EVALUATION OF A CHEMICAL HARDENING PROCESS TO INHIBIT AGGREGATE ABRASION AND POLISHING

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ABSTRACT
Aggregate polishing and degradation is a pavement management problem for state highway agencies. It creates a safety issue by reducing skid resistance and shortening pavement service life. An underutilized pavement preservation tool, *Silicon Reactive Lithium Densifier and Shotblasting,* can harden new and existing pavement and bridge deck surfaces to inhibit polishing and abrasion and retain skid resistance. Research to determine the efficacy of this treatment is limited because of its relatively recent emergence in highway applications. Therefore, the objective of this paper is to evaluate densifier-treated limestone aggregate characteristics in the laboratory that relate to highway performance in terms of abrasion resistance, skid resistance and aggregate polishing using a Micro Deval and *aggregate image analysis* testing methodology. The results demonstrate that chemically treating soft aggregate improves the hardness and durability of the aggregate. Additionally, the angularity of the treated aggregate after polish-wear treatment trended closer to the new aggregate which received no abrasion process at all, indicating that the chemical application does indeed enhance aggregate abrasion resistance. The paper concludes that there is potential benefit to adopting lithium-based treatments as a pavement preservation tool to enhance the ability of pavement engineers to maintain safe surface friction levels, inhibit polishing and *keep good roads good*.

INTRODUCTION

According to the American Society of Civil Engineers US 2013 Infrastructure Report Card, 32% of America's major roads are currently in poor or mediocre condition *(1)*. These conditions are a significant factor in approximately one third of all US traffic fatalities *(1)*. Unfortunately for pavement managers, the budget woes that have plagued their agencies and created these conditions are not expected to ease *(2)*. *Pavement preservation* is a solution for addressing pavement system needs by "keeping good roads good" *(3)*. Pavement preservation treatments are applied to extend the functional service life of the underlying pavement, deferring costly rehabilitation/ reconstruction. "A pavement preservation program aims at preserving investment in the pavement network, extending pavement life, enhancing pavement performance, ensuring cost effectiveness, and reducing user delays" *(3)*. "Considering the annual magnitude of highway investments, the potential savings from following a cost-effective approach to meeting an agency's performance objectives for pavements are significant" *(4)*, thus, allowing agencies to stretch the budget to address safety needs in infrastructure and enhance stewardship.

Polished aggregate in a pavement surface is considered to be a surface defect that must be mitigated by pavement engineers to ensure safety *(5)*. Aggregate quality directly impacts the frequency (cost) of that maintenance. Mineral aggregates with high resistance to abrasion are considered to be of high quality because they provide sufficient microtexture for skid resistance and decrease the likelihood of polishing *(6)*. According to the US DOT, there are roughly 8.6 million lane miles of pavement in the nation. Most of those pavement miles were constructed with natural aggregates originating from the most economical (closest) locations. Considering the distribution of aggregate quality in the US, 21 states have areas where the aggregates are either soft or medium soft, and are commonly limestone *(7)*. In these regions where high quality aggregate is scarce, transportation costs make it hard to justify importing better aggregates. Even in areas that have higher quality aggregate, like California, accelerated surface deterioration still occurs due to frequent exposure to studded tires and snowplows *(8)*.

There is a promising new pavement preservation treatment that aims to enhance the quality of surface aggregate by hardening it through chemical and mechanical processes referred to as *Silicon Reactive Lithium Densifier and Shotblasting (9)*. Research to determine the efficacy of this treatment is limited because of its relatively recent emergence in highway applications. Therefore, the objective of this paper is to evaluate densifier-treated aggregate durability and characteristics, specifically abrasion resistance and gradient angularity, which relate to highway performance in terms of skid resistance and aggregate polishing tendencies.

The study uses a Micro Deval and aggregate image analysis (i.e. AIMS) testing methodology *(10, 11, and 12)*.

BACKGROUND

Skid Resistance and Aggregate Quality

Pavement skid resistance is one of "the most important engineering components of the road from a safety standpoint" *(13, 14)*. Therefore, a common indicator used to assess pavement skid resistance is *microtexture (15)*. Essentially, microtexture is the quantitative measure of aggregate surface friction properties that contribute to skid resistance *(16)*. Pavement managers assess pavement safety and surface performance (service life) by monitoring the microtexture deterioration rate until the surface reaches a certain threshold value that triggers the need for remedial action.

