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FINAL REPORT ~ FHWA-OK-16-02

EVALUATE DENSIFIER-OVER-SHOTBLASTING (DOS) TREATMENT PERFORMANCE FOR PAVEMENTS AND BRIDGE DECKS

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Oklahoma Department of Transportation

DISCLAIMER

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13. Abstract With increased demands on our aging infrastructure, rapidly increasing truck traffic, and shrinking budgets, transportation agencies are continually being asked to "do more with less" in maintaining pavements and bridges. This research provides a method for combining chemical treatment (lithium silicate densifier) and shotblasting, called densifier-over-shotblasting (DOS), to economically harden the aggregates of concrete and asphalt pavements and bridge decks. The DOS method can be added to the pavement preservation toolbox to make surfaces safer and more durable, reduce maintenance costs and increase service life of pavements and bridge decks. The study achieved three objectives, which include: (1) evaluate and measure the treatment's ability to inhibit polishing and abrasion through the chemical hardening of aggregate (laboratory phase), (2) evaluate and measure the extent to which DOS inhibits microtexture deterioration of road surfaces (field testing phase) and (3) develop specifications, design methodology, and construction methods necessary to transfer this novel technology to practice immediately after completion of the project.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl	fluid ounces	29.57	milliliters	mL L
oz	gallons	3.785	liters	m^3
gal	cubic feet	0.028	cubic meters	m^3
ft^3	cubic yards	0.765	cubic	
yd^3		*volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 Celsius or (F-32)/1.8		°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square h	lbf/in^2

Table of Contents

List of Tables

List of Figures

Executive Summary

With increased demands on our aging infrastructure, rapidly increasing truck traffic, and shrinking budgets, transportation agencies are continually being asked to "do more with less" in maintaining pavements and bridges. This research provides a method for combining chemical treatment (lithium silicate densifier) and shotblasting, called densifier-over-shotblasting (DOS), to economically harden the aggregates of concrete and asphalt pavements and bridge decks. The DOS method can be added to the *pavement preservation toolbox* and will make surfaces safer and more durable, reduce maintenance costs and increase service life of asphalt and concrete pavements and bridge decks.

This study has two complementary purposes: (1) evaluate the effectiveness of DOS in increasing the overall durability and wear resistance of aggregate by improving resistance to polishing and abrasion through the application of a chemical treatment; and (2) evaluate the effectiveness of DOS to restore and maintain acceptable microtexture (skid) values for pavements and bridge decks. The DOS treatment will particularly address the issue of marginal aggregates as described below:

- This technology is *the first that seeks to improve the geomorphic composition of the rock itself* through inducing a chemical reaction that results in a hardened surface.
- While shotblasting certainly increases the microtexture of a road surface, its primary role in the process is to *prepare the surface* of the aggregate and *permit a deeper penetration* of the chemical and hence *a thicker, hardened surface* on the aggregate itself.

The primary deliverable of this study is a draft specification and inspector's guide for DOS treatment that can be used by the Oklahoma Department of Transportation (ODOT) in the agency's pavement preservation program. To gain the necessary understanding of the relationship between aggregate polishing and the desired skid resistance-related properties, and to quantify a standard method for maintaining acceptable friction values over time, the following objectives were achieved:

1. *Evaluate and measure the treatment's ability to inhibit polishing and abrasion through the chemical hardening of aggregate*.
2. *Evaluate and measure the extent to which DOS inhibits microtexture deterioration of road surfaces.*
3. *Develop specifications, design methodology, and construction methods necessary to transfer this novel technology to practice immediately after completion of the project*.

The resultant benefits of this study should enhance safety due to maintained surface friction, regardless of season. Benefits also include extending average pavement/bridge deck service life by quantifying the aggregate characteristics that slow surface deterioration as determined by field performance evaluation and laboratory aggregate analysis. Achieving these benefits provides a further benefit of releasing scarce maintenance funds to be used as programmed by reducing the amount of unplanned reactive maintenance that occurs on a statewide basis.

1.0 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" (ASCE 2013). These conditions are a significant factor, contributing to approximately one third of all US traffic fatalities (ASCE 2013). Unfortunately for pavement managers, the budget woes that have plagued their agencies and created these conditions are not expected to ease any time soon (FHWA 2014). As the demand on the nations aging infrastructure increases and transportation budgets become tighter, it is expected that budget shortfalls will reach critical levels by 2030 (FHWA et al. 2008). State transportation agencies are being pushed to search for ways to spend limited transportation funds more effectively and "do more with less" when maintaining road surfaces (AASHTO 2001, Bilal et al. 2009). Pavement preservation is a sustainable solution being implemented for addressing pavement system and safety needs by "keeping good roads good", instead of allowing them to deteriorate to a point where full reconstructive action is required (Galehouse et al. 2003).

A promising new pavement preservation technique, referred to as *Silicon Reactive Lithium Densifier over Shotblasting* (DOS), as shown in Figure 1, seeks to improve the quality of new and existing pavement and bridge deck surfaces (Komas 2011).

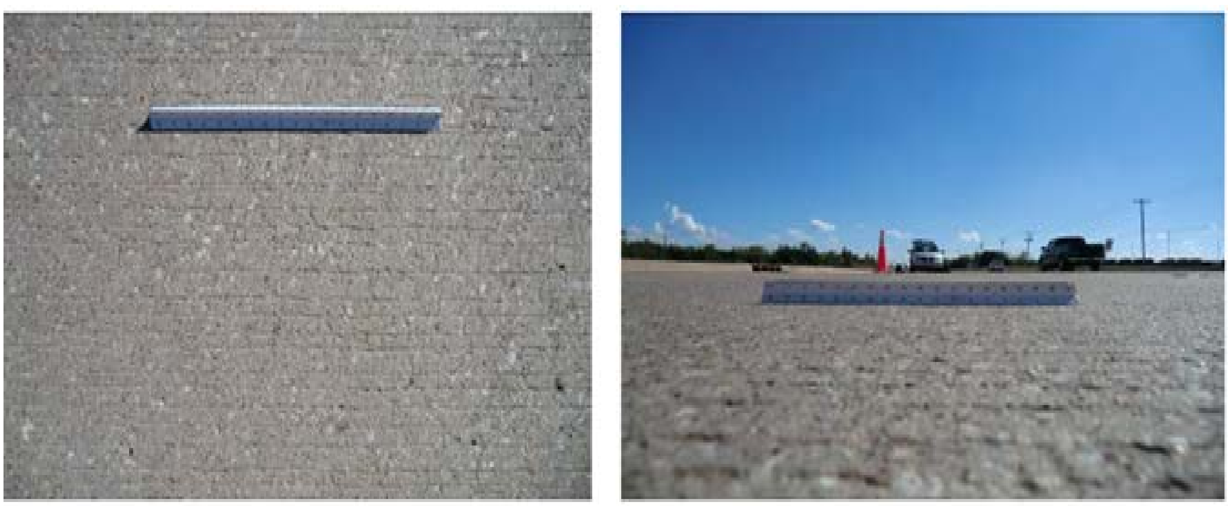

Figure 1 Plan (left) and Elevation (right) Views of DOS on Concrete Pavement (Riemer et al. 2010)

The technique aims to harden the aggregate surface through a combination of chemical (lithium silicate densifier) and mechanical (shotblasting) processes (Gransberg and Pittenger 2012). A harder surface inhibits aggregate abrasion and polishing, allowing the pavement to maintain a greater level of skid resistance for a longer period of time (Lancieri et al. 2005). Figure 2 shows a laser image of the concrete pavement DOS-treated surface texture shown in Figure 1. Retaining skid resistance extends the service life of the pavement and enhances road user safety (NCHRP 2009a).

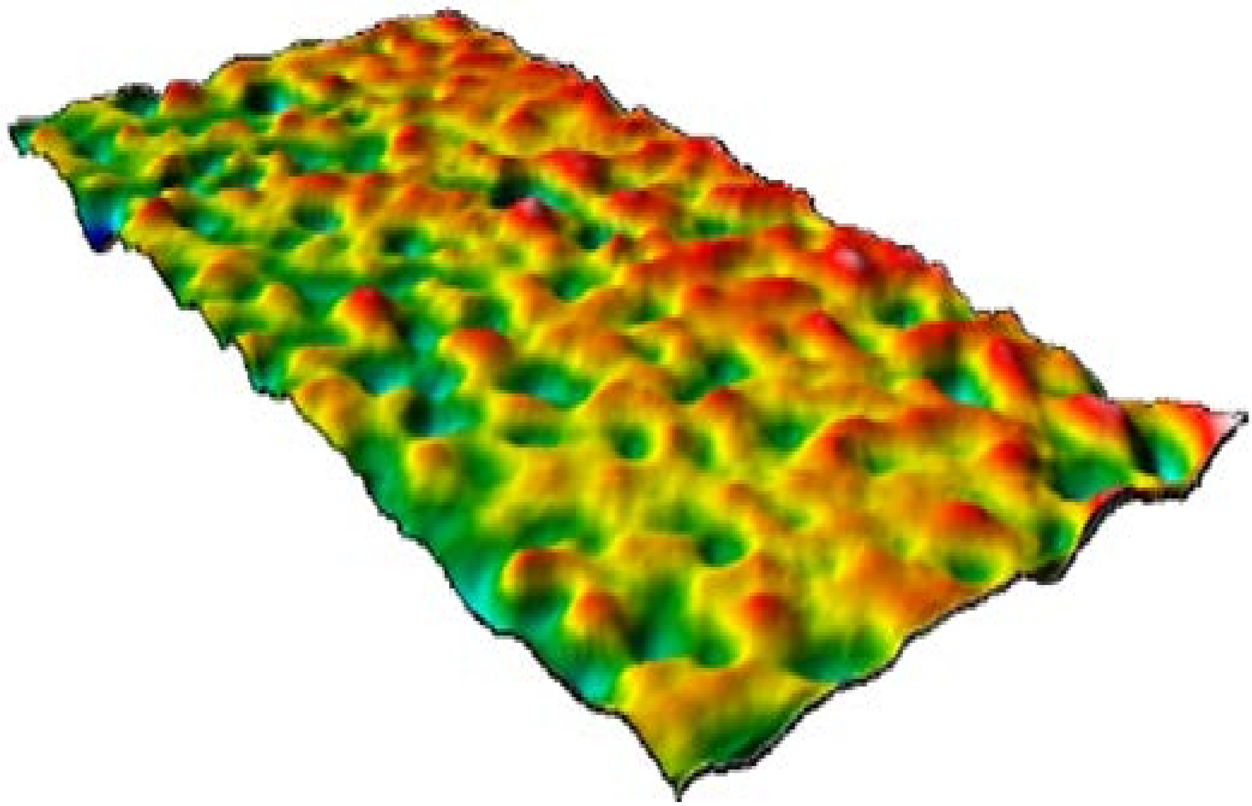

Figure 2 Laser Image of DOS-Treated Concrete Pavement Surface (Riemer et al. 2010)

Large gaps exist in literature regarding the efficacy of the DOS technique due to its relatively recent emergence in heavy civil applications. However, methodologies for assessing performance and cost of pavement preservation treatments are well established. This research seeks to apply these methodologies to evaluate DOS performance and to gauge its economic efficacy to determine if DOS provides a viable pavement preservation treatment option.

1.1 Objectives

This study has three objectives:

1. *Evaluate and measure the treatment's ability to inhibit polishing and abrasion through the chemical hardening of aggregate*. The project evaluates and demonstrates the proposed treatment's ability to enhance an aggregate's resistance to polishing and abrasion, thus improving hardness and microtexture on moderate to soft aggregates.
2. *Evaluate and measure the extent to which DOS inhibits microtexture deterioration of road surfaces.* Road surfaces deteriorate over time due to traffic, environmental and other factors such as weathering, adversely impacting microtexture. As skid resistance and mean texture depth decrease, wet conditions provide an environment that is conducive to hydroplaning of vehicle, skidding and accidents. The project evaluates the extent to which DOS inhibits the rate of deterioration of pavement/bridge deck surfaces (i.e., enhances its resistance to polishing), thus improving (microtexture) skid resistance. Additionally, it demonstrates cost effectiveness of DOS associated with the service life extension.
3. *Develop specifications, design methodology, and construction methods necessary to transfer this novel technology to practice immediately after completion of the project*. Effective technology transfer is a function of technical specifications/ guidance, training of design engineers, maintenance personnel, and construction contractors. It is also a function of determining the appropriate methodology for identifying projects that are good candidates for accruing real benefits from the application of DOS. The project develops all the necessary tools and documentation to satisfy these requirements.

The study has the following major benefits:

i. specifications of the required characteristics of DOS,
ii. identification of polishing tendency of aggregates that are available in each Oklahoma Department of Transportation (ODOT) division, and
iii. documentation of effective construction practice and Inspector's guide.

This should enhance safety due to maintained surface friction, regardless of season. It also accrues benefits by extending average pavement/bridge deck service life by quantifying the aggregate characteristics that slow surface deterioration as determined by field performance evaluation and laboratory aggregate analysis.

1.2 Scope

The scope of work includes testing the efficacy of DOS on asphalt and concrete materials, pavements and bridge decks. The following tasks, completed by the University of Oklahoma (OU) and the National Center for Asphalt Technology (NCAT), constitute the scope of this study:

1. Literature Review
2. ODOT Aggregate Source and Mix Design Identification
3. OU Laboratory Testing of Aggregates
4. NCAT Laboratory Testing of Aggregates and Mixes (Accelerated Polishing)
5. DOS-Treated Pavement/Bridge Deck Field Test Section Construction
6. DOS Test Section Field Performance Testing by OU and NCAT
7. Life Cycle Cost Analysis (LCCA) and Life Cycle Analysis (LCA) of DOS
8. Draft DOS Specifications and Inspector Guide

1.3 Technology Transfer

The major products of this project include a draft specification and an inspector's guide for DOS treatment that can be used by ODOT in the agency's pavement preservation program. Thus, the results of the research will be made immediately available in a form that permits rapid implementation. Additionally, preliminary results of this project have been disseminated in the following venues to date:

1. TRB Annual Meeting (Jan 2015)
2. TRB Webinar: "Rigid Pavement Preservation: Research Results" Continuing Education Program (Apr 2015)
3. TRB's 9th International Conference on Managing Pavement Assets (May 2015)
4. *CP^2 Center News*, Newsletter of the California Pavement Preservation Center, No. 31 (Nov 2014)

1.4 Report Organization

The body of the report is organized in four major sections, following the four primary areas in which the project is organized. Those sections are as follows:

- The history and science of pavement preservation and the aggregate polishing problem: covers the information necessary to understand the laboratory and field test results.
- The recent studies regarding DOS and testing procedures: describes DOS, provides findings related to DOS performance, exposes the current gaps in research for the new technology and describes testing procedures so that the laboratory and field test results can be understood in context.
- Laboratory and field test methodology and protocols: describes the procedures used in the research.
- Laboratory and field test results: provides results and analysis of the laboratory and field research.

The Appendices are as follows:

- Appendix A: provides abbreviations used throughout the report.
- Appendix B: provides data obtained in the study not provided within the report.
- Appendix C: provides a draft specification for the DOS treatment.
- Appendix D: provides a draft inspector’s guide for DOS application.

2.0 Pavement Preservation

2.1 Sustainability

Sustainability has been identified as an important factor in the pavement industry (Willis 2014) due to its struggles with “high user demand, stretched budgets, declining staff resources, increasing complexity, more stringent accountability requirements, rapid technological change and a deteriorating infrastructure” (FHWA 2007). The three components that contribute to sustainability are economic growth, environmental protection, and social equity (Figure 3), and combined are defined as the “Triple bottom line” (Rogers and Ryan 2001). To meet current challenges, transportation agencies are considering all three components as a means of achieving genuine sustainability (Willis 2014, Rogers and Ryan 2001, Slaper and Hall 2011, McDonough and Braungart 2002).

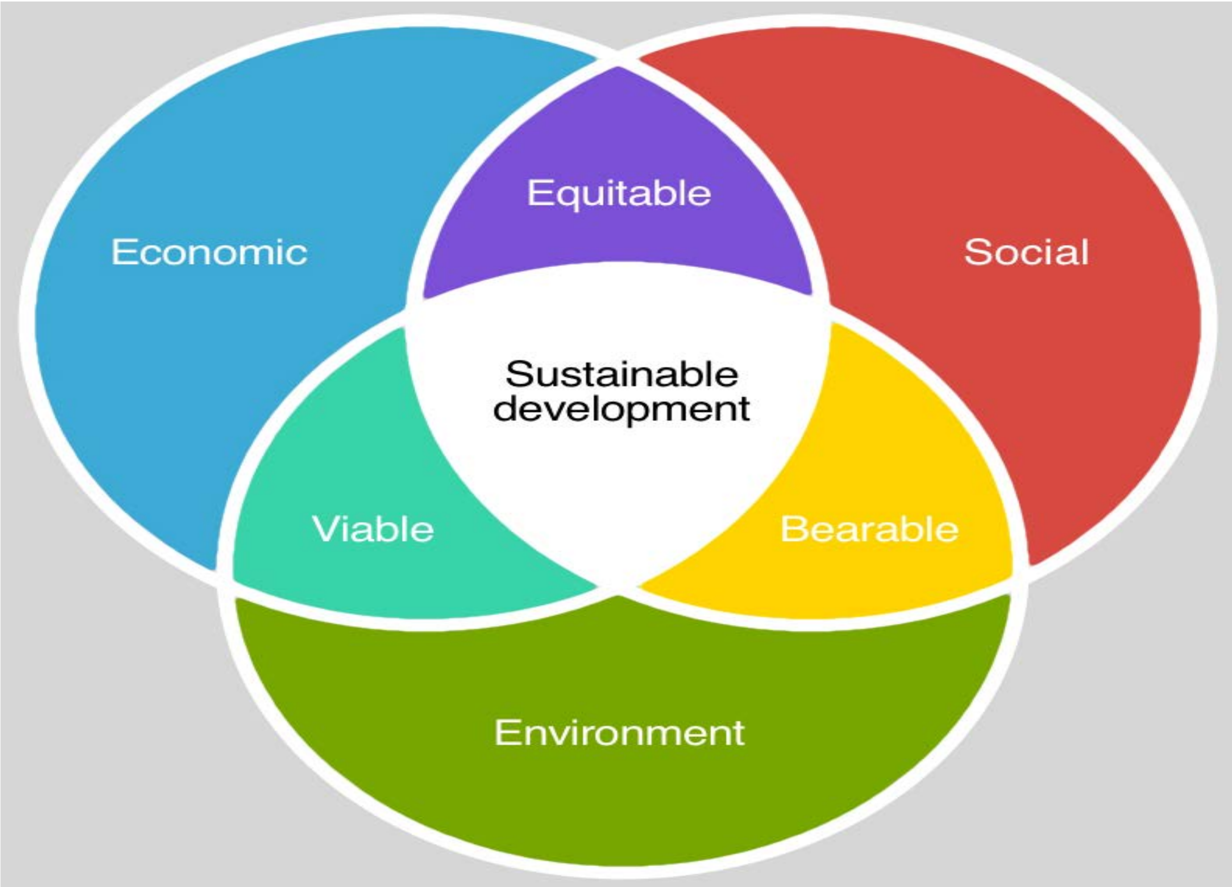

Figure 3 Triple Bottom Line of Sustainability (Willis 2014)

Over the years, pavement managers have shifted the way in which they address pavement management. A traditional, unsustainable practice for pavement managers is to take a reactive approach for maintaining the network. This approach is generally the least cost-effective, as it costs more to fix a pavement in poor condition than it does to maintain one in fair condition (Stroup-Gardiner and Shatnawi 2008, FHWA 2007, TRIP 2001, AASHTO 2001) “because it requires extensive and disruptive work” (FHWA 1998). Following a reactive approach reduces the amount of pavement an agency can tend to each year and results in a decline in the network condition (Peshkin et al. 2004). Poor network condition leads to an increase in “potential for accidents, injuries and fatalities among the motorists and road workers” (FHWA 1998).

Pavement preservation is a concept based on proactively managing assets and is considered to be sustainable (Galehouse et al. 2003). Pavement managers are using preservation to address the triple bottom line in terms of performance and safety. Essentially, properly managed pavement preservation programs can yield better economic performance, as treatments are applied to extend the service life of pavements and defer and reduce costly rehabilitation actions (Peshkin et al. 2004). Preservation can also yield better environmental performance, as raw material consumption is generally less than and construction periods are shorter than those associated with rehabilitation, resulting in fewer emissions and greenhouse gases from manufacturing and idling vehicles in work zones (Galehouse and Chehovits 2010). Pavement preservation can also yield greater social performance, because “keeping good roads goods” provides safer pavements that result in fewer accidents (Peshkin et al. 2004; Galehouse et al. 2003). Additionally, fewer pavement overhauls reduce user delay and enhance stewardship of stakeholder investment (Galehouse et al. 2003).

2.2 Pavement Preservation

Preserving the public investment in the pavement network is the purpose of a state agency’s preservation program. An effective program will “extend pavement life, enhance pavement performance, ensure cost effectiveness and reduce user delays” (Galehouse et al. 2003). Highway programs are becoming more centered on pavement preservation, with emphasis placed on developing effective preservation and preventative maintenance concepts and programs (FHWA 1998, FHWA 1999, Peshkin et al. 2004). Developing an effective pavement preservation plan is critical for the state of Oklahoma due to its relatively small transportation budget (Gransberg et al. 2012). This is emphasized in the states 2010 Asset Preservation Plan which states, “the preservation of our existing transportation system is an absolutely critical part of the Department’s Mission” (ODOT 2010).

Pavement preservation involves applying surface treatments to extend the functional service life of the underlying pavement, deferring expensive rehabilitation costs. “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” (Peshkin et al. 2004). Figure 4 illustrates the pavement preservation concept.

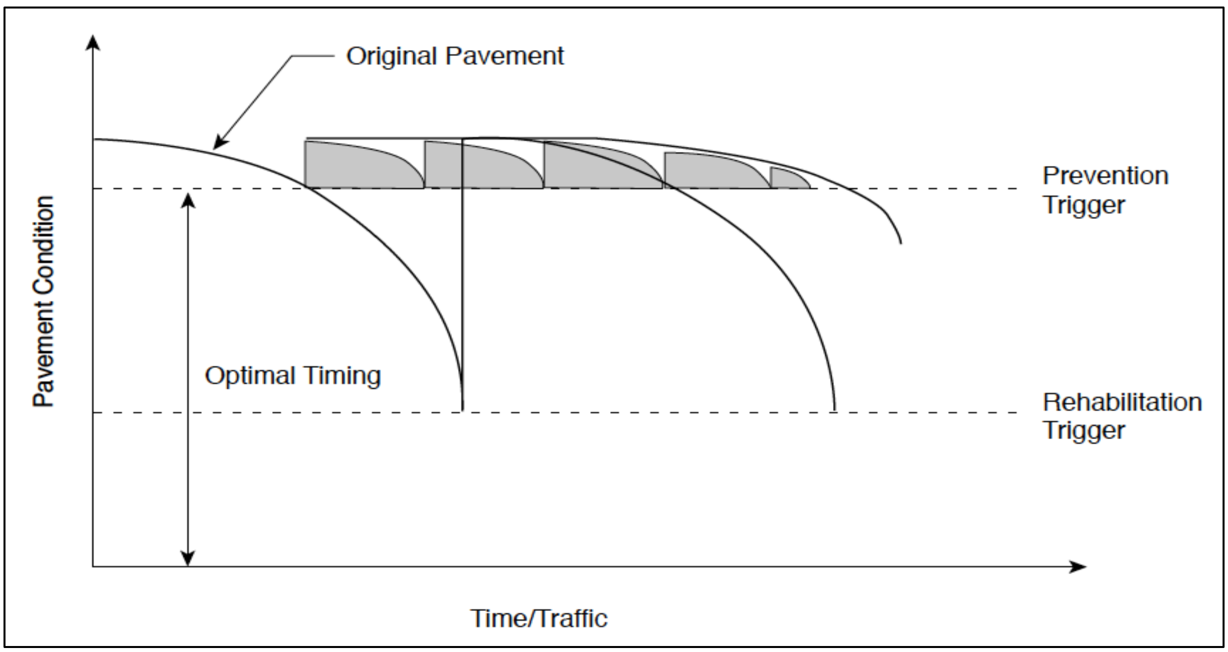

Figure 4 Proactive Approach versus Reactive Approach (Davies and Sorenson 2000)

A pavement preservation program consists of “preventative maintenance, minor rehabilitation (non-structural), and some routine maintenance”, however does not include major rehabilitation to restore serviceability (FHWA 2005). The main goal of a preservation program is to extend pavement service life and is not expected to increase the strength or capacity like a major rehabilitation would (FHWA 2005). This is what delineates pavement preservation treatments, like DOS, from other interventions.

Economic benefits resulting from a pavement preservation program accrue over the long term (Galehouse et al. 2003). Essentially, an initial investment of $1 for preservation may save an agency $3 to $4 in future rehabilitation costs (AirTap 2005).

“Roads that receive preservation treatments are in better condition than those left without treatments” (Galehouse et al. 2003). The challenge of pavement preservation is determining what treatment to apply, when to apply it, and what measureable improvement the treatment will yield (Peshkin et al. 2004). Preventative maintenance treatments are a cost effective way to extend service life when applied to the “right pavement at the right time” (Peshkin et al. 2004). Applying the treatment to the pavement too soon will result in spending money for little or no benefit, and applying the treatment too late is ineffective. A number of tools and procedures have been developed and used by state agencies to determine the optimum pavement preservation strategies.

2.3 Pavement Characteristics

The primary physical characteristic of a pavement that is measured after a traffic accident is surface texture, a key indicator of pavement performance in terms of skid resistance (Manion and Tighe 2007). Pavement skid resistance is one of “the most important engineering components of the road from a safety standpoint” (Gee 2007, NCHRP 1989). Therefore, pavement preservation treatments are commonly applied to rectify loss of skid resistance and enhance safety. Microtexture and macrotexture (illustrated in Figure 5) are physical properties of pavement that affect skid resistance, which is reduced by mechanical wear, polishing, and accumulation of surface contaminants (Neubert 2006).

Microtexture is a quantitative measure of aggregate surface friction properties and is a common indicator used to assess skid resistance (Abdul-Malak et al. 1993, Roque et al. 1991). Mechanical wear of aggregate by repetitive contact with vehicle tires causes the surface to polish and results in a loss of microtexture. 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. Macrotexture characterizes the resistant force given by the pavement surface's overall roughness, which is reduced with the accumulation of contaminants.

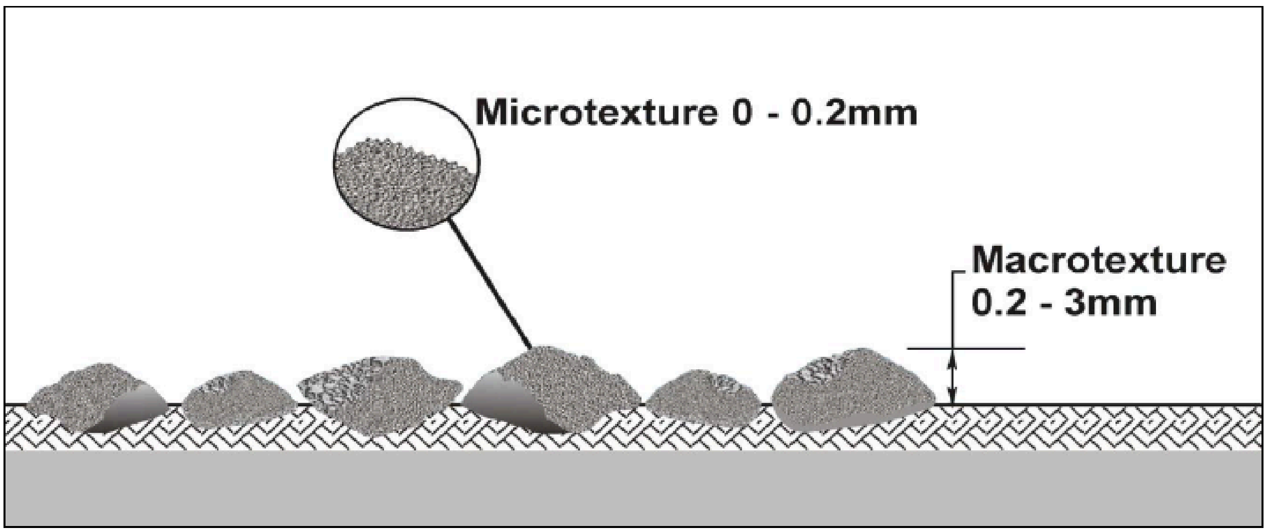

Figure 5 Pavement Surface Microtexture and Macrotexture (Pidwerbesky et al. 2006)

There are two major forces (Figure 6) contributing to the overall skid resistance force of pavement surfaces (NCHRP 2009a). The adhesion force, F_A, and hysteresis force, F_H, are summed to determine the friction force, F, of the pavement surface, as per Equation 1.

$$F = F_A + F_H \quad \text{(Eq. 1)}$$

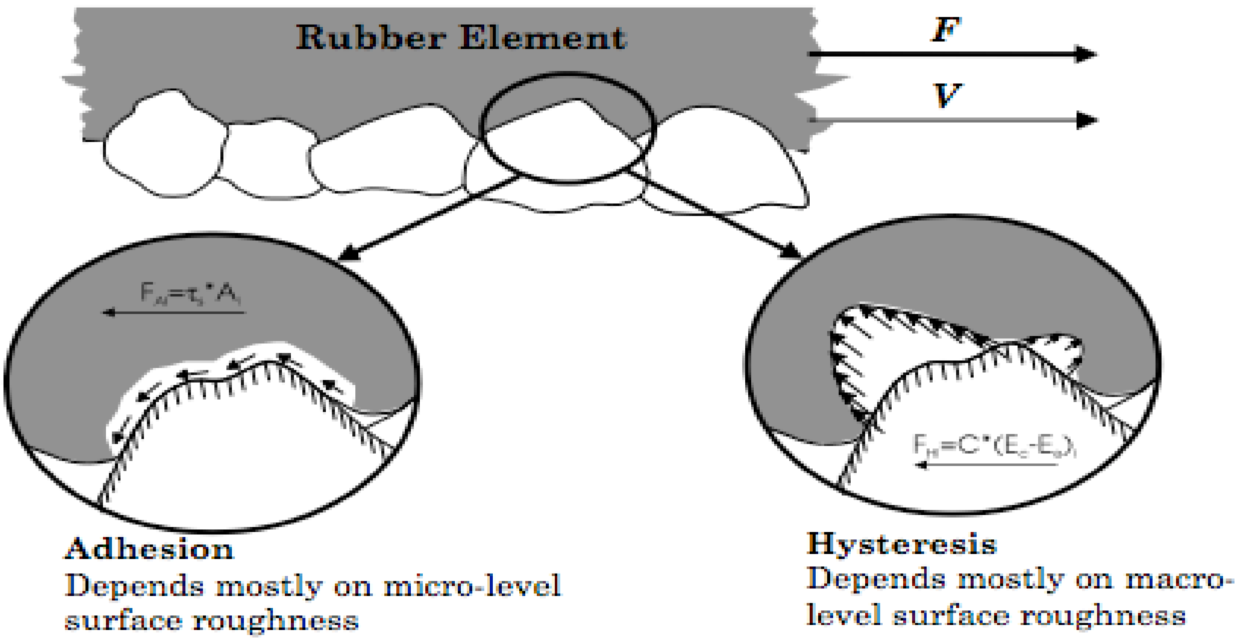

Figure 6 Pavement Friction Model (NCHRP 2009a)

Figure 5 and Figure 6 show the "adhesion force is proportional to the real area of adhesion between the tire and surface asperities" (NCHRP 2009a), and the "hysteresis force is generated within the deflecting and viscoelastic tire tread material, and is a function of speed" (NCHRP 2009a). Therefore macrotexture and microtexture are related to the hysteresis and adhesion forces respectively, both of which must be addressed to improve skid resistance.

2.4 Aggregate Characteristics

Aggregate particles consist of a number of distinguishable geometric aspects (Figure 7), including form, angularity, and surface texture, which due to the difference in size scales, can be used for the purposes of ordering (Masad 2005). "Any of the properties can vary widely without necessarily affecting the other two properties" (Masad 2005). Form relates to variations in the proportions of the particle, angularity is associated with the variations at the corners superimposed on shape, and surface texture describes the irregularity of the surface at a "scale that is too small to affect the overall shape" (Masad, 2005). "For the case of coarse aggregate angularity, there is a distinct difference between angularity and texture, both of which have different effects on performance" (Fletcher et al. 2003).

