (2015) documented an extensive field evaluation conducted by Caltrans to assess fog and rejuvenating seal performance on gap-graded and open-graded asphalt pavement surfaces. Initial pilot projects constructed in 2007 and 2009 evaluated six commercially available products applied to open-graded hot mix asphalt and rubberized gap-graded pavements under low- to moderate-traffic conditions. Field condition surveys conducted approximately 2 years after application indicated that treated sections consistently exhibited reduced raveling and slower surface deterioration compared with untreated controls, with particularly noticeable improvements on open-graded surfaces. Visual inspections showed improved aggregate retention and reduced rock loss, and treated pavements generally maintained better overall surface condition despite continued progression of thermal cracking, reinforcing that treatment benefits were primarily associated with surface durability rather than structural response.

Based on these favorable early outcomes, Caltrans expanded the evaluation through 12 pilot projects in 2012 and 9 additional projects in 2013 across multiple districts, climatic zones, traffic levels, and pavement surface types, including open-graded, gap-graded, dense-graded, and chip-sealed pavements. Field measurements demonstrated that fog and rejuvenating seal applications commonly resulted in reductions in surface macrotexture and short-term decreases in skid resistance immediately following treatment. However, friction levels typically recovered within days to weeks, particularly on projects with sanding or texture sealing implemented as a mitigation measure. Analysis of dynamic friction testing, skid trailer measurements, and sand patch testing showed strong relationships between macrotexture and friction response, leading to the identification of minimum recommended macrotexture thresholds of approximately 1.15 mm for open-graded surfaces and 0.75 mm for rubberized gap-graded surfaces to maintain acceptable skid resistance. The study further emphasized that product performance varied significantly and that successful implementation depends on appropriate pavement selection, controlled application rates, and verification of post-application safety performance.

Several studies have reported limited or inconclusive performance benefits when spray-on rejuvenators are applied to dense-graded pavements under moderate to high traffic. Medina and Clouser (2009) evaluated a soy-based polymer-modified rejuvenator applied to a high-volume roadway in Pennsylvania, with an adjacent untreated lane serving as a control. Field

testing showed no measurable reduction in pavement permeability, and skid resistance was reduced for at least 2 weeks following application, raising short-term safety concerns. Pavement marking retroreflectivity was also measurably reduced. Visual inspections conducted up to 18 months after application showed no discernible differences in surface condition or deterioration between treated and untreated lanes, and no visible evidence of the rejuvenator remained after approximately 18 months. The findings indicated that, under the evaluated conditions, the treatment did not provide measurable preservation benefits sufficient to offset observed safety-related impacts.

Similar variability has been reported in other medium- to high-traffic field evaluations. Von Quintus and Raghunathan (2017) assessed spray-on rejuvenators applied to recently constructed dense-graded asphalt overlays in Ohio and monitored performance for up to 4 years. Results indicated limited and inconsistent improvements in surface condition, with treated and untreated sections exhibiting comparable distress progression trends. Reductions in macrotexture were consistently observed immediately following application and often persisted throughout the monitoring period. Permeability response was mixed and inconsistently sustained, and friction reductions were observed initially and recovered gradually under traffic. The study concluded that penetrating sealers may provide marginal preservation benefits under select conditions, but performance outcomes are highly dependent on pavement characteristics, traffic loading, and application practices.

In contrast, more favorable field performance trends have been documented on low-volume pavements, where surface aging and environmentally driven distress dominate deterioration mechanisms. Kebede (2016) evaluated rejuvenating fog seals applied to 13 low-volume roadways in Indiana, with side-by-side treated and untreated lanes. All products caused immediate friction reductions. However, recovery behavior varied by formulation, with bio-based rejuvenators exhibiting smaller and statistically insignificant losses. Pavement condition surveys conducted approximately 1 year after application showed mixed results, with some treated sections maintaining higher condition ratings than controls. Although performance trends were difficult to quantify during the short monitoring period, the study concluded that rejuvenating fog seals may provide short-term preservation benefits on low-volume pavements, provided friction impacts are appropriately managed.

More definitive long-term evidence has emerged from extended monitoring studies on very low-volume roadways. Yang et al. (2023) evaluated a soybean-derived bio-based rejuvenating fog seal applied to a low-volume asphalt roadway in Iowa and monitored the performance during 5 years. Treated sections exhibited reduced transverse crack growth rates relative to untreated controls, particularly during severe winter conditions. Lower application rates produced the most consistent benefits, suggesting that excessive dosage may not enhance performance. Life-cycle cost analysis incorporating field distress data further suggested that periodic reapplication at 4- to 5-year intervals could reduce equivalent uniform annual costs by up to approximately 30% and extend pavement service life by up to 10 years under the evaluated conditions. These findings support the concept that spray-applied rejuvenators are most effective when surface aging governs performance and traffic-related damage is limited.

Large-scale experimental programs have provided additional insight into surface response and durability under controlled conditions. Field evaluations conducted at the NCAT Test Track during Phases VII and VIII examined the performance of spray-on rejuvenators under heavy accelerated loading (NCAT, 2021, 2024). Across both phases, treatments consistently produced short-term reductions in surface friction and macrotexture, followed by gradual recovery under trafficking. However, cracking performance of treated sections was generally comparable with untreated controls, with no consistent evidence of delayed cracking or structural performance improvement under high traffic loading. Measurements of reflectivity indicated modest short-term changes that diminished with time. Collectively, NCAT findings demonstrated that spray-on rejuvenators primarily influence near-surface functional characteristics and do not provide measurable structural or cracking-related benefits under high-traffic conditions.

Recent MnROAD field studies further refined the understanding of product-specific behavior. Islam et al. (2025) evaluated 12 rejuvenator products during a 3-year period and reported that several treatments slowed near-surface stiffness development during the first 1 to 2 years following application, although only a limited number maintained measurable effects beyond approximately 3 years. Friction reductions were generally minor and recovered over time, particularly for treatments incorporating sand. Mean texture depth remained largely stable, and permeability changes were minimal and inconsistent. Importantly, all treatments reduced pavement marking retroreflectivity, in some cases by more than 30%, reinforcing the need for post-application safety verification. Moraes et al. (2025) similarly reported product-dependent friction and macrotexture responses, with greater surface effects observed in mixtures containing unmodified binders compared with those containing polymer-modified binders. Persistent texture loss was observed for products associated with higher residual oil content, underscoring the importance of dosage control and material selection.

Taken collectively, field performance studies indicate that spray-on rejuvenators can influence near-surface aging characteristics and functional properties, particularly during the first 1 to 3 years following application. However, benefits are highly dependent on pavement condition, traffic level, surface texture, binder type, and product formulation. Short-term reductions in friction and pavement marking visibility are consistently documented and represent the most significant implementation concern. Structural performance improvements and cracking delay under moderate to heavy traffic have not been consistently demonstrated. These findings reinforce the preventive role of spray-on rejuvenators as surface-focused treatments best suited for structurally sound pavements, particularly those experiencing early-stage aging and low to moderate traffic loading. Field evidence further supports the need for conservative application rates, careful pavement selection, and continued post-application monitoring to balance potential preservation benefits against short-term safety and constructability risks.

## Reapplication Strategies and Life-Cycle Considerations

Although numerous studies have examined the short-term material and surface response of spray-on rejuvenators, substantially fewer investigations have evaluated their performance within a life-cycle framework or assessed the implications of repeated applications over time. As a result, guidance related to reapplication timing, durability of benefits, and long-term preservation effectiveness remains limited and, in many cases, inferred rather than directly validated through field performance data.

As discussed repeatedly, the available literature consistently indicates that spray-on rejuvenators provide time-dependent, near-surface benefits that diminish as pavements age under traffic and environmental exposure. Field and laboratory investigations have shown that measurable reductions in near-surface binder stiffness and aging rate are most pronounced within the first 1 to 2 years following application, with treatment effects gradually converging toward untreated conditions thereafter (Islam et al., 2025; Lee et al., 2013; Moraes et al., 2025; NCAT, 2024; Shoenberger, 2003). These observations suggest that rejuvenators do not permanently restore binder properties but rather delay surface aging processes for a finite period.

Due to the limited effective duration of a single application, several studies have emphasized that spray-on rejuvenators should be viewed as repeatable preventive treatments rather than one-time preservation solutions. Monitoring conducted at MnROAD indicated that although some products maintained measurable aging-retardation effects for approximately 2 to 3 years, the magnitude of benefit diminished with time, supporting the need for periodic reapplication if surface preservation objectives are to be sustained (Islam et al., 2025). However, treatment longevity was noted to be product-dependent and influenced by binder type, dosage, and environmental exposure, underscoring the difficulty of defining uniform reapplication intervals (Islam et al., 2025; King and King, 2008).

Longer-term field investigations provide additional, although still limited, insight into reapplication strategies. Historical airfield experience documented by Shoenberger (2003) described repeated applications of a petroleum-based rejuvenator at approximately 4-year intervals, with subsequent binder testing indicating renewed softening of the near-surface material. Although this evidence was largely observational and lacked comprehensive distress modeling, it represents one of the earliest documented examples of multi-cycle rejuvenator use and reinforces the conceptual basis for cyclic surface preservation.

A multi-state study evaluating fog and rejuvenator seals reported that many agencies maintain scheduled application programs for preventive maintenance that begin approximately 2 to 10 years after asphalt pavement construction (King and King, 2008). The authors further suggested that, because material-based trigger testing is generally impractical for most agencies, a scheduled interval approach tailored to climate, traffic, and surface type, such as “every X years or observation of minor distress, whichever comes first,” may be a practical strategy (King and King, 2008). Although such guidance is largely experience based rather than validated through multi-cycle performance datasets, it supports the conceptual framing of rejuvenators as repeatable surface preservation actions.

More recent low-volume roadway studies have attempted to explicitly link reapplication timing with life-cycle performance. Yang et al. (2023) conducted a 5-year field evaluation of a proprietary bio-based fog sealant applied to a low-volume asphalt roadway and quantified preservation benefits using annual distress surveys and life-cycle cost analysis. Treated sections exhibited consistently lower transverse crack growth rates relative to untreated control sections, indicating that environmental mechanisms dominated delayed surface deterioration. Using the observed crack growth rates as inputs, the authors implemented an equivalent uniform annual cost framework in which pavement service life was defined as the time required for treated sections to reach the same cracking condition as the untreated pavement at a nominal 20-year baseline service life. Under this modeling approach, repeated applications of the bio-based fog sealant were estimated to extend pavement service life by up to approximately 10 years, depending on the assumed treatment effectiveness period and the number of reapplications. The life-cycle cost analysis further indicated that appropriate reapplication strategies could reduce equivalent uniform annual costs by approximately 30% relative to untreated conditions, with the most favorable outcomes associated with three applications, each with an assumed 5-year effective period. The authors emphasized that these benefits were derived from the moderation of surface aging and reduced crack propagation rather than improvements in structural capacity, and that the applicability of the findings was most relevant to low-volume pavements where traffic-induced damage is limited.

Von Quintus and Raghunathan (2017) evaluated early-life applications of spray-on rejuvenators on new asphalt overlays and found that treated pavements exhibited slightly slower deterioration than controls, with observed service-life extensions of about 0.5 to 1 year at a pavement condition rating threshold of 75. In their final recommendations, Von Quintus and Raghunathan (2017) note potential extensions up to 2 years under favorable conditions and higher residual application rates, but these observations are extrapolated rather than directly measured during the 4-year monitoring period. Life-cycle cost analysis indicated that even modest extensions can reduce equivalent annual costs when treatments are applied to appropriate pavements at relatively low total unit cost, including traffic control and skid testing, while recognizing an immediate reduction in skid resistance after application. Reapplication strategies were not evaluated, so long-term, multi-cycle performance remains unquantified.