Pavement surfaces are continuously exposed to conditions related to traffic (i.e. volume, loads, turning motions, decelerating/ accelerating motions) and weather (i.e. freeze-thaw, wet-dry cycles) that cause aggregate polishing and degradation. Pavement microtexture is significantly affected by the characteristics of the aggregate contained within the pavement, such as angularity *(12)*. Aggregate polishing and degradation have an adverse impact on these characteristics and result in accelerating the surface deterioration and increasing remediation frequency *(10, 11, and 12)*.Essentially, aggregate less prone to texture loss and abrasion will predictively have better skid resistance in the field *(6)*.

Limestone has been the most commonly used aggregate type in US road construction *(17)*. However, this is problematic for pavement managers because limestone is generally more prone to polishing than other aggregate types, and therefore, yields poorer long-term skid performance and must be remediated more frequently *(17, 18, 19, and 11)*. National Cooperative Highway Research Program *(19)* Report 634 found that surfaces with high quality aggregates retain their microtexture, and hence their skid resistance, for as long as 10 years under heavy traffic *(19)*. The same study reported that skid resistance on concrete and asphalt test sections containing limestone deteriorated at a much more rapid rate, needing to be retextured in as little as 3 years under the same traffic loads *(19)*. Essentially, harder and more durable aggregates retain higher friction values longer, contributing to adequate pavement safety and longer service life *(18, 19)*.

Silicon Reactive Lithium Densifier and Shotblasting

Silicon Reactive Lithium Densifier and Shotblasting (or generally, densifier over shotblasting, DOS) is a pavement preservation treatment used to harden pavement surface against abrasion to retain microtexture and inhibit rutting and polishing, whereby extending the pavement's service life *(9)*. The treatment consists of a mechanical process (shotblasting - high velocity impact method (HVIM)) and a chemical application (Silicon Reactive Lithium Densifier). Shotblasting has been shown to be a cost effective method for restoring surface friction *(20)*. In the DOS application, shotblasting also increases the surface porosity to facilitate the penetration of the densifier, resulting in a deeper hardened surface that is more resistant to wear from abrasion due to traffic and snow plows *(21, 22)*. Therefore, the chemical application works to retain the surface texture and profile that the shotblasting restores. The treatment application is shown in Figure 1.

Figure 1. DOS -Treated Pavement: Shotblasting (Left), Densifier Application (Right)

Recent studies have evaluated the performance, cost effectiveness and sustainability of this pavement preservation treatment and demonstrate the value in its ability to lengthen a pavement's service life *(9)*. Field studies and sustainability analyses have investigated the treatment application on PCCP highway projects. Results support the conclusions that DOS inhibits the rate of deterioration due to abrasion and polishing *(8, 23, 21 and 9)*.

A recent Oklahoma Department of Transportation (ODOT) study demonstrated the treatment's ability to inhibit loss of skid resistance due to aggregate polishing. It evaluated DOS application on existing PCCP test sections on State Highway 77 (average daily traffic = 14,000 vehicles per day). Results from the three-year project showed that DOS-treated test sections outperformed the control section in terms of skid resistance and cost effectiveness *(21)*. The project included application of DOS to existing pavement, as well as shotblasted sections with no chemical application (SB). Monthly measurements were used to develop deterioration models that estimate PCCP preservation treatment service lives *(21)*. The SB section showed friction loss of 11% over the testing period compared to 6.25% for the DOS section.

Another field study, sponsored by the California DOT (Caltrans), concluded that using DOS reduced pavement surface wear by more than 50% *(8, 9)*.It evaluated DOS applied to new PCCP. The study measured surface wear over 12 months on a test section on Interstate Highway 80 (I-80) over Donner Pass in the Sierra Mountains. The test site was subjected to abrasion due to snow plowing and snow chains/studded tires *(23)*. In addition to measuring change in wheel path rut depth, it also measured test section skid numbers.

The Delaware DOT conducted a field study that sought to determine the efficacy of diamond grinding and shotblasting for enhancing the penetration of the lithium silicate densifier *(9)*. Two of the PCCP test sections received DOS, two received densifier application only, two received SB only, and one received diamond grinding with densifier. Core samples were extracted from each test section approximately 6 months after treatments were applied to measure densifier penetration. The results showed that DOS provides the deepest penetration of the three surface preparation methods, supporting the benefit accrued for DOS sections, which were inferred from the data to have a deeper hardened surface than the other options *(9)*.