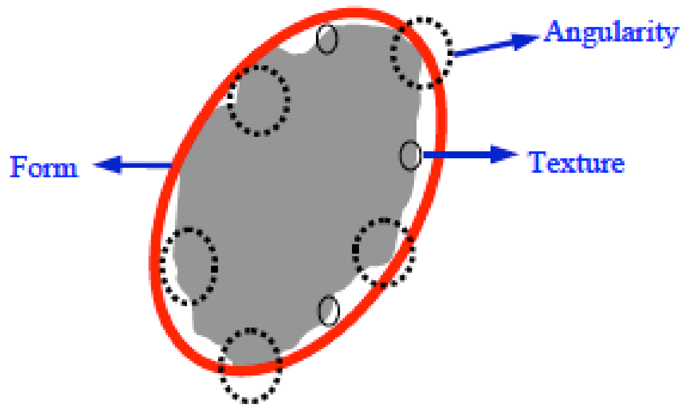

Figure 7 Components of an Aggregate Shape (Masad 2005)

2.5 Aggregate Quality

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 (Moaveni et al. 2014). Aggregate polishing and degradation have an adverse impact on these characteristics and result in accelerating the surface deterioration and increasing remediation frequency (Rezaei et al. 2009, Fowler and Rached 2012, Moaveni et al. 2014). Essentially, aggregate less prone to texture loss and abrasion will predictively have better skid resistance in the field (Lancieri et al. 2005).

Limestone has been the most commonly used aggregate type in US (and Oklahoma) road construction (Csathy et al. 1968). 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 (Fowler and Rached 2012, Csathy et al. 1968, Neaylon 2009, Smith et al. 2009). National Cooperative Highway Research Program (NCHRP) 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 (Smith et al. 2009). 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 (Smith et al. 2009). Essentially, harder and more durable aggregates retain higher friction values longer, contributing to adequate pavement safety and longer service life (Neaylon 2009, Smith et al. 2009).

2.6 Aggregate Polishing

Polished aggregate in a pavement surface is considered to be a surface defect that must be mitigated by pavement engineers to ensure safety (FHWA 2003). 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 (Lancieri et al. 2005). According to the US Department of Transportation (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 (NSP 2010).

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 (Komas 2011).

Most of the state of Oklahoma is comprised of soft aggregates (NSP 2010, Gransberg 2012). Table 1 shows statewide aggregate quality for Oklahoma, classified with polished stone value (PSV) based upon Neaylons’ 2009 definitions of aggregate quality (Gransberg 2012). 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 (Gransberg 2012). 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 (Gransberg 2012). To mitigate the polishing issue, limestone is not used in Oklahoma surface course mixtures on medium to high level roadways for asphalt pavements.

Table 1 Oklahoma Aggregate Geology Based on Average PSV (after Gransberg 2012)

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%

2.7 Economic Analysis

Engineering economic analysis (i.e. LCCA) is used to “evaluate the over-all-long-term economic efficiency between [mutually exclusive] competing alternative investment options” (FHWA 2002). It is a vital component of pavement preservation and has long been promoted by the Federal Highway Administration (FHWA) for application to “highway project planning, design, construction, preservation, and operation” (FHWA 2003) for the evaluation of cost effectiveness and accountability (FHWA 2007). In the short-term (programming implementation level), economic analysis is used for evaluating projects and helps pavement managers facilitate the selection of pavement preservation treatments (FHWA 2007).

2.8 Environmental Analysis

Environmental protection measures have been largely associated with manufacturing products and processes, however methods are now being adopted by the pavement industry (Giustozzi et al. 2012). One method in particular, life cycle assessment (LCA), can be used to evaluate environmental impacts related to pavements (ISO 2006, Giustozzi et al. 2012). “LCA is a quantitative accounting of the cumulative environmental impacts of a product or process across all stages of the life cycle” (EPA 2013). Conducting a LCA comprises of four stages (ISO 2006), which are described by the EPA (2006) as:

1. “Goal Definition and Scoping - Define and describe the product, process or activity. Establish the context in which the assessment is to be made and

identify the boundaries and environmental effects to be reviewed for the assessment.

2. Inventory Analysis - Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).
3. Impact Assessment - Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.
4. Interpretation - Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results" (EPA 2006).

This type of analysis has been used to assess pavement preservation treatment performance (Giustozzi et al. 2012, Mosier et al. 2013).

2.9 Conclusions

Pavement preservation is one way that transportation agencies are enhancing their programs' sustainability. Pavement preservation treatments are commonly applied to rectify loss of skid resistance and enhance safety while extending pavement service life and reducing costs. Oklahoma aggregate is prone to polishing, a condition for which few treatment options exist. However, analysis and proper treatment selection for a given project can contribute to an agency's goals of preserving the investment in the pavement network, enhancing sustainability performance and ensuring proper stewardship.

3.0 DOS Treatment and Testing

Silicon Reactive Lithium Densifier and Shotblasting (or generally, densifier over shotblasting, DOS) is a new pavement preservation treatment being investigated for its ability to harden pavement surfaces against abrasion, enhance macrotexture, retain microtexture (surface friction) and inhibit rutting and polishing, hence extending pavement service life (Gransberg and Pittenger 2012). The treatment consists of a mechanical process (shotblasting - high velocity impact method) and a chemical application (Silicon Reactive Lithium Densifier). The chemical application works to retain the surface texture and profile that the shotblasting restores. Application of the treatment is shown in Figure 8.

Figure 8 DOS Treated Pavement: Shotblasting (Left), Densifier Application (Right) (Convergent 2009)

The DOS process was developed to improve hardness, wear and polishing resistance properties of aggregates whereby reducing the rate at which friction values deteriorate making roads safer and extending the service lives of both asphalt and concrete pavements. However, no work has been conducted to support the previous statement related to chemical densifier effect on aggregate characteristics, nor is there any literature related to DOS-treated pavements. Recent studies have evaluated certain aspects of the performance, cost effectiveness, and sustainability of this pavement preservation treatment when applied to concrete pavements and preliminary results indicate that DOS has the potential to lengthen Portland Cement Concrete Pavement (PCCP) service life (Gransberg and Pittenger 2012). This chapter describes the DOS process and presents previous field studies, common lab-based polishing and skid resistance methodologies, and sustainability analyses on the use of DOS and associated aggregate shape characteristics.

3.1 Densifier-over-Shotblasting

3.1.1 Chemical Densifier

Application of chemical densifiers, in particular lithium silicate, has proven to harden and extend the service life of industrial Portland Cement Concrete (PCC) floors subjected to low speed vehicular traffic (Nasvik 2008). Lithium silicate has the advantage over other hardening agents as it forms a dust rather than a crust when it dries, and it reacts with the calcium hydroxide, a by-product of cement hydration, to increase the concrete strength and resistance to traffic wear and abrasion. During the hydration process, calcium hydroxide dissolves in water and relocates to the surface, where it reacts with the lithium silicate. The calcium silicate hydrate then settles in the pores and voids of the concretes surface, creating a denser, harder surface than untreated concrete. In the process, lithium is used to "stabilize and solubilize the silicate so it can remain in solution until it penetrates the concrete and then can react with the abundant calcium hydroxide found in the concrete" (Nasvik 2008).

Recent developments have led to the use of the technique in the pavement industry, where it makes Portland cement concrete pavement more rut resistant, and increases the ability to resist snowplow abrasion (Riemer et al. 2012, Nasvik, 2008). Additionally, lithium silicate has been investigated for mitigating moisture intrusion and sealing concrete barrier walls exposed to chloride-based deicing salts to reduce chloride-induced corrosion of reinforcing steel in concrete structures and was found to reduce chloride concentration when compared to untreated walls (Guthrie et al 2015).

3.1.2 Shotblasting

The chemical densifier reaction is most advantageous when the chemical is applied to a porous pavement surface, as this allows for greater penetration of the hardening agent, and results in a deeper hardened surface (Nasvik 2008, Gransberg and Pittenger 2012).

Hence, shotblasting is an important factor in improving the concrete densification process.Shotblasting is a recent development being used by pavement managers as a preservation technique that retextures concrete and asphalt road surfaces. It has proved to be a cost effective method for restoring surface friction (MarylandDOT 2013). The technique involves a machine that blasts small steel balls or pellets onto the surface, which adds texture to each individual piece of aggregate in the surface, and therefore increases skid resistance (Blastrac 2013). A vacuum system is used to recover the shot along with the material removed from the surface, after which a magnet removes the shot for reuse. There are generally two types of shotblasting equipment, vehicular mounted and ground mounted.

Vehicular-mounted units consist of a shot propelling mechanism and magnetic retrieval system, with cutting widths that vary from approximately 6 to 12 feet, depending on the manufacturer and type. The ground-mounted type is smaller and is “capable of cutting six to twenty inches at a pass” (Speidel 2002). Two of the smaller shotblasters can be mounted over the wheel paths to shotblast the polished sections of the surface in order “to achieve a higher rate of production while reducing the overall unit cost per lineal unit” (Gransberg 2009). A typical shotblasting system includes:

- “Shot propelling apparatus,
- Vacuum system,
- Magnetic separator,
- Residue container, and
- Follow on magnetic brush and loom to pick up any debris” (Gransberg 2009).

A typical shotblasting setup is shown in Figure 9. The impellor propels the steel shot to abrade the surface, upon which the steel shot and abraded material are collected through a vacuum system. The material is then separated with the steel shot returned to the hopper and the debris sent to the dust collector. Shotblasting is considered sustainable, with vehicle fuel the only petroleum product consumed (Gransberg 2009).

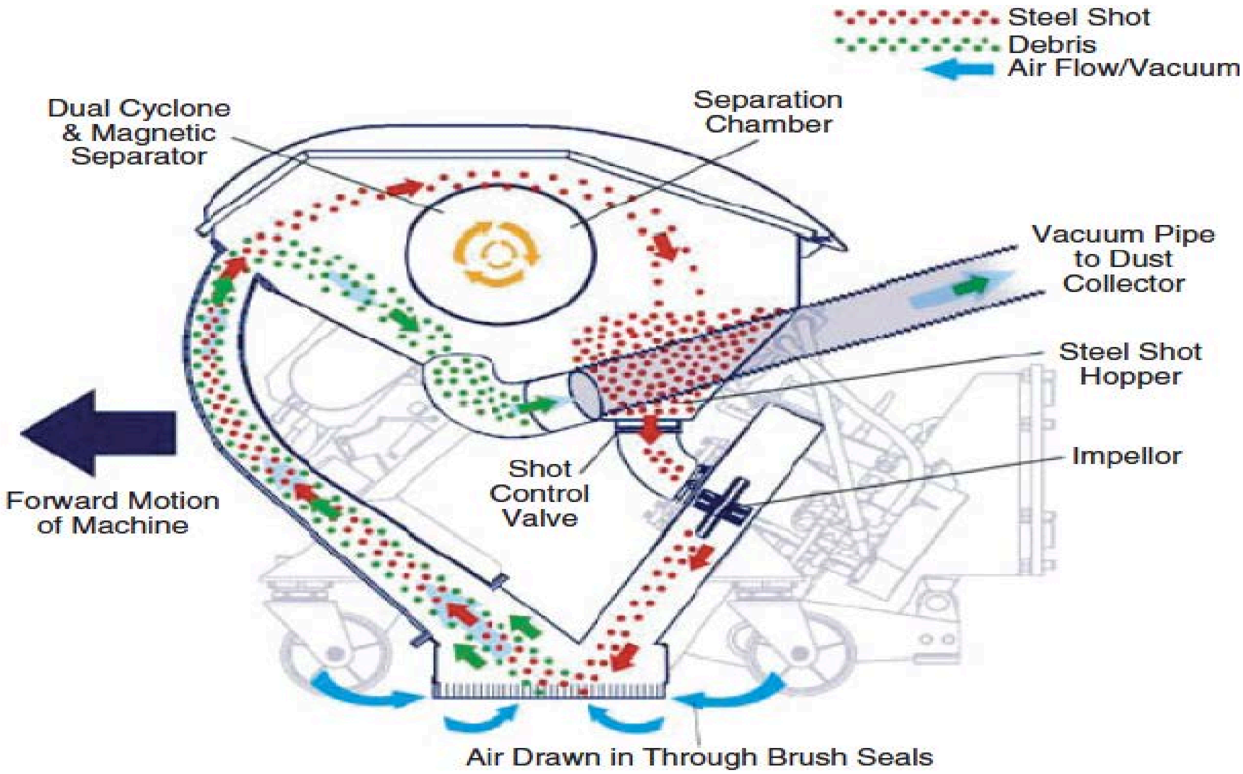

Figure 9 Typical Shotblasting Apparatus and Process (Jenman 2006)

The most in-depth study on road surface retexturing using the shotblasting technique was carried out in Australia (Bennett 2007). The project included the retexturing of polished HMA surfaces. Bennett reported that

> "[The shotblasting] system has shown that it is a fast and efficient means of reinstating texture to road surfaces. At each trial site, the treatment increased texture depth by at least 0.2 to 0.8 mm . . . The SCRIM [Sideway force Coefficient Routine Investigation Machine] data clearly shows that an increase in microtexture can also be achieved using this technology . . . the trial has proven that the shotblasting technology is very effective in reinstating both macro and microtexture to a wide variety of road surfaces. The process has the added advantage in that it uniformly treats all areas of the road surface without excessively damaging surface integrity, and effectively improves both macro and microtexture. It is environmentally friendly in that it is a dust free process and recycles all materials used and generated by the process" (Bennett 2007, p. 23).

The major factor affecting the speed in which the shotblaster can operate is the relative hardness of the asphalt binder (Gransberg 2009). As temperature increases, asphalt binder becomes softer and is able to absorb more of the shots impact. This reduces the operating speed of the shotblaster and production rate decreases, which increases the cost per square yard. Aggregate hardness does not affect operation rate, however it does affect surface friction gain. Initially, softer aggregate gains a larger amount of microtexture than harder aggregate, however softer aggregate loses this microtexture faster than harder aggregate (Gransberg 2009). This is where the application of the lithium silicate densifier can provide benefit (Gransberg and Pittenger 2012).

3.1.3 Oklahoma Study

A recent ODOT study demonstrated the DOS treatment's ability to inhibit loss of skid resistance due to aggregate polishing. The study explored the use of the DOS technique applied as a concrete preservation treatment for locations subjected to studded tires, snow chains and snow plowing. The technique has been used for a number of years to preserve concrete industrial floors, subjected to slow moving traffic, however there were concerns over its use in highway applications.

The three-year field test evaluated different pavement preservation treatments, including DOS, on existing PCCP test sections on State Highway 77 in Oklahoma (Riemer et al. 2010). Average daily traffic (ADT) on the road section is approximately 14,000 vehicles per day (Gransberg and Pittenger 2012). The study included a test section that was shotblasted and treated with the lithium silicate concrete densifier as well as shotblasted sections with no treatment. Among other measurements, the study took monthly measurements of skid numbers for 33 months. One objective of the study was to track the change in skid number over time, which directly addresses the concerns over safety related to applying a chemical that may reduce skid resistance.

The Oklahoma results (Table 2, Figure 10) from the 3-year project demonstrate that DOS-treated test section outperformed the control section in terms of skid resistance, and although the sections were not subject to snow chain abrasion, snow plowing was experienced 2 to 3 times per year (Riemer et al. 2012).

Table 2 DOS Study Results - Oklahoma (Gransberg and Pittenger 2012)

Surface	Skid Number @ Start	Skid Number @ 33 months
Shotblasted	54	48
DOS	48	45

The shotblasted-only section showed a total friction loss of 11.1% over the testing period compared to 6.3% for the DOS section. Figure 10 also shows that the DOS section (diamond designation) retained its skid number for 26 months at a skid number of roughly 44 (Riemer et al. 2012).

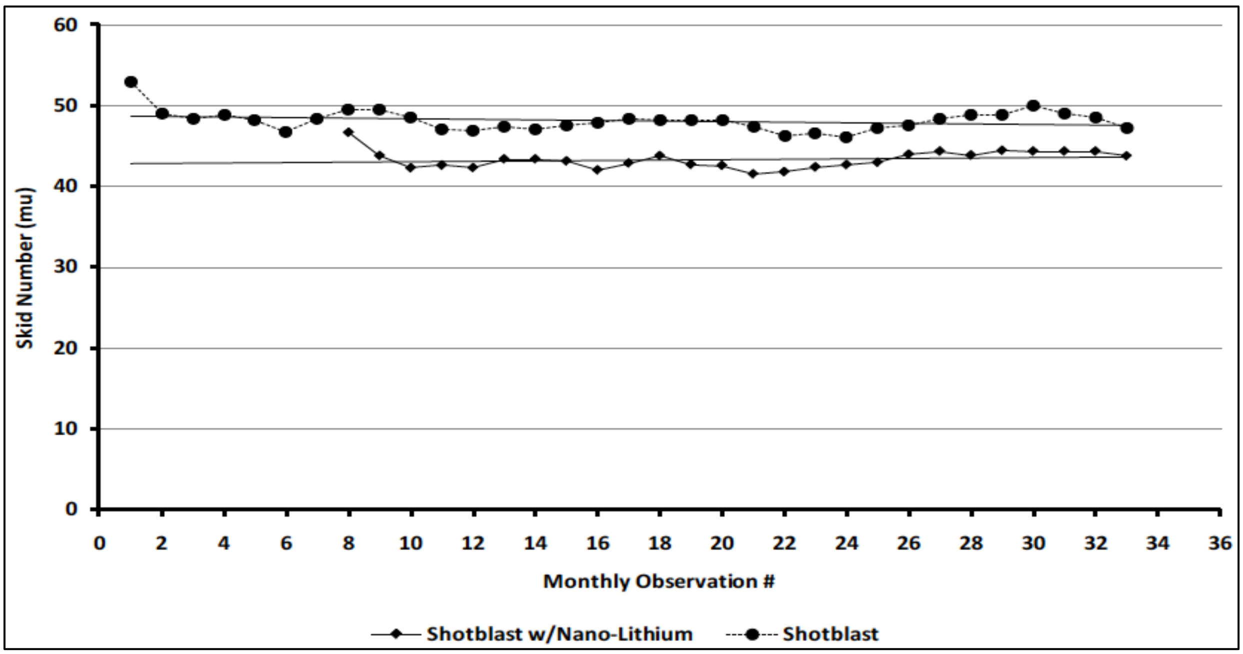

Figure 10 Oklahoma DOT Study Results of Skid Number Change over Time (Riemer et al. 2010)

3.1.4 California Studies

Another field study, conducted by California State University, Chico sponsored by California's Department of Transportation, CALTRANS, was conducted on a test site on Interstate Highway 80 over Donner Pass in the Sierra Mountains. This site was selected as it "sees some of the worst conditions in the country in terms of deicing salts, chain traffic, and snow removal" (Howarth 2011). The test site was designed around previous research that demonstrated shotblasting a pavements surface before applying a densifier greatly enhances penetration, resulting in a thicker surface of hardened concrete (Stokes 2010).

The study evaluated DOS applied to new PCCP and evaluated surface wear over 12 months. The test site was three lanes wide and one mile long and included three different test sections. One section, the control, was not shotblasted or treated with densifier. Another section was only treated with the densifier and the final section was shotblasted and treated with the densifier. Measurements of rut depth were taken before treating the test sections and then again after 12 months. Table 3 contains the outcome of the study. The CALTRANS research oversight engineer concluded, "in general the [lithium silicate densifier over shotblasting] treated areas appeared to have about half the wear of untreated section" (Howarth 2011). In addition to measuring change in wheel path rut depth, the study also measured skid numbers of the test sections. At the conclusion of the 12-month study, the average across the three-lane test site was found to be 45 for the DOS section and 42 for the shotblasted section.

Table 3 DOS Study Results - California (Haworth 2011)

Surface	Rut @ 12 months (mm)	Skid Number @ 12 months
Shotblasted	5.29	42
DOS	2.12	45

A current, unpublished study from the CP2 laboratory in California (Thor et al. 2016) tested densifier-treated cement mortar to determine potential for concrete pavement preservation and rutting mitigation. The results demonstrate the efficacy of densifier application indicated by the treated samples outperforming the control samples.

Figure 11 shows the lab results for the comparison of treated and control samples with the cumulative mass lost in the test for the three types of mortar mixtures. Treated samples demonstrated a significant reduction in the mass loss when compared to untreated samples (Thor et al. 2016).

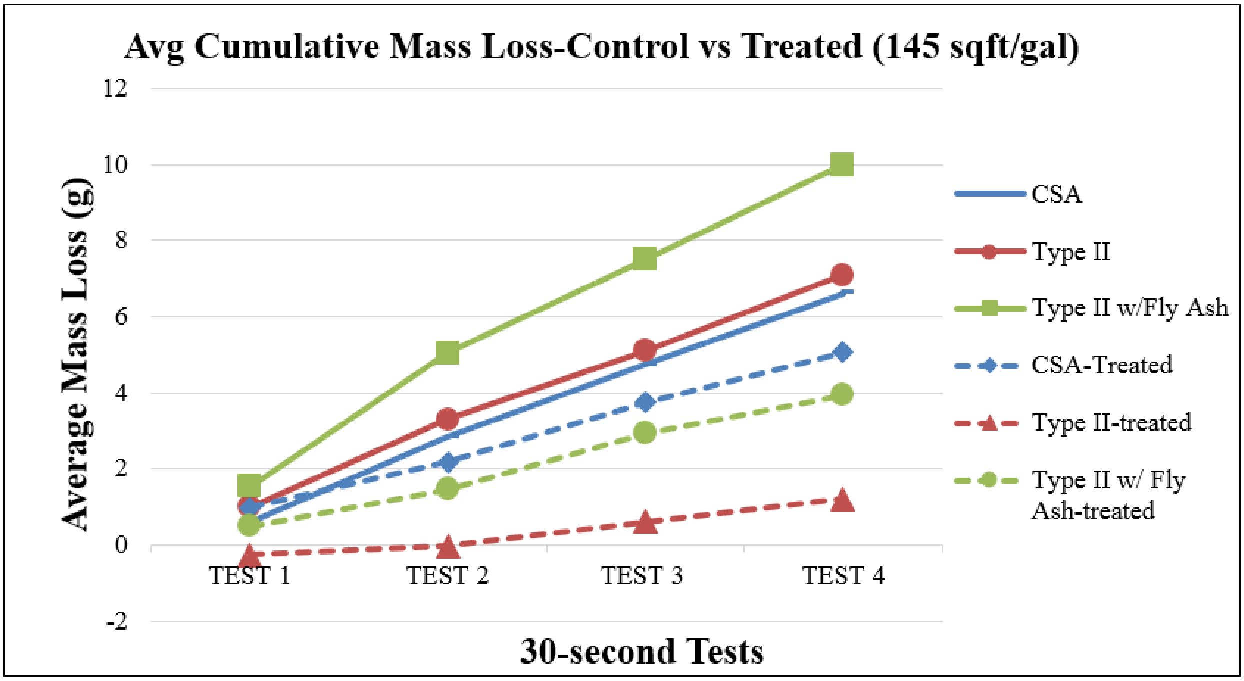

Figure 11 Control vs Treated Cement Average Cumulative Mass Loss (Thor et al. 2016, unpublished)

3.1.5 Delaware Study

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 densifier (Gransberg and Pittenger 2012). The study involved 7 different surface conditions at the field test site. Two of the PCCP test sections received DOS, two received lithium treatment application only, two received shotblasting only, and one received diamond grinding with the treatment. Core samples were extracted from each test section approximately 6 months after treatments were applied to measure the penetration of the lithium. The results showed that DOS provides the deepest penetration of the three surface preparation methods, with 81% of the lithium applied to the shotblasted section found in the core (Table 4). These results support the benefit accrued for DOS sections, which were inferred from the data to have a deeper hardened surface than the other options (Gransberg and Pittenger 2012).

Table 4 DOS Study Results - Delaware (DelawareDOT, unpublished)

Surface	Percent Lithium Remaining @ 6 months
Control	20
Diamond Ground	12
Shotblasted	81
Diamond Ground and Shotblasted	32

3.1.6 Maryland Study

A current study by the Maryland DOT involves accelerated polishing testing of DOS-treated and untreated molds containing limestone in the NCAT laboratory (Figure 12). [Note: the initial scope of work for this project was for NCAT to cast concrete samples with ODOT materials for this research effort. However, there was difficulty in creating samples adequate for testing. Therefore, the industry host and NCAT replaced the scope with this work.]

Figure 12 Samples of Maryland Limestone at the NCAT Laboratory

Figure 13 shows the friction results obtained after exposure to the specified number of cycles by the three-wheel polishing device (TWPD). Essentially, the densifier-treated sample (designated by the purple line, hashed) outperformed the untreated sample (designated by the red line, circles). Additionally, the untreated sample shows a decreasing trend in friction, while the friction exhibited by the densifier-treated sample is maintained after 10,000 cycles.

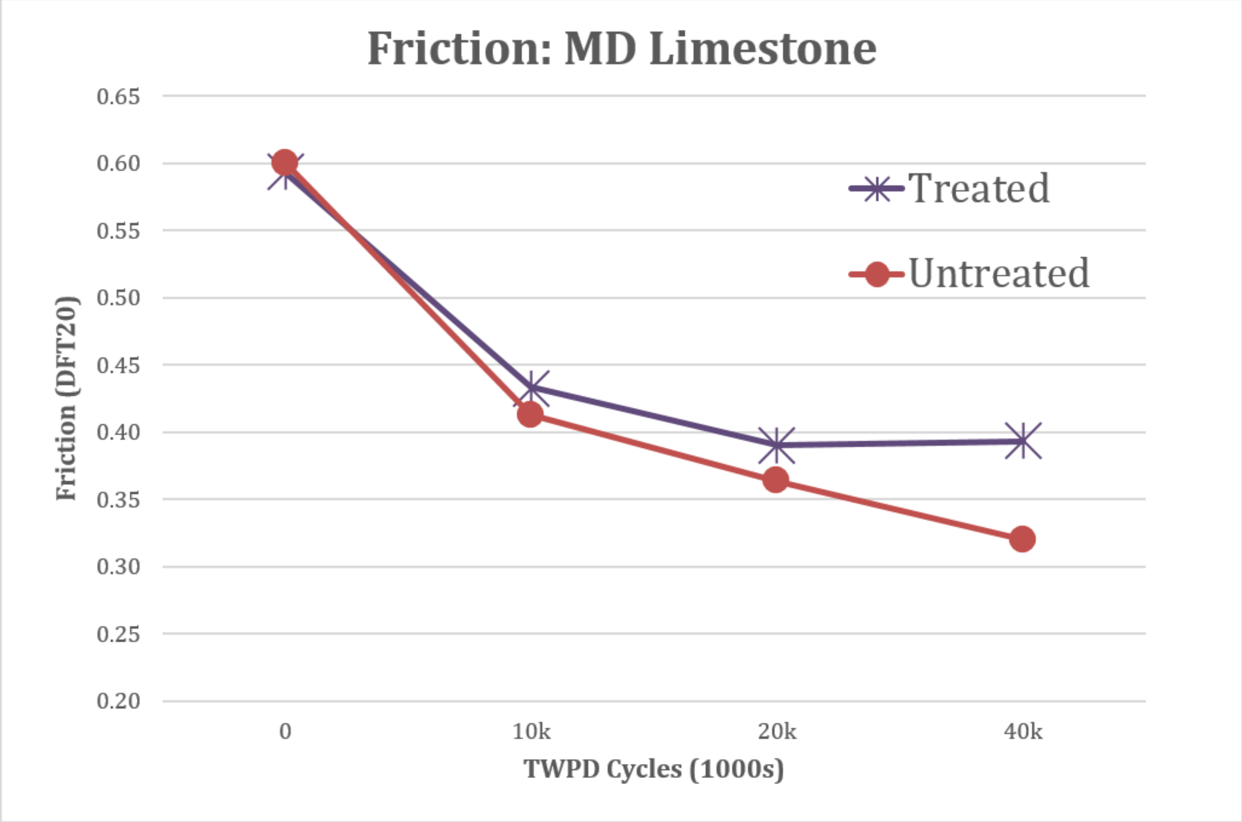

Figure 13 NCAT Results: MD Limestone Friction - Treated vs. Untreated

3.2 Aggregate Characteristic Tests

The Federal Highway Administration provides guidance for *Surface Texture for Asphalt and Concrete Pavements* (FHWA 2005b). It identifies four aggregate properties that influence pavement surface texture: toughness, polish resistance, angularity and soundness. In this study, LA Abrasion and Micro-Deval are tests used to indicate aggregate durability, British Pendulum is used to indicate aggregate polishing, AIMS is used to indicate angularity, texture, shape and potentially polishing, and the sodium sulfate test is used to determine aggregate soundness. This section describes each test method.

It should be noted that correlating the data from different friction measuring devices is not advised due to the inherent differences in the devices (Lu and Steven 2006). There are also many complexities related to the friction behavior of rubber and tires, of adhesion and hysteresis and the relative contribution of each to pavement surface texture that inhibit a 1:1 correlation (Lu and Steven 2006).

Aggregates are subjected to substantial levels of wear throughout the construction process. In general, aggregate should be hard enough to resist degradation imposed by manufacturing, stockpiling, production, placing, and compaction (Roberts et al. 1996). The amount of degradation is a function of the aggregates ability to resist abrasion and impact. The Micro-Deval test and Los Angeles (LA) Abrasion test (Figure 14 and Figure 15) are laboratory tests that were developed to provide insight relating to aggregate abrasion and impact resistance.

Figure 14 Micro-Deval Testing Apparatus, Canisters and Steel Spheres (Pavement Interactive 2011)


Figure 15 LA Abrasion Testing Apparatus

The aggregate characteristics of shape, angularity, and texture significantly affect microtexture and can be used to predict pavement performance (Moaveni et al. 2014, Masad 2005). 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 AIMS (AASHTO Provisional Specification) to quantify aggregate shape and texture property changes resulting from exposure to standard Micro-Deval testing (AASHTO T 327), which simulates field polishing and abrasion of aggregate (Rezaei et al. 2009, Fowler and Rached 2012, Moaveni et al. 2014, Mahmoud and Masad 2007).

3.2.1 Micro-Deval

Development of Micro-Deval began in France in the 1870's to evaluate road aggregate, and was initially adopted by the American Society for Testing and Materials (ASTM) in 1908 (Amirkhanian et al. 1991). Wu et al. (1998) determined that the only commonly used test that could adequately predict toughness and abrasion resistance was the Micro-Deval. The Micro-Deval test simulates aggregate resistance due to abrasion and weathering. The test evaluates the abrasion resistance and durability of coarse aggregate by evaluating the percentage aggregate weight loss subsequent to rotation in a jar with an abrasion charge (steel balls). A lower Micro-Deval percentage loss indicates aggregate that is more durable and resistant to abrasion.

The wet conditions in the Micro-Deval test are thought to better simulate the field conditions of aggregate abrasion compared to the dry conditions of the LA Abrasion test (Rogers 1998). According to the American Association of State Highway and Transportation Officials (AASHTO) (2012), "many aggregates are more susceptible to abrasion when wet than dry, and the use of water in this test incorporates this reduction in resistance in degradation, in contrast to some other tests that are conducted on dry aggregate". Previous research has also shown there is no correlation in aggregate percentage loss between the Micro-Deval and the LA Abrasion tests (Kandhal and Parker 1998, Cooley and James 2003). Essentially, Micro-Deval tends to polish the aggregate, whereas LA Abrasion tends to break it.

3.2.2 Los Angeles Abrasion

The LA Abrasion test is the most widely specified test for evaluating the resistance of course aggregate degradation and was originally developed in the mid-1920's by the Municipal Testing Laboratory of the City of Los Angeles, California (Kandhal and Parker 1998). According to AASHTO (2010), the LA Abrasion test measures aggregate "degradation of mineral aggregates of standard gradings resulting from a combination of actions including abrasion or attrition, impact, and grinding". However, other studies have determined that LA Abrasion primarily measures an aggregate's resistance to mechanical breakdown rather than abrasion due to wear (Rogers 1998, Lane et al. 2000).

The LA Abrasion test simulates and measures degradation that is experienced by course aggregate during the construction process. Unlike the Micro-Deval test, the LA Abrasion test is not carried out in the presence of water, and the steel spheres and drum are much larger. Essentially, the LA Abrasion test is used to assess the abrasion and impact resistance of coarse aggregate by evaluating the percentage aggregate weight loss subsequent to rotation in a drum with steel spheres. A lower LA Abrasion percentage loss indicates aggregate that is more resistant to breakage.