These studies suggest that potential life-cycle benefits from spray-on rejuvenators are closely tied to early application and repeated use within a preservation framework. Rather than restoring distressed pavements, rejuvenators appear most effective when applied to pavements in good structural condition to moderate near-surface aging and delay the onset of environmentally driven deterioration. However, despite these findings, substantial gaps remain in the current understanding of reapplication timing and long-term performance. Few studies have monitored treated pavements beyond a single preservation cycle, and even fewer have evaluated the cumulative effects of multiple applications under varying traffic, climatic, and material conditions. Reported reapplication intervals, typically ranging from approximately 2 to 5 years, are largely based on short-term performance trends, experience, or modeling assumptions rather than validated multi-cycle field data. In addition, life-cycle cost analyses are highly sensitive to assumptions regarding treatment effectiveness period, distress progression rates, and pavement classification. Consequently, reported estimates of service-life extension and economic benefit

should be interpreted cautiously, particularly when extrapolated beyond low-volume or environmentally dominated pavement systems.

Overall, the current literature supports the concept that spray-on rejuvenators may provide life-cycle preservation benefits when applied early and reapplied periodically. However, the magnitude and reliability of these benefits remain uncertain. The limited availability of long-term, multi-cycle field performance data represents one of the most significant gaps in current understanding of spray-on rejuvenator effectiveness. Addressing this gap through extended monitoring and multi-cycle field validation would strengthen the basis for performance-based guidance on reapplication timing and expected life-cycle benefit.

### **Agency Experience and Implementation Considerations (Minnesota Local Agency Survey)**

In addition to controlled laboratory and field research, practitioner experience provides important context regarding the constructability, operational challenges, and perceived benefits associated with spray-on rejuvenator applications. To document agency-level experience, a statewide survey was conducted to capture Minnesota local agencies' use of spray-on rejuvenators, including application practices, observed performance, and lessons learned (Marti and Salum, 2026).

Survey responses were received from 50 local agencies representing both county and city jurisdictions. Approximately one-half of the responding agencies reported applying spray-on rejuvenators, and the remaining agencies indicated no prior use. Among agencies with experience, several reported applying multiple rejuvenator treatments during different years, often as pilot projects or trial sections intended to evaluate feasibility before broader implementation. Reported application rates and unit costs varied across agencies, reflecting differences in pavement condition, surface characteristics, and contractor practices. Application rates generally ranged from approximately 0.02 to 0.10 gal/yd<sup>2</sup>, with reported costs typically ranging from approximately \$0.69 to \$3.55 per square yard, depending on project-specific conditions.

Agency feedback regarding performance was largely qualitative in nature and primarily based on visual observations rather than formal testing. Many respondents indicated that it was still too early to assess long-term performance, particularly for applications placed within the previous 1 to 3 years. Nevertheless, several consistent observations were reported. Agencies frequently noted improvements in pavement appearance following application, including darker surface color and enhanced water shedding. Some respondents indicated that treated surfaces appeared to exhibit reduced visible oxidation when applications were performed on relatively new asphalt pavements.

Several agencies also identified spray-on rejuvenators as a potential alternative to aggregate-based surface treatments, particularly in locations where traditional applications had experienced material loss or durability concerns related to winter maintenance operations. In these cases, rejuvenators were viewed as less disruptive to traffic, smoother for the traveling public, and less susceptible to surface damage during snowplow operations.

At the same time, agencies reported multiple implementation challenges. Tracking applied material onto adjacent concrete surfaces, driveways, and sidewalks was one of the most frequently cited concerns, particularly for applications requiring longer curing or absorption periods. Staining of pavement markings was also commonly noted, emphasizing the importance of protecting markings or planning for post-application mitigation. Weather sensitivity was repeatedly identified as a critical risk factor, with rainfall shortly after application contributing to runoff, uneven distribution, and extended cleanup efforts. Traffic control and return-to-traffic timing were identified as additional challenges, particularly on roadways with higher traffic volumes. Agencies reported that extended curing times increased staff demands and required proactive public communication. Contractor experience and quality of surface preparation were consistently cited as important contributors to successful outcomes, with thorough sweeping prior to application identified as a key prerequisite.

Across responses, pavement selection and timing of application emerged as dominant themes. Agencies consistently reported more favorable outcomes when rejuvenators were applied to relatively new pavements, commonly within approximately 1 to 3 years after construction. Applications placed on older pavements or surfaces exhibiting raveling, cracking, or limited permeability were generally perceived as less effective. These observations reinforce published guidance that spray-on rejuvenators function best as early, preventive treatments rather than corrective maintenance measures.

Overall, survey findings indicate that although many agencies view spray-on rejuvenators as potentially useful preservation tools, confidence in long-term performance remains limited because of the lack of objective performance data collected at the local-agency level. The frequent characterization of treatment effectiveness as “too early to tell” highlights the importance of systematic performance evaluation to support implementation decisions and to distinguish short-term surface effects from sustained preservation benefit.

### **Prior VDOT Experience with Spray-on Rejuvenators**

Prior to the field trials conducted as part of this study, documented experience with spray-on rejuvenators within VDOT was limited. The only known application identified by the authors occurred on a parking lot in the NoVA District. The parking lot was documented to be in generally good condition in 2011, prior to any preservation treatments (Figure 3). A spray-on rejuvenator was applied to the pavement in 2016, followed by crack sealing during the same year. No additional surface treatments or overlays have been applied to the parking lot since that time. A site review conducted in late 2025 indicated that the pavement surface remains in generally good condition.

Although the presence of wide cracks was noted, these cracks were identified as existing prior to the rejuvenator application, a distress the rejuvenator is not intended to address. Minor areas of alligator cracking were also observed. However, these distresses were not considered representative of surface aging or deterioration mechanisms targeted by spray-on rejuvenators. Importantly, limited surface oxidation was observed, and the pavement surface continued to exhibit an appearance consistent with relatively low permeability.



**Figure 3. Surface Condition of a Northern Virginia District Parking Lot Prior to Spray-on Rejuvenator Application (2011) and during a Follow-up Site Visit in Late 2025. The spray-on rejuvenator was applied in 2016, followed by crack sealing. No additional surface treatments were applied between 2011 and 2025. Images provided by David Shiells of VDOT Northern Virginia District.**

Although this single application does not provide sufficient data to establish treatment effectiveness or quantify service life extension, the observed surface condition suggests that the parking lot has not experienced rapid surface aging or widespread oxidation during the nearly decade-long period following treatment. This experience highlights the potential durability-related benefits often cited in the literature for spray-on rejuvenators when applied to pavements that remain structurally sound and are supported by appropriate crack sealing and maintenance practices.

### **Lynchburg District Field Trials**

#### **Documentation of Existing Pavement Condition and Application Process**

##### *Existing Pavement Condition*

Prior to application, walk-through inspections were conducted on the Lynchburg District routes (640 and 750) to document existing pavement conditions and identify visible surface distresses. For Route 640, the pavement condition across all four segments was generally good, with only localized areas of minor cracking observed. These cracks were limited in extent and did not indicate widespread surface or structural deterioration. Following application, some cracking became more visually apparent because of surface darkening associated with the spray-on rejuvenator, which increased contrast between cracked and uncracked areas. Figure 4 shows representative images of areas exhibiting good condition and localized cracking.

Route 750 exhibited a lower overall pavement condition than Route 640. Areas of cracking and raveling were observed across multiple segments, with more pronounced distress noted within Segment P2. Longitudinal cracking was observed along the center of the control lane, likely associated with construction-related practices, with crack widths approaching approximately 0.5 inch in some locations. Additional areas of raveling and interconnected cracking were also observed. Similar to Route 640, application of the spray-on rejuvenators increased visual contrast, making existing cracks and surface defects more noticeable,

particularly while the surface remained wet following application. Figure 5 shows representative images from distressed areas on Route 750.



**Figure 4. Images of Pavement Surface Condition on Route 640 with Areas of Good Condition and Localized Cracking**



**Figure 5. Images of Pavement Surface Condition on Route 750 with Areas of Cracking, Raveling, and Interconnected Surface Distress**

#### *Application Scheduling and Weather Conditions*

Applications for both routes were initially scheduled for September 12, 2023. Route 750 was treated as planned on September 12th. However, application on Route 640 was postponed because of rainfall later that day. A walk-through conducted on the morning of September 13th indicated that the pavement surface remained damp from overnight rainfall, and application was further delayed to ensure suitable surface conditions. Route 640 was subsequently treated on September 14th after the pavement surface had adequately dried.

Weather conditions at the time of application were documented for both routes. For Route 640, application activities began at approximately 9:35 a.m., 10:05 a.m., and 11:20 a.m. for Segments P2, P1, and P3, respectively. Air temperatures were approximately 70°F and rising, pavement temperatures were approximately 94°F, relative humidity was about 66%, and conditions were sunny. For Route 750, the application began at approximately 10:35 a.m., 11:35 a.m., and 12:35 p.m. for Segments P2, P1, and P3, respectively. Air temperatures were approximately 81°F and rising, pavement temperatures were approximately 105°F, relative humidity was about 63%, and conditions were also sunny until about 4 p.m. For both routes, the application duration for each segment (about 1,850 feet long) was approximately 3 minutes.

### *Application Equipment and Procedures*

Pavement surfaces were prepared using a vacuum-based cleaning system to remove loose debris and surface contaminants prior to spray-on rejuvenator application.

Two different application systems were used. Segments P1 and P3 on each route were treated using a pickup truck-mounted prototype spray system equipped with separate calibrated pumps and spray bars for the rejuvenator and polymer components. The system included an automated control unit to regulate and measure application rates during spraying. Initial passes on some segments exhibited non-uniform application, characterized by visible streaking (Figure 6). However, uniform coverage was achieved once spraying progressed, as shown in Figure 6. These observations highlight the importance of initial system checks and the potential benefit of short test strips to verify application rate and uniformity prior to full-scale application.



**Figure 6. Images of Spray-on Rejuvenator Application Using the Pickup Truck-Mounted Prototype Spray System, Illustrating Initial Non-Uniform Coverage and Subsequent Uniform Application Following Continued Spraying**

Segment P2 on each route was treated using a small three-wheeled application unit equipped with a tank and spray nozzle system (Figure 7). Brushes were used to assist with distributing the rejuvenator across the pavement surface. Application rates for this system were determined using a yield-based measurement approach.



**Figure 7. Application of Spray-on Rejuvenator Using a Three-Wheeled Application Unit**

### *Application Rates*

Application rates varied by product and route. For Route 640, Segment P1 received approximately 0.025 gal/yd<sup>2</sup> of rejuvenator with a latex emulsion applied at approximately 0.016 gal/yd<sup>2</sup>. Segment P2 received approximately 0.07 gal/yd<sup>2</sup> of rejuvenator, and Segment P3 received approximately 0.06 gal/yd<sup>2</sup> of rejuvenator along with approximately 0.016 gal/yd<sup>2</sup> of latex emulsion. For Route 750, Segment P1 received approximately 0.025 gal/yd<sup>2</sup> of rejuvenator with a latex emulsion applied at approximately 0.013 gal/yd<sup>2</sup>. Segment P2 received approximately 0.07 gal/yd<sup>2</sup> of rejuvenator, and Segment P3 received approximately 0.03 gal/yd<sup>2</sup> of rejuvenator with approximately 0.016 gal/yd<sup>2</sup> of latex emulsion.

### *Field Observations During and After Application*

Several field observations were documented during and shortly after application. In one instance, a localized spill of spray-on rejuvenator was observed (Figure 8), highlighting the importance of promptly addressing excess material to minimize potential friction concerns. In addition, a utility truck entered the treated lane within the curing timeframe of Segment P1, braking abruptly over an estimated distance of 75 to 100 feet. This condition resulted in the formation of small polymer balls on the pavement surface (Figure 9). The incident occurred despite traffic control measures being in place, emphasizing the importance of strict access control during curing periods.