Other studies have concluded that DOS is a technically and sustainably viable PCCP preservation treatment that inhibits polishing. A life cycle cost analysis (LCCA) was used to compare DOS-treated PCCP pavement with non-treated pavement (do nothing case) *(9)*. The data from the three field studies mentioned in the preceding paragraphs were used to provide DOS input. The study also used untreated test sections in a Washington State DOT study as a baseline measure. The LCCA revealed that the DOS-treated sections provided for lower life cycle cost due to the pavement service life extension, offsetting the marginally higher initial construction costs. The study also conducted a life cycle inventory (LCI) to compare the environmental impact of two pavement preservation treatments used for addressing pavement abrasion/rutting: DOS and microsurfacing (a bituminous-based seal). The LCI revealed that the DOS application process for inhibiting rutting requires less energy and creates fewer emissions than using microsurfacing to fill ruts.

A carbon footprint cost index (CFCI) was developed for the purpose of comparing pavement preservation treatment alternatives on a basis of enhanced sustainability (Mosier 2013). It was demonstrated on an airport case study using six treatment alternatives. Although the analysis methodology is the core of the study, the case study revealed that the DOS treatment had the lower CFCI and would have been the preferred treatment to restore surface friction and slow underlying pavement deterioration.

Beyond these studies, there was nothing found in literature with regard to the effect of the hardening agent on aggregate shape characteristics and durability. Therefore, the objective of this paper is to evaluate densifier-treated limestone aggregate characteristics that relate to highway performance in terms of abrasion resistance, skid resistance and aggregate polishing.

Aggregate Testing in Relation to Overall Project

The main hypothesis to be tested by this two-phase study is that frictional characteristics of different aggregate types and pavement surfaces can be improved using the DOS process and enhance the surface friction performance of pavements. Laboratory and field tests will be conducted to get a more comprehensive assessment of DOS efficacy. Asphalt and concrete mix designs commonly used in Oklahoma pavements will be molded in the laboratory and DOS will be applied. Polishing tests will be conducted via the British Pendulum Skid Tester and the National Center for Asphalt Technology (NCAT) Three-Wheel Polishing Device (TWPD). The second phase of the study includes field tests: DOS-treating asphalt and concrete pavements and bridge decks. It will evaluate treatment performance by measuring the pavement surface for microtexture, macrotexture, rutting and polishing. The project is currently in its first phase, which involves applying the lithium silicate densifier directly to the aggregate to evaluate the difference between treated and untreated samples. Preliminary results are presented in this paper, which evaluates the efficacy of treating soft aggregate with *Silicon Reactive Lithium Densifier.* Treatment will potentially enhance the aggregate's durability, hardness and ability to maintain a sufficient level of microtexture whereby inhibiting degradation and polishing.

Oklahoma Aggregate

Most of the state of Oklahoma is comprised of soft aggregates *(7, 25)*. Of the six commonly-used aggregate sources identified by ODOT to be evaluated in this study, four are limestone quarries, one is a rhyolite quarry and one is a granite quarry. Table 1 shows statewide aggregate quality for Oklahoma, classified with polished stone value (PSV) based upon Neaylon's *(18)* definitions of aggregate quality. Aggregate PSVs of 55 or above are associated with high resistance to polishing and PSVs less than 45 indicate low resistance to polishing. Good aggregate is available in the geologic strata of Oklahoma *(25)*. However, there is no indication of the accessibility of that stone (property ownership) or if it can be economically mined. Table 1 shows that most of the state's aggregate (almost 65%) is prone to polishing *(25)*.

TABLE 1 Oklahoma Aggregate Geology Based on Average PSV (after Gransberg NJ)

Aggregate Quality Description	Oklahoma Aggregate Quality (%)
Good (Average PSV > 55, Minimum PSV > 45)	21.20%
Marginal (Average PSV < 55, Minimum PSV > 45)	15.17%
Poor (Average PSV < 45)	63.63%

METHODOLOGY

General Testing Procedure

The aggregate characteristics of shape, angularity, and texture significantly affect microtexture and can be used to predict pavement performance *(26, 12)*. Therefore, there have been recent efforts to develop testing methodologies that evaluate these characteristics in relation to polishing and degradation. One such methodology includes the use of aggregate image analysis systems (i.e. AIMS - AASHTO Provisional Specification) to quantify aggregate shape/texture property changes resulting from exposure to standard Micro Deval testing (AASHTO T-327) , which simulates field polishing and abrasion of aggregate *(27, 10, 11 and 12)*. This laboratory testing methodology is being used in this paper to investigate the effect of lithium silicate densifier (no shotblasting) on selected Oklahoma aggregates.