LA Abrasion is an empirical test and therefore a poor predictor of field performance (Wu et al. 1998). The test may not be suitable for certain materials, including limestones, as they typically display a high percentage loss, but may exhibit satisfactory field performance (Pavement Interactive 2011).

3.2.3 British Pendulum

The British Pendulum Tester (BPT) (Figure 16) is a test historically used to obtain polished stone values (PSV) for evaluating an aggregate's potential to polish under traffic. The dynamic impact-type test was developed by the British Road Research Laboratory (RRL, now the Transportation Research Laboratory, TRL), in which a swinging rubber edge makes contact with test surface and the energy loss recorded. BPT results are reported as British Pendulum Numbers (BPNs) to associate the results directly with the tester and not that of another polishing device.

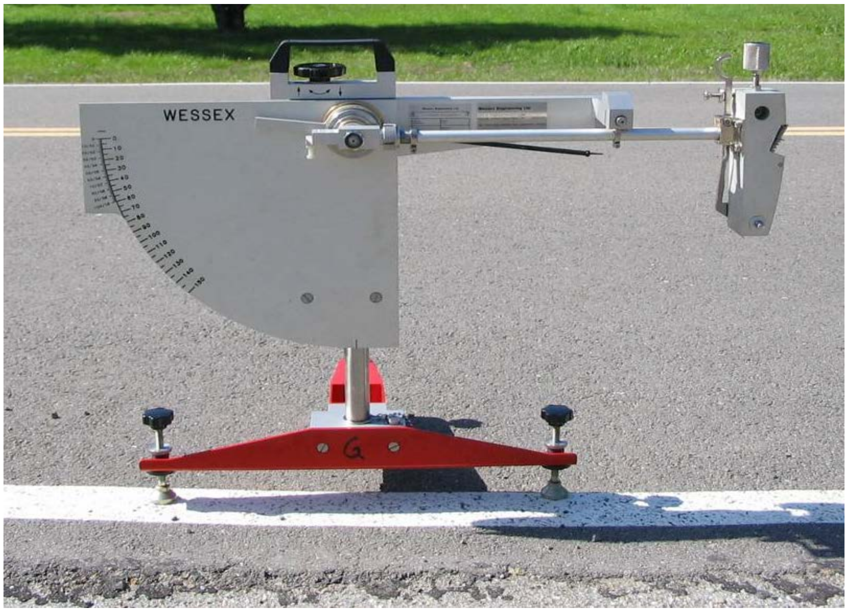

Figure 16 British Pendulum Tester (Lu and Steven 2006)

The tester has a low swing speed, about 6 mph, which measures skid resistance related to microtexture only. As both microtexture and macrotexture affect pavement friction, the BPT does not correlate well with, full-size tire, field polishing devices operating at high speeds of 40 mph or more (NCHRP 1972). The BPT is typically used with the British Wheel, an accelerated polishing device, for determining the change in PSV the aggregate over time. Alternative methods to BPT have been developed for several reasons, including the substantial time and cost required to execute BPT testing, as well as its limitation to provide reliable correlation between PSV and surface friction in the field (Neaylon 2009, Kassem et al. 2013, Shabani et al. 2013). Recent developments include the Micro-Deval and AIMS methodology as described in section 3.2.4, and the Three Wheel Polishing Device (TWPD), as described in section 3.3.1.

3.2.4 Aggregate Imaging System (AIMS)

Digital vision and the associated motion control software made significant developments in the early 2000's, which provided the basis of computerized methods for evaluating individual aggregate particle shape characteristics. A number of techniques were developed for directly measuring aggregate characteristics, including physical measurements of aggregate dimensions, image analysis techniques, and laser scanning (Jahn 2000, Tutumluer et al. 2000, Kim et al. 2001). These systems are limited as they mostly focus on aggregate form with little consideration towards texture and angularity characteristics.

A study by Masad (2003) addressed these issues, and sought to develop an automated system for analyzing all aggregate shape characteristics, known as AIMS (Masad 2003). One of the main objectives of the study was to "correlate the aggregate shape characteristics to the aggregate samples with known laboratory performance to demonstrate the system capabilities" (Masad 2003). The study developed a system that "provides rapid and accurate determination of aggregate shape properties with minimum interference from the operator" (Masad 2003). Fine and coarse aggregate samples common to asphalt mix designs with known laboratory performance were used to demonstrate the system. The study concluded that:

> “[AIMS] has the ability to analyze the shape of fine and coarse aggregates. It measures the three-dimensions of form through the use of a single camera and autofocus microscope. Aggregate texture is quantified by analyzing gray scale images, and angularity is quantified by analyzing black and white images” (Masad, 2003).

The [first-generation] aggregate imaging system, like the one in the University of Oklahoma (OU) Binder’s Laboratory, was developed to capture images and analyze aggregate shape and texture characteristics. The AIMS setup (Figure 17) uses two separate lighting schemes and a camera to capture images of aggregates at varying resolutions, upon which aggregate characteristics can be measured (Masad 2005). The camera unit has an optem zoom 160 video microscope that operates in the y and z directions over the aggregate measurement tray, which travels in the x direction. The movement of the camera and aggregate tray is controlled by a closed loop direct current servo, which can achieve highly consistent focus.

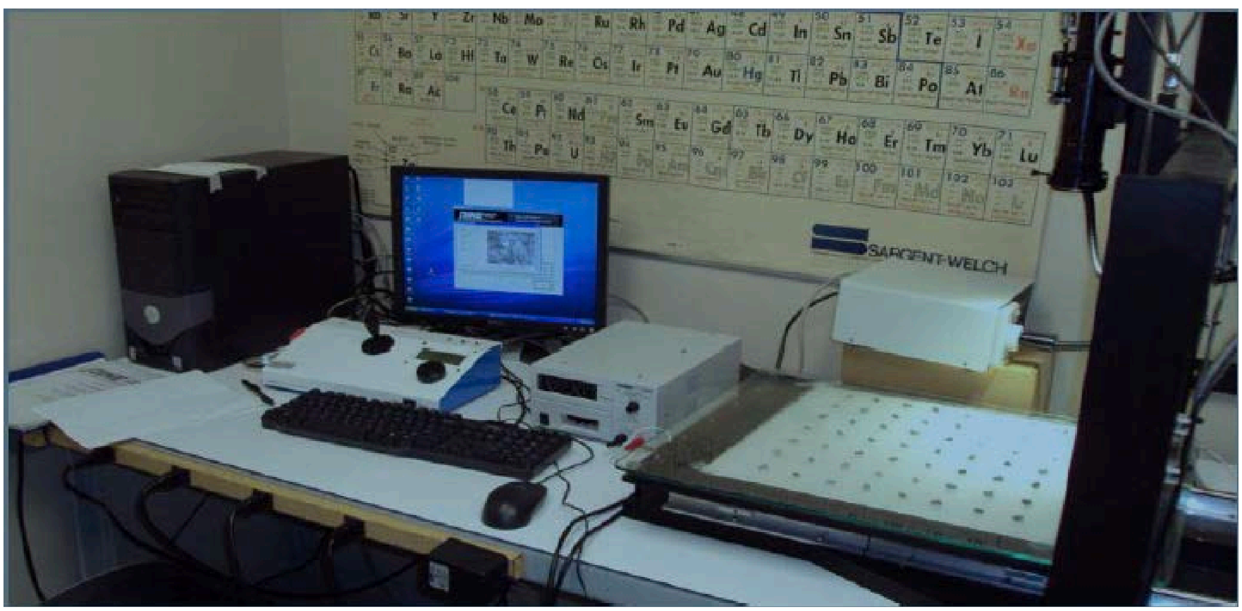

Figure 17 Aggregate Imaging System (AIMS I, First Generation) in OU Binders Laboratory

Coarse aggregate particles are placed on the measurement tray at marked locations, and the camera captures black and white, and gray images of the sample using separate lighting schemes. AIMS software analyzes the captured images and produces characteristic measurements (Masad 2005, Al-Rousan 2004). One way in which aggregate angularity can be analyzed is using the gradient method (Masad et al. 2001). The images are stored in a computer, upon which the AIMS software analyzes the images and exports the data to a text file for later use in data analysis.

3.2.3.1 Angularity Analysis

The gradient method (Figure 18) “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” (Masad 2003) and is used to analyze the black and white images (Chandan 2002). The classifications of gradient angularity are shown in Figure 19.

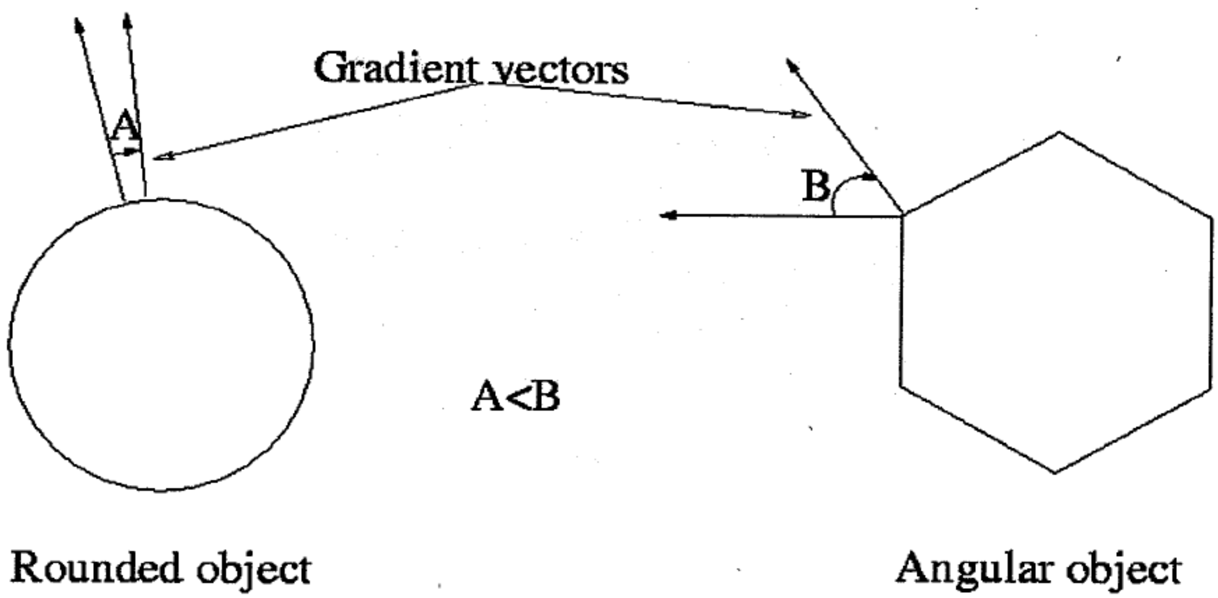

Figure 18 Illustration of the Difference in Gradient Between Particles (Masad 2003)

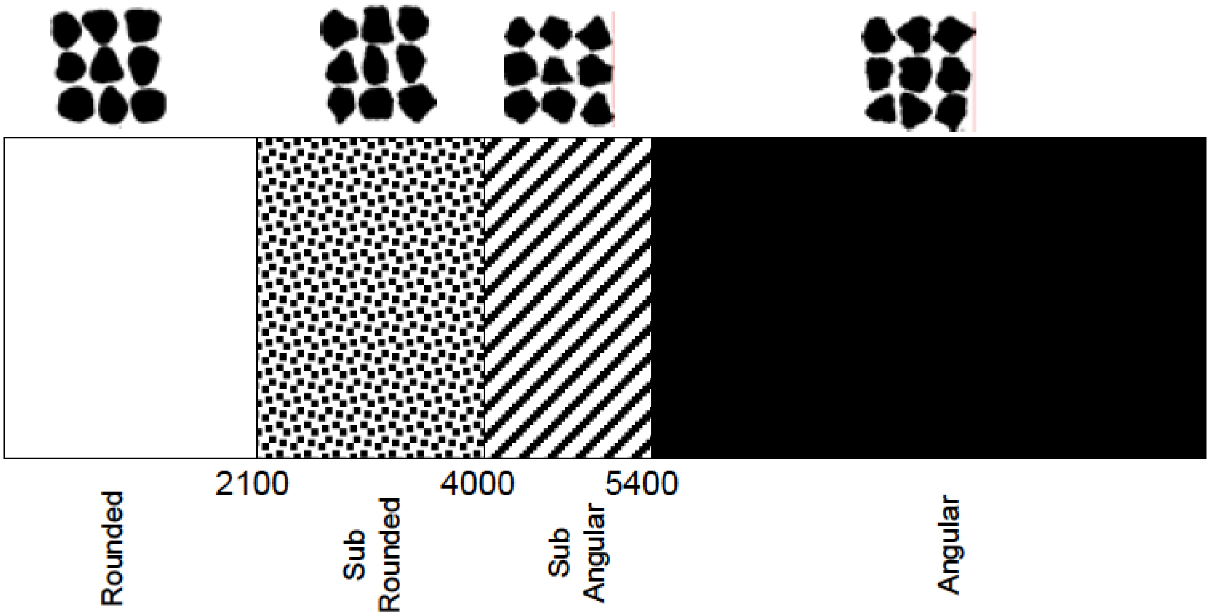

Figure 19 Gradient Angularity Classification Chart (Masad 2005)

Angularity is calculated based on the values of angle of orientation of the edge points (θ) and the magnitude of the difference of these values (Δθ). The sum of the angularity index values for all the boundary points are accumulated around the edge to get angularity index, as show in Equation 2.

$$Angularity\ Index\ (Gradient) = \sum_{\theta=0}^{n} |\theta_i - \theta_{i+3}| \qquad \text{(Eq. 2)}$$

Where n is the total number of points in the edge of the particle with the subscript i denoting the i^{th} point on the edge of the particle (Masad 2005).

3.2.3.2 Micro-Deval and Aggregate Imaging System

A recent study carried out by the Texas Transportation Institute (TTI) sought to develop a predictive model for friction loss of pavement surfaces (Kassem et al. 2013). In particular the study demonstrated and validated the use of AIMS to evaluate the change in aggregate characteristics, after Micro-Deval abrasion and polishing (Kassem et al. 2013). The study included two limestone aggregates, obtained from different locations around Texas, and asphalt mix designs included a fine dense-graded mixture (Type F), coarse dense-graded mixture (Type C), Stone Matrix Asphalt mixture, and Permeable Friction Course asphalt mixture.

The Micro-Deval lab testing apparatus was used to measure the abrasion resistance and durability of coarse aggregates and carried out in accordance with the AASHTO procedure. The results (Figure 20) showed that the sandstone had the least weight loss, an indication of good resistance to abrasion and polishing, while the soft limestone had the greatest weight loss, an indication of poor resistance to abrasion and polishing. Literature shows that a Micro-Deval weight loss of 18 percent after 105 minutes separates good aggregate from poor aggregate with regard to degradation resistance (Kandhal and Parker 1998), although each agency determines limits based upon actual historical performance. Therefore, the soft limestone exhibited poor abrasion resistance while the sandstone exhibited good abrasion resistance.

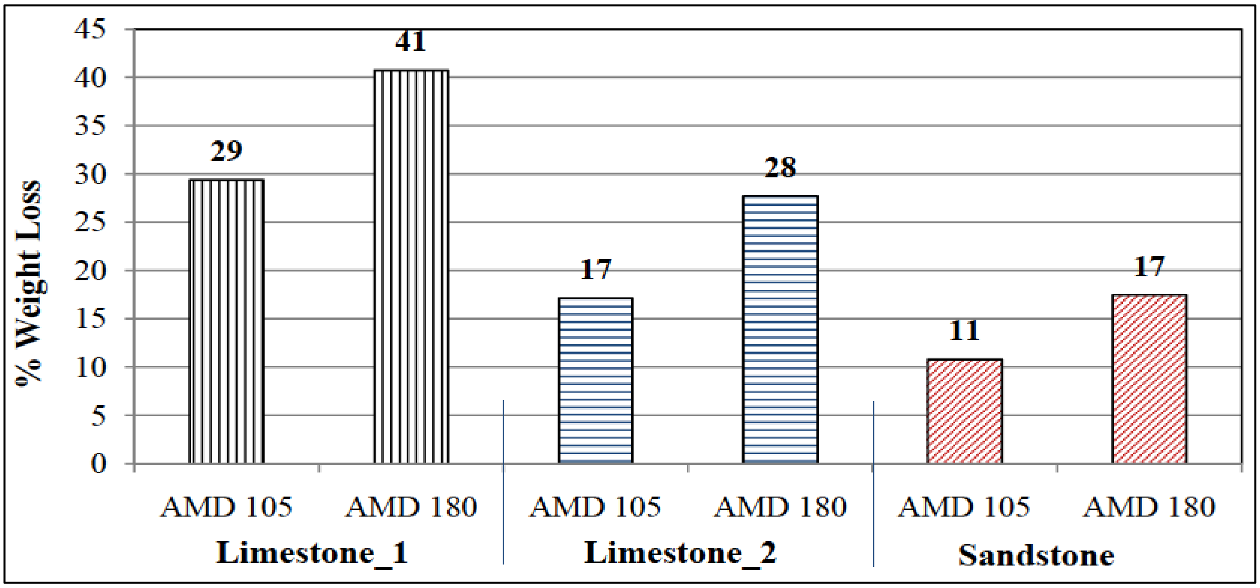

Figure 20 TTI Micro-Deval Results Using the Micro-Deval and AIMS Methodology (Kassem et al. 2013)

The AIMS system was to determine shape characteristics of the aggregate, in particular gradient angularity. Gradient angularity was determined both before and after the aggregate samples had been run through the Micro-Deval test. Three different size fractions were analyzed for each aggregate type: passing 12.5 mm and retained on 9.5 mm, passing 9.5 mm and retained on 6.35 mm, and passing 6.35 mm and retained on

4.75mm. The results (Figure 21) show similar gradient angularities before Micro-Deval testing; however after Micro-Deval testing, the sandstone had a higher angularity index than the soft and intermediate hardness limestones.

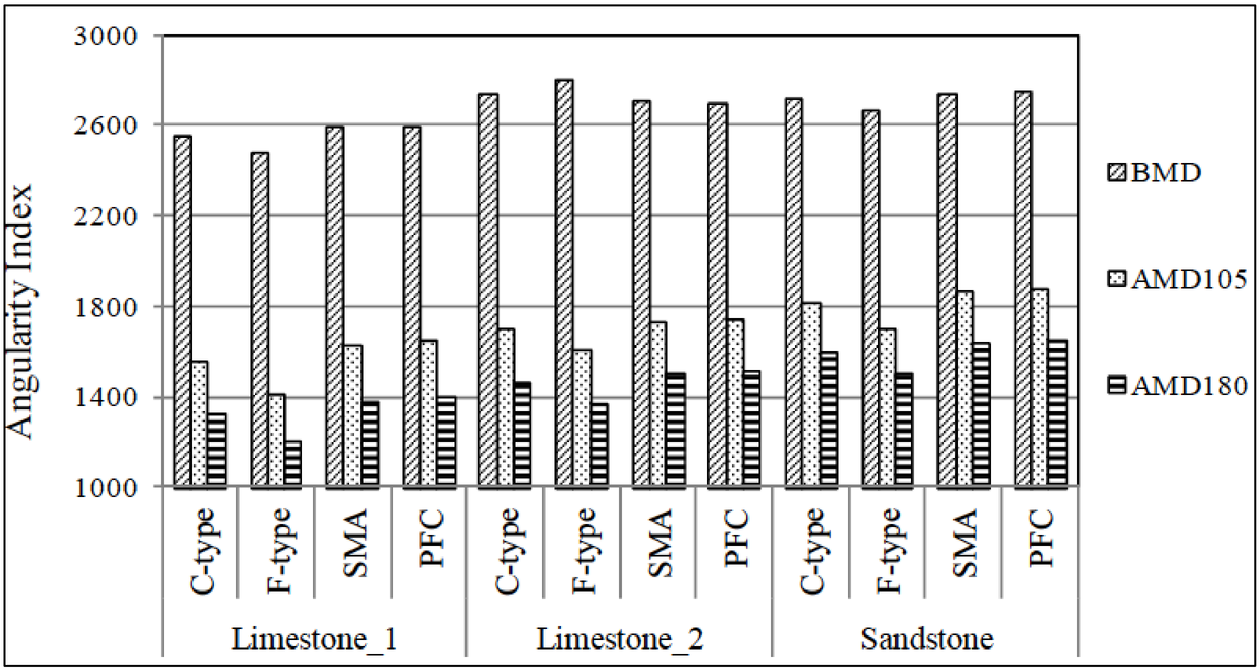

Figure 21 TTI AIMS Angularity Results (Kassem et al. 2013)

Although the main objective of the TTI study was to develop a model for predicting friction loss of pavement surfaces, the study also determined that:

> "[The Micro-Deval test and AIMS] were found to be effective tools for evaluating the abrasion and degradation resistance of aggregates and quantifying the change in the shape characteristics respectively. Aggregates with good resistance to abrasion and polishing demonstrated better skid resistance compared to aggregates with poor resistance to abrasion and polishing. In addition, mixtures with coarser aggregates gradation exhibited better skid resistance than those with finer aggregate gradation" (Kassem et al. 2013).

Another recent study carried out by Moaveni, Mahmoud, Ortiz, Tutumluer and Beshears (2014) "demonstrated the effectiveness and applicability of implementing advanced image analysis systems for practical and routine testing and quantification of aggregate shape property changes from standard Micro-Deval tests" (Moaveni et al. 2014). AIMS systems were used to capture the changes in shape and size properties of aggregate particles caused by Micro-Deval, simulating field degradation and polishing. Aggregate materials with different mineralogical properties were collected from the state of Illinois and surrounding states. More than 26,000 aggregate particles were scanned using two separate imaging systems at different Micro-Deval time intervals to record the changes in shape characteristics. Previous studies using the Micro-Deval and AIMS methodology had only run the Micro-Deval testing for 105 and 180 minutes, however this study polished the material until no further degradation was seen (terminal polishing). Aggregate samples from each source were polished using a modified one aggregate size Micro-Deval methodology at 15-minute time intervals for 105 minutes, and then a further 75 minutes for a total polishing time of 180 minutes. Statistical analysis determined some sources were still degrading at the end of the polishing period; however it was determined 210 minutes was sufficient for evaluation purposes (Mahmoud and Ortiz 2014). Although the image acquisition and processing capabilities of the imaging systems used were different, both of the systems successfully quantified changes in morphological properties of particles from the Micro-Deval tests (Moaveni et al. 2014).

3.2.5 Soundness

Aggregate soundness "refers to a [fine and/or coarse] aggregate's ability to resist degradation [breakdown] caused by climatic/ environmental effects (i.e., wetting and drying, freezing and thawing)" (NCHRP 2009a). AASHTO T 104 is a test method used to determine aggregate soundness. Its protocol includes immersion of aggregate samples in a sodium sulfate solution (16 to 18 hours at a temperature of 70 °F (21 °C)). Following the immersion period, the samples are removed, drained and oven-dried to a constant weight. This process is typically repeated five times. Then the samples are sieved over appropriate sized sieves and weighted average losses are obtained.

The soundness tests essentially allow salt solution to penetrate the aggregate during immersion, then dehydrate in the aggregate pores during the drying periods. The "internal expansive force of the rehydration upon re-immersion simulates the expansion of water upon freezing. Higher percentages of loss indicate less sound or durable aggregate” (Khandal et al. 1997). Maximum loss should not exceed 20% (NCHRP 2009a).

The Texas Department of Transportation developed a similar protocol entitled *Soundness of Aggregate Using Sodium Sulfate or Magnesium Sulfate (Tex-411-A).* Essentially, testing gradations are specified according to expected field exposure to freeze/thaw action.

The limitations of testing aggregate using a soundness procedure have been well documented. The test is time consuming and the results have been highly variable with little correlation to actual pavement performance (Williams and Cunningham 2012, NCHRP 2009a/b, AASHTO 2009). Therefore, it has been recommended that soundness results only be used to supplement other testing results and not be the basis for aggregate selection (NCHRP 2009a).

3.3 Laboratory Asphalt Mix Tests

“To adequately assess the pavement friction for operational vehicles, the effects of both the microtexture and macrotexture need to be evaluated in testing and analysis” (Lu and Steven 2006). There are a number of ways to measure and report microtexture and macrotexture. A common procedure involves obtaining *dynamic friction tester* (DFT) results for microtexture and *circular track meter* (CTM) results for macrotexture. DFT and CTM tests require a device to simulate the abrasion and polishing due to traffic on the hot mix asphalt (HMA) samples. Recently, the National Center for Asphalt Technology (NCAT, University of Auburn) developed the *three-wheel polishing device* (TWPD), specifically for use with the DFT and CTM, which provides a better alternative to the polishing process than historically used procedures such as the British Pendulum (Heitzman 2011). One way to combine and report both measurements is to use the International Friction Index (IFI) (Lu and Steven 2006).

3.3.1 Three Wheel Polishing Device (TWPD)

NCAT developed the TWPD (Figure 22) to provide a more cost effective alternative to the BPT that can produce laboratory results that more closely correlate with field results observed at the NCAT Test Track. Figure 23 shows the high correlation (R^2 = 0.95) between the field results (y axis) and the laboratory results (x-axis) (Heitzman, 2011). This "portable" testing apparatus is unique because it can test mix molds in the laboratory, as well as pavement sections in the field, for both concrete and asphalt pavements, for correlation purposes. The device was designed to use caster wheels which track in a circular path to polish the surface and simulate field polishing of aggregate in the HMA mix (Voller and Hanson, 2006). The wheels on the device are also free to move in the vertical direction, allowing the loading weight applied at the surface to be varied. A water spray system is used to "wash away abraded particles to allow polishing of the aggregates and also to simulate wet conditions" (Voller and Hanson, 2006).

Figure 22 NCAT Three Wheel Polishing Device (TWPD) (Heitzman 2011)

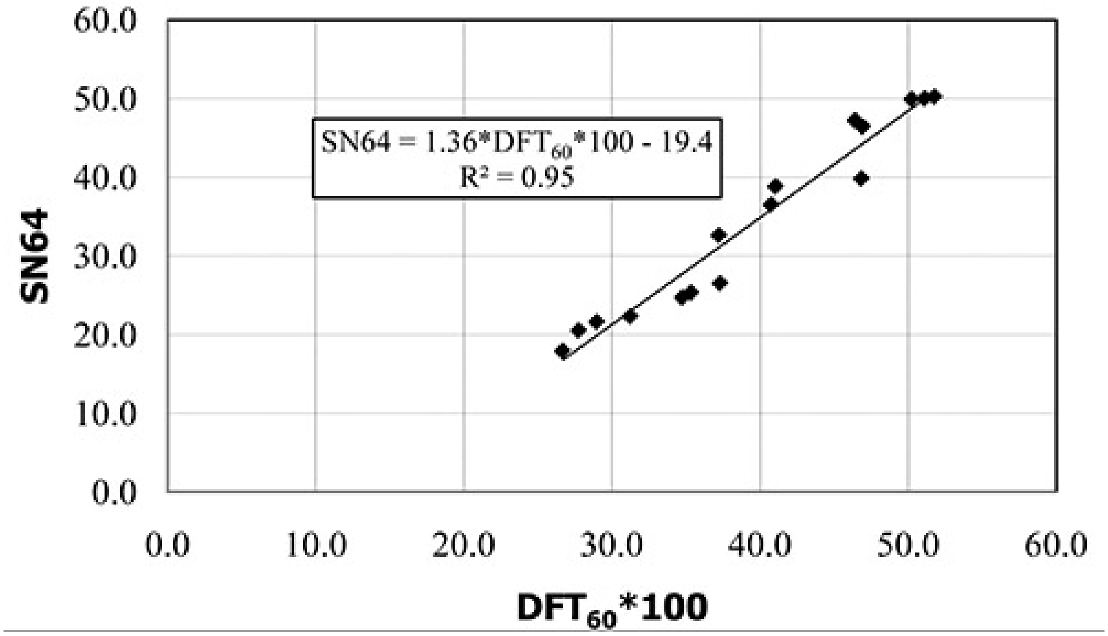

Figure 23 NCAT Laboratory/Field Results Correlation (Heitzman 2011)

3.3.2 Dynamic Friction Tester (DFT)

Another portable device increasingly used to measure pavement friction characteristics is the DFT (Figure 24). The DFT is an electronically controlled device that "measures friction as a function of slip speed from 0 to 55mph" (NCHRP 2009a) and has the ability to determine how the surface friction varies for different speeds (Saito et al. 1996). The device measures the loss in kinetic energy of a rotating disk and converts that energy into a force. The DFT Testing has proven that the DFT provides more reproducible results than the BPN at 20 mph (Henry 2000).

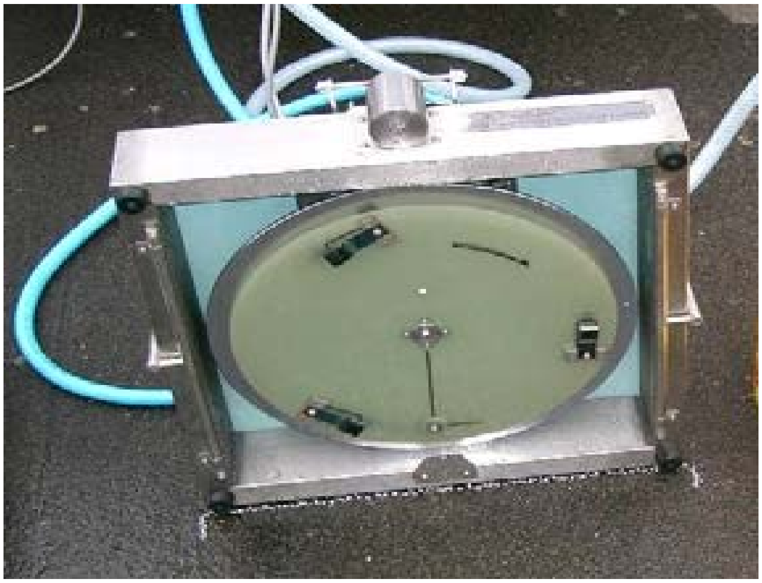

Figure 24 Dynamic Friction Tester (NCHRP 2009a)

3.3.3 Circular Track Meter (CTM)

The CTM (Figure 25) is a non-contact device is equipped with a laser used to measure surface texture (macrotexture). The device measures surface profile along circular path, taking measurements every 0.34 in and stores the information in a computer. Macrotexture indices can then be computed and are reported as Mean Profile Depth (MPD) or Root Mean Square (RMS). MPD is a two dimensional estimate of the three dimensional Mean Texture Depth (MTD) (Flintsch et al. 2003) and RMS is a statistical measure of the deviation from the best fit of the data (McGhee and Flintsch 2003).

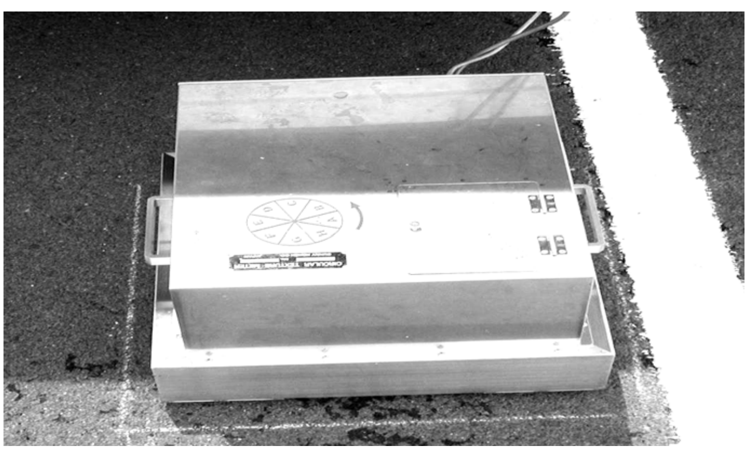

Figure 25 Circular Track Meter (Voller et al. 2006)

3.3.4 International Friction Index (IFI)

Friction indices are useful in indicating overall surface friction based upon macrotexture and microtexture data and allow for harmonization of various friction measurement principles. Skid Number was first introduced by ASTM (ASTM E 274) in 1965 as an alternative to the coefficient of friction, and upon formation of AASHTO, was renamed Friction Number. In 1992 the World Road Association (Formerly, Permanent International Association of Road Congress (PIARC)) sponsored a study involving sites from the US and Europe, and resulted in the development of the IFI, governed by ASTM E 1960 (2003), which addresses the dependency of various tire speeds.