**Figure 8. Localized Spill of Spray-on Rejuvenator Observed during Application**



**Figure 9. Formation of Polymer Balls on the Pavement Surface Following Premature Vehicle Entry and Braking within the Treated Lane during the Curing Period**

Approximately 15 minutes after application, walk-through inspections indicated that the treated surfaces did not exhibit material tracking. Although the surface felt slick under footwear, it was tacky to the touch, with no observable residual material transfer to the hand. Furthermore, a site visit conducted the following day on Route 750, after rainfall occurred overnight, did not reveal any evidence of runoff or uneven material distribution for any of the segments.

Visual observations made shortly after application indicated noticeable surface color contrast between treated segments and adjacent untreated lanes. Figures 10 and 11 show representative photographs documenting surface appearance for Routes 640 and 750, respectively. For Segment P3 on Route 750, minimal color contrast was evident relative to the adjacent untreated lane. It must be noted that, based on these observations, the treated segments could have been reopened to traffic within approximately 1 hour following application under

normal conditions. However, traffic reopening was delayed for the Lynchburg District trials to accommodate post-application coring activities required for laboratory testing.



**Figure 10. Images of Surface Appearance Shortly after Spray-on Rejuvenator Application for Route 640. P1–P3 denote segments receiving spray-on rejuvenator application.**

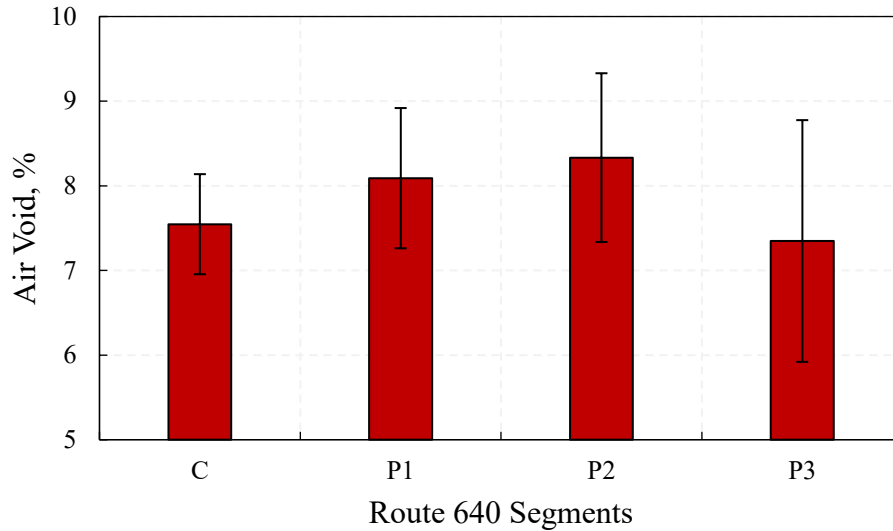


**Figure 11. Images of Surface Appearance Shortly after Spray-on Rejuvenator Application for Route 750. P1–P3 denote segments receiving spray-on rejuvenator application.**

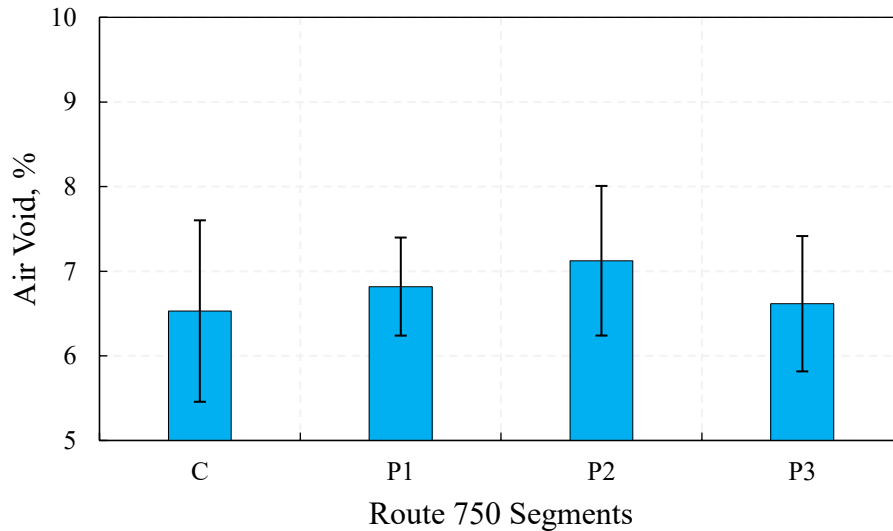
### **Near-Surface Air Void Characteristics**

Figures 12 and 13 present the near-surface air void content, determined from the top approximately 9.5 mm of field cores, for Routes 640 and 750, respectively. Field cores for the treated sections (P1–P3) were obtained following the spray-on rejuvenator application, and cores from the untreated control sections were collected concurrently to ensure consistent sampling conditions. For Route 640, near-surface air void contents generally ranged between approximately 7.3 and 8.3% across all segments (Figure 12). Minor differences were observed among sections. However, these differences were within the expected variability associated with

near-surface field coring and reflect spatial heterogeneity along the pavement surface. Similar trends were observed for Route 750 (Figure 13). Near-surface air void contents were generally in the range of approximately 6.5 to 7.1%, with variability consistent with that observed on Route 640.



**Figure 12. Near-Surface Air Void Content for Route 640.** Error bars represent the variability (standard deviation) observed among replicate cores collected within each segment. C denotes the untreated control segment, and P1–P3 denote segments receiving spray-on rejuvenator application.



**Figure 13. Near-Surface Air Void Content for Route 750.** Error bars represent the variability (standard deviation) observed among replicate cores collected within each segment. C denotes the untreated control segment, and P1–P3 denote segments receiving spray-on rejuvenator application.

The air void contents measured following application did not indicate any measurable effect of the spray-on rejuvenator on near-surface volumetric characteristics, indicating no observable alteration of the volumetric structure of the surface mixture. The near-surface air void contents measured for both routes are also consistent with ranges identified in prior field and

laboratory investigations as potentially favorable for spray-on rejuvenator interaction. Previous studies have reported that surface air void contents on the order of approximately 7 to 8%, or greater, may facilitate improved material penetration by providing a more interconnected void structure, thereby reducing the potential for surface pooling or runoff (Brown, 1988; Estakhri and Agarwal, 1991; King and King, 2008; Prapaitrakul et al., 2005; Shoenberger, 2003).

### Binder Rheological Response

Table 4 summarizes the near-surface binder rheological properties measured at 60°C and 10 rad/s for Routes 640 and 750. The binder data were evaluated with respect to FAA Item P-632, which is among the most commonly referenced specifications in both research and industry practice. For pavements more than 3 years old, FAA Item P-632 specifies that an acceptable rejuvenator response should result in a minimum 40% decrease in  $|G^*|$  at 60°C, with phase angle reported for informational purposes (FAA, 2018). Both Routes 640 and 750 fall within this age category, being approximately 5 years old at the time of application, and were therefore evaluated relative to this criterion.

**Table 4. Near-Surface Binder Rheological Properties for Routes 640 and 750**

Route	Segments	$ G^* $ at 60°C and 10 rad/s, kPa	% Reduction in $ G^* $ Relative to Control	$\delta$ at 60°C and 10 rad/s, °
640	C	73.7	N/A	67.5
	P1	38.4	47.9	70
	P2	57.0	22.7	68.9
	P3	82.6	a	65.4
750	C	134.3	N/A	65.2
	P1	b	N/A	b
	P2	63.7	52.3	67.3
	P3	81.8	39.1	66.7

a = an increase in  $|G^*|$ ; therefore, a percentage reduction is not applicable. b = binder rheological data were not available;  $G^*$  = dynamic shear complex modulus; N/A = not applicable;  $\delta$  = phase angle. C denotes the untreated control segment; P1–P3 denote segments receiving spray-on rejuvenator application.

For Route 640, the untreated control segment exhibited a  $|G^*|$  value of 73.7 kPa. Segment P1 exhibited a reduction in  $|G^*|$  of approximately 47.9% relative to the control, exceeding the FAA Item P-632 minimum reduction criterion. Segment P2 exhibited a reduction of approximately 22.7%, which is below the FAA-specified threshold. Segment P3 exhibited an increase in  $|G^*|$  relative to the control. Therefore, no percentage reduction is reported for this segment. This outcome is attributed to variability associated with near-surface field sampling and specimen handling. Phase angle values for Route 640 ranged from approximately 65° to 70°F. Slight increases in  $\delta$  were observed for Segments P1 and P2 relative to the control, indicating a modest shift toward more viscous behavior in the near-surface binder.

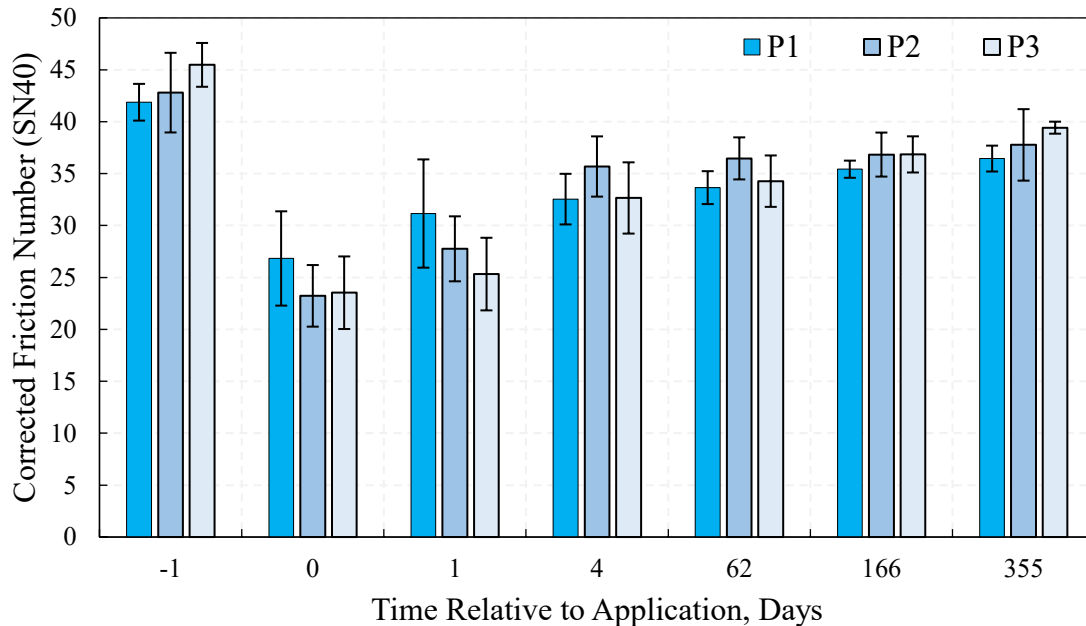
For Route 750, the untreated control segment exhibited a  $|G^*|$  value of 134.3 kPa. Binder rheological data were not available for Segment P1. For the remaining treated segments, Segment P2 exhibited a reduction in  $|G^*|$  of approximately 52.3% relative to the control, exceeding the FAA Item P-632 minimum reduction criterion. Segment P3 exhibited a reduction of approximately 39.1%, which is slightly below the FAA-specified threshold. Corresponding

phase angle values for Segments P2 and P3 increased modestly relative to the control, indicating a shift toward more viscous binder behavior following application.

Overall, the binder rheological results indicate that some treated sections exhibited reductions in near-surface binder stiffness meeting or exceeding the minimum  $|G^*|$  reduction specified in FAA Item P-632 for pavements more than 3 years old, whereas other sections exhibited partial or limited response. It is important to note that FAA Item P-632 criteria are intended to support material-level verification and are not intended to imply mixture-scale or structural modification or long-term performance improvement. The observed rheological changes reflect only the near-surface binder response and should be interpreted accordingly.