Micro Deval (AASHTO T-327)

Micro Deval provides insight regarding the ability of the densifier application to harden limestone aggregate, as the test output directly relates to aggregate hardness *(11)*. The Micro-Deval test measures the abrasion resistance and durability of coarse aggregate. The testing is carried out in accordance with the American Association of State Highway and Transportation Officials (AASHTO) T-327 "Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus".

Aggregate Imaging System (AIMS - AASHTO Provisional Specification)

The [first-generation] aggregate imaging system (AIMS), an aggregate image analysis system, was developed to capture images and analyze aggregate shape and texture characteristics. AIMS setup consists of one camera and two different types of lighting schemes to capture images of aggregates at different resolutions, from which aggregate shape properties are measured *(26)*. Coarse aggregate particles are placed on the sample tray with marked grid points. AIMS describes aggregate angularity by measuring the irregularity of a particle's surface using the radius and gradient methods (angularity index). The gradient method is based on the principle that at sharp corners of the image, the direction of the gradient vector changes rapidly, whereas it changes slowly along the outline of rounded particles. The angularity is calculated based on the values of angle of orientation of the edge points and the magnitude of difference of these values. The sum of angularity values for all the boundary points are accumulated around the edge to get the angularity index for each particle. An analysis of variance was used to determine the significance in the angularity indices between the treated and non-treated samples.

Treatment Procedure

Three replicates of non-treated limestone aggregates and densifier-treated aggregates were subjected to Micro-Deval and AIMS testing to determine if the chemical treatment enhances aggregate abrasion resistance, hardness and durability. The Micro Deval test provided weight loss measurements. Both pre- and post- Micro Deval aggregate particles were collected and analyzed for angularity using AIMS.

Direct treatment of aggregate using a lithium silicate densifier is a new procedure, so there are no documented standards or standard protocol regarding treatment methodology in literature. Therefore, aggregate was treated per the manufacturers' specifications. Aggregate samples were washed and oven dried to a constant temperature, then submerged into the lithium-based densifier and agitated for 60 seconds to ensure as much uniformity in application as possible. The samples were then removed from the densifier and left to air dry for 24-48 hours. Testing was then initiated.

RESULTS AND DISCUSSION

The preliminary Micro Deval results, as shown in Figure 2, reveal that the aggregate samples with directly-applied lithium silicate densifier (triangle designation) had less weight loss than the non-treated samples (diamond designation). Good friction performance has been correlated with aggregates that exhibit Micro Deval weight loss values of 12% or less *(11)*. Therefore, the results indicate that the treated aggregate would facilitate good pavement surface friction and better performance than the non-treated aggregate. Due to the nature of Micro-Deval testing and the nature of the shotblasting process, shotblasting the aggregate prior to densifier application was not possible. However, one could infer that if shotblasting had been applied to deepen densifier penetration, the weight loss would be even less *(9)*.