> "IFI includes measurements of both macrotexture and friction on wet pavements: a speed constant derived from the macrotexture measurement that indicates the speed-dependence of the friction and a friction number corresponding to a slip speed of 60km/h (38 mph). The IFI is based on the assumption that the friction is a function of speed and macrotexture and that for a specific pavement surface macrotexture, the value of friction is reduced as the speed increases" (Lu and Steven 2006).

This section presents the ASTM methodology for determining IFI from application of the PIARC Friction Model (ASTM E 1960). Data obtained from DFT results (section 3.3.2) and CTM results (section 3.3.3) can be combined to obtain IFI, which is comprised of two numbers, F(60) and S_P. IFI can be calculated using the following set of equations:

$$S_P = a + b \times TX \qquad \text{(Eq. 3)}$$

Where S_P is the IFI speed number, a and b are calibration constants depending on whether macrotexture is measured as MPD (a = 14.2 and b = 89.7) or MTD (a = -11.6 and b = 113.6), and TX is the macrotexture measurement (MPD or MTD) in mm.

$$FR(60) = FR(S) \times e^{\left(\frac{S-60}{S_P}\right)} \qquad \text{(Eq. 4)}$$

Where FR(60) is the adjusted value of friction measurement FR(S) at a slip speed of S to 60 km/hr, FR(S) is the friction value at a selected slip speed S, and S is the selected slip speed in km/hr.

$$F(60) = A + B \times FR(60) + C \times TX \quad \text{(Eq. 5)}$$

Where F(60) is the IFI friction number, A and B are calibration constants depending on the friction measuring device, and C is the calibration constant required for measurements using ribbed tire.

3.4 Field Testing of Pavement Preservation Treatments

Some DOTs rely less on the friction-related laboratory tests, like those tests listed in the preceding section, and more on the friction performance of actual pavements, "linking the results to the respective aggregates/aggregate sources" (NCHRP 2009a).

Two common field measurements used to assess pavement surface performance are *microtexture* and *macrotexture,* which are surface texture characteristics (Lu and Steven 2006). Essentially, microtexture is the quantitative measure of aggregate surface friction properties that contribute to skid resistance, while macrotexture is the quantitative measure of aggregate physical properties (size, shape and spacing) that contribute to "drainability", whereby enhancing surface friction and skid resistance (Abdul-Malak et al 1993). Microtexture and macrotexture deteriorate over time due to traffic and environmental conditions. Pavement managers can pavement treatment performance (service life) by monitoring the deterioration rate until the surface reaches a certain threshold value that signals remedial action is required.

3.4.1 Microtexture

Microtexture (skid number) can be an indicator of aggregate polishing in pavements. Various methods can be used to measure skid number, but the common method is to use an ASTM E 274 skid tester equipped with either with a smooth tire or a ribbed tire. The testing apparatus is towed behind a vehicle at the desired speed (Figure 26).


Figure 26 ODOT Skid Truck

Forty miles per hour is the standard for towing the ODOT skid tester. Water is applied in front of the tire just before the tire's brakes force the tire to lock up. The resultant force is then measured and converted into a skid number value (ASTM E274).

3.4.2 Macrotexture

Macrotexture is an indicator of aggregate loss or depth of surface texture in pavement surfaces. The New Zealand Transport Agency (NZTA) considers macrotexture measurement to be one of the key performance indicators (KPI) of surface treatments (Manion and Tighe 2007). If the average macrotexture of a road surface drops below 0.9mm (0.04 in) on roads with posted speed limits greater than 70 km/hr (43.5 mph), then the NZTA requires remedial action to restore surface texture. Based on this failure criterion, NZTA maintenance engineers have developed trigger points based on local conditions that allow the programming of pavement preservation treatments before the macrotexture loss becomes critical (Pidwerbesky et al 2006). Macrotexture can be assessed by measuring mean texture depth (MTD) with the New Zealand Sand Circle testing procedure (TNZ T/3), which provides information about surface “drainability”.

Figure 27 shows the TNZ T/3 test being conducted in the field. The TNZ T/3 testing procedure feeds the TNZ P/17 performance specification which can then be used as a metric to judge the success or failure of the surface treatments in their first 12 months based on a field-proven standard (TNZ 2002). A pavement surface texture research project in Texas proved the validity of both the test procedure and the performance specification for use in the US (Gransberg 2007).

Figure 27 TNZ T/3 Sand Circle Testing in Progress (Riemer et al. 2010)

The sand circle test is a volumetric test, performed by placing a known volume of sand, in this case 45 mL, which is then spread by revolving a straight edge in a circle until the sand is level with the tops of the surface aggregate and can no longer be moved around (TNZ 2002). Once the known volume has been spread in a circle on the surface of the roadway and can no longer be moved, two measurements are taken to determine the average diameter of the circle. These values are then averaged and inserted into Equation 6.

$$Mean\ Texture\ Depth\ (mm) = \frac{57{,}300}{Diameter\ (mm^2)} \qquad \text{(Eq. 6)}$$

The surface texture is inversely proportional to the diameter of the circle produced on the surface. This testing protocol is relatively simple but has limitations: it is susceptible to operator inconsistency, environmental issues with rain and wind, and roadway imperfections, such as abnormal aggregate heights on the surface of the road. A wind shield is used to shelter the circle from winds and prevent loss of test sand during the test. However, The TNZ T/3 sand circle test provides better reliability than the ASTM sand patch test, as demonstrated in previous studies (Gransberg 2007, Doty 1974). Additionally, studies have shown no statistically significant difference exists between the results of the TNZ T/3 sand circle test and other tests, like circular track meter and RoboTex, which measure macrotexture (Gransberg et al. 2010).

3.5 Treatment Selection Methods

3.5.1 Life Cycle Cost Analysis

Equivalent Uniform Annual Cost (EUAC) is an alternative engineering economic analysis method for conducting LCCA. EUAC is the appropriate methodology for conducting LCCA in pavement preservation treatment applications because service lives are relatively short and differ in length for given alternatives, and annualized output is consistent with transportation programming (Sinha and Labi 2007, Bilal et al. 2009). EUAC cost models provide information by quantifying and ranking various alternatives and can be used to support decisions (Bilal et al. 2009). However, having good data is key. Unfortunately, quality data is lacking for pavement preservation treatments. Specifically, service life values for which to set the periods of analysis, so input values are generally estimated because performance data is not available (Reigle and Zaniewski 2002).

In a previous DOS study, a LCCA was used to compare DOS-treated PCCP pavement with non-treated pavement (do nothing case) (Gransberg and Pittenger 2012). The data from the three field studies mentioned previously (sections 3.1.3, 3.1.4, and 3.1.5) were used to provide DOS input. The study also used untreated test sections in a Washington State DOT study (Table 5) as a baseline measure. Essentially, it evaluated the wear resistance of both asphalt and concrete pavements. It is used to provide benchmarking data for untreated PCCP and rational failure criteria for the life cycle cost analysis (LCCA).

Table 5 DOS Study Results - Washington (Gransberg and Pittenger 2012)

Surface	Rut @ 60 months
Whitetopping – 3 inch	9.0
Whitetopping – 4 inch	8.0
Whitetopping – 5 inch	8.1

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.

3.5.2 Life Cycle Analysis

Environmental impact assessment is becoming mandatory in many countries and therefore the need to evaluate the various aspects of pavement sustainability, including consumptions and emissions, is increasing (Giustozzi et al 2012). A study by Gransberg and Pittenger (2012) constructed a 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.

Another study developed a carbon footprint cost index (CFCI) for the purpose of comparing pavement preservation treatment alternatives on a basis of enhanced sustainability (Mosier et al. 2013). Carbon footprint aims to quantify sustainability based on the amount of energy used and greenhouse gas emissions that are produced during the production, transportation, and installation of common pavement construction materials (Chehovits and Galehouse 2010). The study used a method that sought to “combine cost and carbon footprint measurements into a single index that can permit the direct comparison of two or more alternatives simultaneously and thus provide a measure of cost effectiveness in the context of each alternatives carbon footprint” (Mosier et al. 2013). The method was demonstrated on an airport case study using six treatment alternatives. Although the analysis methodology was the core of the study, the case study revealed that the DOS treatment had the lower CFCI and would have been the preferred treatment for the given input parameters to restore surface friction and slow underlying pavement deterioration.

3.5.3 Triple Bottom Line Analysis

In order to be effective, a mechanism for assessing the cost-effectiveness of alternatives for implementation should be included in every programming framework (Sinha and Labi 2007). The selection process for assessing the effectiveness of pavement preservation strategies is rapidly changing and it is no longer sufficient to make decisions based on cost and performance. Developing a multi-attribute approach expands to include environmental factors when analytically evaluating potential pavement preservation strategies and allows decisions to be made based on cost, performance, and the environment (Giustozzi et al. 2012). A multi-attribute model allows weightings to be assigned to each of the attributes (cost, performance and environment), and therefore depending on the specifics of the project and the importance of each attribute, the optimal, most sustainable pavement preservation strategy can be selected.

3.6 Conclusions

Previous studies provide support that the DOS technique is a viable and effective pavement preservation technique that can be used by pavement managers to preserve concrete pavements. However, beyond these studies, there was nothing found in literature with regard to the effect of the hardening agent on aggregate shape characteristics and durability, nor the impact of DOS on pavement surface texture. However, a number of established and experimental methodologies exist for assessing performance and cost of pavement preservation treatments like DOS.

4.0 Methodology

The research methodology and protocols were established for the purpose of achieving the study objectives. Modifications were made to accommodate reduced budget and scope revisions. Figure 28 and Figure 29 show the modified (designated by strikethroughs) and summarized scope that includes laboratory testing (Phase I) and field testing (Phase II), respectively. The goal was to determine the performance of chemically-treated aggregate and DOS-treated surfaces.

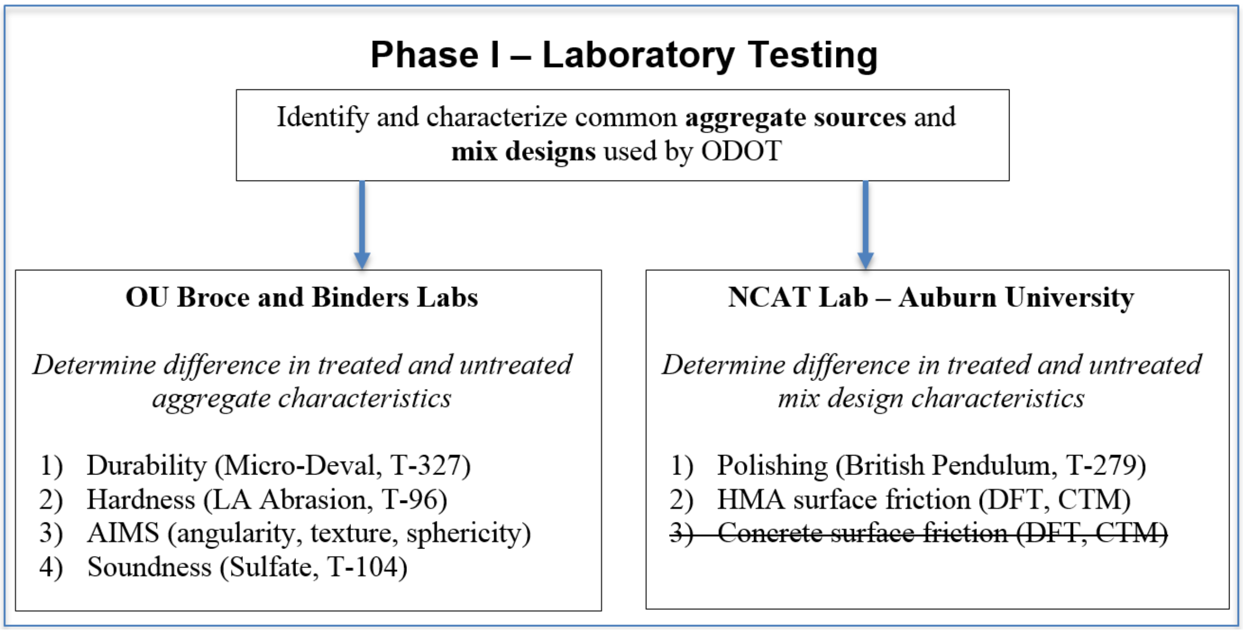

Figure 28 Research Methodology: Phase I – Laboratory Testing

Figure 28 shows the components of the laboratory testing phase in which chemically treated and untreated Oklahoma aggregates were tested for durability, hardness, angularity, texture, sphericity, soundness and polishing. Aggregate sources and mix designs commonly used in Oklahoma pavements and bridge decks were identified and characterized. Aggregate testing for treated and untreated samples were conducted for each major aggregate source. Materials for common asphalt and concrete mix designs were shipped to NCAT for accelerated polishing testing of DOS-prepared surfaces. Unfortunately, a suitable concrete sample was unable to be molded due to the testing limitations. Therefore, this study will supplement this scope of work with the California and Maryland results presented in section 3.1.4 and section 3.1.6. Results were analyzed, compared and correlated, where applicable.

Figure 29 shows the components of the field testing phase, which included collecting, reducing, and analyzing the data from each field test section, as well as synthesizing the information collected into forms that permit immediate implementation via the transfer to practice tools.

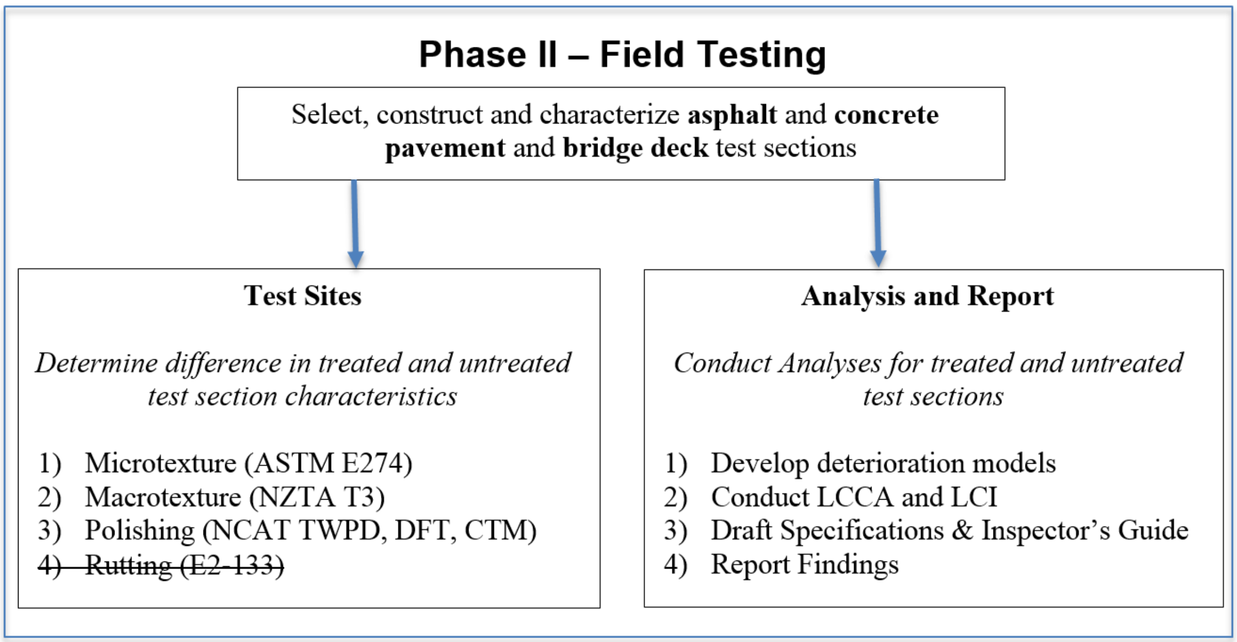

Figure 29 Research Methodology: Phase II – Field Testing

The first task in this phase was to work with ODOT Division 3 to identify pavement and bridge deck treatment candidates. Then test sections were constructed and characterized. Convergent and Blastrac, located in Edmond, Oklahoma, donated DOS (material, labor and installation) pavement sections and bridge deck surfaces. Each test section contained an untreated control section. Microtexture and macrotexture measurements (AASHTO R 48/NZTA T3, ASTM E 274-11) were obtained on each test section monthly (10-month period) to determine deterioration rates. Additionally, continued testing on the DOS section (Highway 77) from a previous Oklahoma Transportation Center project (OTCREOS9.1-21) was included for longer term service life/performance data. Linear regression was to be used to model rates of deterioration of each test section. However, the testing period was limited to ten months due to ODOT's skid truck being unavailable. Due to the short monitoring period, little observable deterioration occurred, but not enough to apply regression. Accelerated polishing testing was conducted (control and non-control segments) to develop full performance (failure) curves. However, due to NCAT equipment failure and short on-site time window, only concrete pavement data was obtained (unable to obtain accurate bridge deck and HMA pavement data). This phase also involved various analyses (life cycle cost analysis, life cycle inventory) to determine DOS effectiveness. The final tasks involved developing the required research reports and DOS specifications and inspector's guide.

4.1 Laboratory Aggregate Characteristic Testing

The laboratory phase investigated the efficacy of chemical application when used on selected aggregate commonly used in ODOT pavement surfaces. In cooperation with ODOT Division 3, aggregate was identified and collected from the following six quarries (locations designated by stars in Figure 30):

- Dolese Cooperton (limestone),
- Dolese Davis (limestone),
- Dolese Hartshorne (limestone),
- Pryor Stone (limestone),
- Martin Marietta Mill Creek (granite), and
- Hanson Davis (rhyolite).

Figure 30 Quarry Locations for Aggregates Tested in this Study

Testing involved Micro-Deval, LA Abrasion, British Pendulum, AIMS and Soundness. The goal of the coarse aggregate testing was to gain a better understanding of the effects of densifier on the aggregate characteristics related to durability, hardness, angularity, shape, texture, polishing and soundness.

No shotblasting was involved in the coarse aggregate characteristic testing, only application of the lithium silicate densifier directly to the aggregate. Direct treatment of aggregate using lithium silicate densifier is a new procedure, so there are no documented standards or standard protocol regarding treatment methodology in literature. Therefore, to treat the required aggregate samples, the lithium silicate densifier was applied to the Oklahoma aggregate per the manufacturers' specifications. The aggregate sample was washed and oven dried to a constant temperature. The combined aggregate sample was then submerged into the lithium silicate densifier and gently agitated in a bucket by hand for 60 seconds to ensure as much uniformity in application as possible (Figure 31). After 60 seconds the sample was removed from the densifier and left to air dry for 24-48 hours to ensure sample was dry for testing. Once dry, testing was conducted on the treated samples.

Figure 31 Aggregate Being Treated with Densifier

4.1.1 Micro-Deval Test

Micro-Deval testing was carried out in accordance with the AASHTO T 327 (2012) “Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus”, and conducted on three replicates of each treated and non-treated samples. Material was washed and oven dried at 110 ± 5 °C to substantially constant mass and separated into individual size fractions. The material was then recombined to meet the grading as shown in Table 6. Note, the treated aggregate samples were washed, dried, and combined to meet the grading before being treated, as described in section 4.1.

Table 6 Micro-Deval Material Grading: Oven Dried Sample of 19.0 mm

Passing (millimeter)	**Retained** (millimeter)	**Mass** (gram)
19.0	16.0	375
16.0	12.5	375
12.5	9.5	750

A sample of 1500 ± 5 g was then immersed in 2.0 ± 0.05 liters of tap water at a temperature of 20 ± 5 °C for a minimum of 1 hour in the Micro-Deval container. 5000 ± 5 g of stainless steel balls were then added to the sample in the Micro-Deval container and then rotated at 100 ± 5 rpm for 12,000 revolutions. The material was then sieved over the 4.75mm superimposed on the 1.18 mm sieve in accordance with AASHTO T 27 (2014) “Sieve Analysis of Fine and Coarse Aggregates”. The retained material was then combined and oven dried to constant mass at 110 ± 5 °C. The oven-dried sample was then weighed and the Micro-Deval percentage loss was calculated using Equation 7.

$$Percent\ Loss = \frac{Mass\ Before - Mass\ After}{Mass\ Before} \times 100 \qquad \text{(Eq. 7)}$$

Upon completion of the Micro-Deval testing, the material was then washed, dried, sieved into separate size fractions, and then analyzed using AIMS (Rezaei et al. 2009, Fowler and Rached 2012, Moaveni et al. 2014, Mahmoud and Masad 2007). The AIMS methodology performed post Micro-Deval testing can be seen in section 4.1.4.

4.1.2 Los Angeles Abrasion

LA Abrasion testing was carried out in accordance with AASHTO T 96 (2010) “Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine”, and conducted on three replicates of each treated and untreated samples. Material was washed and oven dried at 110 ± 5 °C to substantially constant mass and separated into individual size fractions. The material was then recombined to meet the grading as shown in Table 7. Note, the treated aggregate samples were washed, dried, and combined to meet the grading before being treated, as described in section 4.1.

Table 7 LA Abrasion Material Grading: Grading B

Passing (millimeter)	**Retained** (millimeter)	**Mass** (gram)
19.0	12.5	2500 ± 10
12.5	9.5	2500 ± 10

A sample of 5000 ± 10 g was placed in the Los Angeles testing machine along with 11 steel spheres averaging 46.8 mm. The aggregate and steel spheres were then rotated at a speed of 30 to 33 revolutions/minute for a total 500 revolutions. The material was then sieved on the 1.70 mm sieve in accordance with AASHTO T 27 (2014) “Sieve Analysis of Fine and Coarse Aggregates”. The retained material was then combined and oven dried to constant mass at 110 ± 5 °C. The oven-dried sample was then weighed and the LA Abrasion percentage loss was calculated using Equation 7.

4.1.3 British Pendulum

The study aggregates were sampled and shipped to NCAT for British Pendulum testing and mix testing. British Pendulum testing was carried out in accordance with ASTM D3319-2011 “Accelerated Polishing of Aggregates Using the British Wheel” at NCAT. Test specimens were created for 5 non-treated samples and 5 treated samples, with treatment of the aggregate in accordance with section 4.1. Material passing the 12.5 mm sieve and retained on the 9.5 mm sieve was sieved in accordance with AASHTO T 27-2014 “Sieve Analysis of Fine and Coarse Aggregates” and then washed and oven dried at 110 ± 5 °C to substantially constant mass. Each material sample was then combined with the appropriate amount of sand and bonding material in the mold. Once cured the test specimens were then removed from the mold and the initial friction value was determined using ASTM E303-2013 “Measuring Surface Frictional Properties using the British Pendulum Tester”.

To determine the initial friction values, first, each sample was cleaned of all loose particles and then secured in place. Water was then applied to cover the surface of the test area thoroughly. One swing of the British Pendulum was then applied to the surface, followed by four more swings. The test area was rewet each time and the final four BPN’s were recorded. The specimens were then returned to the accelerated polishing device (British Wheel) and secured in place. The road wheel was then brought to a speed of 320 ± 5 rpm and the pneumatic-tired wheel load to 88 ± 1 lbf. Polishing was then conducted for a period of 10 hours with the temperature of the specimen, water and apparatus maintained at 75 ± 5 °F. Upon completion of the polishing, final friction values of the specimens were determined using the same method as the initial friction values.

4.1.4 Aggregate Imaging System

The AIMS system was used to analyze aggregate samples both before Micro-Deval testing and after Micro-Deval testing. Testing was carried out in accordance with AASHTO PP64-11-2013 "Determining Aggregate Source Shape Values from Digital Image Analysis Shape Properties". Post Micro-Deval AIMS analysis was conducted on both treated and non-treated samples of three different size fractions, as shown in Table 8. It should be noted that AIMS was performed on only one treated sample after Micro-Deval and one non-treated sample after Micro-Deval for the largest size fraction tested due to the lack of availability of the larger particles after Micro-Deval polishing. However, each Micro-Deval sample yields an adequate AIMS sample size (n=56) for analysis.

Table 8 Number of Micro-Deval Samples (x56 for AIMS) and the Size Fractions Analyzed

Passing Sieve Size (millimeter)	**Retained Sieve Size** (millimeter)	**Pre MD Samples** (Number)	**Post MD Samples - Non-treated** (Number)	**Post MD Samples - Treated** (Number)

Passing Sieve Size (millimeter)	**Retained Sieve Size** (millimeter)	**Pre MD Samples** (Number)	**Post MD Samples - Non-treated** (Number)	**Post MD Samples - Treated** (Number)
12.5	4.75	3	3	3
16	12.5	3	3	3
19	16	3	1	1

Before conducting the image acquisition, the AIMS system was calibrated. Individual aggregate particles were then placed on the locations marked on the aggregate tray. The AIMS software was then set to collect black and white images and the computer-automated acquisition ran again. Once images had been collected, the software analysis was run before beginning the next sample. This process was carried out for each of the different size fraction samples. The setup only needed to be conducted before the first image acquisition of each session. Using statistical software, an analysis of variance (ANOVA) was then performed to determine the significance between the treated and non-treated, before and after Micro-Deval, samples for each of the shape characteristics.

4.1.5 Soundness

Soundness testing was carried out in accordance with AASHTO T 104 “Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate” and the Texas Department of Transportation protocol, “Soundness of Aggregate Using Sodium Sulfate or Magnesium Sulfate (Tex-411-A)”. Two replicates were conducted for each treated and untreated samples. Material was washed and oven dried at 110 ± 5 °C to substantially constant mass and separated into individual size fractions. The material was then recombined to meet the grading per the Texas Department of Transportation protocol, *Soundness of Aggregate Using Sodium Sulfate or Magnesium Sulfate (Tex-411-A)*, listed in the Table 9.

Table 9 Sulfate Soundness Material Grading: Oven Dried Sample of 19.0 mm

Passing (millimeter)	**Retained** (millimeter)	**Mass** (gram)
19.0	12.5	670 ± 10
12.5	9.5	330 ± 5

The samples were placed in a sodium solution of 215 grams of anhydrous sodium sulfate per liter of water. Successive immersion and oven drying periods were conducted for five cycles. Per the AASHTO T 104 protocol, the material was then sieved and the retained material was combined and oven dried to constant mass at 110 ± 5 °C. The oven-dried samples were then weighed and the percentage loss was calculated using Equation 7, then combined for a weighted average. Figure 32 shows the damage to the limestone sample (cracking) after being subjected to the immersion-oven drying cycles.

Figure 32 Oklahoma Limestone Sample after Subjection to Sulfate Soundness Procedure

4.2 Laboratory Asphalt Mix Testing

The laboratory phase also investigated the efficacy of DOS when used on selected HMA used by ODOT. Accelerated polishing testing of HMA samples was conducted at the NCAT laboratory with the dynamic friction tester (DFT) and circular track meter (CTM), facilitated by the three wheel polishing device (TWPD). Aggregate from the Dolese-Davis Quarry and mix materials that comprise a common hot mix asphalt (HMA) mix design used by ODOT were shipped to NCAT and testing was performed on molded HMA samples. The goal of the NCAT accelerated polishing testing was to gain a better understanding of the effects of the DOS technique on polishing tendency of Oklahoma limestone aggregate characteristics related to surface friction and texture. A total of four surface treatments were selected for the HMA testing:

1. control (no treatment),
2. lithium densifier only,
3. shotblasting only, and
4. densifier applied to the shotblasted surface (DOS).

HMA slabs, 20 in. wide and 3½ in. deep, were molded and treated for each of the surface treatment designs (Figure 33). This involved shipping the samples to Blastrac NA in Oklahoma City for shotblasting, then returning them to NCAT for chemical application, polishing and testing.

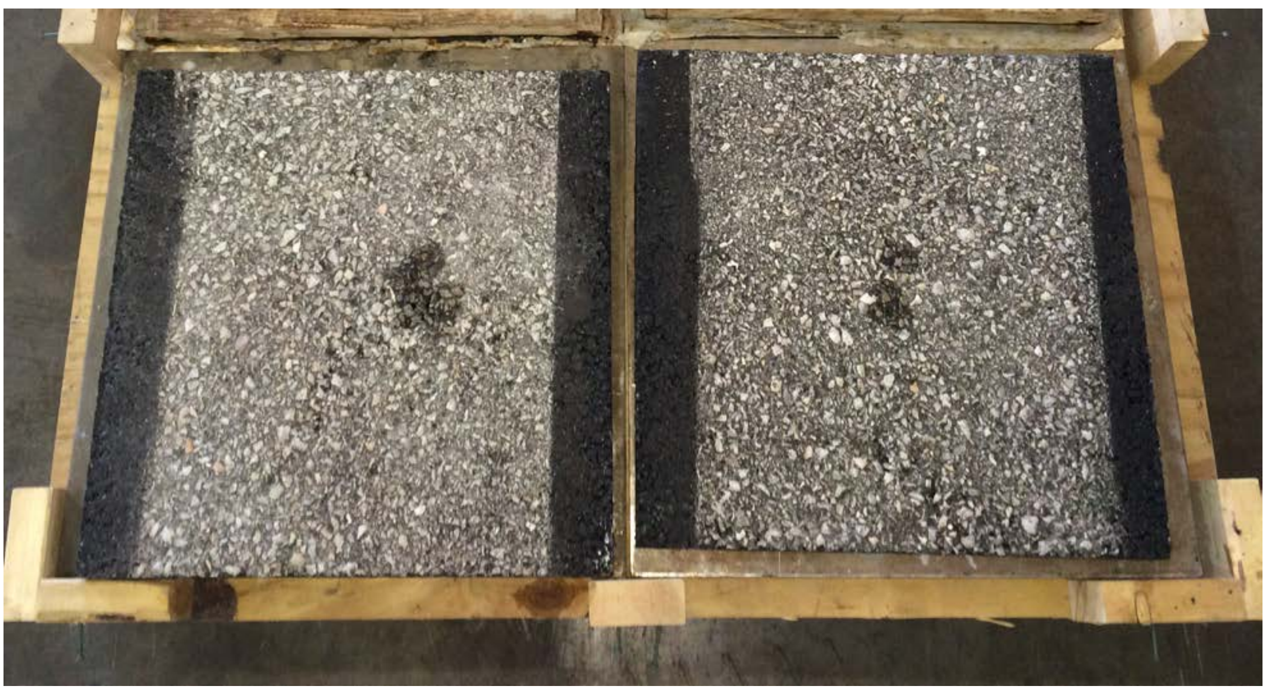

Figure 33 ODOT HMA Mix Design Samples at NCAT

The three wheel polishing device (TWPD) was used to simulate traffic abrasion on the HMA samples with the change in texture monitored over 140,000 polishing cycles. However, there has been no substantive work completed that correlates polishing cycles with traffic counts. Measurements using the dynamic friction tester (DFT) and circular track meter (CTM), according to sections 4.2.1 and 4.2.2 respectively, were taken initially and then after 20,000, 70,000 and 140,000 polishing cycles. To ensure the same polished area was evaluated, each sample was marked accordingly so that readings were taken in the same location.

4.2.1 Dynamic Friction Tester (DFT)

Testing was carried out in accordance with ASTM E1911 (2009) “Paved Surface Frictional Properties Using the Dynamic Friction Tester”. The DFT was calibrated using the manufacturers supplied calibration panel. Once calibrated, the HMA sample was secured and the surface cleaned of all loose particles. The DFT was then placed level on the sample and rotation of the disk and water supply was started. Once the rotating disk achieved the desired speed the water flow was closed and the driving device was lowered to the test surface. Once the test stopped the DFT numbers were recorded. The process was repeated three times for three disk speeds: 20 km/h, 40 km/h and 60 km/h.

4.2.2 Circular Track Meter (CTM)

Testing was carried out in accordance with ASTM E2157 (2009) “Measuring Pavement Macrotexture Using the Circular Track Meter”. Calibration of the CTM was checked using the calibration panel provided by the manufacturer. Once calibration was checked, the HMA sample was secured and the surface cleaned of all loose particles. The CTM was then placed on the same location marked for the DFT, and orientated accordingly. Measurement of MPD and Root Mean Square (RMS) was initiated and the values were recorded and repeated five times.

4.2.3 International Friction Index (IFI)

To determine overall DOS technical attributes in terms of friction performance, IFI values were calculated in accordance with ASTM E 1960 (2003) “Calculating International Friction Index of a Pavement Surface”. Once the DFT and CTM results had been obtained, IFI values for each of the four surface treatments at each of the polishing intervals were determined using Equation 8.

$$F_{60} = 0.081 + 0.732 \times DFT_{20} \times e^{\frac{-40}{14.2+89.7 \times MPD}} \qquad \text{(Eq. 8)}$$

Where F_{60} is the International Friction Index, DFT_{20} is the friction number obtained using the DFT at 20 km/h, and MPD is the mean profile depth obtained using the CTM.