### Friction Performance

Figure 14 presents the corrected SN40 values for Route 640. Prior to application, corrected friction numbers ranged from 41.9 to 45.5 across the treated segments (P1–P3), with an average variability of approximately 5.1% along each segment.



**Figure 14. Corrected Friction Number (Skid Numbers at 40 mph) Measured Using a Locked-Wheel Tester with Smooth Tire for Route 640 Before and After Spray-on Rejuvenator Application. Error bars represent variability observed along each segment. P1–P3 denote segments receiving spray-on rejuvenator application. The 0-day measurement represents data collected immediately following application.**

Friction measurements collected on the day of application indicated a temporary reduction in surface friction. Corrected SN40 values decreased to 26.8, 23.2, and 23.5 for Segments P1, P2, and P3, respectively, corresponding to friction reductions of approximately 35.9, 45.7, and 48.3% relative to pre-application conditions. This short-term reduction is consistent with the presence of residual material on the pavement surface immediately following application.

Subsequent measurements indicated progressive friction recovery. Four days after application, corrected SN40 values increased to 32.5, 35.7, and 32.7 for Segments P1, P2, and P3, representing approximately 77.7, 83.4, and 71.8% of pre-application friction levels, respectively. Continued recovery was observed during long-term monitoring. At approximately 355 days following application, corrected SN40 values of 36.5, 37.8, and 39.4 were recorded for Segments P1, P2, and P3, corresponding to approximately 87 to 88% of pre-application friction levels.

Variability along each segment increased slightly during the early post-application period, with an average variability of approximately 7.4% within the first 62 days following application, and then decreased to an average value of approximately 5.9% for the remaining measurements.

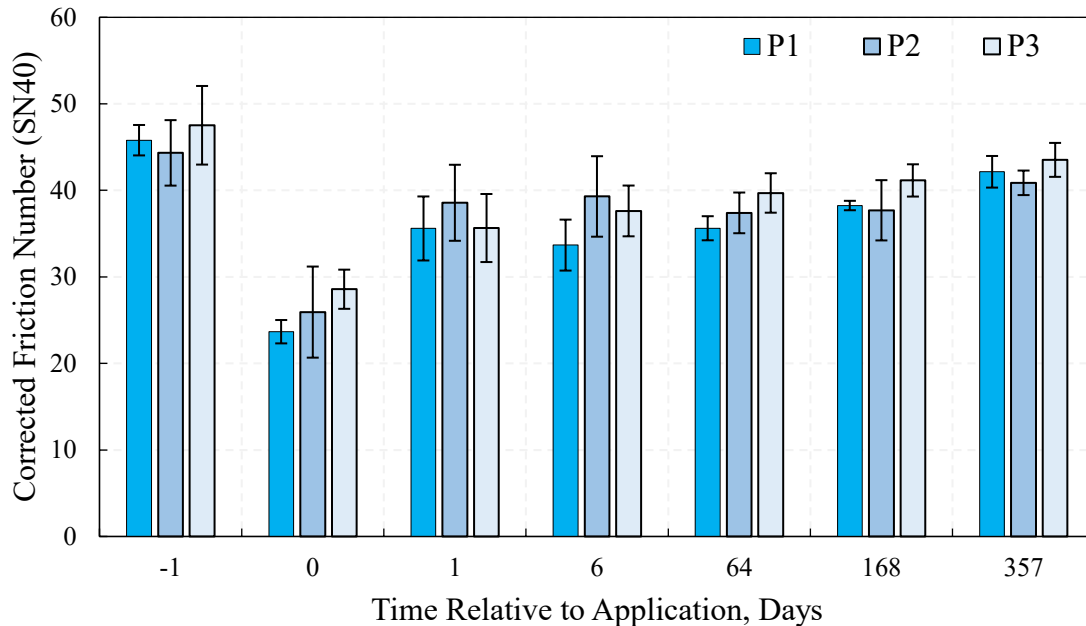
For context, corrected friction numbers remained above a reference value of 20 throughout the monitoring period. A prior Virginia Transportation Research Council (VTRC) study by Mahone and Sherwood (1995) recommended an SN40 value of 20 as a minimum acceptable wet pavement friction level for locked-wheel testing with a smooth tire, noting that values below this level should be considered unacceptable and may warrant immediate attention. Although VDOT does not specify friction acceptance criteria for asphalt surface mixtures, VTM 122 similarly indicates that friction numbers below 20 should be reported to the district as soon as possible. Accordingly, the reference value of 20 is provided solely for contextual interpretation and should not be construed as a specification or acceptance threshold.

Figure 15 shows the corrected SN40 results for Route 750. Pre-application friction values ranged from 44.3 to 47.5 across the treated segments, with an average variability of approximately 7.3% along each segment.

Immediately following application, corrected SN40 values decreased to 23.7, 25.9, and 28.6 for Segments P1, P2, and P3, respectively. These values correspond to friction reductions of approximately 48.3, 41.5, and 39.9% relative to pre-application levels. Similar to Route 640, this reduction reflects short-term surface effects associated with the presence of rejuvenator material prior to full curing and traffic exposure.

Friction recovery was observed within the first week following application. Six days after application, corrected SN40 values increased to 33.7, 39.3, and 37.6 for Segments P1, P2, and P3, representing approximately 73.5, 88.7, and 79.2% of pre-application friction levels. Long-term monitoring conducted approximately 357 days following application showed further recovery, with corrected SN40 values of 42.2, 40.9, and 43.5, corresponding to approximately 91 to 92% of pre-application friction levels.

Segment-level variability increased during the early post-application period, with an average variability of approximately 10.6% within the first 64 days, before decreasing to an average value of approximately 4.8% during later measurements. Consistent with observations on Route 640, corrected friction numbers for Route 750 remained above the reference value discussed previously throughout the monitoring period (Mahone and Sherwood, 1995).

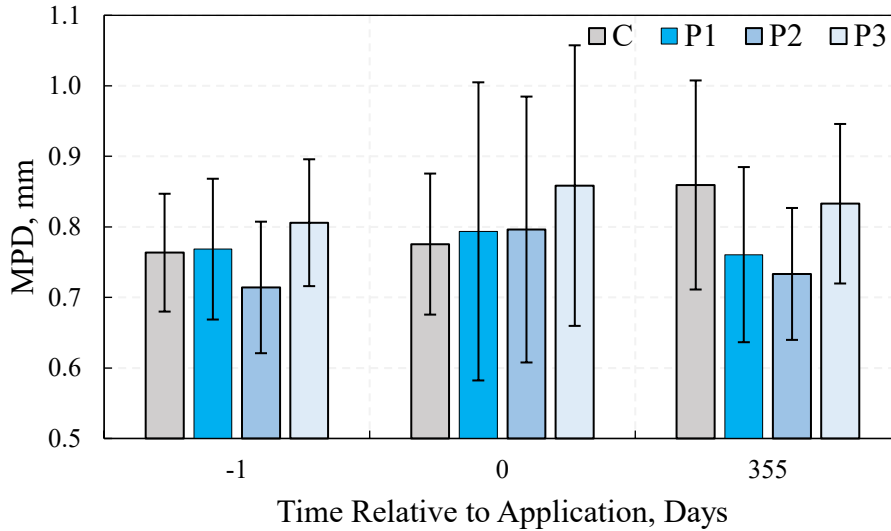


**Figure 15. Corrected Friction Number (Skid Numbers at 40 mph) Measured Using a Locked-Wheel Tester with Smooth Tire for Route 750 Before and After Spray-on Rejuvenator Application. Error bars represent variability observed along each segment. P1–P3 denote segments receiving spray-on rejuvenator application. The 0-day measurement represents data collected immediately following application.**

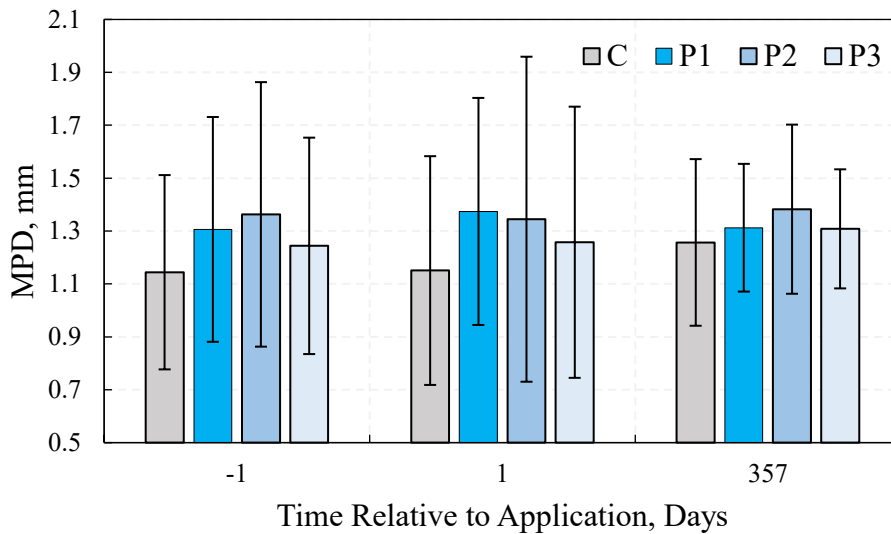
For both routes, application of spray-on rejuvenators resulted in an immediate but temporary reduction in surface friction, followed by progressive recovery with time and traffic. The friction recovery trends observed in this study are consistent with prior findings reported in the literature for spray-on rejuvenator treatments. Importantly, friction values remained above the reference level throughout the monitoring period, and no long-term adverse friction behavior was observed under the conditions evaluated. At the time of report preparation, the research team had not been notified of any crashes on the evaluated sections following application.

### Surface Texture Characteristics

Figures 16 and 17 present surface macrotexture, quantified using MPD, for Routes 640 and 750, respectively. MPD measurements were collected before application (-1 day), immediately following application (0 or 1 day), and approximately 355 to 357 days after application, depending on the route. For Route 640, MPD values remained generally consistent across all sections throughout the monitoring period (Figure 16). No notable changes in macrotexture were observed following application of the spray-on rejuvenators. Similar behavior was observed on Route 750 (Figure 17). The results indicate that spray-on rejuvenator application did not result in measurable changes in pavement macrotexture during the evaluation period.



**Figure 16. Surface Texture Quantified Using Mean Profile Depth (MPD) at Selected Intervals Relative to Spray-on Rejuvenator Application for Route 640.** Error bars represent the variability (standard deviation) observed along the measured length of each segment. C denotes the untreated control segment, and P1–P3 denote segments receiving spray-on rejuvenator application. The 0-day measurement represents data collected immediately following application.