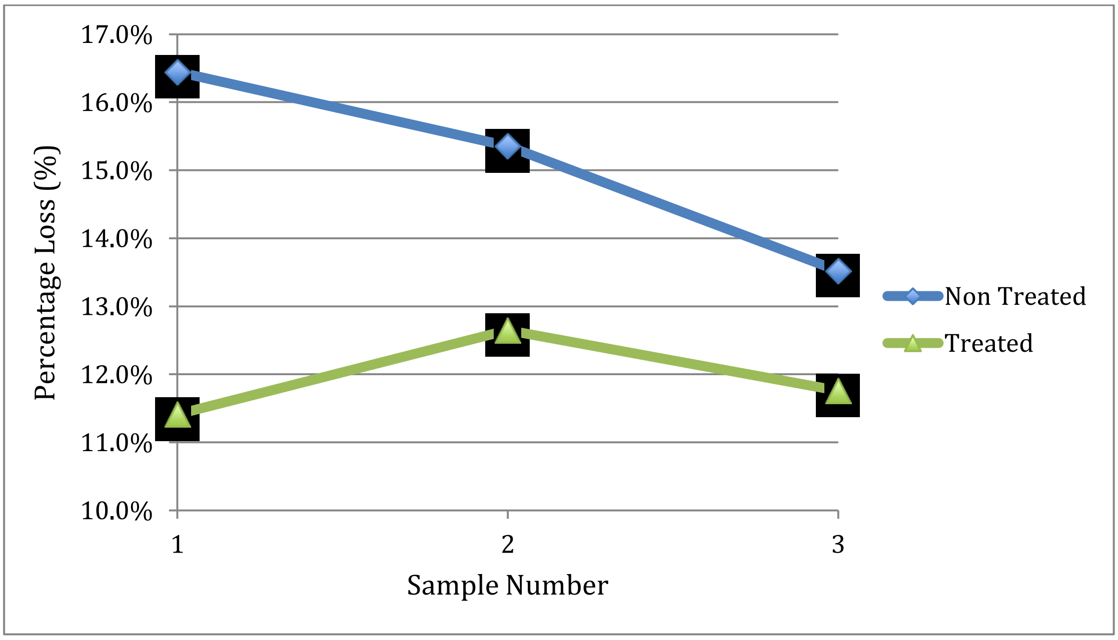

FIGURE 2 Micro Deval results for DOS-treated and non-treated aggregate.

Preliminary AIMS results show that applying the lithium silicate densifier directly to the aggregate also enhances the aggregate's ability to retain angularity. Figure 3 shows the angularity results (gradient method) from the 5/8-inch (16mm) limestone particle testing. In general, an angularity value of 4000 or above indicates an angular particle, whereas a value below 2100 indicates a rounded particle *(28)*. Figure 3 shows the angularity values for the (a) pre-Micro Deval particles (dashed line), (b) densifier-treated particles, post Micro Deval (solid line), and (c) non-treated particles, post Micro Deval (hashed line).

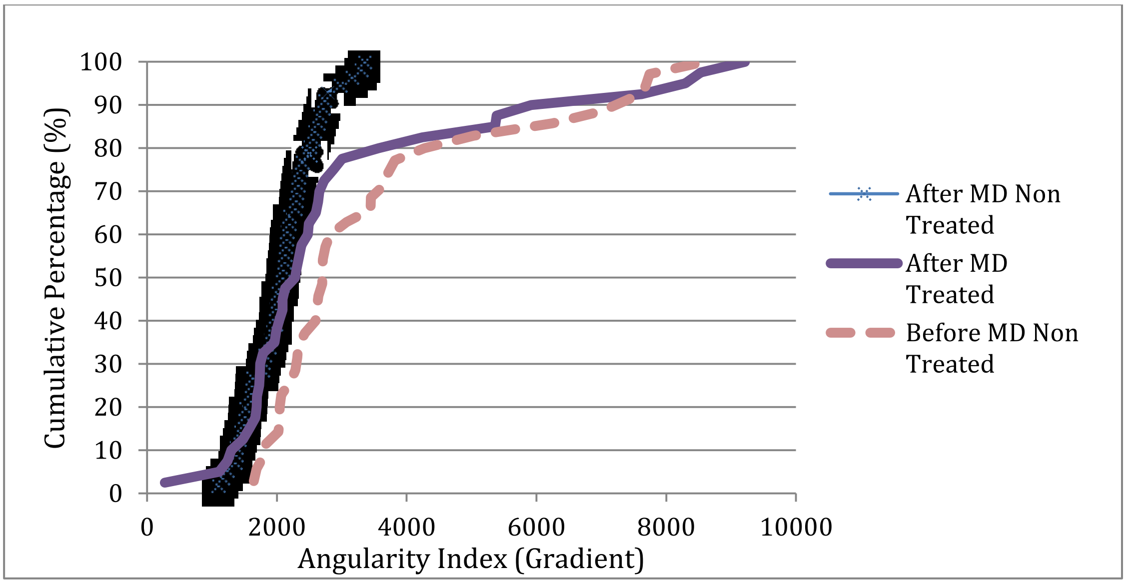

FIGURE 3 AIMS results: gradient angularity for DOS-treated and non-treated samples.