4.3 Field Testing of DOS Treatment

The field testing phase investigated the efficacy of DOS when used on selected asphalt and concrete pavement sections and bridge decks in Oklahoma. In cooperation with ODOT Division 3, four new DOS test sections were constructed on Highway 77 in Norman, Oklahoma. Coupled with the existing DOS test section from the previous study and the control sections, ten total field sections were tested in this study. The concrete pavement sections (new DOS section, old DOS section and control sections) were located in northbound lanes of Flood Ave (AADT ~24000). The asphalt pavement (one treated section, one untreated section) and bridge deck (two treated, two untreated sections) were located in westbound lanes of Tecumseh Road (AADT ~9000). Figure 34 shows the test section layout.

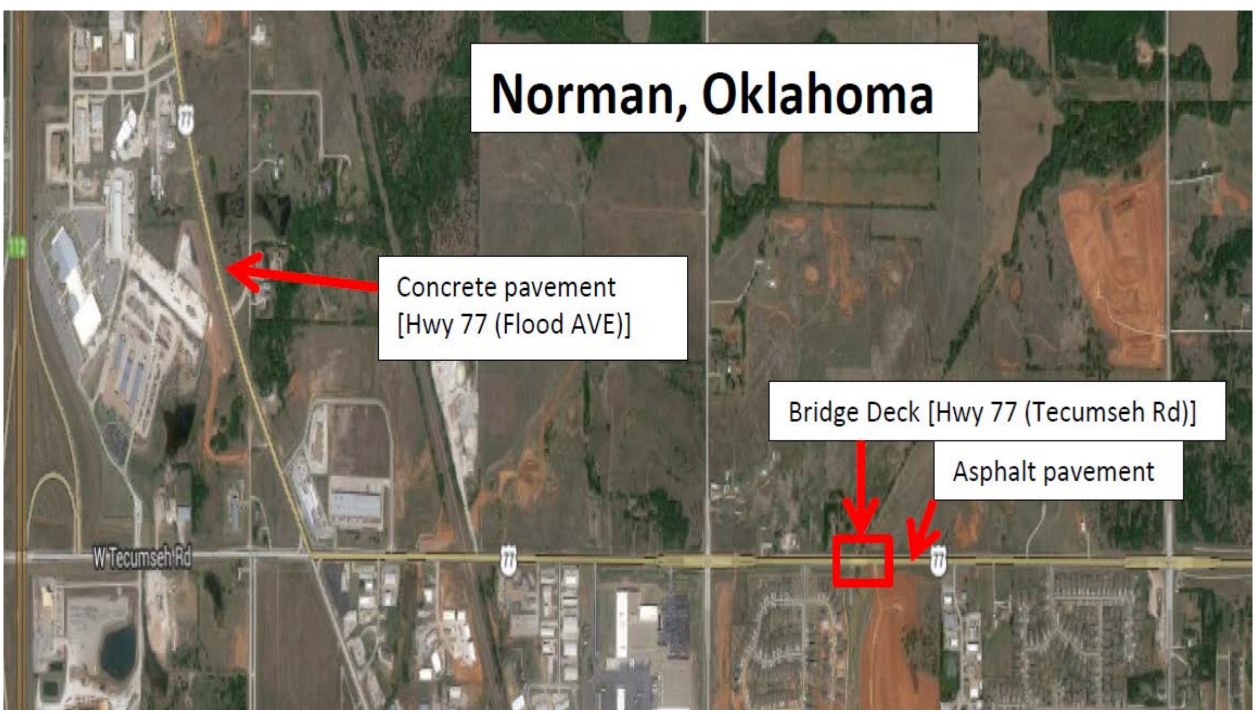

Figure 34 Field Test Section Layout

Test section description, location and lengths are listed in Table 10. Pavement test sections were created long enough to accommodate the ODOT skid truck testing. The bridge decks are short and were tested with some testing methods, but were not long enough to be tested by the skid truck.

Table 10 Test Section Description, Location and Lengths

Test Section	**Description**	**Location (HWY 77)**	**Treated** (length in feet)	**Control** (length in feet)
TS 1	Asphalt Pvmt	Tecumseh (westbound, right lane)	1,300	1,300
TS 2	Conc. Bridge Deck	Tecumseh (westbound, right lane)	100	100
TS 3	Conc. Bridge Deck	Tecumseh (westbound, left lane)	100	100
TS 4	Concrete Pvmt (existing section)	Flood Ave (northbound, left lane)	1,300	1,300
TS 5	Concrete Pvmt	Flood Ave (northbound, right lane)	1,300	1,300

NCAT's accelerated polishing testing sections would be located in the same areas as the test sections on Tecumseh Road. However, due to the test's 24-hour lane closure requirement, the short accelerated polishing testing location for concrete pavement on Flood Avenue was constructed in the center unused (field entrance) turn lane to avoid lane closures on this busy section of road.

Test section performance comparison requires uniform test sections. Therefore, the project eliminated as many ancillary factors as possible. The sections were placed in lanes of travel with care to avoid major turning motions at intersections and driveways.

All sections were characterized prior to construction to obtain baseline measurements. Macrotexture measurements were taken on all sections, while microtexture (skid) data was obtained on the pavement sections only as length allowed. To reduce variability in subsequent monthly measurements, the research team identified the locations of the baseline measurements and marked them so that macrotexture testing occurs as close to the same locations as possible. Photos were also taken for future locating reference.

Sections were constructed in March 2015 when weather conditions permitted. Shotblasting was applied to sections at an approximate rate of 16,000 square feet per hour. The asphalt pavement section received heavier shotblasting, while the concrete pavement and decks received lighter shotblasting in an effort to retain existing grooving. The chemical treatment was applied to the shotblasted surfaces at a rate of approximately one gallon per 145 square feet of surface (1 gal/145 sf). The chemical dried within 30 minutes of application in the following conditions:

- no rain in the forecast,
- ambient temperature of 74 ºF,
- wind speed of 8 mph,
- dew point of 45 ºF.

The manufacturer representative stated that it can take up to 4 hours to dry in colder/wetter conditions. Figure 35 shows the treated bridge deck section.

Figure 35 DOS-Treated Concrete Bridge Deck Test Section

4.3.1 Microtexture

Microtexture of the pavement surface (skid resistance) was measured by ODOT’s skid tester (ASTM E274). ODOT’s skid trailer used a ribbed tire to produce three skid measurements per test section each month. The skid numbers were then averaged to eliminate any irregularities due to slight variations in the test location to provide the average skid number for a given test section. Tests were all conducted on the outside wheel path. The failure point considered for this project for microtexture was a skid number less than 25.

One purpose of obtaining surface texture measurements on this project was to facilitate the creation of deterioration models to compare the performance of DOS-treated and untreated test sections. However, linear regression could not be appropriately applied to the field trial microtexture data due to insufficient data. Insufficiency was due to the lack of availability of the ODOT Skid Tester, which was rear-ended (non-project related) and was unavailable for the initial construction season. Because of this, construction was delayed for more than six months and yielded only 9 data sets (9 months), which is not enough to adequately support neither statistical significance nor deterioration models. The deterioration at this point in the service life of the study test sections is not well modeled by the logarithmic equation since the data has not started to “level off”, due to variables such traffic levels and weathering, etc. Applying the logarithmic equation on the current data results in a premature “leveling off” of the deterioration rate and subsequently yields unreasonably long service life estimates (i.e. 20+ years). Therefore, the researchers are unable to approximate the deterioration rate and extrapolate the remaining service life of each treatment. However, insight can be gained by evaluating the performance over time.

4.3.2 Macrotexture

For macrotexture measurement, the New Zealand sand circle was completed on a monthly basis using the NZTA TNZ T/3 standard (NZTA 2002). Three sand circles were taken on the outside wheel path, then averaged together to eliminate any irregularities caused due to slight variations in the test location. The same process was followed when placing three sand circles between wheel paths. Figure 36 shows the tests in test section 5.

Figure 36 New Zealand Sand Circle Test in Test Section 5

The test sections were first tested in April 2015 after one month of service. Eight data sets were obtained during the ten-month testing period. Measurements were not obtained for two of the months due to inclement weather and lack of ODOT traffic control availability. As noted in the previous section, development of deterioration curves was not possible due to the limited data obtained. NZTA uses 0.9 mm of macrotexture as the failure criterion for macrotexture.

4.3.3 Accelerated Polishing Testing

For accelerated polishing in the field, the NCAT three wheel polishing device (TWPD) was used to polish the treated and untreated concrete surfaces. The goal of the NCAT accelerated polishing testing was to gain a better understanding of the effects of the DOS technique on polishing tendency of Oklahoma pavement surfaces related to friction and texture and to see if the various test method results could be correlated. The setup for the Highway 77/Flood Avenue section is shown in Figure 37.

Figure 37 NCAT Accelerated Polishing Setup on Highway 77 Concrete Pavement

The three wheel polishing device (TWPD) was used to simulate traffic abrasion on the surfaces with the change in texture monitored over 140,000 polishing cycles. However, there has been no substantive work completed that correlates polishing cycles with traffic counts. Measurements using the dynamic friction tester (DFT) and circular track meter (CTM), according to sections 4.2.1 and 4.2.2 respectively, were taken initially and then after 20,000, 70,000 and 140,000 polishing cycles. To ensure the same polished area was evaluated, each sample was marked accordingly so that readings were taken in the same location.

Initially, NCAT planned to conduct the accelerated polishing testing on DOS treated and untreated sections of the concrete and asphalt pavements and the bridge deck (six sections total). However, a number of factors contributed to being able to obtain data only from two sections, the treated and untreated concrete pavement section shown in Figure 39. First, the testing took place in May 2015 according to NCAT's availability, when there was much inclement weather that hindered the effort. Second, ODOT Traffic Control and NCAT had limited availability due to the length of time required by the testing (20 hours per testing area). Lastly, it was determined later that the data obtained from the bridge deck section (Figure 38) was unusable due to equipment malfunction.

Figure 38 NCAT Accelerated Polishing Setup on Tecumseh Road Bridge Deck Test Section

4.4 Treatment Selection Model

To compare the DOS technique with current pavement preservation treatment options, a multi-attribute analysis was performed. A deterministic EUAC LCCA was conducted to obtain the cost values and then combined with LCA data obtained from literature to perform the multi-attribute analysis.

A total of four surface treatment options used to restore surface friction were selected for the analysis:

1. 1” HMA Mill and Inlay,
2. Shotblasting,
3. DOS, and
4. Microsurfacing.

[Microsurfacing is a pavement preservation treatment commonly used that is essentially an enhanced slurry seal that consists of asphalt emulsion, polymer modifiers, aggregate, mineral filler and water (NCHRP 2010).]

4.4.1 Life Cycle Cost Analysis

Cost input data and treatment service lives for the LCCA were obtained from literature (Riemer et al. 2012, NCHRP 2010, NCHRP 2009a, Burgé et al. 2002, Stroup-Gardiner and Shatnawi 2008, Bausano et al. 2004). The LCCA input values are shown in Table 11.

Table 11 Treatment Input Values Used in Deterministic LCCA

Pavement Treatment	Worst Case Service Life	Most Likely Service Life	Best Case Service Life	Deterministic Value ($/SY)
1" HMA Mill and Inlay	8	10	12	4.00
Shotblasting	3	4	5	1.77
DOS	-	7	-	3.00
Microsurfacing	5	7	9	2.00

A deterministic LCCA was completed for three scenarios: 1) worst case (minimum service life), 2) most likely case, and 3) best case (maximum service life). The two most sensitive LCCA parameters are service life and discount factor, and therefore these two factors were varied across the three scenarios, with the discount rate of 3%, 4% and 5% selected according to FHWA guidelines (FHWA 2002). The deterministic LCCA included both the initial construction cost and the crack seal maintenance cost for the duration of each treatment’s service life. The installation times for all of the alternatives are similar, therefore, the user delay costs were not considered in the analysis (FHWA 2002).

4.4.2 Life Cycle Analysis

Environmental impact data was obtained from literature, including consumption data and emissions data for the production, transportation and installment related to the treatments (Chehovits and Galehouse 2010, Gransberg and Pittenger 2012). The LCA data used in the multi-attribute analysis is shown in Table 12.

Table 12 LCA Input Data for Multi-Attribute Analysis

Pavement Treatment	**Consumption (BTU/SY)**	**Emissions (lb CO_2/SY)**
1" HMA Mill and Inlay	38700	7.00
Shotblasting	385	0.15
DOS	470	0.2
Microsurfacing	5130	0.6

To appropriately compare the treatments, which have different service life lengths, the consumption and emissions data needed to be annualized (Chehovits and Galehouse 2010). To annualize the data, the consumption and emissions values were divided by the service life for each treatment option.

4.4.3 Multi-Attribute Analysis

To combine the cost and environmental data, standard utility theory (West and Riggs 1986) was used to unitize the data using Equation 9:

$$U_{factor} = 1 - \frac{Value_{factor}}{Value_{max,factor}} \quad \text{(Eq. 9)}$$

Where U_{factor} is the unitized value, $Value_{factor}$ is the individual value for each of the cost, consumption, and emissions factors, and $Value_{max,factor}$ is the maximum value for each of the cost, consumption, and emissions factors.

Once unitized, each factor was then combined, with a percentage weighting associated with each factor (West and Riggs 1986), to obtain the multi-attribute score for each treatment option as shown in Equation 10:

$$Score = \%_{cost} \times U_{cost} + \%_{cons.} \times U_{cons.} + \%_{emis.} \times U_{emis.} \qquad \text{(Eq. 10)}$$

Where $\%_{cost}$ is the percentage weighting applied to the cost factor, $\%_{cons.}$ Is the percentage weighting applied to the consumption factor and $\%_{emis.}$ is the percentage weighting applied to the emissions factor, with the sum of the percentages for each factor equal to 100. The percentage weighting on each factor can be varied depending on the project specifics as to whether the decision is cost driven, environmentally driven, or a balance of the two.

4.5 Conclusions

To determine the efficacy of the DOS treatment, a wide range of testing procedures were conducted. Initial testing was completed on aggregate with the use of the Micro-Deval and AIMS methodology, LA Abrasion testing, and British Pendulum accelerated polishing testing. Coarse aggregate testing was performed to gain insight about lithium based densifier application to Oklahoma limestone aggregate and to provide effects on aggregate shape, texture, durability and hardness characteristics. Oklahoma limestone was then used to mold HMA mixes. The HMA mix samples were then treated with the various components included in the DOS technique and polished using NCAT's TWPD. Microtexture and macrotexture values were determined using the DFT and CTM respectively over time, which allowed calculation of IFI. Testing was performed on the HMA samples to gain a better understanding of the effects of the DOS treatment on Oklahoma limestone HMA mixes. Finally a multi-attribute analysis was conducted to compare the DOS technique as a pavement preservation option, alongside other surface treatments commonly used by DOTs to restore skid resistance. The analysis allowed treatment comparison based on cost, performance (service life) and environmental factors. Additionally, a methodology was presented for various weighting scenarios depending on project specifics.

5.0 Results

This chapter presents the results obtained using standard testing procedures and accepted methodologies for assessing DOS performance and cost. Results demonstrate the value of hardening aggregate through lithium silicate densifier application. Applying the densifier directly to the Oklahoma limestone aggregate can improve its abrasion and polishing resistance and durability. The nature of AIMS-Micro-Deval and British Pendulum testing methodologies are not conducive with shotblasting, but one could infer from previous studies and the results of this study that deeper densifier penetration would increase angularity, texture and friction values (Gransberg and Pittenger 2012). The results show that the treatment helps the aggregate retain its angularity and texture under polish-wear conditions, which enhances skid resistance and inhibits polishing.

5.1 Aggregate Testing

Current aggregate testing methods provide insightful results that "can be considered as basic guidance in establishing friction performance-related test criteria" (NCHRP 2009a). However, the results must be considered in context and in conjunction. "Just as no single test can distinguish good friction performance from bad, no single test value can be used as a standard for the same purpose. The factors that influence friction performance do so in an interactive manner and on a continuous scale, making it difficult to pinpoint specific discrimination values" (NCHRP 2009a). Additionally, "it is impossible to obtain a 1:1 correlation between friction measuring devices [because] different testers measure different aspects of pavement friction" (Lu and Steven 2006). Therefore, this section does not attempt to show correlation, but only highlights trends in data resulting from the various methods.

The objective of this study included determining if the application of chemical and/or shotblasting treatment would provide different results when compared to the control samples. This section provides the results from the laboratory testing at OU and NCAT, as well as the field results.

5.1.1 Micro-Deval

The Micro-Deval results obtained in the OU Broce Laboratory for Dolese Davis limestone showed the greatest contrast between treated and non-treated aggregate (shown in Figure 39, with the aggregate percentage loss represented on the y-axis). The results reveal that applying the lithium silicate densifier directly to the Oklahoma limestone aggregate (red square designation) decreases the amount of mass lost due to Micro-Deval abrasion than the sample not treated with the densifier (blue diamond designation).

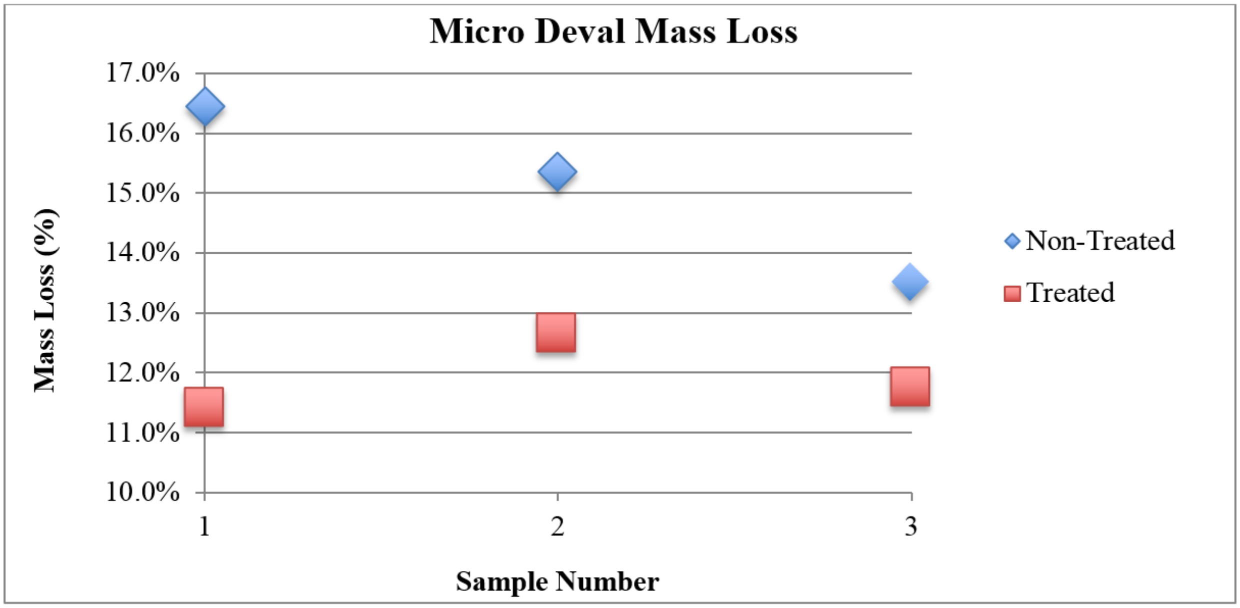

Figure 39 Micro-Deval Results for Lithium Silicate Densifier Treated Dolese Davis Limestone Aggregate

Good friction performance has been correlated with aggregates that exhibit Micro-Deval weight loss values of 12% or less (Fowler and Rached 2012). Therefore, the results indicate that the treated Oklahoma limestone aggregate would facilitate good pavement surface friction and better performance than the non-treated aggregate.

Due to the nature of the Micro-Deval testing and the nature of the shotblasting process, shotblasting the aggregate prior to applying the densifier to the aggregate was not a viable option. However, one could infer that if shotblasting had been applied to the aggregate to deepen penetration of the densifier, the Micro-Deval mass loss would be even less (Gransberg and Pittenger 2012). In this study, the IFI results from TWPD testing and field testing further support this statement (as presented in subsequent sections).

Table 13 shows the average Micro-Deval values for the aggregate sources. In general, treated limestone aggregate loss values were lower than the control. However, with the exception of the Dolese Davis aggregate, non-treated and treated values were similar for each source. The treatment is not expected to enhance granite or rhyolite properties, which is supported by these results. While ODOT does not specify Micro-Deval for preservation treatments, it does use a standard of less than or equal to 25% allowable percentage loss for other applications (such as Superpave). Both the treated and the non-treated aggregate would meet specification. These results further justify the need for shotblasting to allow greater densifier penetration.

Table 13 Micro-Deval Values (Average) for Non-Treated and Treated Aggregate

Source	**Type**	**Non-Treated** (average %)	**Treated** (average %)
Martin Marietta Mill Creek	Granite	4.9	5.2
Hanson Davis	Rhyolite	8.5	9.1
Dolese Davis	Limestone	15.1	11.9
Dolese Cooperton	Limestone	11.7	10.9
Dolese Hartshorne	Limestone	10.9	10.1
Kemp Stone Pryor	Limestone	21.2	20.1

5.1.2 LA Abrasion

The LA Abrasion results for the Dolese Davis limestone are shown in Figure 40, with the aggregate percentage loss represented on the y-axis. The results do not indicate that applying the lithium silicate densifier directly to the Oklahoma limestone aggregate (red square designation) affects the mass loss due to LA Abrasion compared to the sample not treated with the densifier (blue diamond designation), although the average value of the treated aggregate is marginally lower. It is important to note that LA Abrasion is an empirical test and therefore a poor predictor of field performance (Wu et al 1998).

Additionally, the Micro-Deval test has been found to better simulate the field conditions of aggregate abrasion compared to the dry conditions of the LA Abrasion test (Rogers 1998). Previous research has also shown there is no correlation in aggregate percentage loss between the Micro-Deval and the LA Abrasion tests (Kandhal and Parker 1998; Cooley and James 2003), which is also the case in this study. Essentially, Micro-Deval tends to polish the aggregate, whereas LA Abrasion tends to break it.

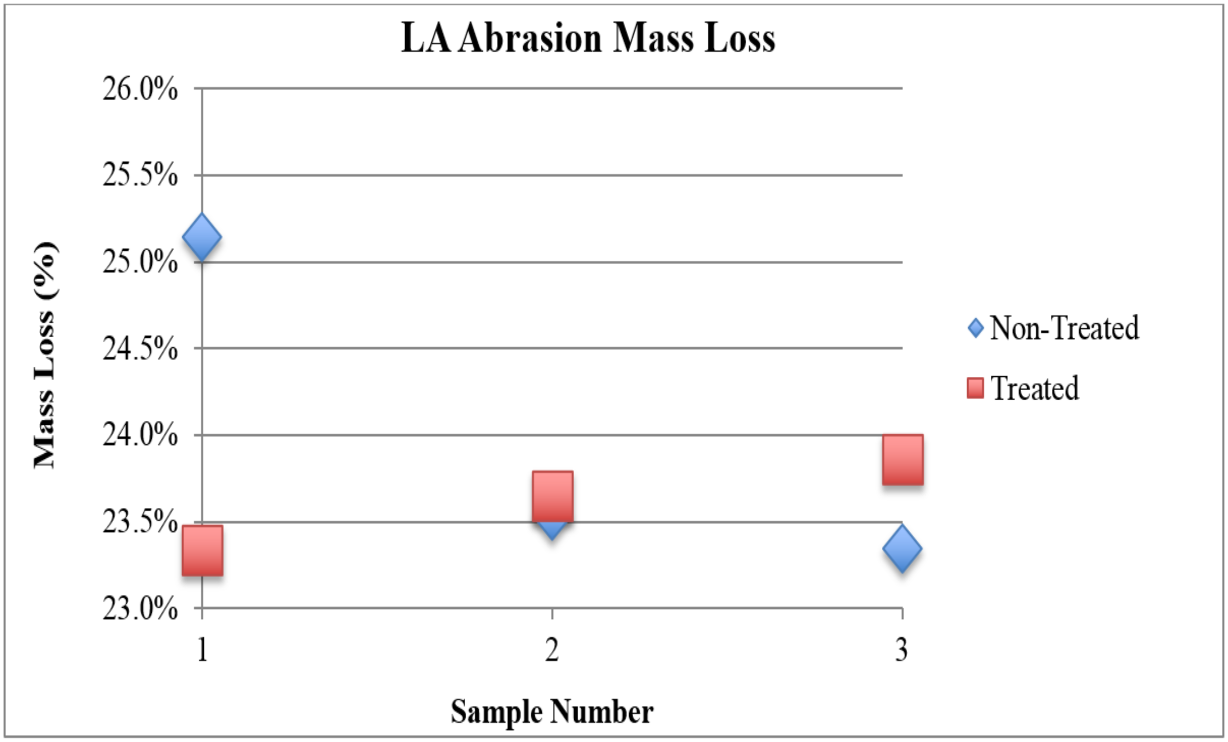

Figure 40 LA Abrasion Results for Lithium Silicate Densifier Treated and Non-Treated Dolese Davis Limestone Aggregate

Table 14 shows the average LA Abrasion values for the aggregate sources. Non-treated and treated values were similar for each source. LA abrasion test specification in these applications is either less than or equal to 30% or 40% depending on the aggregate's use. It is apparent that both samples would be accepted for use.

Table 14 LA Abrasion Values (Average) for Non-Treated and Treated Aggregate

Source	Type	**Non-Treated** (average %)	**Treated** (average %)
Martin Marietta Mill Creek	Granite	20.7	20.1
Hanson Davis	Rhyolite	12.0	12.5
Dolese Davis	Limestone	24.0	23.6
Dolese Cooperton	Limestone	21.3	22.9
Dolese Hartshorne	Limestone	16.1	16.2
Kemp Stone Pryor	Limestone	20.3	18.4

5.1.3 British Pendulum

Figure 41 shows the results of the NCAT British Pendulum testing. Non-treated aggregate samples (solid blue bars) had a greater rate of friction loss (percentage) than the treated aggregate samples (patterned red bars) after a 10-hour polishing period for four of the six aggregate sources.

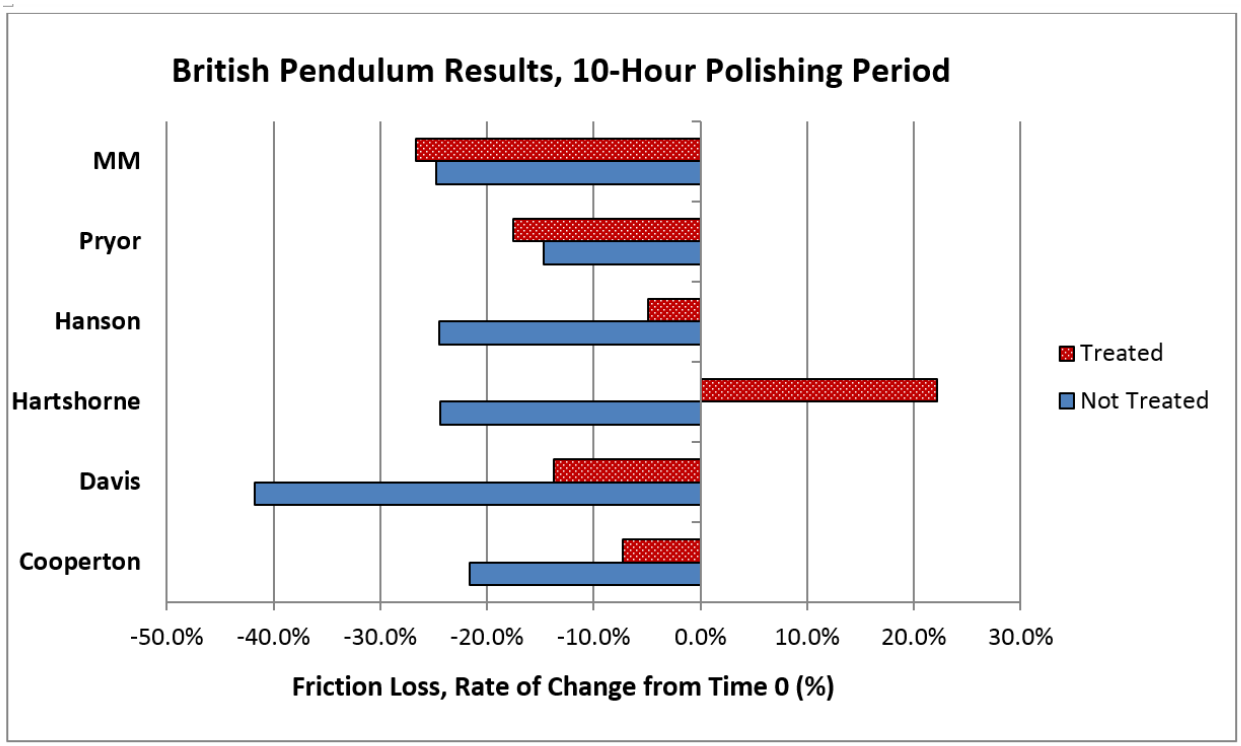

Figure 41 British Pendulum results for Six Aggregate Sources

Three of the four aggregate sources that exhibited differences between untreated and treated aggregate are limestone sources, so these results are in line with expectations and AIMS/Micro-Deval and NCAT *three wheel polishing* results. However, the Pryor material, also a limestone, does not follow this trend. The Hartshorne material friction actually increased over the 10-hour period (all 5 samples). It is thought that the initial polishing action served to wear the chemical treatment from the surface, enhancing the friction. The Martin Marietta material exhibited no real difference between treated and untreated samples, most likely due to the fact that it is granite.

Table 15 shows the initial (0 Hours) and final friction (10 Hours) values for the treated and untreated aggregate materials that support Figure 43. In general, a value of 25 or less is considered a failure criterion. It is apparent that the initial friction values for the treated samples are quite low, demonstrating the need for shotblasting to reduce the initial "slickness" by increasing the microtexture of a road surface. However, this test is not conducive to shotblasting specimens.

Table 15 British Pendulum Results for Treated and Non-Treated Aggregate

Quarry	Non-Treated @ 0 Hours	Treated @ 10 Hours	Non-Treated @ 0 Hours	Treated @ 10 Hours
Dolese-Cooperton	37.4	29.8	22.6	20.9
Dolese-Davis	41.8	24.3	31.5	27.2
Dolese-Hartshorne	44.7	33.8	26.1	31.9
Kemp Stone-Pryor	44.3	37.8	28.9	23.8
Martin Marietta Mill Creek	40.2	30.2	35.1	25.7
Hanson Davis	39.0	29.4	32.9	31.3

5.1.4 Aggregate Imaging System (AIMS)

AIMS results were obtained in the OU Binders Laboratory for the aggregate material and show that applying the lithium silicate densifier directly to the aggregate can enhance the aggregate's ability to retain angularity. Figure 42 and Figure 43 show the angularity results (gradient method) from the 5/8-inch (16 mm) and ½-inch (12.5 mm) Dolese Davis limestone particle testing, with the cumulative percentage of sample particles represented on the y-axis. In general, a more durable aggregate should exhibit lower mass loss, greater retention of angularity, and therefore, better friction performance (Fowler and Rached 2012). An angularity value of 4,000 or above indicates an angular particle, whereas a value below 2,100 indicates a rounded particle (FHWA 2006). Figure 42 and Figure 43 show the angularity values, represented on the x-axis, for the pre-Micro-Deval particles (baseline, green triangle line), the densifier-treated particles, post Micro-Deval (red square line), and the non-treated particles, post Micro-Deval (blue diamond line).