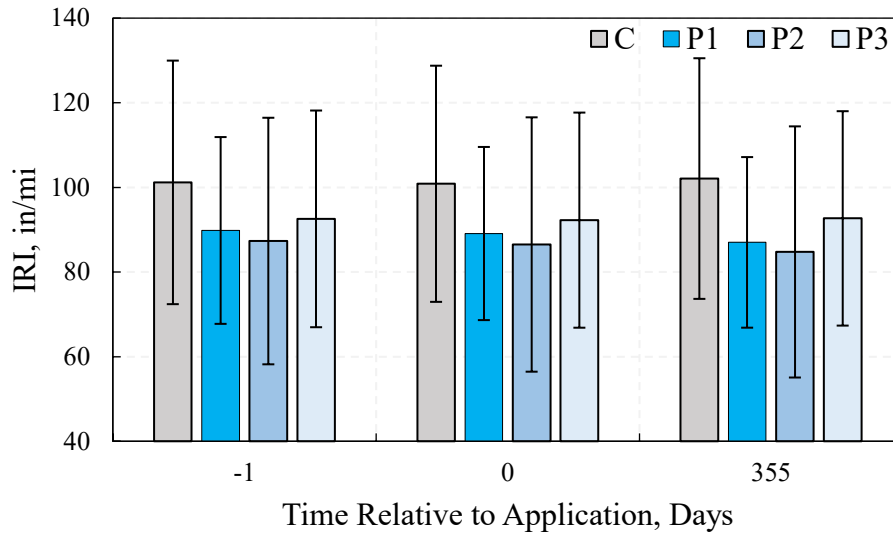


**Figure 17. Surface Texture Quantified Using Mean Profile Depth (MPD) at Selected Intervals Relative to Spray-on Rejuvenator Application for Route 750.** Error bars represent the variability (standard deviation) observed along the measured length of each segment. C denotes the untreated control segment, and P1–P3 denote segments receiving spray-on rejuvenator application.

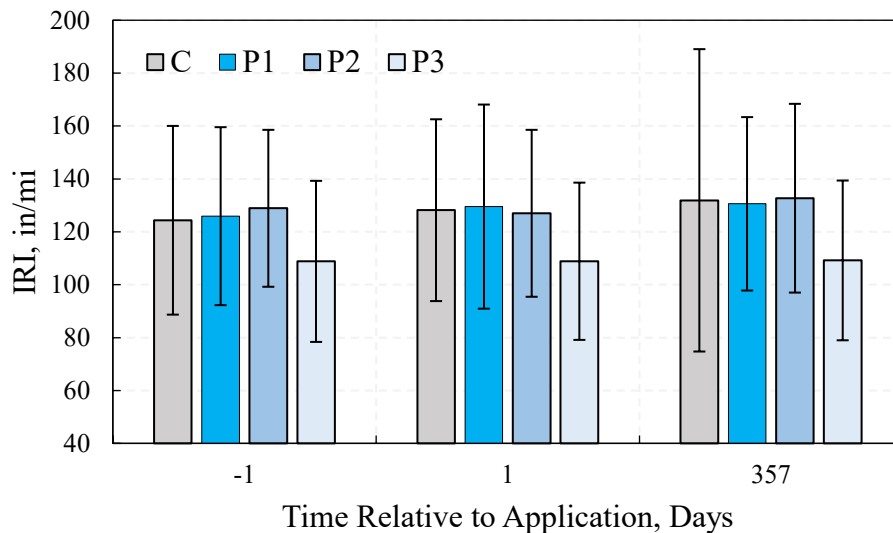
### Ride Quality

Figures 18 and 19 present ride quality, quantified using IRI, for Routes 640 and 750, respectively. IRI measurements were collected before application (-1 day), immediately following application (0 or 1 day), and approximately 355 to 357 days after application, depending on the route. For Route 640, IRI values remained relatively consistent across all

sections throughout the monitoring period (Figure 18). No consistent trend indicating improvement or deterioration in ride quality was observed following application of the spray-on rejuvenators. Similar behavior was observed on Route 750 (Figure 19). The results indicate that spray-on rejuvenator application did not result in measurable changes in pavement smoothness during the timeframe evaluated.



**Figure 18. Ride Quality Measured Using the International Roughness Index (IRI) at Selected Intervals Relative to Spray-on Rejuvenator Application for Route 640.** Error bars represent the variability (standard deviation) observed along the measured length of each segment. C denotes the untreated control segment, and P1–P3 denote segments receiving spray-on rejuvenator application. The 0-day measurement represents data collected immediately following application.



**Figure 19. Ride Quality Measured Using the International Roughness Index (IRI) at Selected Intervals Relative to Spray-on Rejuvenator Application for Route 750.** Error bars represent the variability (standard deviation) observed along the measured length of each segment. C denotes the untreated control segment, and P1–P3 denote segments receiving spray-on rejuvenator application.

## Rutting Performance

Rutting performance was evaluated as part of the Lynchburg District field trials to verify that spray-on rejuvenator application did not produce any short-term adverse effects on pavement deformation characteristics. Rut depth measurements were collected approximately 1 week prior to application and again 1 day following application for both Routes 640 and 750. Appendix B provides a detailed presentation of the rutting data, figures, and an associated discussion.

In summary, differences were observed between pre-application and post-application rut depth measurements. However, the magnitude and direction of these differences varied among treated and untreated sections. Given the very short interval between measurements and the fact that the pavements had been in service for approximately 5 years at the time of application, the observed differences are not indicative of rut development. Rather, they are attributed to normal variability associated with field rut depth measurements collected using a five-laser measurement configuration.

## Visual Evaluation and Pavement Condition

### *Visual Evaluation*

Visual evaluations were conducted approximately 6 and 12 months following application of the spray-on rejuvenators to document surface appearance and identify any observable changes in pavement condition. Figures 20 and 21 present representative images of Routes 640 and 750 at the 6-month interval, and Figures 22 and 23 show representative images collected after approximately 12 months in service, respectively.



**Figure 20. Images of Surface Appearance Approximately 6 Months after Spray-on Rejuvenator Application for Route 640. Treated lane is shown on the left, and untreated lane is shown on the right. P1–P3 denote segments receiving spray-on rejuvenator application.**



**Figure 21. Images of Surface Appearance Approximately 6 Months after Spray-on Rejuvenator Application for Route 750. Treated lane is shown on the left, and untreated lane is shown on the right. P1–P3 denote segments receiving spray-on rejuvenator application.**



**Figure 22. Images of Surface Appearance Approximately 12 Months after Spray-on Rejuvenator Application for Route 640. P1–P3 denote segments receiving spray-on rejuvenator application.**



**Figure 23. Images of Surface Appearance Approximately 12 Months after Spray-on Rejuvenator Application for Route 750. P1–P3 denote segments receiving spray-on rejuvenator application.**

At the 6-month evaluation, noticeable color contrast was observed between treated and untreated lanes for products P1 and P2 on both routes (Figures 20 and 21). In Figures 20 and 21, the treated lane is on the left side of each image, and the adjacent untreated lane is on the right. The treated lanes exhibited a darker surface appearance relative to the untreated lanes. In contrast, minimal to no color difference was observed for the P3-treated sections. Similar surface appearance trends were observed on both Routes 640 and 750.

By the 12-month evaluation, color differences between treated and untreated lanes were no longer visually distinguishable for any of the products evaluated (Figures 22 and 23). Surface appearance across all segments appeared generally uniform, indicating that the initial color contrast diminished with time. In addition to surface color, the pavement sections were evaluated for visible signs of distress, including rutting, cracking, raveling, or other surface irregularities. No visually discernible differences in surface condition were observed between treated and untreated sections at either the 6- or 12-month inspection intervals. Overall, the surface condition of all segments appeared comparable with pre-application observations, with no evidence of treatment-related distress or adverse surface behavior.

#### *Pavement Condition*

Tables 5 and 6 present the NDR and LDR indices for Routes 640 and 750, respectively. Both routes received asphalt overlays in 2018, resulting in condition index values of 100 across all segments at that time. Spray-on rejuvenators were applied in 2023, and condition surveys were conducted approximately 78 days following application and again in 2024, approximately 1 year after application.

**Table 5. Non–Load-Related Distress and Load-Related Distress Indices for Route 640**

Index	Survey Year	P1	P2	P3	C
Non–Load-Related Distress	2018	100	100	100	100
	2023 <sup>a</sup>	100	100	93	99
	2024	100	98	94	97
Load-Related Distress	2018	100	100	100	100
	2023 <sup>a</sup>	100	100	99	100
	2024	99	98	99	98

<sup>a</sup> Condition survey conducted approximately 78 days following spray-on rejuvenator application. The 2024 survey was conducted approximately 1 year after application. C denotes the untreated control segment; P1–P3 denote segments receiving spray-on rejuvenator application.

**Table 6. Non–Load-Related Distress and Load-Related Distress Indices for Route 750**

Index	Survey Year	P1	P2	P3	C
Non–Load-Related Distress	2018	100	100	100	100
	2022	99	95	100	92
	2023 <sup>a</sup>	80	61	90	84
	2024	80	80	90	80
Load-Related Distress	2018	100	100	100	100
	2022	99	93	100	95
	2023 <sup>a</sup>	86	43	89	87
	2024	90	83	96	84

<sup>a</sup> Condition survey conducted approximately 78 days following spray-on rejuvenator application. The 2024 survey was conducted approximately 1 year after application. C denotes the untreated control segment; P1–P3 denote segments receiving spray-on rejuvenator application.

Table 5 presents the NDR and LDR indices for Route 640. NDR values for all segments were 100 in 2018, reflecting the excellent condition of the newly overlaid surface. During the post-application survey conducted in 2023, NDR values remained at or near 100 for most segments. Segment P3 exhibited a lower value of 93, and the untreated control segment exhibited a value of 99. These minor reductions occurred within a relatively short period following application and are considered indicative of early-stage surface aging rather than treatment-related effects. During the 2024 survey, conducted approximately 1 year after spray-on rejuvenator application, modest reductions in NDR values were observed across several segments. NDR values ranged from 94 to 100 for treated segments and 97 for the control segment. The magnitude and pattern of change were similar between treated and untreated segments, indicating no discernible difference in NDR progression attributable to the spray-on rejuvenator application. Overall, NDR results for Route 640 indicate limited surface condition changes during the monitoring period.

LDR values for all segments were also 100 in 2018, confirming the absence of LDR following overlay placement. During the 2023 post-application survey, LDR values remained at or near 100 across all segments, with only a minor reduction observed in Segment P3. By the 2024 survey, small reductions in LDR values were observed across both treated and untreated segments, with values ranging from 98 to 99. These changes were minor in magnitude and consistent across segments, warranting conditioned monitoring to better understand condition trends.

Table 6 presents the NDR and LDR indices for Route 750. NDR values for all segments were 100 in 2018, reflecting the excellent condition of the newly overlaid surface. By 2022, prior to spray-on rejuvenator application, reductions in NDR values were observed across both treated and untreated segments. During the 2023 post-application survey, further reductions in NDR values were observed across all segments. The magnitude of reduction varied by segment, with the most pronounced decrease observed in Segment P2. These reductions occurred within a relatively short time following application and likely reflect pre-existing pavement condition and spatial variability rather than treatment-related effects. During the 2024 survey, NDR values for the treated segments (P1–P3) either remained stable or increased relative to 2023 values, whereas the untreated control segment did not exhibit comparable improvement. Although these observations may suggest potential stabilization or partial recovery of surface condition in treated areas, the underlying causes cannot be conclusively determined based on the available data. The observed changes may reflect treatment-related effects, measurement variability, or differences in inspection conditions between survey years. As such, these results should be interpreted cautiously, and continued monitoring is warranted to determine whether these trends persist over time.

LDR values were uniformly high across all segments in 2018, consistent with the structural integrity of the newly overlaid pavement. By 2022, modest reductions in LDR values were observed across several segments. During the 2023 post-application survey, notable reductions in LDR values were observed across all segments, particularly within Segment P2. Given the short interval following application, these changes are not indicative of treatment-related deterioration. By the 2024 survey, LDR values in the treated segments exhibited partial recovery or stabilization relative to 2023 values, whereas the untreated control segment remained at a comparatively lower level. Although these trends may suggest improved or stabilized conditions in treated sections, the underlying causes cannot be conclusively determined based on the available data. The observed changes may reflect treatment-related effects, inherent variability in condition survey measurements, or differences in inspection conditions across survey years. Continued monitoring is recommended to confirm long-term performance trends.