The results show that the angularity of the untreated limestone aggregate is greatly reduced after exposure to Micro Deval, as one would expect. Only about 20% of pre-Micro Deval particles were considered rounded. However, the impact of abrasion is apparent in the untreated, post- Micro Deval particles, as most of the particles lost angularity. In contrast, the densifier-treated aggregate trends more closely with the aggregate that received no Micro Deval treatment at all, indicating that the chemical application does indeed enhance aggregate abrasion resistance, and by extension, skid resistance. The nature of AIMS testing is also not conducive with shotblasting, but one could infer that deeper densifier penetration would increase angularity *(9)*.

Figure 4 shows the descriptive statistics and distributions for the AIMS angularity data for treated (dashed lines) and untreated (solid line) particles. The analysis of variance showed that there was a statistically significant difference (p = 0.009) between the treated aggregate (more angular) and the untreated aggregate (more rounded) based upon a 95% confidence interval (Tukey's Method). Additionally, there was no difference between treated samples.

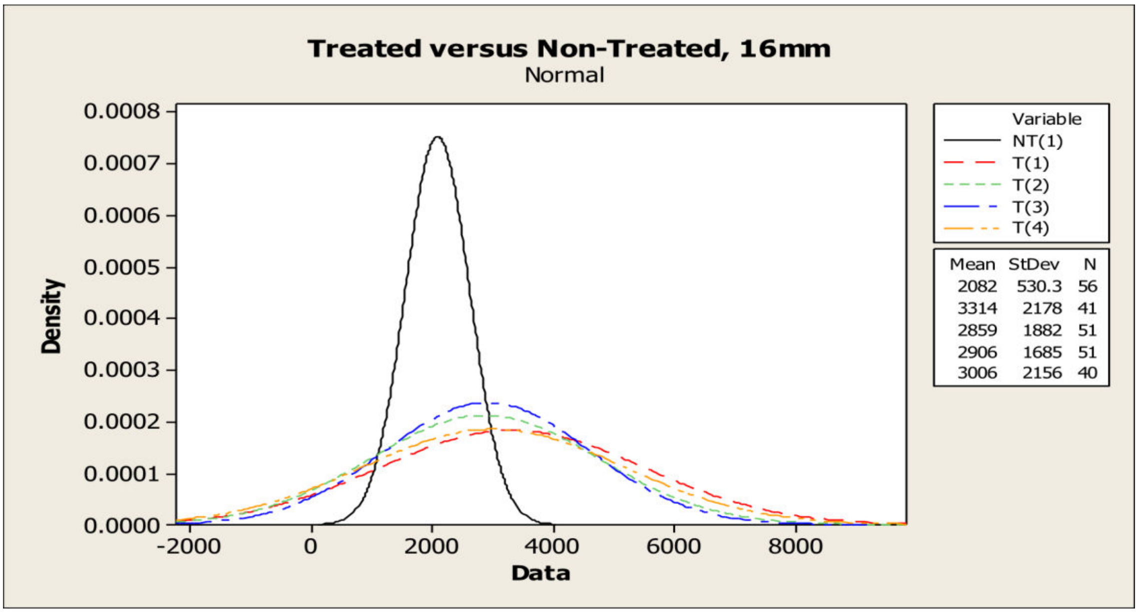

FIGURE 4 AIMS ANOVA results: gradient angularity for aggregate samples.

There is a correlation between abrasion resistance and polishing resistance, especially for aggregate that is highly susceptible to abrasion like limestone *(6)*. Essentially, when aggregate angularity is reduced, the aggregate becomes more susceptible to polishing. These results show that lithium silicate densifier application hardens the aggregate and, therefore, enhances the likelihood of inhibiting polishing.

CONCLUSIONS

This study demonstrates the value of hardening aggregate through lithium silicate densifier application. Laboratory results show that applying the densifier directly to the Oklahoma limestone aggregate improves its abrasive resistance, hardness and durability. It also shows that the treatment helps the aggregate retain its angularity under polish-wear conditions, which will enhance skid resistance and inhibit polishing. The potential viability and sustainability of this pavement preservation treatment has been demonstrated in recent research. *Silicon Reactive Lithium Densifier and Shotblasting* provides another tool for the pavement preservation toolbox that can contribute to stretching the budget by extending pavement service life. It will also enhance the ability of pavement engineers to maintain safe surface friction levels, inhibit polishing and *keep good roads good*.

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