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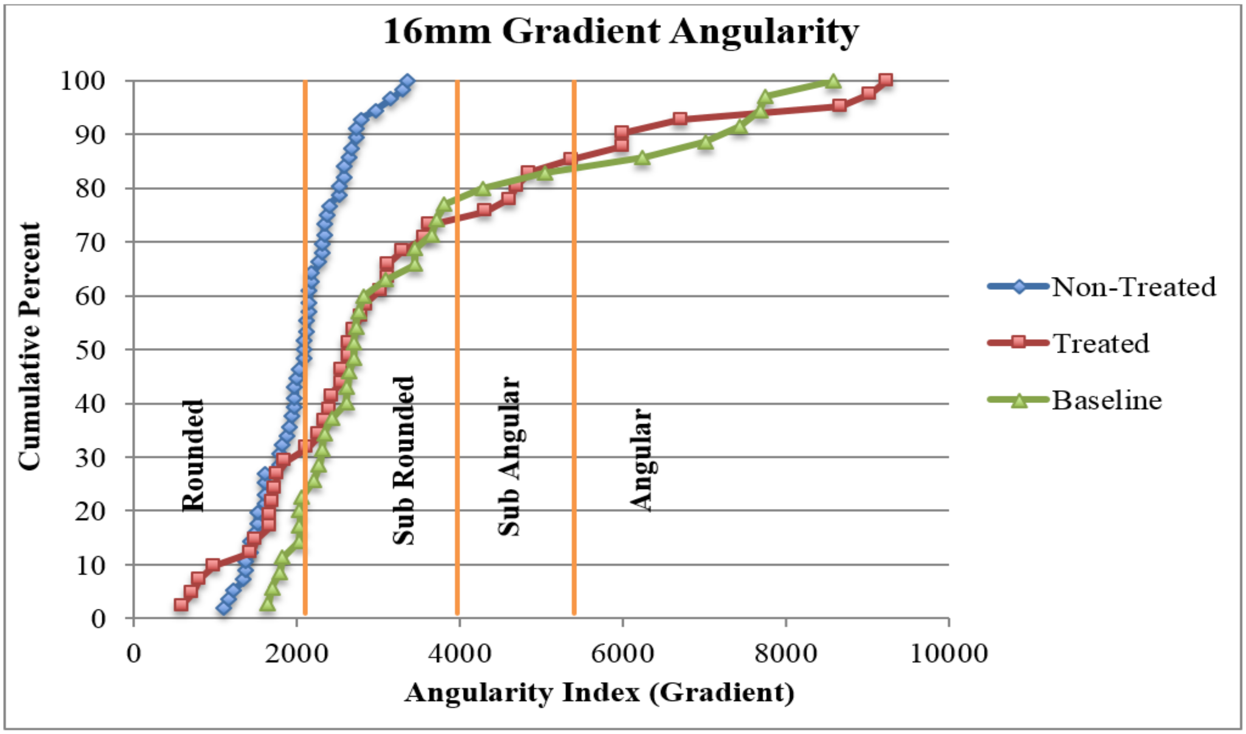

Figure 42 AIMS Results for 16 mm Angularity Index by Gradient Method for Chemically Treated and Non-Treated Samples

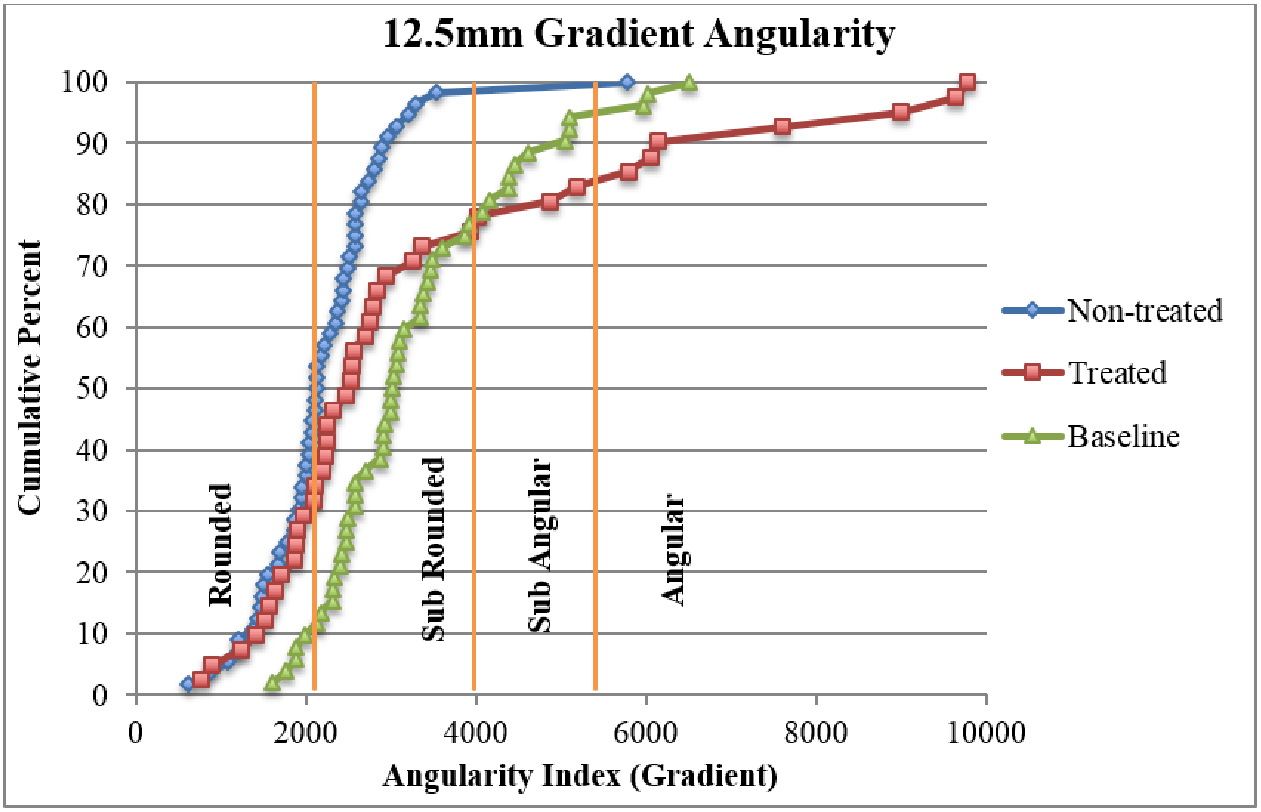

Figure 43 AIMS Results for 12.5 mm Angularity Index by Gradient Method for Chemically Treated and Non-Treated Samples

The results show that the angularity of the untreated limestone aggregate is greatly reduced after exposure to Micro-Deval, as one would expect. Only 20-25% of pre-Micro-Deval (baseline) particles were considered to be rounded/sub-rounded for both size fractions. However, the impact of abrasion is apparent in the untreated, post Micro-Deval particles, as most of the particles lost angularity with 100% of the particles classed as rounded/sub-rounded. 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 (Gransberg and Pittenger 2012).

Tables 16, 17 and 18 show the descriptive statistics, analysis of variance (ANOVA) and comparison of means output, respectively, based upon gradient angularity for the 16 mm particles. The tables show the comparisons between treatments. The ANOVA showed that there was a statistically significant difference for the 16 mm samples, with p = 0.009 between the treated aggregate (more angular) and the untreated aggregate (more rounded) using Tukey's Method at a 95% confidence level. Additionally, there was no difference between treated samples.

Table 16 Gradient Angularity Descriptive Statistics for 16 mm Aggregate

Sample	Mean	Standard Deviation
Baseline	3526.3	1979.4
Non-treated	2081.5	530.3
Treated	3314.3	2177.9

Table 17 Gradient Angularity ANOVA Summary for 16 mm Aggregate

	df	Sum Sq	Mean Sq	F-Value	Pr(>F)
Treatment	2	5.79×10^7	28959010	11	3.8×10^{-5}
Residuals	129	3.38×10^8	2623422		

Table 18 Tukeys Multiple Comparison of Means for 16 mm Aggregate

Treatment 1	Treatment 2	diff	lower	upper	P adj
Non-treated	Baseline	-1445	-2272.3	-617.3	0.0002
Treated	Baseline	-212	-1095.8	671.8	0.8370
Treated	Non-treated	1233	443.4	2022.2	0.0009

Tables 19, 20 and 21 show the descriptive statistics, ANOVA and comparison of means output, respectively, based upon gradient angularity for the 12.5 mm particle. The tables show the comparisons between treatments. The analysis of variance showed that there was a statistically significant difference for the 12.5 mm samples, with p = 0.008, between the treated aggregate (more angular) and the untreated aggregate (more rounded) using Tukey's Method at a 95% confidence level. Additionally, there was no difference between treated samples.

Table 19 Gradient Angularity Descriptive Statistics for 12.5 mm Aggregate

Sample	Mean	Standard Deviation
Baseline	3286.9	1130.5
Non-treated	2212.4	775.0
Treated	3334.5	2309.5

Table 20 Gradient Angularity ANOVA Summary for 12.5 mm Aggregate

	df	Sum Sq	Mean Sq	F-Value	Pr(>F)
Treatment	2	4.20×10^{7}	20998228	9.84	9.8×10^{-5}
Residuals	146	3.12×10^{8}	2134003		

Table 21 Tukeys Multiple Comparison of Means for 12.5 mm Aggregate

Treatment 1	Treatment 2	diff	lower	upper	P adj
Non-treated	Baseline	-1074	-1740.6	-408.3	0.0006
Treated	Baseline	48	-674.8	770.1	0.9866
Treated	Non-treated	1122	411.1	1833.1	0.0008

There is a correlation between abrasion resistance and polishing resistance, especially for aggregate that is highly susceptible to abrasion like limestone (Lancieri 2005). Essentially, when aggregate angularity is reduced, the aggregate becomes more susceptible to polishing. These results show that lithium silicate densifier application hardens the Oklahoma limestone and, therefore, should inhibit polishing.

AIMS results for the Dolese Hartshorne material show that applying the lithium silicate densifier directly to the aggregate enhances the aggregate’s ability to retain texture. Figure 46 shows the texture results from the limestone particle testing, with the cumulative percentage of sample particles represented on the y-axis. In general, a texture value of 350 or above indicates a particle with moderate roughness, whereas a value below 165 indicates a polished particle (FHWA 2006). Figure 44 shows the texture values, represented on the x-axis, for the pre-Micro-Deval particles (baseline, solid green line), the densifier-treated particles, post Micro-Deval (red-blocked line), and the non-treated particles, post Micro-Deval (blue hashed line).

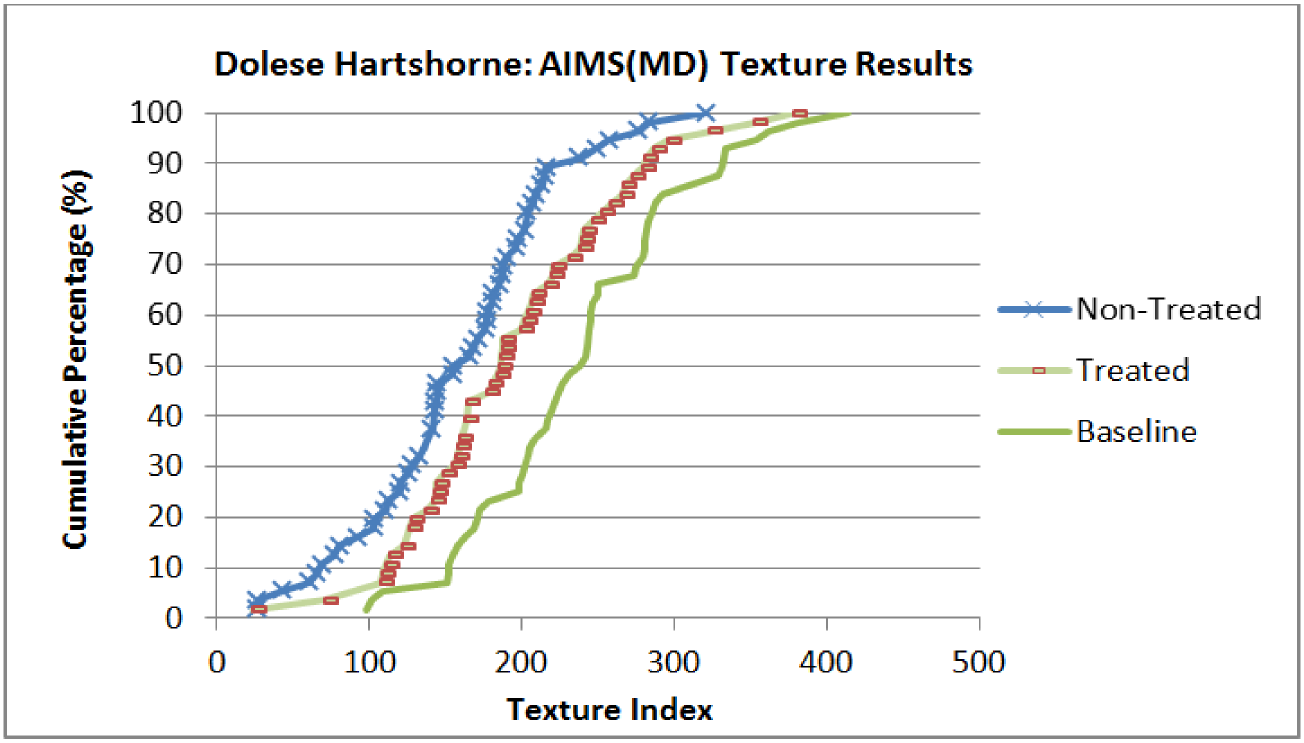

Figure 44 AIMS results for Dolese Hartshorne: texture for chemically-treated and non-treated samples

The results show that the texture of the untreated limestone aggregate is greatly reduced after exposure to Micro-Deval, as one would expect. Only about 7% of pre-Micro-Deval particles were considered to have a polished-like surface. However, the impact of abrasion is apparent in the untreated, post- Micro-Deval particles, as approximately 50% of the particles became polished. 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 polishing 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 (Gransberg and Pittenger 2012). The analysis of variance showed that there was a statistically significant difference between the treated aggregate (less polished) and the untreated aggregate (more polished) based upon a 95% confidence interval (Tukey’s Method).

The rest of the AIMS/MD testing results were analyzed using ANOVA. There was a slight trend that showed the treated aggregate yielded better results than untreated aggregate. However, there was no statistically significant difference in results, except as noted in this section. AIMS data are provided in Appendix B.

5.1.5 Soundness

The soundness results for the limestone samples are shown in Figure 45, with the aggregate percentage loss represented on the y-axis. The results indicate that applying the lithium silicate densifier directly to the Oklahoma limestone aggregate (red square designation) reduces the mass loss due to sulfate treatment compared to the sample not treated with the densifier (blue diamond designation).

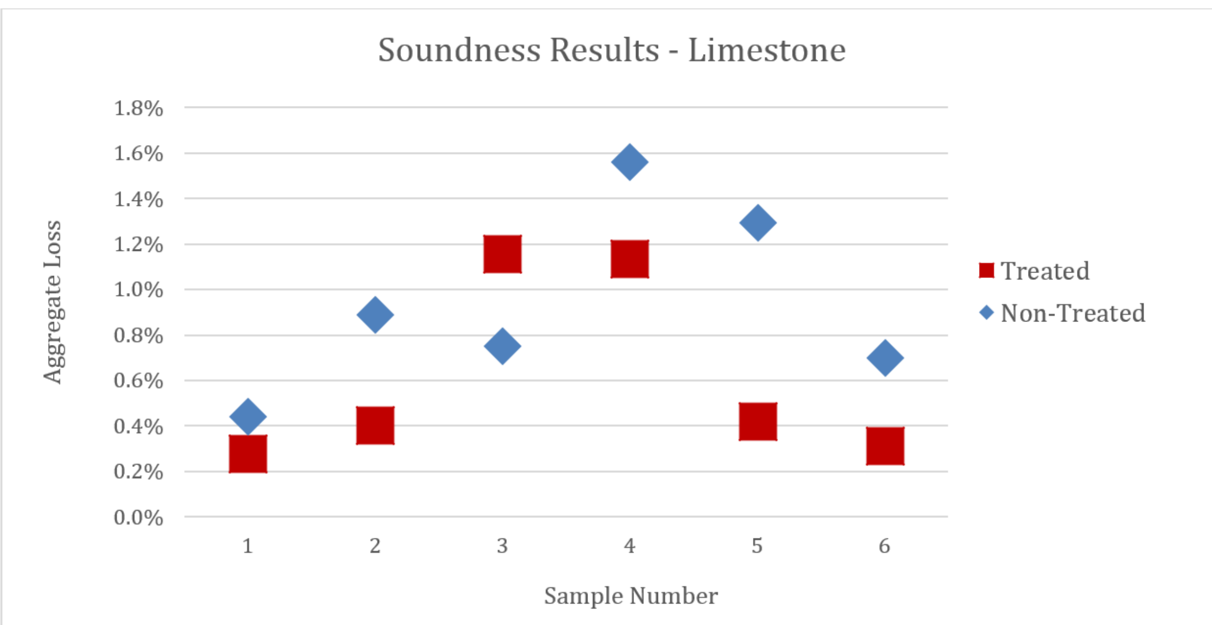

Figure 45 Limestone Aggregate Soundness Testing Results

5.2 Laboratory Asphalt Mix Testing

The NCAT laboratory testing results of the HMA samples containing the Dolese Davis limestone mix design presented in this section are consistent with the OU Laboratory results for Micro-Deval, LA Abrasion, AIMS and soundness, as well as NCAT's BP results, as presented in preceding sections. [Unfortunately, NCAT was unable to obtain the concrete mix design sample data.]

Specifically, the results show that chemical application/DOS treatment enhances the aggregate's properties that influence pavement surface texture: toughness, polish resistance, angularity and soundness. When these properties are improved or maintained, it is expected that surface texture performance should be enhanced. This is the case in this study, as described in this section, as the microtexture and macrotexture results related to surface texture of the HMA mix in terms of International Friction Index (IFI), DOS-treated samples did outperform the untreated or minimally treated samples. Results indicate that the shotblasting enhances the densifier penetration, while the densifier application enhances shotblasting performance.

5.2.1 Dynamic Friction Testing

The microtexture measurements obtained with the DFT are shown in Figure 46, with the coefficient of friction (DFT_{20}) values shown on the y-axis and the number of polishing cycles on the x-axis. The testing was conducted on the HMA slabs with the four different surface treatments:

1) control with no treatment applied (blue diamond designation),
2) lithium silicate densifier only (red square designation),
3) shotblasted surface only (green triangle designation), and
4) lithium silicate densifier applied over a shotblasted surface, or DOS (purple cross designation).

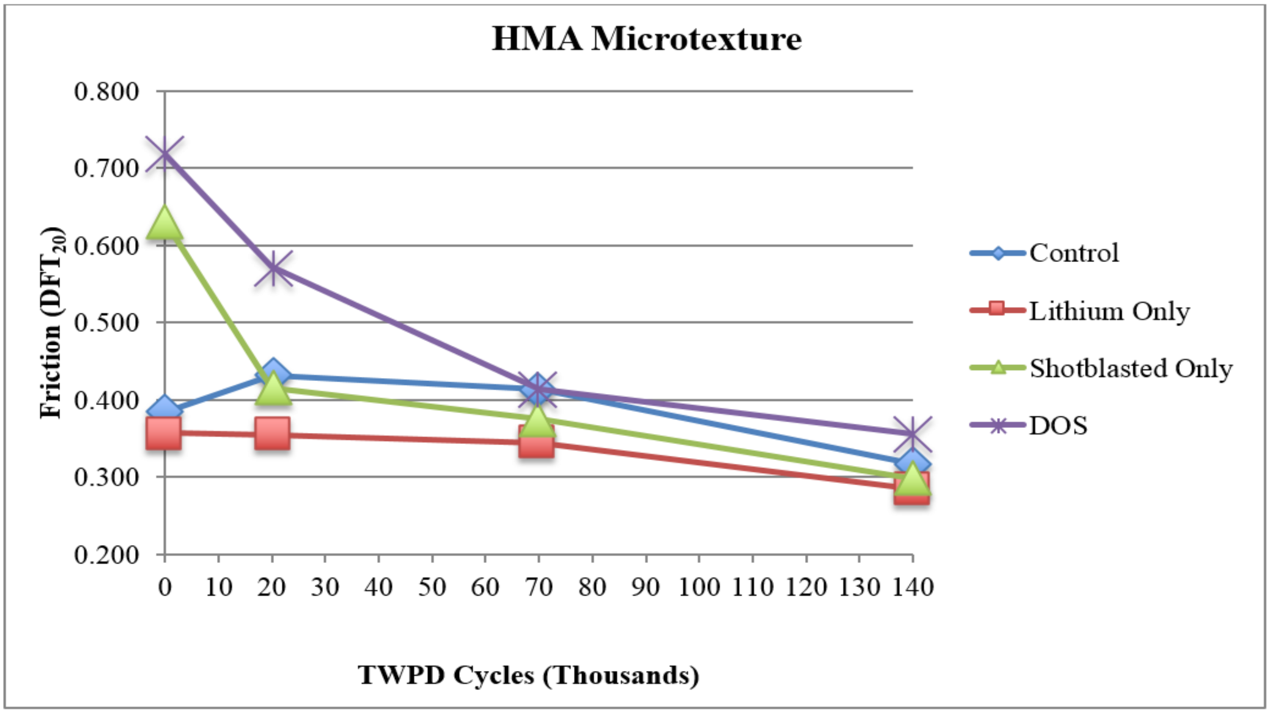

Figure 46 HMA Microtexture Measurements using DFT and TWPD

The results in Figure 46 show that friction values for all treatment samples decreased over the period of polishing cycles. The DFT_{20} for the samples involving shotblasting (both DOS and shotblasting only samples) were initially higher than the other treatments although values decreased rapidly over the 20,000 - 70,000 cycle period for the shotblasted only and the DOS treated samples respectively. Per the TWPD test creator, no correlation has been established between polishing cycles in the laboratory and traffic levels, although a high level of correlation was established between field and laboratory tests (Heitzman 2011). Table 22 shows the descriptive statistics [mean (μ) and standard deviation (σ)]. Data are provided in the Appendix B.

Table 22 Friction (DFT20) Descriptive Statistics

Samples	0 Cycles (μ, σ)	20,000 Cycles (μ, σ)	70,000 Cycles (μ, σ)	140,000 Cycles (μ, σ)
Control	0.385, 0.029	0.432, 0.034	0.414, 0.027	0.317, 0.002
Densifier Only	0.357, 0.017	0.355, 0.030	0.344, 0.009	0.285, 0.006
Shotblasted Only	0.739, 0.190	0.416, 0.029	0.375, 0.032	0.298, 0.003
DOS	0.772, 0.095	0.572, 0.044	0.414, 0.019	0.356, 0.027

The DOS treated samples maintained the greatest level of DFT_{20} throughout the polishing cycles, illustrating the efficacy of DOS. However, microtexture (DFT) can provide only partial insight into surface friction; macrotexture (CTM) must also be considered to understand a treatment's contribution to a pavement's surface friction (Lu and Steven 2006).

5.2.2 Circular Track Meter

The macrotexture measurements obtained using the circular track meter (CTM) to measure mean profile depth (MPD) are shown in Figure 47 with the MPD values shown on the y-axis and the number of polishing cycles on the x-axis.

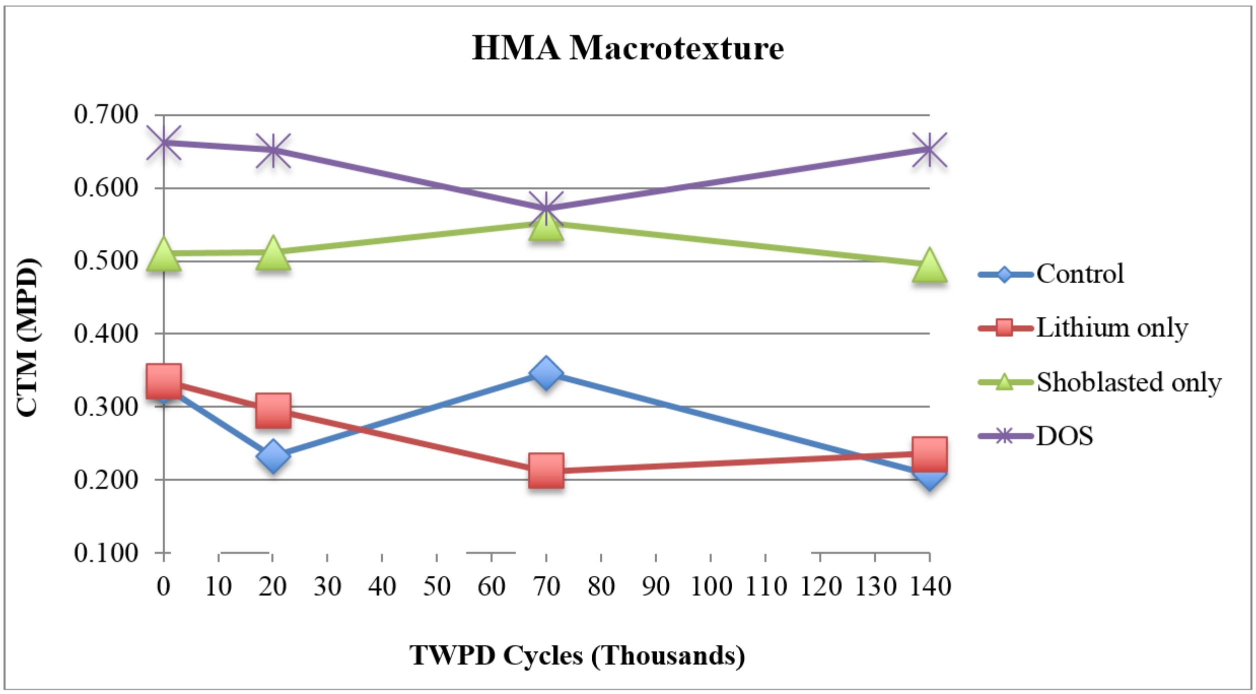

Figure 47 HMA Macrotexture Measurements using CTM and TWPD

The results show that samples with DOS and shotblasting initially exhibited and maintained a greater level of MPD throughout the polishing cycles than the other treatment samples (control and lithium only). Table 23 provides the descriptive statistics [mean (μ) and standard deviation (σ)]. Data are provided in the Appendix B. The results indicate the efficacy of DOS.

Table 23 CTM (MPD) Descriptive Statistics

Samples	0 Cycles (μ, σ)	20,000 Cycles (μ, σ)	70,000 Cycles (μ, σ)	140,000 Cycles (μ, σ)
Control	0.31, 0.025	0.28, 0.008	0.30, 0.051	0.28, 0.004
Densifier Only	0.33, 0.015	0.27, 0.022	0.28, 0.009	0.28, 0.013
Shotblasted Only	0.77, 0.004	0.90, 0.021	0.88, 0.009	0.83, 0.004
DOS	0.90, 0.011	0.94, 0.013	0.91, 0.008	0.98, 0.011

5.2.3 International Friction Index

To quantify potential skid resistance, the macrotexture and microtexture measurements described in the preceding sections were combined to calculate the International Friction Index (IFI). Results of the calculated IFI for each of the treatment samples are shown in Figure 48, with the IFI on the y-axis and the number of polishing cycles on the x-axis.

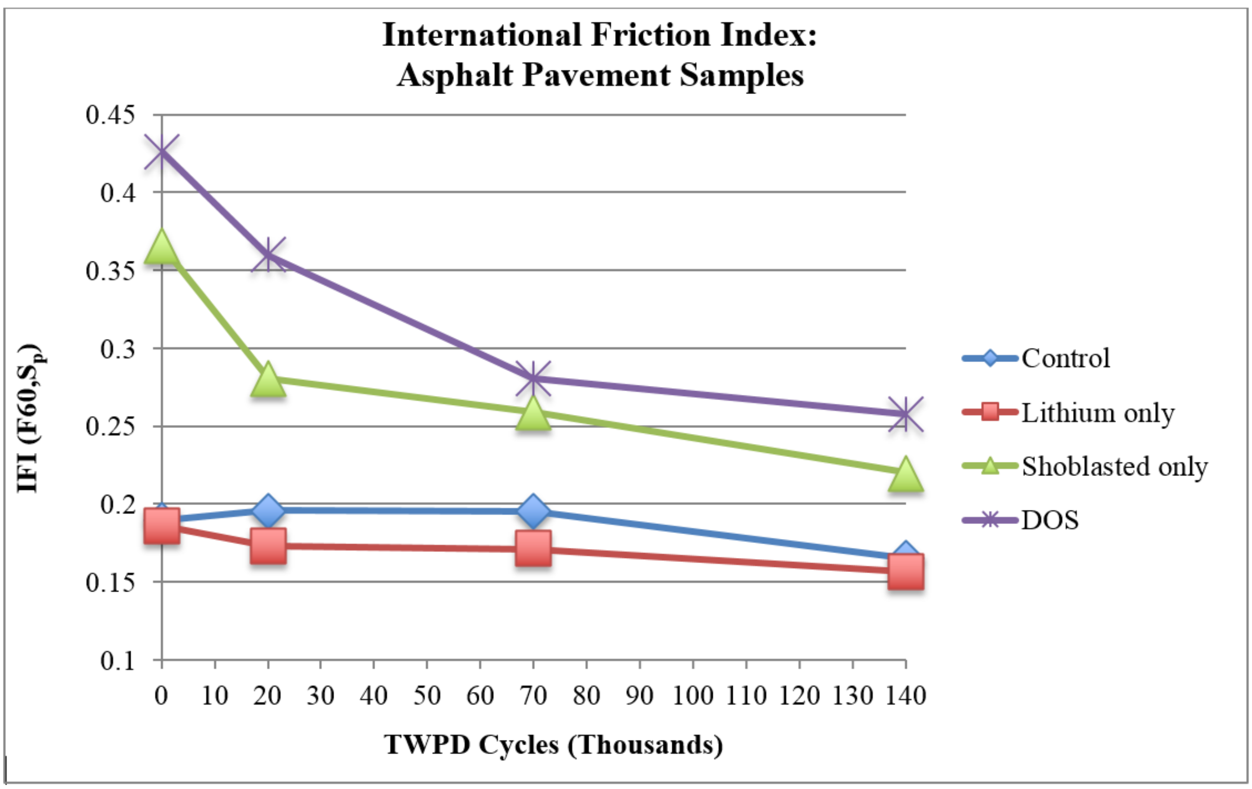

Figure 48 HMA Skid Resistance Quantified by IFI

The results in Figure 48 show that the shotblasted samples have greater IFIs initially, then decrease, with the DOS treated samples decreasing more gradually than the shotblasting only samples. In contrast, the samples not subjected to the shotblasting process had a lower initial IFI and a minimal decrease over the polishing period. The results shown in Figures 46 and 47 validate the statements made in preceding sections that better performance would have been expected had shotblasting aggregate prior to Micro-Deval and British Pendulum testing been a practical option. Figure 48 also shows that the DOS treated samples retained the greatest IFI throughout the polishing process, hence confirming the potential benefit of applying the lithium silicate densifier to shotblasted asphalt pavement surfaces. Ultimately the NCAT results, supported by the OU results, show that treating asphalt pavement surfaces containing Oklahoma limestone with the DOS technique provides superior skid resistance performance.

5.3 Field Testing

The general trend in the field testing results is that the DOS-treated sections outperformed untreated sections on the basis of microtexture and macrotexture. This is consistent with the trend in the laboratory data, although the aggregate source in the field test sections is unknown. Based upon failure criteria, all sections performed satisfactorily during the testing period. As expected, the sections with less traffic (AADT 9,000) exhibited higher microtexture and macrotexture values over the testing period than sections with greater traffic (AADT 24,000). Deterioration models could not be created since no discernable trend of deterioration was exhibited over the short testing period. However, some insight is provided by examining the results, as presented in this section.

5.3.1 Microtexture

Microtexture results show a general trend of DOS-treated asphalt and concrete pavement sections yielding higher skid number values over the testing period of nine months. [Bridge decks were omitted due to the deck length being too short for testing by the ODOT skid truck.] The asphalt section, which had a deeper shotblasting application, exhibited a greater difference between treated and untreated areas than did the concrete sections. The concrete sections received less shotblasting in an effort to retain the existing tining or grooving.

It is important to note that data variability results from this testing method, as it is practically impossible to test in the exact same locations every month due to the nature of the skid tester. Therefore, apparent anomalies exist in the following figures that may be attributed to this field testing variability. However, insight can be gained from evaluating the field results in the context of all of this study's results.

Figure 49 shows the microtexture (skid) results for the asphalt test sections. Time 0 is the baseline (pre-construction) measure. Results are consistent with the NCAT laboratory results provided in the preceding section: the treated asphalt section (dashed, red triangle line) is outperforming the untreated section (solid, blue circle line). However, both sections yielded higher skid number values than the failure criterion of 25. Neither section shows any discernable deterioration trend over the testing period (AADT ~9000).