## **The Northern Virginia District Field Trials**

### **Documenting the Existing Pavement Condition and Application Process**

#### *Existing Pavement Condition*

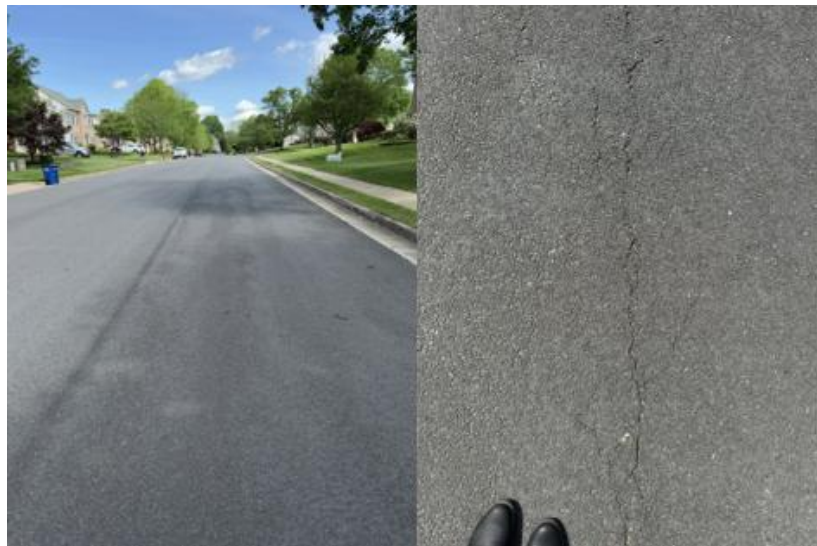
Prior to application, walk-through inspections were conducted on the residential streets selected in the NoVA District (Walney Park Drive, Leighfield Valley Drive, Point Pleasant Drive, and Star Flower Drive) to document existing pavement conditions and identify visible surface distresses.

For Walney Park Drive and Leighfield Valley Drive, the pavement condition was generally observed to be in good repair. Having been resurfaced within the past 4 years and being exposed to almost exclusively low-speed (25 mph) residential traffic, the primary distress was mild surface oxidation. Throughout both streets, minor cracking (less than 0.6 mm) and varying separation along the longitudinal joint were identified (Figures 24 and 25). However,

these distresses did not indicate evidence of any structural deterioration. It should be noted that the most recently reported CCI value for Leighfield Valley Drive was 72. This value did not reflect the pavement's appearance at the time of location selection and treatment. Leighfield Valley Drive had a nearly identical appearance to that of Walney Park Drive, which had a CCI of 100.



**Figure 24. Images of Pavement Surface Condition on Walney Park Drive prior to Treatment**



**Figure 25. Images of Pavement Surface Condition on Leighfield Valley Drive prior to Treatment**

For Point Pleasant Drive and Star Flower Drive, the pavement conditions presented more distress than the previous two streets. Having been resurfaced 8 years prior to application, this condition was to be expected. Both routes presented with moderate oxidation and scattered minor cracking (less than 0.8 mm). Point Pleasant Drive, however, contained isolated areas of complete failure (Figure 26). These isolated areas were repaired at least 4 weeks prior to spray-on rejuvenator application. Figure 27 shows an area of cracked surface prior to the treatment of Star Flower Drive.



**Figure 26. Images of Pavement Surface Condition on Point Pleasant Drive prior to Treatment**



**Figure 27. Image of Pavement Surface Condition on Star Flower Drive prior to Treatment**

### *Application Scheduling and Weather Conditions*

Application scheduling was conducted in pairs and completed by two separate contractors. First, Walney Park Drive and Leighfield Valley Drive were treated on October 9, 2025. Initially, the two streets were scheduled for treatment the week prior. However, because of equipment failure, the treatment was postponed. Treatment of Walney Park Drive began at approximately 9:45 a.m., with air temperatures of approximately 55°F and rising, and pavement temperatures of approximately 65°F. Treatment of Leighfield Valley Drive began at approximately 12:45 p.m., with air temperatures of approximately 61°F and rising, and pavement temperatures of approximately 70°F. Conditions remained sunny throughout the curing process with a relative humidity of 45%.

Point Pleasant Drive and Star Flower Drive were treated on October 16 and 17, 2025. The outside lanes of both streets were treated on October 16th. Treatment was originally scheduled to begin at 8:30 a.m., however, temperatures were lower than allowable, and the start time was delayed until 11 a.m. Air temperatures were approximately 55°F and rising, and pavement temperatures were approximately 60°F. The inside lanes of both streets were treated on October 17th. Treatment was delayed until 11 a.m., as had been done the previous day. Air temperatures were approximately 55°F and rising, and pavement temperatures were approximately 60°F. Conditions on both treatment days remained sunny with a relative humidity of 45%.

#### *Application Equipment and Procedures*

All pavement surfaces were prepared to remove loose debris and surface contaminants prior to spray-on rejuvenator application. The small three-wheeled application equipment used in the Lynchburg District field trials was also used on Walney Park Drive and Leighfield Valley Drive. An emulsion spray truck, equipped with calibrated pumps and spray bars for rejuvenator and polymer components (Figure 28), was used on Point Pleasant Drive and Star Flower Drive.



**Figure 28. Application of Spray-on Rejuvenator Using an Emulsion Sprayer Truck**

#### *Application Rates*

Application rates varied by product and route. For Walney Park Drive, an application rate of approximately 0.07 gal/yd<sup>2</sup> was achieved. A similar application rate of approximately 0.07 gal/yd<sup>2</sup> was applied on Leighfield Valley Drive. For Product C, applied to the outside lanes of Point Pleasant Drive and Star Flower Drive, an application rate of approximately 0.025 gal/yd<sup>2</sup> of rejuvenator and 0.012 gal/yd<sup>2</sup> of latex emulsion was achieved. For Product D, applied to the inside lanes of Point Pleasant Drive and Star Flower Drive, an application rate of approximately 0.028 gal/yd<sup>2</sup> of rejuvenator with 0.012 gal/yd<sup>2</sup> of latex polymer was achieved.

### *Field Observations During and After Application*

Several field observations were documented during and shortly after application for all streets treated. For Walney Park, Product A yielded a white cast on the pavement surface. When fully cured and dried, the pavement surface appeared “damp” and slightly darker than before treatment. Figure 29 shows the condition of Walney Park Drive before and after treatment. Product B used on Leighfield Valley Drive left a black cast across the pavement surface and maintained a similar appearance when fully cured. Figure 30 shows the condition of Leighfield Valley Drive before and after treatment.



**Figure 29. Images of Walney Park Drive Before and After Treatment**



**Figure 30. Images of Leighfield Valley Drive Before and After Treatment**

The application and curing process of Product C on the outside lanes of both Point Pleasant Drive and Star Flower Drive presented notable differences from previously used products. Like Product A used on Walney Park Drive, Product C had a white cast when initially

applied and dried clear after fully curing. However, Product C required a longer curing window. Traffic entered the treated lane within the curing timeframe and tracked the actively curing polymer on the pavement surface throughout the street, leaving a “stringy” appearance on the pavement surface. Ultimately, inadequate traffic control allowed traffic to enter the section before the product was fully cured. Figure 31 shows the condition of Point Pleasant Drive after treatment with Product C.



**Figure 31. Images of Point Pleasant Drive Before and After Treatment with Product C**

Product D, which was applied on the inside lanes of both Point Pleasant Drive and Star Flower Drive, was visually similar to Product A used on Walney Park Drive. Product D had a white cast when initially applied and dried clear after fully curing. Traffic was kept off this section until the rejuvenator was fully cured and dry to the touch. Figure 32 shows Point Pleasant Drive before and after treatment with Product D. All products used during the NoVA District field trials required approximately 2 to 3 hours of curing time prior to reopening the treated sections to traffic. This curing duration was longer than observed during the Lynchburg District field trials and is attributed to less favorable weather conditions at the time of application, including lower ambient and pavement temperature. These observations highlight the importance of selecting application windows for spray-on rejuvenators with favorable weather conditions to facilitate timely curing and minimize delays in reopening treated sections to traffic.



Figure 32. Images of Point Pleasant Drive Before and After Treatment with Product D

### Binder Rheological Response

Table 7 summarizes the near-surface binder rheological properties measured at 60°C and 10 rad/s for the NoVA District field trials. As with the Lynchburg District field trials, binder response was evaluated relative to FAA Item P-632, which specifies that for pavements more than 3 years old, acceptable rejuvenator response should result in a minimum 40% reduction in  $|G^*|$  at 60°C, with phase angle ( $\delta$ ) reported for informational purposes (FAA, 2018). The NoVA District field trials fall within this age category and were therefore assessed relative to this criterion.

Table 7. Near-Surface Binder Rheological Properties at 60°C and 10 rad/sec for the Northern Virginia District Field Trials

Product Used	Location	Pre Treatment		Post Treatment		% Reduction in $ G^* $
		$ G^* $	$\delta$	$ G^* $	$\delta$	
A	Walney Park Drive	13.7	78.5	13.5	71.6	1.8
B	Leighfield Valley Drive	52.4	73.5	32.5	69.9	38.1
C	Point Pleasant Drive outside	46.7	66.7	51.9	66.6	a
C	Star Flower Drive outside	69.8	64.2	50.9	59.6	27.2
D	Point Pleasant Drive inside	46.7	66.7	128.4	56.3	a
D	Star Flower Drive inside	69.8	64.2	33.5	70.4	52.0

a = an increase in  $|G^*|$ ; therefore, a percentage reduction is not applicable;  $G^*$  = dynamic shear complex modulus;  $\delta$  = phase angle.

For Product A at Walney Park Drive, the reduction in  $|G^*|$  was minimal (1.8%), indicating limited measurable softening of the extracted near-surface binder. The phase angle decreased from 78.5° to 71.6°, suggesting a shift toward slightly more elastic behavior.

For Product B at Leighfield Valley Drive,  $|G^*|$  decreased by 38.1% relative to the pretreatment condition, approaching but not fully meeting the 40% reduction criterion specified in FAA Item P-632. The phase angle decreased modestly. The magnitude of  $|G^*|$  reduction suggests measurable binder softening, although the rheological shift was not accompanied by a pronounced increase in  $\delta$ .

For Product C, responses differed by location. At Point Pleasant Drive (outside),  $|G^*|$  increased following treatment. At Star Flower Drive (outside),  $|G^*|$  decreased by 27.2%, which is below the FAA threshold. Similarly, Product D exhibited contrasting behavior between locations: at Point Pleasant Drive (inside),  $|G^*|$  increased substantially, whereas at Star Flower Drive (inside),  $|G^*|$  decreased by 52.0%, exceeding the FAA criterion. At this latter location,  $\delta$  increased from 64.2° to 70.4°, indicating a shift toward more viscous binder behavior consistent with softening.

Several factors inherent to near-surface binder extraction and field sampling may influence the variability observed among products and locations. The intended extraction depth of approximately 9.5 mm may not have been achieved uniformly across all cores. In some cases, post-treatment specimens may have included a portion of untreated binder beneath the effective penetration depth of the rejuvenator, thereby diluting the measured response.

For Products C and D, which include polymer-modified formulations, the observed increases in  $|G^*|$  at certain locations may reflect localized effects of polymer concentration within the extracted binder sample. Polymer-modified systems can exhibit complex rheological behavior, and increases in stiffness at a specific frequency and temperature do not necessarily preclude chemical interaction or near-surface modification.

Overall, although not all sections met the FAA Item P-632 40% reduction criterion, several locations exhibited meaningful reductions in near-surface binder stiffness. When considered collectively, the data suggest that spray-on rejuvenators may alleviate near-surface binder stiffness to varying degrees under field conditions. Continued monitoring of these sections is necessary to determine whether the spray-on rejuvenator applications translate into sustained functional or durability-related benefits over time.