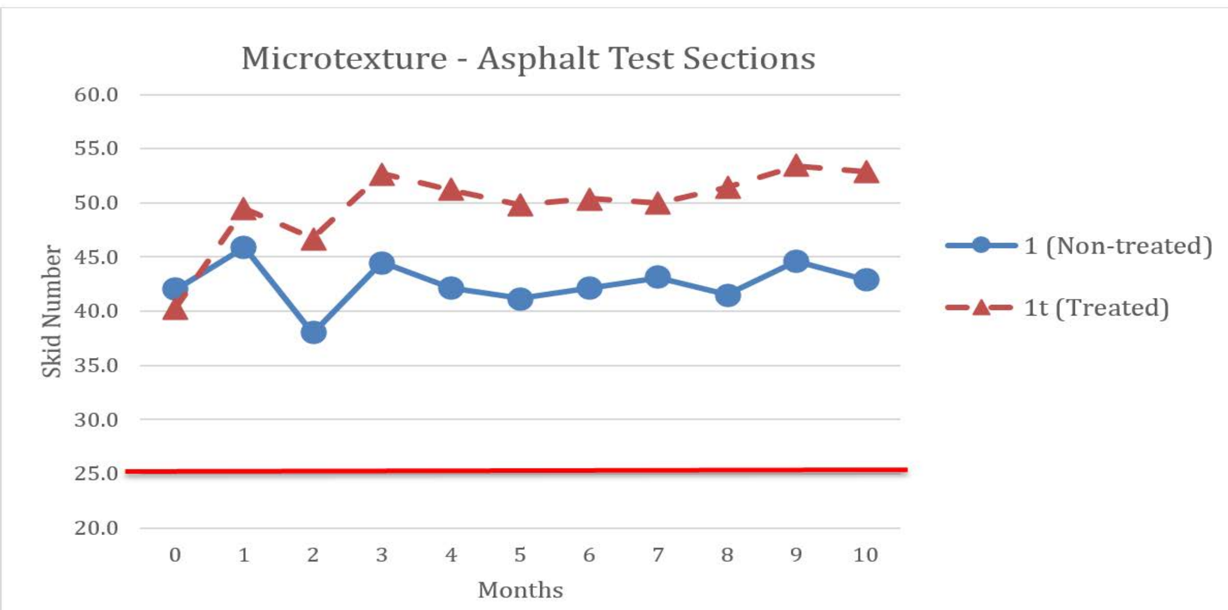

Figure 49 Microtexture Results (ODOT Skid Tester) for Field Test Section 1: Asphalt

Figure 50 shows the microtexture (skid) results for the 6-year-old DOS-concrete pavement test sections constructed in the previous study. Time 0 is the baseline (pre-construction) measure. Although the first few months of the testing period yielded similar results for the treated section (dashed, red triangle line) and the untreated section (solid, blue circle line), the latter months show a growing difference where the treated section has greater skid numbers. However, both sections yielded higher skid number values than the failure criterion of 25 period (AADT ~24,000).

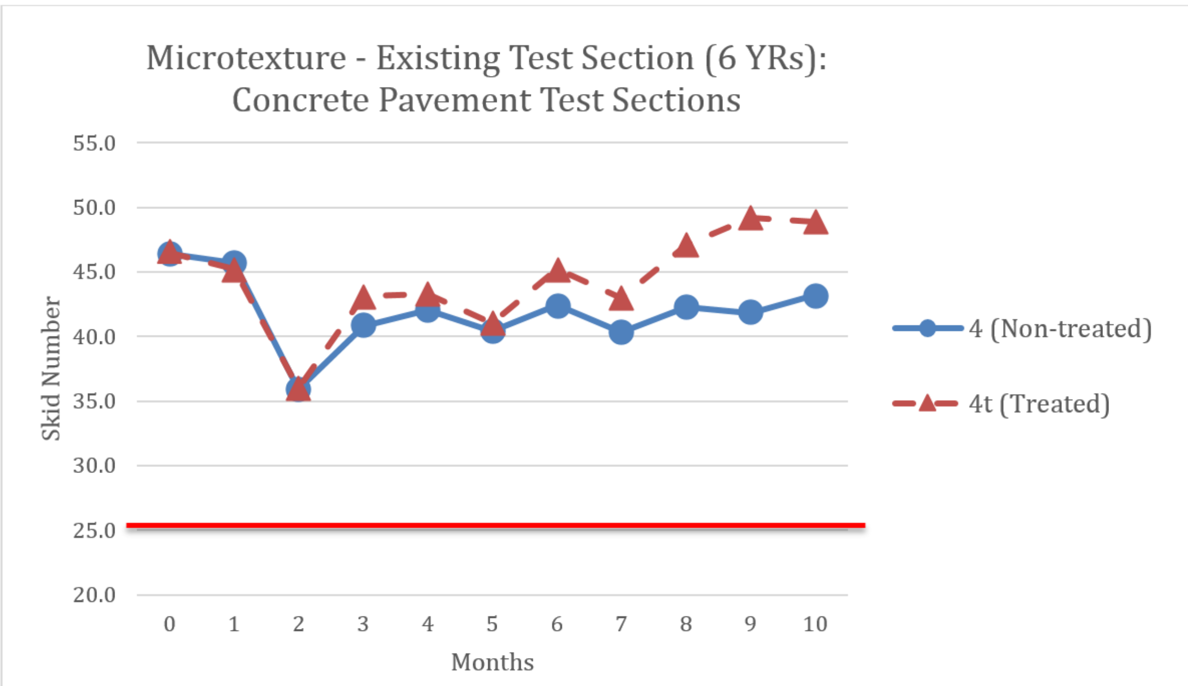

Figure 50 Microtexture Results (ODOT Skid Tester) for Field Test Section 4: Existing Concrete DOS Section

Neither section shows any discernable deterioration trend over the testing period. Therefore, the results indicate that the DOS treatment service life estimate of 7 years is reasonable, if not conservative.

Figure 51 shows the microtexture (skid) results for the DOS-concrete pavement test sections constructed for this study. Time 0 is the baseline (pre-construction) measure. Results were similar for the treated section (dashed, red triangle line) and the untreated section (solid, blue circle line), although the treated section tended to have greater skid numbers. However, both sections yielded higher skid number values than the failure criterion of 25 (AADT ~24,000).

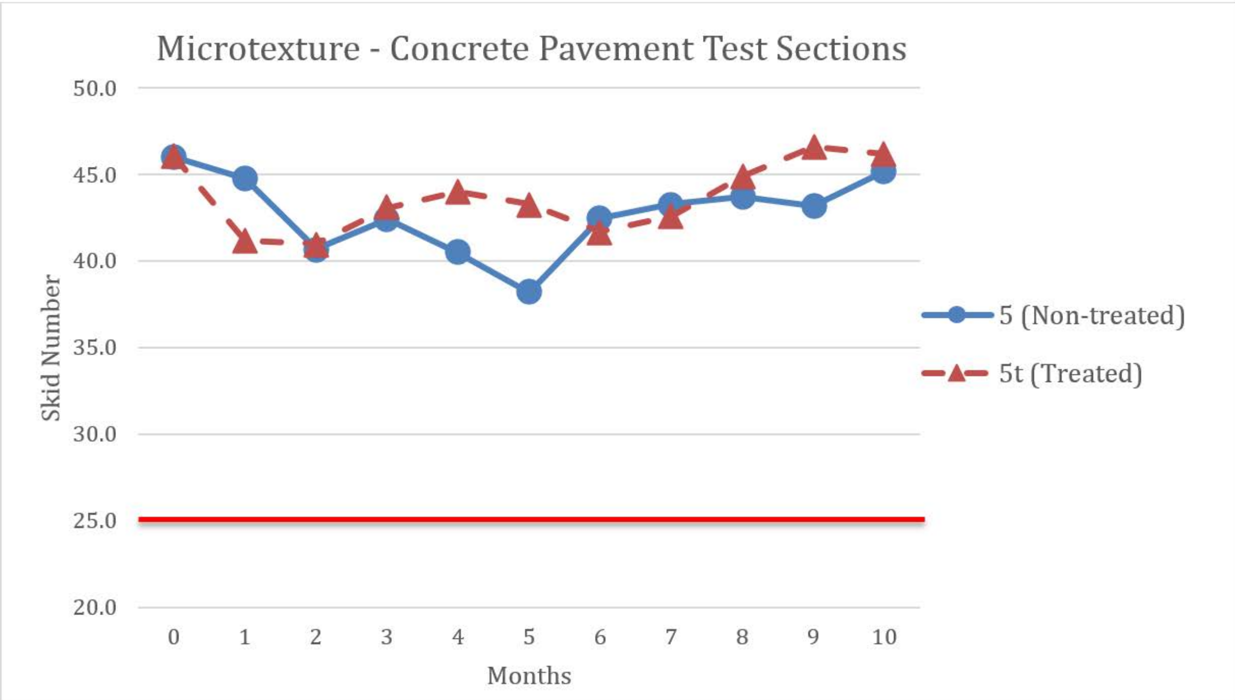

Figure 51 Microtexture Results (ODOT Skid Tester) for Field Test Section 5: New Concrete Pavement DOS Section

5.3.2 Macrotexture

Macrotexture results also show a general trend of DOS-treated asphalt and concrete pavement sections yielding higher mean texture depth (MTD) values over the testing period of eight months. The asphalt section, which had a deeper shotblasting application, exhibited a greater difference between treated and untreated areas than did the concrete sections. The concrete and bridge deck sections received less shotblasting in an effort to retain the existing tining or grooving.

Figure 52 shows the macrotexture (MTD) results for the asphalt test sections. Time 0 is the baseline (pre-construction) measure. Results are consistent with the NCAT laboratory results and the skid number results provided in the preceding section: the treated asphalt section (dashed, red triangle line) is outperforming the untreated section (solid, blue circle line). However, both sections yielded higher MTD values than the failure criterion of 0.9 mm (AADT ~9,000).

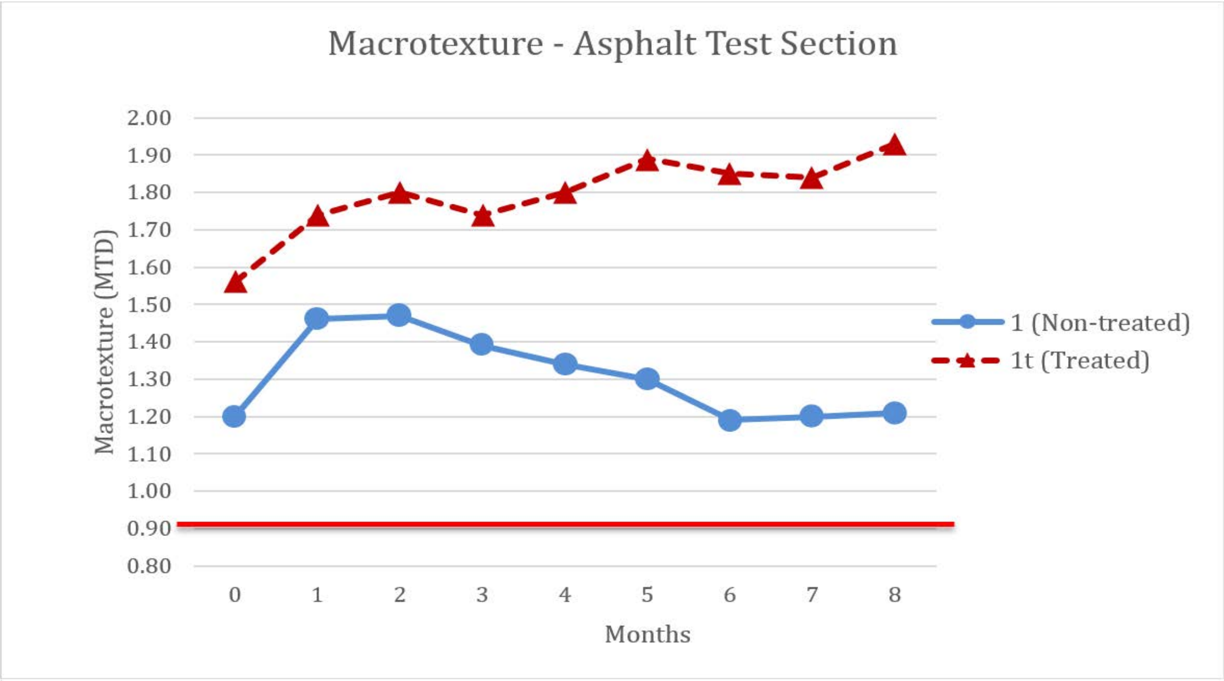

Figure 52 Macrotexture Results (NZ Sand Circle) for Field Test Section 1: Asphalt

The untreated section does show some deterioration over the testing period. The treated section shows no discernable deterioration trend.

Figure 53 shows the MTD results for the concrete bridge deck from test section 2 (TS2). Time 0 is the baseline (pre-construction) measure. Results show that the DOS-treated section (dashed, red triangle line) is outperforming the untreated section (solid, blue circle line). However, both sections yielded higher MTD values than the failure criterion of 0.9 mm (AADT ~9,000). Both sections show slight but irregular deterioration over the testing period, which may be attributed to field testing variability.

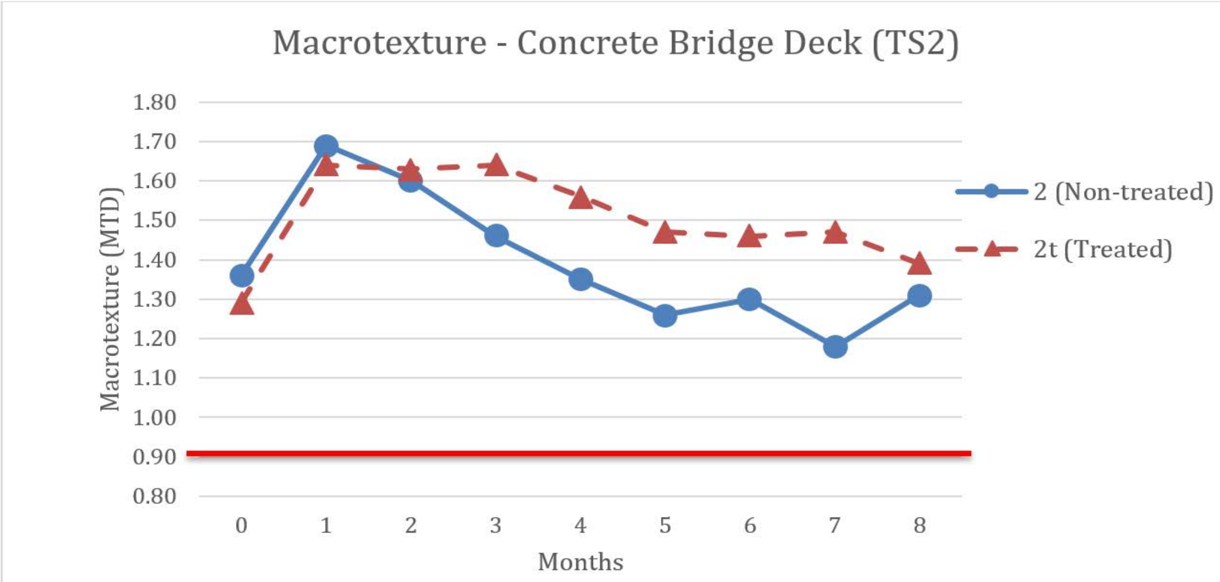

Figure 53 Macrotexture Results (NZ Sand Circle) for Field Test Section 2: Concrete Bridge Deck

Figure 54 shows the MTD results for the concrete bridge deck from test section 3 (TS3). Results show no discernable difference between the DOS-treated section (dashed, red triangle line) and the untreated section (solid, blue circle line). Both sections yielded higher MTD values than the failure criterion of 0.9 mm (AADT ~9,000). Both sections show slight but irregular deterioration over the testing period.

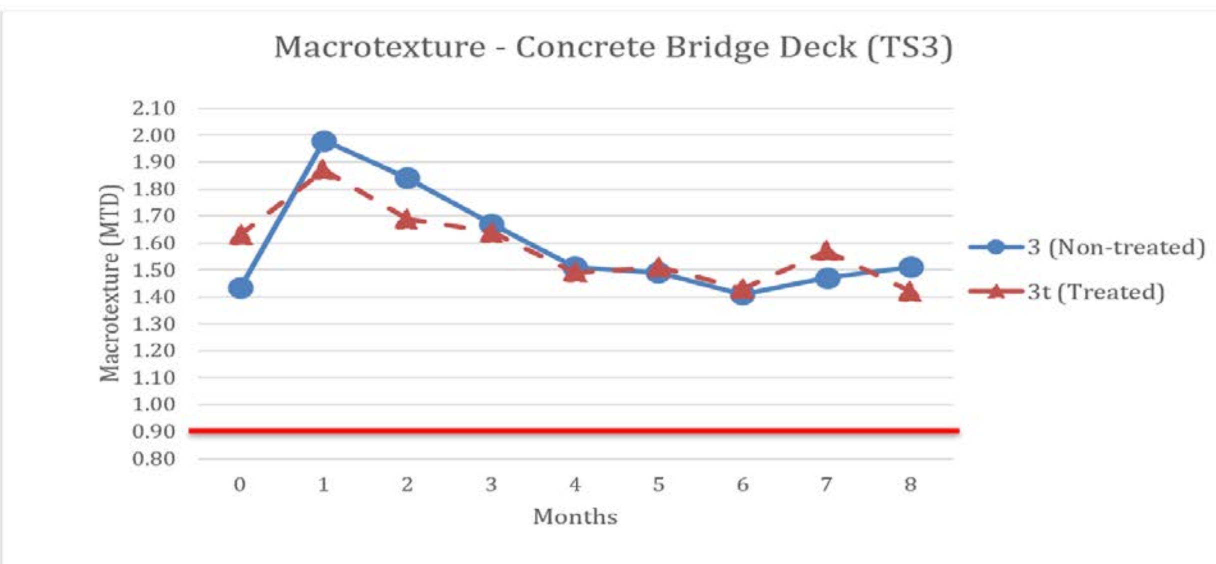

Figure 54 Macrotexture Results (NZ Sand Circle) for Field Test Section 3: Concrete Bridge Deck

Figure 55 shows the MTD results for the existing concrete pavement test sections. Results show that the DOS-treated section (dashed, red triangle line) slightly outperformed the untreated section (solid, blue circle line). Both sections yielded higher MTD values than the failure criterion of 0.9 mm (AADT ~24,000). Therefore, the results indicate that the DOS treatment service life estimate of 7 years is reasonable, if not conservative. Both sections show slight but irregular deterioration over the testing period.

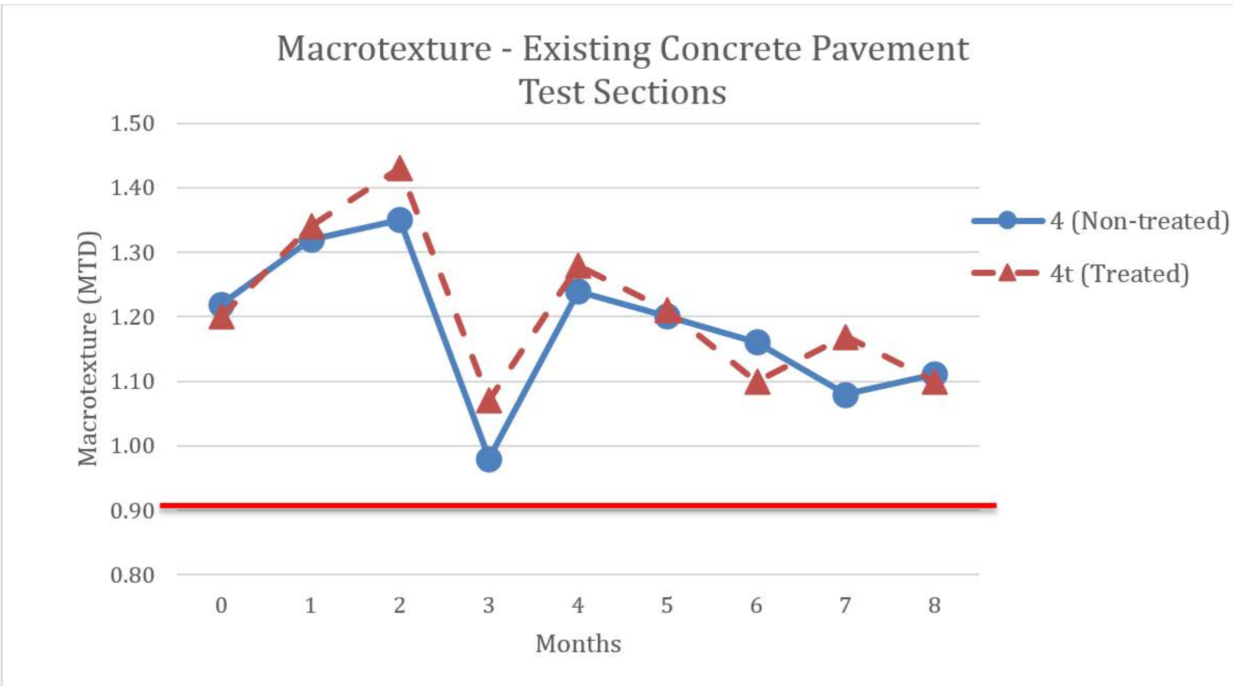

Figure 55 Macrotexture Results (NZ Sand Circle) for Field Test Section 4: Existing Concrete Pavement

Figure 56 shows the MTD results for the new concrete pavement test sections. Results show that performance data trended together for the DOS-treated section (dashed, red triangle line) and the untreated section (solid, blue circle line). Both sections seem to reach the failure criterion of 0.9 mm at month 9. Both sections show irregular deterioration over the testing period. The rapid deterioration is attributed to the greater amount of traffic experienced at this location versus other test sections: right lane with traffic levels of AADT ~24,000.

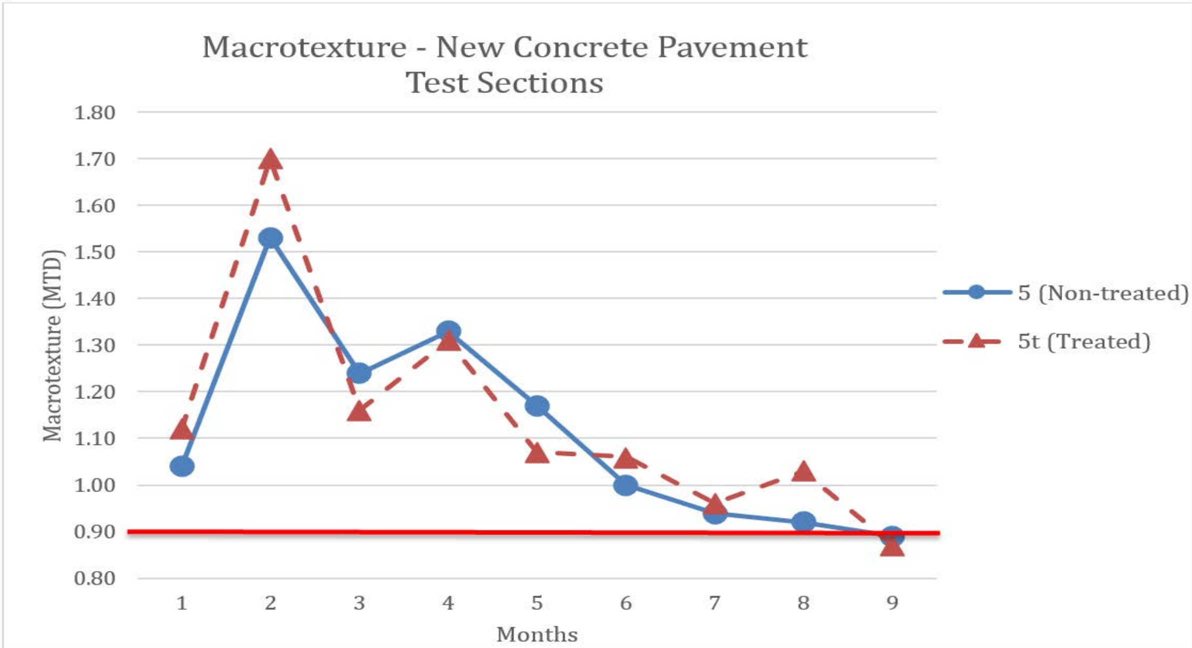

Figure 56 Macrotexture Results (NZ Sand Circle) for Field Test Section 5: Concrete Pavement

5.3.3 Accelerated Polishing

Figure 57 shows the International Friction Index results for the new concrete pavement test section. Results show that the DOS-treated section (dashed, red triangle line) outperformed the untreated section (solid, blue circle line).

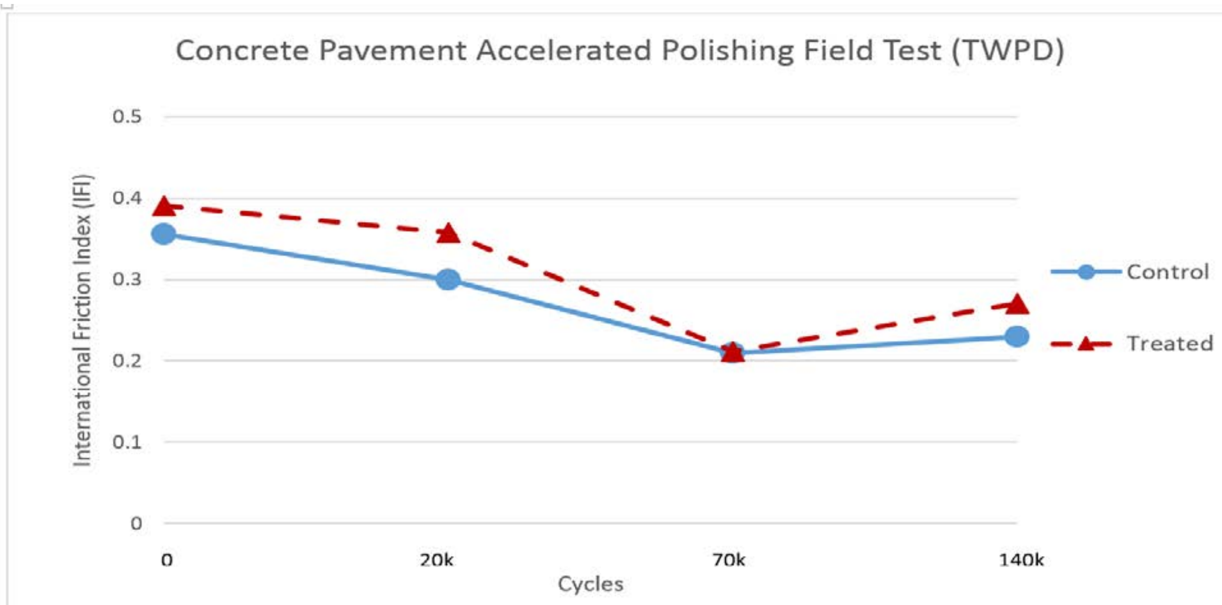

Figure 57 Accelerated Polishing (NCAT TWPD) of Test Section 5: Concrete Pavement

The consistent trend in results is that there was greater difference in performance between DOS-treated and untreated asphalt laboratory samples and field section than in the concrete field sections. However, in both cases, DOS-treated surfaces generally outperformed untreated surfaces.

5.4 Treatment Selection Model

5.4.1 Life Cycle Cost Analysis

To gain insight regarding the economic viability of DOS, a deterministic life cycle cost analysis (LCCA) was performed with four surface treatments:

1. 1” asphalt (HMA) Mill and Inlay,
2. Shotblasting,
3. DOS, and
4. Microsurfacing.

The results from the LCCA are shown in Table 24. The values, which were unitized for use in the multi-attribute analysis, are provided in Table 25.

Table 24 Deterministic LCCA and Sensitivity Analysis Results

Pavement Treatment	3% EUAC (Service Life)	4% EUAC (Service Life)	5% EUAC (Service Life)
1" HMA mill & inlay	$3,858 (12 yr)	$4,666 (10 yr)	$5,370 (8 yr)
Shotblasting	$3, 533 (5 yr)	$4,429 (4 yr)	$4,576 (3 yr)
DOS	-	$4,656 (7 yr)	-
Microsurfacing	$2,724 (9 yr)	$3,883 (7 yr)	$4,063 (5 yr)

Although DOS has a higher initial cost (Table 11), the results of the LCCA indicate that it has a comparable life cycle cost related to the other surface treatments. The sensitivity analysis reveals that there is no sensitivity with regard to service life and discount rate in this case, as the rank order remains the same for the treatments. However, in practice, these factors, along with commodity volatility, could greatly impact the output. HMA and microsurfacing prices are driven by the volatile crude oil market, and therefore, DOS and shotblasting may yield lower initial and life cycle costs when binder prices rise (Pittenger et al. 2011). Due to inherent uncertainty, LCCA cannot provide “the answer”, it can only provide insight and decision makers should consider LCCA on a project-by-project basis (FHWA 2002).

5.4.2 Life Cycle Analysis

To gain insight regarding the environmental performance of DOS, a life cycle analysis (LCA) was conducted using treatment data. The results from annualizing and unitizing the consumptions and emissions data are shown in Table 25.

Table 25 Unitized LCA and LCCA Data

Pavement Treatment	Cost	Unitized	Cons. (BTU/SY)	Unitized	Emis. (lb CO_2/SY)	Unitized
1" HMA Mill & Inlay	$4,666	1.000	3870	1.000	0.700	1.000
Shotblasting	$4,429	0.949	77	0.020	0.030	0.043
DOS	$4,656	0.998	67	0.017	0.029	0.041
Microsurfacing	$3,883	0.832	855	0.221	0.100	0.143

The results show that the DOS technique exhibits better environmental performance than the other treatments on a life cycle basis. DOS consumes the smallest amount of annualized energy and emits the least amount of annualized greenhouse gases of the pavement treatments analyzed.

5.4.3 Multi-attribute Analysis

To combine both the cost and environmental impacts of the four selected treatments, a multi-attribute analysis was conducted. Three separate scenarios were analyzed. The first analysis considers a cost driven scenario (Table 26) where 80% of the decision is based on cost, and 20% based on environment (with 10% to each of consumption and emissions). The second analysis represents a balanced scenario (Table 27), with 50% of the decision based on cost, and 50% based on environment (with 25% to each of consumption and emissions). The final analysis considers an environmentally driven scenario (Table 28) where 20% of the decision is based on cost, and 80% based on the environment (with 40% to each of consumption and emissions).

Table 26 Cost Driven Multi-Attribute Analysis Scores

Pavement Treatment	Cost (80%)	Cons. (10%)	Emis. (10%)	Total	Rank
1" HMA Mill & Inlay	0.800	0.100	0.100	1.000	4
Shotblasting	0.759	0.002	0.004	0.766	2
DOS	0.798	0.002	0.004	0.804	3
Microsurfacing	0.666	0.022	0.014	0.702	1

Table 27 Balanced Multi-Attribute Analysis Scores

Pavement Treatment	Cost (50%)	Cons. (25%)	Emis. (25%)	Total	Rank
1" HMA Mill & Inlay	0.500	0.250	0.250	1.000	4
Shotblasting	0.475	0.005	0.011	0.490	1
DOS	0.499	0.004	0.010	0.513	3
Microsurfacing	0.416	0.055	0.036	0.507	2

Table 28 Environmentally Driven Multi-Attribute Analysis Results

Pavement Treatment	Cost (20%)	Cons. (40%)	Emis. (40%)	Total	Rank
1" HMA Mill & Inlay	0.200	0.400	0.400	1.000	4
Shotblasting	0.190	0.008	0.017	0.215	1
DOS	0.200	0.007	0.016	0.223	2
Microsurfacing	0.166	0.088	0.057	0.312	3

Based upon the DOS rankings in the tables, the results demonstrate that DOS is an economically and environmentally competitive treatment. The goal of pavement preservation treatment analysis is not to determine the “best” treatment, but to determine the “right treatment for the right pavement at the right time” (Galehouse et al. 2003). Depending on the project specifics and priorities, DOS can provide a “right treatment” option for DOTs.

6.0 Conclusions

The densifier-over-shotblasting (DOS) treatment was found to address the issue of marginal aggregates commonly used in Oklahoma. This study achieved two complementary purposes:

1. it evaluated the effectiveness of DOS in increasing the overall durability and wear resistance of aggregate by improving resistance to polishing and abrasion through the application of a chemical treatment, and
2. it evaluated the effectiveness of DOS to restore and maintain acceptable microtexture (skid) values and macrotexture for pavements and bridge decks.

The study found that the chemical application or DOS treatment was able *to inhibit polishing and abrasion through the chemical hardening of aggregate* and *inhibit microtexture and macrotexture deterioration of road surfaces.* The multi-attribute analysis indicates that the DOS technique is a viable and sustainable alternative that can be included in the ODOT *Pavement Preservation Treatment Toolbox*. The project produced *specifications, design methodology, and construction methods necessary to transfer this novel technology to practice immediately after completion of the project*.