### **Summary of Findings**

From the literature review:

- Spray-on rejuvenators are preventive treatments intended for structurally sound pavements. The literature consistently indicates that spray-on rejuvenators are most appropriate for pavements exhibiting early-stage surface aging while remaining structurally sound. These treatments are not intended to correct structural deficiencies or advanced surface distress.
- Expected treatment benefits are limited to the near-surface region of the asphalt layer. Published studies indicate that rejuvenator influence is typically confined to the upper portion of the asphalt layer, generally within the top several millimeters.
- Appropriate pavement selection and application timing are critical to treatment effectiveness. The literature emphasizes that pavements exhibiting extensive distress, low texture or friction, and limited surface permeability may exhibit inconsistent or limited response. Early application on pavements in relatively good condition is a critical implementation consideration.

- Traffic level influences the applicability of available performance evidence. Most documented field performance data for spray-on rejuvenators are associated with low-volume roadways. Application on higher-volume roadways has been less extensively evaluated, and extrapolation of results should be approached cautiously.
- Re-application strategies remain uncertain and are not well defined in current practice. The literature does not provide consistent guidance regarding optimal re-application intervals. Reported practices typically range from approximately 3 to 6 years and are largely based on engineering judgment rather than quantified performance thresholds.
- Long-term performance benefits remain uncertain. Although short-term material responses are frequently reported, the literature provides limited conclusive evidence regarding linking spray-on rejuvenators to measurable long-term service life extension. Most studies emphasize the need for continued field monitoring to better quantify durability-related benefits.
- Life-cycle cost benefits cannot be reliably quantified based on existing data. Although spray-on rejuvenators are frequently described as low-cost preventive treatments, limited quantitative evidence exists to directly associate their use with documented life-cycle cost savings. Reported benefits are typically inferred from assumed delays in surface aging rather than from verified performance outcomes.

From the Virginia field trials and supported by the literature review:

- Spray-on rejuvenators can influence near-surface binder properties under field conditions. The field trials demonstrated that measurable changes in near-surface binder rheological properties can occur following application.
- Treatment response is variable and influenced by product formulation and pavement condition. Observed variability in near-surface binder response across treated segments reinforces the idea that performance depends on product characteristics, surface condition, and mixture properties, rather than being uniform across applications.
- Application practices and traffic control are critical to successful application. The field trials confirmed the importance of application rate control, spray uniformity, adequate curing time, and strict access control. Curing behavior was sensitive to ambient and pavement temperature conditions, with less favorable conditions contributing to extended curing durations. Premature traffic entry during curing resulted in localized surface effects and safety concerns, underscoring the importance of effective traffic management and proactive communication when treatments are applied on residential roadways.
- Traffic opening decisions currently rely on engineering judgment rather than formal acceptance criteria. During the field trials, reopening decisions were based on visual assessment of surface appearance, evaluation of tackiness and slipperiness through manual inspection, and consideration of site-specific operating conditions. These practices highlight the need for more objective evaluation metrics and clearer guidance to support consistent and

defensible traffic opening decisions across varying roadway types and traffic and environmental conditions.

- Short-term surface friction reduction occurs following application, followed by recovery. The Lynchburg District field trials confirmed an immediate but temporary reduction in surface friction after application, followed by recovery with time.
- No evidence of short-term adverse functional effects was identified under the conditions evaluated. Within the limited monitoring period, spray-on rejuvenator application did not indicate a discernible change attributable to functional pavement characteristics such as surface texture, ride quality, or rutting.
- Short-term field trials are valuable for implementation understanding rather than performance confirmation. Consistent with prior studies, the Virginia field trials primarily served to document construction practices, short-term material response, and implementation considerations. The results establish baseline performance conditions but do not support definitive conclusions regarding service life extension or cost-effectiveness.

## CONCLUSIONS

- Spray-on rejuvenators provide measurable short-term improvements in near-surface binder properties and can temporarily reduce surface friction, but their influence is confined to the upper asphalt layer. Current evidence does not confirm long-term service life extension or reliable life-cycle cost benefits, highlighting the need for continued monitoring and research.
- *The effectiveness of spray-on rejuvenators depends heavily on appropriate pavement selection, timing of application, and adherence to best practices during construction.* These treatments are most suitable for structurally sound pavements and exhibiting early-stage surface aging. This study resulted in the development of a draft special provision (Appendix A) to support potential future spray-on rejuvenator applications.

## RECOMMENDATIONS

1. *VDOT should continue monitoring the existing field trial sections in the Lynchburg and NoVA Districts.* Continued evaluation would help determine whether spray-on rejuvenators translate into measurable preservation-related benefits over time. As part of this effort, consideration should be given to evaluating potential re-application strategies, including timing and frequency of re-application, where appropriate. Any future re-applications conducted on these sections should use the special provision draft developed as part of this study to ensure consistency in materials, application practices, and documentation. Information gained through continued monitoring and re-application trials would support refinement of the draft provision and improve understanding of treatment durability under Virginia conditions.

2. *VDOT should consider identifying appropriate pavement categories for spray-on rejuvenator applications and incorporating a broader set of field executions into routine pavement preservation schedules.* Candidate applications may include residential and non-residential roadways, parking facilities, and other low-risk facilities that are structurally sound and exhibit early-stage surface aging. Selection criteria may be informed by pavement age, condition indices, traffic characteristics (volume and speed), and functional condition.

## **IMPLEMENTATION AND BENEFITS**

The researcher and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

### **Implementation**

*Regarding Recommendation 1*, VTRC, with the support of the Maintenance Division and the NOVA and Lynchburg Districts, will establish a long-term monitoring project by September 2026. Monitoring activities may include reviewing condition survey indices (e.g., CCI), collecting field cores for near-surface binder evaluation, and other performance indicators, as appropriate. The monitoring program may also consider evaluation of potential re-application timing and performance where warranted.

*Regarding Recommendation 2*, VDOT's Maintenance Division will update guidance documents by September 2026 to include spray-on rejuvenator applications for the preventive maintenance treatment category. The guidance will identify appropriate candidate pavements, which may include structurally sound sections with surface asphalt mixtures generally less than approximately 5 years old and exhibiting early-stage surface aging. Selection criteria may also consider pavement condition indicators such as CCI to identify pavements in relatively good condition and suitable for early preventive application.

*Regarding Recommendation 2*, VTRC, in coordination with VDOT's Maintenance Division, will work with the districts to increase awareness of spray-on rejuvenator applications and encourage consideration of their inclusion in future contracts by December 2026. This effort would be accomplished through information dissemination at Pavement Management Leadership Group meetings and by assisting districts in identifying candidate sites for potential spray-on rejuvenator applications.

### **Benefits**

Although spray-on rejuvenator treatments are frequently described as low-cost preventive options, quantitative data linking their use to documented cost savings remains insufficient. Continued monitoring and research are necessary to establish durability-related benefits and cost-effectiveness. If spray-on rejuvenators are shown to provide durable preservation benefits

through continued monitoring and broader field implementation, their use could offer meaningful advantages to VDOT's pavement management program.

The field trials conducted as part of this study were necessarily limited in scope and represented a narrow range of pavement ages and operating conditions. As such, they do not capture the full range of conditions under which spray-on rejuvenators may be most effective. Broader field deployments are warranted to better understand treatment performance across varying pavement conditions and to support meaningful evaluation of preservation benefits.

As a result of this study, a draft special provision was developed to document material requirements, application practices, construction considerations, and evaluation procedures. The provision is intended to support consistent implementation, facilitate future field trials, and provide a framework for continued evaluation under Virginia conditions. As additional field experience is gained, the provision may be further refined to incorporate lessons learned from future applications and long-term performance monitoring.

Implementing spray-on rejuvenators as part of planned preservation activities, rather than as isolated research applications, would allow VDOT to gain experience at a scale that supports meaningful evaluation while minimizing inefficiencies and cost increases associated with small-scale trials. This approach would provide an opportunity to systematically evaluate application timing, re-application strategies, potential life-cycle cost implications, durability-related performance trends, and potential service life extension under Virginia conditions. These deployments should be conducted using the draft special provision developed through this study to promote consistent application and data collection and to support continued refinement of the provision based on field performance and constructability observations.

Extended evaluation of existing field trials and future deployments may help determine whether spray-on rejuvenators can delay the onset of surface-related distresses and contribute to incremental service-life extension for structurally sound pavements. Even modest delays in surface deterioration could reduce the frequency of more costly maintenance or rehabilitation treatments.

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## APPENDIX A

### VIRGINIA DEPARTMENT OF TRANSPORTATION SPECIAL PROVISION FOR SPRAY-ON REJUVENATOR TREATMENT

February 29, 2026

#### I. DESCRIPTION

This work shall consist of furnishing all labor, materials, and equipment necessary to perform all operations for the application of an asphalt pavement rejuvenation treatment, a spray-on rejuvenator treatment (SRT), to existing bituminous pavement surfaces in accordance with these specifications, the contract requirements, and as directed by the Engineer. The SRT is a preventive, spray-applied treatment that penetrates and modifies oxidized asphalt binder within the near-surface region of the pavement (typically the top 3/8 inch) and without causing an unacceptable reduction in surface friction.

#### II. DEFINITION OF TERMS

**Spray-on Rejuvenator Treatment**—A spray application of a petroleum- or bio-based rejuvenating agent designed to modify aged asphalt binder characteristics in the near-surface region of the pavement, typically in the top 3/8 inch of pavement.

**Blotter Material**—Clean, dry, manufactured sand or fine crushed stone used immediately after SRT application in areas where surface friction is not adequate to restore early-life skid resistance.

**Effective Penetration**—Uniform absorption of SRT into the pavement surface without runoff, ponding, excessive residue, or delayed curing.

**Control Section (Test Strip)**—A short trial application constructed prior to production work to verify application rate, spray uniformity, and curing behavior.

#### III. MATERIALS

The rejuvenating agent shall be petroleum- or bio-based and capable of penetrating and modifying the oxidized asphalt binder in the near-surface region.

The blotter materials (sand) shall be clean, dry, manufactured sand or fine crushed rock free from organic matter, clay, or other deleterious materials. Blotter material shall be used only in areas where friction tests show the SRT alone has not achieved adequate skid resistance.

The blotter material shall meet the following gradation:

Sieve Size	Percent Passing
3/8 inch	100
No. 4	95–100
No. 16	25–60
No. 30	10–30
No. 200	0–5

#### IV. EQUIPMENT

The Contractor shall provide all equipment required for the scope of work.

The rejuvenating agent shall be applied via a computer rate-controlled distributor that contains no contaminants, diluents, or residual materials and is in working order. Application rates of 0.05 to 0.25 gallons per square yard must be achievable. Distributor application rates shall be calibrated in accordance with ASTM D2995 within 30 days of first use. Use the manufacturer's rejuvenating material for calibration. Document all calibration results. The application rate shall be controlled by an onboard computer control system designed to control the selected application rate in gallons per square yard, regardless of the forward speed of the distributor truck. The distributor equipment shall include full circulation spray bars, a pump tachometer, a volume-measuring device, and a hand-hose attachment for manual application of the product and shall be capable of circulating and agitating the product within the tank.

Use a spray bar suitable for the project-specific lane width, fitted with fan-type nozzles (1/4-inch or 3/16-inch brass tips) spaced no more than 12 inches apart. Adjust nozzle pressure to maintain a consistent spray fan. The spreader bar tips must be capable of maintaining the required flow rates at a constant pressure during application, and the tips must be clean and of appropriate size to maintain an even distribution. Replace any nozzles that are worn, clogged, or that produce an uneven pattern prior to starting the project.

The truck used for sanding shall have a spreader that allows the sand to be uniformly distributed onto the pavement surface at a rate of 1/2 pound to 3 pounds of sand per square yard in a single pass, regardless of the forward speed of the truck. The spreader shall be adjustable to avoid applying sand onto driveways, lawns, and personal property. The spreader calibration per ASTM D5624 must be completed within 30 days prior to use. The Contractor must provide mechanical sweepers or a combination broom-vacuum unit that can remove excess sand or rejuvenating material efficiently without damaging the pavement surface or existing markings.

The Contractor shall furnish all necessary traffic control, barricades, signs, and flaggers to ensure the safety of the traveling public and all working personnel in accordance with VDOT specifications.

## **V. CONSTRUCTION PROCEDURES**

### **a. Weather and Seasonal Restrictions**

Do not apply SRT when the air temperature is below 50°F (10°C) or the pavement temperature is below 60°F (16°C), as measured in the shade immediately before starting application.

Do not apply SRT on wet or damp pavement. Suspend work if rain is forecast within the 12 hours following the application time. If rain falls before the SRT has "broken" (penetrated), the SRT must be reapplied at no extra cost.

Do not apply when sustained winds exceed 10 mph (16 km/h) to avoid spray drift and uneven coverage.

### **b. Control Section**

Prior to beginning full production application, the Contractor shall construct a control section of not less than 300 feet in length at the proposed application rate and under representative project conditions. The purpose of the control section is to demonstrate that the selected equipment settings and application procedures produce a uniform spray pattern, without streaking, ponding, or runoff, and that the material exhibits acceptable curing behavior under prevailing environmental conditions. The control section shall also confirm that the intended target application rate can be achieved and maintained.

Production application shall not proceed until the Engineer has inspected and approved the control section.

**c. Resident Notification**

The Contractor shall distribute a typed notice that includes a local phone number that residents may call to ask questions to all residences and businesses on the street to be treated. The notice will be delivered no less than 24 hours prior to construction. The notice shall be of the door hanger type, which secures to the door handle of each dwelling. The notice shall also be placed on the windshield of any parked cars on the street. For SRT performed on residential streets or other low-speed local roadways, the Contractor shall implement enhanced resident notification and public communication procedures to minimize premature traffic entry onto uncured pavement surfaces and to reduce the potential for tracking, property staining, and safety-related concerns.

**d. Surface Preparation**

Repair potholes, severe cracks (> 3/8-inch width), and structural distresses shall be treated at least 4 weeks before SRT application. If moderate or low severity crack sealing is required, perform it at least 24 hours after SRT application, unless otherwise directed by the Engineer.

Immediately prior to SRT application, remove all dust, loose aggregate, dirt, vegetation, and any oil or grease from the pavement. Use mechanical sweepers or air blowers. If grease or oil is present, scrub with a detergent solution and flush with water; allow at least 24 hours for the pavement to dry fully before applying SRT.

**e. Protection of Adjacent Areas**

Cover and protect curbs, gutters, driveways, manhole frames, drainage inlets, and all pavement markings (e.g., raised pavement markers, thermoplastic paint) to prevent overspray. Remove any protective coverings only after the SRT has completely cured.

**f. Rejuvenating Treatment Application**

The target application rate of the rejuvenating agent shall be within the range of 0.015 to 0.15 gallons per square yard of pavement surface covered, or otherwise directed by the Engineer. The application rate shall achieve an even coating without product runoff or increasing curing times.

The asphalt-rejuvenating agent shall be applied via distributor truck at the temperature recommended by the manufacturer and at the pressure required for the proper distribution. Do not allow the asphalt rejuvenating agent to streak on the road surface. If the Engineer determines that streaking is occurring, operations shall be ceased, and streaking shall be eliminated to the Engineer's approval. If a nozzle becomes clogged or fails to spray a proper pattern, the operation shall be halted immediately until all appropriate repairs are completed. Distribution shall begin with a running start to ensure a full rate of spread over the entire current treatment area. The distributor shall move forward at the proper application speed when the spray bar is opened.

**g. Blotter Sand Application**

Blotter sand shall be applied only in locations where post-application friction testing indicates that the SRT-treated roadway did not achieve the minimum skid resistance—a skid number of 20 using a locked-in wheel tester with a smooth tire in accordance with ASTM E274. The friction testing is required before opening to traffic for routes with speed

limits greater than 30 mph. If friction is acceptable, the Engineer may waive sand application.

Apply blotter sand promptly after SRT has cured, typically within 20 to 30 minutes of SRT application. The blotter sand must be removed no later than 24 hours after treatment of a roadway. All turnouts, cul-de-sacs, and so on must be cleaned of any material to the satisfaction of the Engineer. Street sweeping will be included in the price bid per square yard for SRT. If, after blotter sand is swept and in the opinion of the Engineer a hazardous condition exists on the roadway, the Contractor must apply additional manufactured sand and sweep the same no later than 24 hours following reapplication. No additional compensation will be allowed for reapplication and removal of materials.

Using the calibrated spreader, distribute blotter sand uniformly at 1.0 lb/yd<sup>2</sup> ( $\pm$  0.2 lb/yd<sup>2</sup>) only in the areas identified by the Engineer. Adjust the rate if directed. Do not allow sand to accumulate in gutters or blow off the pavement.

#### **h. Traffic Reopening**

Traffic shall not travel on freshly applied rejuvenator until penetration, in the opinion of the Engineer, is complete and the area is suitable for traffic.

#### **i. Performance Verification (Core Testing)**

The Contractor shall take one core sample (minimum 6-inch diameter) prior to application and one core sample after the treatment (typically 15 to 30 days after SRT application) from the same area within the same lane. Take a minimum of one pair per route of treated pavement or as directed by the Engineer. The core holes shall be patched using a H<sub>2</sub>O activated cold mix product from VDOT Materials Division's Approved List No. 78.

Trim the top 3/8 inch of pavement from each core. Test the extracted and recovered binder from each trimmed core (untreated and treated) using a dynamic shear rheometer per AASHTO T 315 at 64°C. Confirm that the recovered binder from treated cores exhibits a viscosity reduction of at least 25% for pavements less than 2 years old, or at least 40% for pavements more than 2 years old compared with untreated binder. If these criteria are not met, reapply SRT at no additional cost until compliance is achieved. Verify that treated areas show no evidence of binder flush or distress and that the surface has adequate friction.

### **VI. MEASUREMENT AND PAYMENT**

The SRT quantity shall be measured in square yards of pavement surface that has been properly treated and accepted by the Engineer. Measurements will be calculated from the exact length and width of each lane segment treated.

Payment at the contract unit price per square yard shall constitute full compensation for:

- All labor, materials, and equipment to complete the SRT application, including test strips (if any) and distributor calibration.
- Blotter material (if required) and its application.
- Cleaning and protection of adjacent areas.
- Sweeping.
- Resident notification and traffic control devices.
- Core sampling, laboratory testing, and performance verification.

If certain areas require SRT to be reapplied because the initial treatment did not meet penetration or performance requirements, no additional payment will be made.

If rain or adverse weather occurs before the SRT has broken, necessitating full reapplication, the Contractor shall perform the reapplication at no extra cost to the Department.

## APPENDIX B

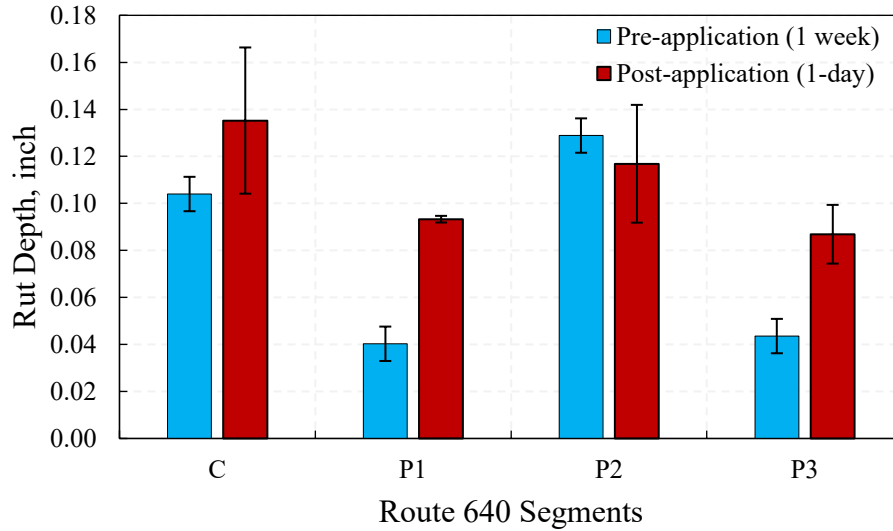
### Rutting Performance

Figures B1 and B2 present rut depth measurements for Routes 640 and 750, respectively. Rut depth data were collected approximately 1 week prior to application and again 1 day following application for both routes.

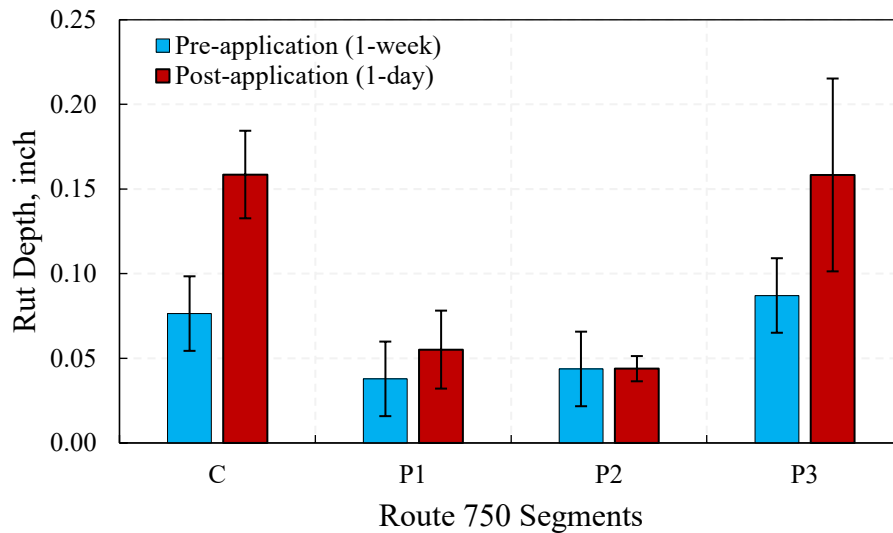
As Figures B1 and B2 show, differences were observed between pre-application and post-application rut depth measurements. However, the magnitude and direction of these differences varied among sections, including the untreated control sections. Given the very short interval between measurements and the fact that the pavements had been in service for approximately 5 years at the time of application, the observed differences are not indicative of rut development. Most rutting is expected to have occurred earlier in the pavement life, and the differences observed are therefore attributed to variability associated with rut depth data collected using the five-laser measurement configuration. Discussions with the data collection vendor confirmed this limitation of the measurement system.

The differences observed between pre- and post-application rut depth measurements are consistent with the known variability associated with field rut data collection, as documented in prior studies evaluating the repeatability and precision of automated rut measurement systems (Serigos et al., 2012). The short monitoring interval precludes meaningful rut progression, and the observed differences are therefore considered to reflect measurement variability rather than application-related effects.

Overall, rut depth measurements collected immediately following application did not indicate any adverse rutting behavior associated with spray-on rejuvenator application. In addition, no visible signs of rutting were identified during field observations.



**Figure B1. Rut Depth Measurements Before and After Spray-on Rejuvenator Application for Route 640.** Error bars represent the variability (standard deviation) observed along the measured length of each segment. C denotes the untreated control segment, and P1–P3 denote segments receiving spray-on rejuvenator application.



**Figure B2. Rut Depth Measurements Before and After Spray-on Rejuvenator Application for Route 750.** Error bars represent the variability (standard deviation) observed along the measured length of each segment. C denotes the untreated control segment, and P1–P3 denote segments receiving spray-on rejuvenator application.