The study provided the following:

i. specifications of the required characteristics of DOS,
ii. identification of polishing tendency of aggregates that are available in each ODOT division, and
iii. documentation of effective construction practice and Inspector’s guide.

This should enhance safety due to maintained surface friction, regardless of season. It also accrues benefits by extending average pavement/bridge deck service life by quantifying the aggregate characteristics that slow surface deterioration as determined by field performance evaluation and laboratory aggregate analysis. Achieving these benefits provides a further benefit of releasing scarce maintenance funds to be used as programmed by reducing the amount of unplanned reactive maintenance that occurs on a statewide basis.

The objective of the laboratory portion of this study included determining if the application of chemical and/or shotblasting treatment to specific sources of Oklahoma aggregates would provide different results when compared to the control samples. Specifically, the results show that chemical application/DOS treatment enhances the limestone aggregate's properties that influence pavement surface texture: toughness, polish resistance, angularity and soundness. When these properties are improved or maintained, it is expected that surface texture performance should be enhanced. Results from the laboratory testing at OU and NCAT were generally consistent and showed that chemical/DOS application enhanced limestone aggregate characteristics, summarized in the following findings:

- Micro-Deval results showed that applying the lithium silicate densifier directly to the Dolese Davis limestone aggregate decreases the amount of mass loss (to less than 12%) due to Micro-Deval abrasion than the untreated sample, which indicates that the treated aggregate would facilitate good pavement surface friction and better performance than the untreated aggregate.
- Due to the nature of the Micro-Deval testing and the nature of the shotblasting process, shotblasting the aggregate prior to applying the densifier to the aggregate was not a viable option. However, one could infer from previous studies that if shotblasting had been applied to the aggregate to deepen penetration of the densifier, the Micro-Deval mass loss would be even less. In this study, the International Friction Index (IFI) results from accelerated polishing testing and field testing further support this statement.
- Micro-Deval values for the limestone aggregate sources (other than Dolese Davis) showed that the treated limestone aggregate loss values were slightly lower than the control.
- The LA Abrasion results do not indicate that applying the lithium silicate densifier directly to the Oklahoma limestone aggregate reduces the mass loss due to LA Abrasion compared to the sample not treated with the densifier, although the average value of the treated aggregate is marginally lower.
- Previous research has also shown there is no correlation in aggregate percentage loss between the Micro-Deval and the LA Abrasion tests, which is also the case in this study. It has been noted that LA Abrasion is an empirical test and therefore a poor predictor of field performance. Additionally, the Micro-Deval test has been

found to better simulate the field conditions of aggregate abrasion compared to the dry conditions of the LA Abrasion test.

- British Pendulum (BP) results showed that the untreated aggregate samples had a greater rate of friction loss (%) than the treated aggregate samples after a 10-hour polishing period for the limestone aggregate sources. This indicates that the treatment inhibits polishing. The nature of BP testing is also not conducive with shotblasting, but one could infer that deeper densifier penetration would reduce friction loss. IFI results from this project support this statement.
- AIMS results show that applying the lithium silicate densifier directly to the limestone aggregate enhances the aggregate's ability to retain angularity, and by extension, should contribute to better friction performance.
- There is a correlation between abrasion resistance and polishing resistance; the AIMS-Micro-Deval results show that lithium silicate densifier application hardens the Oklahoma limestone and aids in retaining angularity and texture, and therefore, should inhibit polishing. The nature of AIMS testing is also not conducive with shotblasting, but one could infer that deeper densifier penetration would increase angularity. International Friction Index (IFI) results from this project support this statement.
- Soundness results for the limestone samples indicate that applying the lithium silicate densifier directly to the Oklahoma limestone aggregate reduces the mass loss compared to the untreated samples, although the average value of the treated aggregate is marginally lower.
- The NCAT laboratory testing results of the ODOT asphalt mix samples containing the Dolese Davis limestone mix design are consistent with the OU Laboratory results for Micro-Deval, LA Abrasion, AIMS and soundness, as well as NCAT's British Pendulum results. Microtexture and macrotexture results related to surface texture of the asphalt mix in terms of International Friction Index (IFI) obtained after exposure to NCAT's accelerated polishing device indicated that the DOS-treated samples outperformed the untreated samples and the samples treated with only shotblasting and only chemical.

- The NCAT accelerated polishing results indicate that shotblasting does enhance the chemical penetration. This validates the assumption stated throughout the laboratory results section of this report that there would be greater differences in laboratory results of chemically treated and untreated aggregate had the shotblasting been a practical option.
- The NCAT accelerated polishing results also indicate that chemical treatment does enhance shotblasting performance.

The objective of the field portion of this study included determining if the application of DOS treatment to asphalt and concrete pavements and bridge decks would provide different results when compared to the control sections. Specifically, the results show that DOS treatment enhances surface texture. Results from the OU and NCAT testing were generally consistent and showed that DOS application enhanced pavement surface characteristics, summarized in the following findings:

- The general trend in the field testing results is that the DOS-treated sections outperformed untreated sections on the basis of microtexture and macrotexture.
- These results are consistent with the trend in the laboratory data, although the aggregate source in the field test sections is unknown.
- Based upon failure criteria, all sections performed satisfactorily during the testing period.
- As expected, the sections with less traffic (AADT 9,000) exhibited higher microtexture and macrotexture values over the testing period than sections with greater traffic (AADT 24,000).
- Deterioration models could not be created since no discernable trend of deterioration was exhibited.
- Microtexture (skid) results for the asphalt test sections showed that the treated section is outperforming the untreated section. However, both sections yielded higher skid number values than the failure criterion of 25. Neither section shows any discernable deterioration trend over the testing period (AADT ~9,000).
- The results from the existing DOS test section (6-years old) built in a previous study indicate that the DOS treatment service life estimate of 7 years is reasonable, if not

conservative, as microtexture and macrotexture values remain well above failure criteria.

- Microtexture (skid) results for the 6-year-old DOS-concrete pavement test sections constructed in the previous study showed that the first few months of the testing period yielded similar results for the treated section and the untreated section, but in the latter months there was a growing difference where the treated section had greater skid numbers. However, both sections yielded higher skid number values than the failure criterion of 25 period (AADT ~24,000). Neither section shows any discernable deterioration trend over the testing period.
- Microtexture (skid) results for the DOS-concrete pavement test sections constructed for this study were similar for the treated section and the untreated section, although the treated section tended to have greater skid numbers. However, both sections yielded higher skid number values than the failure criterion of 25 (AADT ~24,000).
- Macrotexture results also show a general trend of DOS-treated asphalt and concrete pavement sections yielding higher mean texture depth (MTD) values over the testing period of eight months.
- The asphalt section, which had a deeper shotblasting application, exhibited a greater difference between treated and untreated areas than did the concrete sections. The concrete and bridge deck sections received less shotblasting in an effort to retain the existing tining or grooving.
- Macrotexture (MTD) results for the asphalt test sections were consistent with the NCAT laboratory results and the skid number results provided in the preceding section: the treated asphalt section is outperforming the untreated section. However, both sections yielded higher MTD values than the failure criterion of 0.9 mm (AADT ~9,000). The untreated section does show some deterioration over the testing period. The treated section shows no discernable deterioration trend.
- Macrotexture (MTD) results for the concrete bridge deck from test section 2 (TS2) show that the DOS-treated section is outperforming the untreated section. However, both sections yielded higher MTD values than the failure criterion of 0.9 mm (AADT ~9,000). Both sections show slight but irregular deterioration over the testing period.

- Macrotexture (MTD) results for the concrete bridge deck from test section 3 (TS3) show no discernable difference between the DOS-treated section and the untreated section. Both sections yielded higher MTD values than the failure criterion of 0.9 mm (AADT ~9,000). Both sections show slight but irregular deterioration over the testing period.
- Macrotexture (MTD) results for the existing concrete pavement test sections show that the DOS-treated section slightly outperformed the untreated section. Both sections yielded higher MTD values than the failure criterion of 0.9 mm (AADT ~24,000). Both sections show slight but irregular deterioration over the testing period.
- Macrotexture (MTD) results for the existing concrete pavement test sections show that the DOS-treated section slightly outperformed the untreated section. Both sections yielded higher MTD values than the failure criterion of 0.9 mm (AADT ~24,000). Both sections show slight but irregular deterioration over the testing period.
- Macrotexture (MTD) results for the new concrete pavement test sections show that performance data trended together for the DOS-treated section and the untreated section. Both sections seem to reach the failure criterion of 0.9 mm at month 9. Both sections show irregular deterioration over the testing period. The rapid deterioration is attributed to the greater amount of traffic experienced at this location versus other test sections: right lane with traffic levels of AADT ~24,000.
- International Friction Index (IFI) results for accelerated polishing (TWPD) of the new concrete pavement test section show that the DOS-treated section outperformed the untreated section.

The consistent trend in results is that there was greater difference in performance between DOS-treated and untreated asphalt laboratory samples and field section than in the concrete field sections. However, in both cases, DOS-treated surfaces generally outperformed untreated surfaces.

To gain insight regarding the economic viability and environmental performance of DOS, a deterministic life cycle cost analysis (LCCA) and a life cycle assessment (LCA) was conducted with four surface treatments: 1-inch asphalt (HMA), shotblasting, microsurfacing and DOS. The results are summarized as follows:

- Although DOS has a higher initial cost, the results of the LCCA indicate that it has a comparable life cycle cost related to the other surface treatments.
- The sensitivity analysis reveals that there is no sensitivity with regard to service life and discount rate in this case, as the rank order remains the same for the treatments. However, in practice, these factors, along with commodity volatility, could greatly impact the output. HMA and microsurfacing prices are driven by the volatile crude oil market, and therefore, DOS and shotblasting may yield lower initial and life cycle costs when binder prices rise.
- The results of the LCA show that the DOS technique exhibits better environmental performance than the other treatments on a life cycle basis.
- DOS consumes the smallest amount of annualized energy and emits the least amount of annualized greenhouse gases of the pavement treatments analyzed.
- The multi-attribute analysis, which involved various weighting scenarios for combining cost and environmental impacts, demonstrated that DOS is an economically and environmentally competitive treatment.

Collectively, this research and previous studies demonstrate the potential benefits and viability of the DOS technique and support DOS inclusion in the ODOT pavement preservation toolbox for preserving asphalt and concrete pavements.

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Appendix A: Abbreviations

AIMS	Aggregate Imaging System
ASTM	American Society for Testing and Materials
BPN	British Pendulum Number
BPT	British Pendulum Tester
CFCI	Carbon Footprint Cost Index
CTM	Circular Track Meter
DFT	Dynamic Friction Texture
DOS	Silicon Reactive Lithium Densifier over Shotblasting
DOT	Department of Transportation
EUAC	Equivalent Uniform Annual Cost
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
HMA	Hot Mix Asphalt
IFI	International Friction Index
LA	Los Angeles (Abrasion)
LCA	Life Cycle Analysis or Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
MPD	Mean Profile Depth
MTD	Mean Texture Depth
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NZ	New Zealand
ODOT	Oklahoma Department of Transportation
OU	University of Oklahoma
PCC	Portland Cement Concrete
PCCP	Portland Cement Concrete Pavement
PIARC	Permanent International Association of Road Congress
PSV	Polished Stone Value
RMS	Root Mean Square
RRL	Road Research Laboratory
TRL	Transportation Research Laboratory
TWPD	Three Wheel Polishing Device

Appendix B: Data

Asphalt Laboratory Sample

DFT Results - NCAT

Sample	km/h	Run 1: 0k Cycles	Run 2: 0k Cycles	Run 3: 0k Cycles	Avg	Run 1: 20k Cycles	Run 2: 20k Cycles	Run 3: 20k Cycles	Avg	Run 1: 70k Cycles	Run 2: 70k Cycles	Run 3: 70k Cycles	Avg	Run 1: 140k Cycles	Run 2: 140k Cycles	Run 3: 140k Cycles	Avg
Control	20	0.392	0.410	0.353	0.385	0.472	0.412	0.413	0.432	0.386	0.416	0.440	0.414	0.317	0.319	0.315	0.317
Control	40	0.392	0.409	0.325	0.375	0.467	0.413	0.411	0.430	0.399	0.424	0.478	0.434	0.322	0.325	0.321	0.323
Control	60	0.394	0.426	0.328	0.383	0.470	0.414	0.411	0.432	0.400	0.426	0.478	0.435	0.322	0.326	0.322	0.323
DOS Treated Aggregate	20	0.353	0.342	0.376	0.357	0.342	0.389	0.333	0.355	0.338	0.354	0.339	0.344	0.286	0.279	0.291	0.285
DOS Treated Aggregate	40	0.205	0.212	0.249	0.222	0.335	0.397	0.345	0.359	0.366	0.373	0.373	0.371	0.314	0.305	0.317	0.312
DOS Treated Aggregate	60	0.208	0.223	0.269	0.233	0.337	0.397	0.347	0.360	0.366	0.374	0.374	0.371	0.319	0.311	0.323	0.318
Shot	20	0.957	0.651	0.609	0.630	0.407	0.448	0.393	0.416	0.412	0.352	0.361	0.375	0.300	0.299	0.295	0.298
Shot	40	0.845	0.599	0.580	0.590	0.427	0.448	0.396	0.424	0.440	0.383	0.389	0.404	0.329	0.325	0.324	0.326
Shot	60	0.756	0.586	0.573	0.580	0.418	0.453	0.399	0.423	0.455	0.388	0.397	0.413	0.340	0.336	0.334	0.337
Shot and DOS	20	0.880	0.735	0.701	0.718	0.622	0.540	0.554	0.572	0.419	0.393	0.429	0.414	0.387	0.340	0.342	0.356
Shot and DOS	40	0.759	0.694	0.670	0.708	0.611	0.522	0.532	0.555	0.440	0.421	0.453	0.438	0.393	0.349	0.349	0.364
Shot and DOS	60	0.717	0.685	0.644	0.682	0.613	0.512	0.535	0.553	0.419	0.407	0.447	0.424	0.395	0.362	0.359	0.372

CTM Results - NCAT

Sample	Measurement	Run 1: 0 cycles	Run 2: 0 cycles	Run 3: 0 cycles	Run 4: 0 cycles	Run 5: 0 cycles	Average: 0 cycles	Run 1: 20k cycles	Run 2: 20k cycles	Run 3: 20k cycles	Run 4: 20k cycles	Run 5: 20k cycles	Average: 20k cycles
Control	Mean Profile Depth (Average)	0.28	0.31	0.30	0.31	0.35	0.31	0.29	0.28	0.28	0.29	0.27	0.28
	% Dropouts (Average)	3%	4%	4%	3%	4%	4%	1%	2%	2%	2%	2%	2%
	RMS (Average)	0.26	0.27	0.23	0.28	0.60	0.33	0.25	0.22	0.21	0.27	0.21	0.23
DOS Treated Aggregate	Mean Profile Depth (Average)	0.33	0.34	0.35	0.31	0.33	0.33	0.26	0.30	0.26	0.25	0.29	0.27
	% Dropouts (Average)	7%	6%	6%	5%	5%	6%	3%	3%	3%	2%	3%	3%
	RMS (Average)	0.24	0.45	0.48	0.24	0.27	0.34	0.22	0.39	0.22	0.21	0.44	0.30
Shot	Mean Profile Depth (Average)	0.76	0.77	0.77	0.77	0.77	0.77	0.90	0.88	0.88	0.89	0.93	0.90
	% Dropouts (Average)	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	1%	0%
	RMS (Average)	0.51	0.51	0.51	0.51	0.51	0.51	0.47	0.47	0.46	0.46	0.70	0.51
Shot and DOS	Mean Profile Depth (Average)	0.90	0.90	0.92	0.89	0.91	0.90	0.95	0.94	0.95	0.92	0.93	0.94
	% Dropouts (Average)	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	1%
	RMS (Average)	0.66	0.66	0.66	0.66	0.67	0.66	0.60	0.60	0.88	0.59	0.59	0.65

CTM Results – NCAT (continued)

		Run 1: 70k cycles	Run 2: 70k cycles	Run 3: 70k cycles	Run 4: 70k cycles	Run 5: 70k cycles	Average: 70k cycles	Run 1: 140k cycles	Run 2: 140k cycles	Run 3: 140k cycles	Run 4: 140k cycles	Run 5: 140k cycles	Average: 140k cycles
Control	Mean Profile Depth (Average)	0.36	0.27	0.35	0.27	0.25	0.30	0.28	0.28	0.29	0.28	0.28	0.28
	% Dropouts (Average)	2%	2%	1%	1%	2%	2%	1%	1%	1%	1%	1%	1%
	RMS (Average)	0.41	0.19	0.65	0.29	0.19	0.35	0.21	0.21	0.21	0.20	0.21	0.21
DOS Treated Aggregate	Mean Profile Depth (Average)	0.27	0.27	0.27	0.28	0.29	0.28	0.30	0.27	0.27	0.28	0.29	0.28
	% Dropouts (Average)	1%	2%	2%	1%	2%	2%	2%	3%	2%	3%	2%	2%
	RMS (Average)	0.21	0.21	0.21	0.22	0.21	0.21	0.23	0.22	0.22	0.22	0.29	0.24
Shot	Mean Profile Depth (Average)	0.87	0.87	0.89	0.87	0.88	0.88	0.83	0.84	0.83	0.83	0.83	0.83
	% Dropouts (Average)	0%	0%	1%	0%	0%	0%	0%	1%	0%	0%	0%	0%
	RMS (Average)	0.50	0.49	0.76	0.49	0.52	0.55	0.49	0.49	0.50	0.49	0.51	0.50
Shot and DOS	Mean Profile Depth (Average)	0.91	0.92	0.90	0.92	0.91	0.91	0.99	0.98	0.98	1.00	0.97	0.98

		% Dropouts (Average)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		RMS (Average)	0.58	0.58	0.56	0.57	0.57	0.57	0.64	0.67	0.65	0.66	0.65	0.65

Concrete Pavement Field Test Section

DFT Results - NCAT

Sample	**km/h**	**Run 1: 0 Cycles**	**Run 2: 0 Cycles**	**Run 3: 0 Cycles**	**Avg: 0 Cycles**	**Run 1: 20k Cycles**	**Run 2: 20k Cycles**	**Run 3: 20k Cycles**	**Avg 20k Cycles**	**Run 1: 70k Cycles**	**Run 2: 70k Cycles**	**Run 3: 70k Cycles**	**Avg 70k Cycles**	**Run 1: 140k Cycles**	**Run 2: 140k Cycles**	**Run 3: 140k Cycles**	**Avg: 140k Cycles**
US 77 Control	20	0.560	0.550	0.540	0.550	0.400	0.460	0.450	0.437	0.410	0.420	0.390	0.407	0.350	0.370	0.380	0.367
	40	0.560	0.550	0.540	0.550	0.420	0.480	0.460	0.453	0.420	0.430	0.410	0.420	0.350	0.370	0.370	0.363
	60	0.520	0.520	0.520	0.520	0.410	0.470	0.460	0.447	0.420	0.420	0.400	0.413	0.290	0.310	0.290	0.297
US 77 Treat	20	0.650	0.650	0.620	0.640	0.530	0.510	0.510	0.517	0.440	0.440	0.440	0.440	0.410	0.440	0.410	0.420

Sample	km/h	Run 1: 0 Cycles	Run 2: 0 Cycles	Run 3: 0 Cycles	Avg: 0 Cycles	Run 1: 20k Cycles	Run 2: 20k Cycles	Run 3: 20k Cycles	Avg 20k Cycles	Run 1: 70k Cycles	Run 2: 70k Cycles	Run 3: 70k Cycles	Avg 70k Cycles	Run 1: 140k Cycles	Run 2: 140k Cycles	Run 3: 140k Cycles	Avg: 140k Cycles
ed	40	0.600	0.610	0.580	0.597	0.520	0.500	0.490	0.503	0.420	0.430	0.430	0.427	0.370	0.410	0.380	0.387
	60	0.540	0.550	0.540	0.543	0.490	0.480	0.470	0.480	0.400	0.410	0.420	0.410	0.350	0.340	0.320	0.337

CTM Results - NCAT

Section	Measurement	Run 1: 0 Cycles	Run 2: 0 Cycles	Run 3: 0 Cycles	Run 4: 0 Cycles	Run 5: 0 Cycles	Avg 0 Cycles	Run 1: 70k Cycles	Run 2: 70k Cycles	Run 3: 70k Cycles	Run 4: 70k Cycles	Run 5: 70k Cycles	Avg 70k Cycles	Run 1: 140k Cycles	Run 2: 140k Cycles	Run 3: 140k Cycles	Run 4: 140k Cycles	Run 5: 140k Cycles	Avg 140k Cycles
US 77 Control	Mean Profile Depth (Avg)	0.53	0.54	0.51	0.54	0.53	0.53	0.51	0.53	0.51	0.53	0.54	0.52	0.51	0.51	0.51	0.56	0.50	0.52
	% Dropouts (Avg)	0%	0%	0%	0%	0%	0%	1%	2%	2%	2%	1%	2%	0%	1%	0%	1%	1%	1%

Section	Measurement	**Run 1: 0 Cycles**	**Run 2: 0 Cycles**	**Run 3: 0 Cycles**	**Run 4: 0 Cycles**	**Run 5: 0 Cycles**	**Avg 0 Cycles**	**Run 1: 70k Cycles**	**Run 2: 70k Cycles**	**Run 3: 70k Cycles**	**Run 4: 70k Cycles**	**Run 5: 70k Cycles**	**Avg 70k Cycles**	**Run 1: 140k Cycles**	**Run 2: 140k Cycles**	**Run 3: 140k Cycles**	**Run 4: 140k Cycles**	**Run 5: 140k Cycles**	**Avg 140k Cycles**
	RMS [Avg]	0.30	0.31	0.30	0.30	0.30	0.30	0.32	0.32	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.56	0.31	0.36
US 77 Treated	Mean Profile Depth (Avg)	0.56	0.56	0.57	0.56	0.56	0.56	0.50	0.51	0.50	0.51	0.50	0.50	0.55	0.54	0.58	0.54	0.54	0.55
	% Dropouts (Avg)	0%	0%	0%	0%	0%	0%	1%	1%	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%
	RMS [Avg]	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.28	0.28	0.28	0.35	0.27	0.60	0.27	0.27	0.35

Aggregate Laboratory Samples

BP Results - NCAT

Dolese Davis - Untreated

Sample No.	BPN - 0 Hours	BPN - 10 Hours
1	40	22
	40	21
	40	20
	39	20
2	44	25
	44	25
	43	25
	43	25
3	42	27
	42	27
	42	26
	41	26
4	41	25
	41	25
	40	25
	40	24
5	44	25
	44	25
	43	24
	42	24

Dolese Davis - Treated

Sample No.	BPN - 0 Hours	BPN - 10 Hours
1	30	28
	30	28
	30	27
	30	27
2	32	27
	32	26
	31	26

Sample No.	BPN - 0 Hours	BPN - 10 Hours
	31	25
3	31	28
	31	27
	30	26
	30	26
4	32	29
	32	29
	31	29
	31	28
5	35	28
	34	27
	34	27
	33	26

Cooperton - Untreated

Sample No.	BPN - 0 Hours	BPN - 10 Hours
1	38	31
	37	30
	37	30
	36	29
2	39	30
	39	30
	39	29
	38	28
3	40	30
	40	30
	39	30
	39	30
4	37	30
	37	29
	36	29
	36	29
5	36	28
	35	28
	35	28
	34	28

Cooperton - Treated

Sample No.	BPN - 0 Hours	BPN - 10 Hours
1	25	23
	25	22
	25	22
	25	22
2	20	22
	20	22
	20	22
	20	22
3	25	22
	25	22
	25	21
	24	21
4	20	20
	20	20
	20	19
	20	19
5	23	20
	23	19
	23	19
	23	19

Hartshorne - Untreated

Sample No.	BPN - 0 Hours	BPN - 10 Hours
1	45	33
	45	32
	45	32
	45	31
2	45	35
	45	34
	44	34
	43	33
3	46	38

Sample No.	BPN - 0 Hours	BPN - 10 Hours
	46	38
	45	37
	45	36
4	45	34
	45	34
	44	33
	44	33
5	45	32
	44	32
	44	32
	43	32

Hartshorne - Treated

Sample No.	BPN - 0 Hours	BPN - 10 Hours
1	25	30
	25	30
	25	29
	25	29
2	30	35
	30	35
	29	35
	29	35
3	27	34
	27	34
	26	33
	26	33
4	25	32
	25	32
	24	31
	24	30
5	26	31
	25	30
	25	30
	24	30

Kemp Pryor - Untreated

Sample No.	BPN - 0 Hours	BPN - 10 Hours
1	49	39
	49	38
	48	38
	48	37
2	45	39
	44	38
	44	38
	44	37
3	43	40
	43	40
	43	39
	43	38
4	45	38
	45	38
	45	37
	45	37
5	41	37
	41	36
	40	36
	40	35

Kemp Pryor - Treated

Sample No.	BPN - 0 Hours	BPN - 10 Hours
1	30	26
	30	25
	30	25
	29	25
2	30	25
	30	25
	30	25
	30	25

Sample No.	BPN - 0 Hours	BPN - 10 Hours
3	28	23
	28	23
	28	22
	28	22
4	28	26
	28	26
	28	26
	28	25
5	29	21
	29	21
	28	20
	28	20

Martin Marietta - Untreated

Sample No.	BPN - 0 Hours	BPN - 10 Hours
1	43	34
	43	34
	42	33
	42	32
2	40	30
	40	30
	39	30
	40	30
3	40	30
	40	29
	40	28
	41	28
4	40	30
	40	30
	39	29
	39	29
5	40	30
	39	30
	38	29

Sample No.	BPN - 0 Hours	BPN - 10 Hours
	38	29

Martin Marietta - Treated

Sample No.	BPN - 0 Hours	BPN - 10 Hours
1	40	25
	40	25
	39	25
	39	25
2	35	28
	35	28
	34	27
	34	27
3	32	25
	32	25
	31	24
	30	24
4	35	25
	35	25
	35	25
	35	25
5	35	27
	35	27
	35	26
	35	26

Hanson - Untreated

Sample No.	BPN - 0 Hours	BPN - 10 Hours
1	36	28
	35	28
	35	28
	35	28

Sample No.	BPN - 0 Hours	BPN - 10 Hours
2	38	30
	38	30
	37	30
	36	30
3	41	30
	40	29
	40	28
	40	28
4	42	31
	42	31
	41	30
	41	30
5	41	30
	41	30
	40	30
	40	29

Hanson - Treated

Sample No.	BPN - 0 Hours	BPN - 10 Hours
1	32	30
	31	29
	30	29
	30	29
2	34	30
	34	30
	34	29
	34	29
3	35	35
	34	34
	34	34
	33	33
4	33	33
	32	33
	32	32
	32	32
5	34	32

Sample No.	BPN - 0 Hours	BPN - 10 Hours
	33	31
	33	31
	33	30

AIMS (OU Laboratory)

Limestone: Angularity 12.5 mm, Not Treated (Baseline), Pre-Micro-Deval

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	1527.18	1.786	1605.28	1.923	1328.67	1.818
12.5 mm	1541.53	3.571	1770.1	3.846	1374.3	3.636
12.5 mm	1611.14	5.357	1880.18	5.769	1783.27	5.455
12.5 mm	1799.05	7.143	1888.9	7.692	2078.05	7.273
12.5 mm	1964.45	8.929	1981.03	9.615	2107.8	9.091
12.5 mm	2028.45	10.714	2125.89	11.538	2115.47	10.909
12.5 mm	2084.41	12.5	2175.25	13.462	2160.78	12.727
12.5 mm	2127.58	14.286	2319.22	15.385	2195.19	14.545
12.5 mm	2135.1	16.071	2322.28	17.308	2218.82	16.364
12.5 mm	2191.38	17.857	2335.81	19.231	2335.42	18.182
12.5 mm	2196.03	19.643	2405.43	21.154	2479.63	20
12.5 mm	2222.96	21.429	2426.82	23.077	2515.92	21.818
12.5 mm	2294.93	23.214	2475.07	25	2517.47	23.636
12.5 mm	2299.53	25	2483.28	26.923	2553.33	25.455
12.5 mm	2309.12	26.786	2494.04	28.846	2573.63	27.273
12.5 mm	2316.66	28.571	2574.9	30.769	2584.55	29.091
12.5 mm	2409.21	30.357	2577.82	32.692	2600.87	30.909
12.5 mm	2411.45	32.143	2579.65	34.615	2613.9	32.727
12.5 mm	2558.46	33.929	2701.46	36.538	2618.47	34.545

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	2574.99	35.714	2871.18	38.462	2621.61	36.364
12.5 mm	2581.49	37.5	2912.76	40.385	2657.16	38.182
12.5 mm	2617.57	39.286	2919.92	42.308	2674.79	40
12.5 mm	2635.45	41.071	2931.51	44.231	2707.87	41.818
12.5 mm	2663.64	42.857	2995.86	46.154	2713.65	43.636
12.5 mm	2733.67	44.643	3002.52	48.077	2770.98	45.455
12.5 mm	2735.95	46.429	3014.48	50	2797.44	47.273
12.5 mm	2736.16	48.214	3038.03	51.923	2809.97	49.091
12.5 mm	2772.42	50	3061.52	53.846	2827.53	50.909
12.5 mm	2875.68	51.786	3080.17	55.769	2832.48	52.727
12.5 mm	2878.63	53.571	3109.05	57.692	2873.41	54.545
12.5 mm	2915.94	55.357	3153.34	59.615	2905.26	56.364
12.5 mm	2940.22	57.143	3337.66	61.538	2967.28	58.182
12.5 mm	2953.64	58.929	3349.64	63.462	2972.51	60
12.5 mm	2967.87	60.714	3376.79	65.385	3056.26	61.818
12.5 mm	2998.26	62.5	3434.62	67.308	3071.63	63.636
12.5 mm	3075.16	64.286	3462.48	69.231	3126.15	65.455
12.5 mm	3099.13	66.071	3486.34	71.154	3161.34	67.273
12.5 mm	3122.04	67.857	3608.72	73.077	3175.93	69.091
12.5 mm	3135.33	69.643	3867.94	75	3191.28	70.909
12.5 mm	3176.57	71.429	3923.48	76.923	3295.72	72.727
12.5 mm	3194.78	73.214	4081	78.846	3303.68	74.545
12.5 mm	3195.41	75	4164.49	80.769	3460.89	76.364
12.5 mm	3228.78	76.786	4382.51	82.692	3474.09	78.182
12.5 mm	3255.86	78.571	4388.81	84.615	3504.93	80
12.5 mm	3265.5	80.357	4461.03	86.538	3515.78	81.818

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	3379.98	82.143	4607.84	88.462	3663.29	83.636
12.5 mm	3415.89	83.929	5043.93	90.385	3686.52	85.455
12.5 mm	3474.25	85.714	5103.74	92.308	3717.48	87.273
12.5 mm	3480.03	87.5	5107.64	94.231	3777.99	89.091
12.5 mm	3526.23	89.286	5971.43	96.154	3996.19	90.909
12.5 mm	3569.65	91.071	6031.31	98.077	4161.2	92.727
12.5 mm	3677.71	92.857	6512.82	100	5482.56	94.545
12.5 mm	3682.96	94.643			6582.92	96.364
12.5 mm	3690.99	96.429			6665.93	98.182
12.5 mm	3942.59	98.214			7061.39	100
12.5 mm	4251.57	100				

Limestone: Angularity 12.5 mm, Not Treated, Post-Micro-Deval

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	472.62	2.222	624.18	1.786	917.16	3.125
12.5 mm	860.21	4.444	872.85	3.571	1194.65	6.25
12.5 mm	1064	6.667	1093.73	5.357	1420.11	9.375
12.5 mm	1179.19	8.889	1208.69	7.143	1461.05	12.5
12.5 mm	1187.78	11.111	1211.05	8.929	1512.96	15.625
12.5 mm	1344.08	13.333	1380.32	10.714	1738.47	18.75
12.5 mm	1348.81	15.556	1435.78	12.5	1756.77	21.875
12.5 mm	1492.81	17.778	1467.67	14.286	1784.03	25
12.5 mm	1526.87	20	1479.62	16.071	1804.78	28.125
12.5 mm	1685.54	22.222	1504.49	17.857	1814.78	31.25
12.5 mm	1731.73	24.444	1561.79	19.643	2032.73	34.375
12.5 mm	1745.14	26.667	1674.65	21.429	2035.08	37.5

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	1746.47	28.889	1695.96	23.214	2074.91	40.625
12.5 mm	1813.83	31.111	1781.25	25	2097.05	43.75
12.5 mm	1898.32	33.333	1868.8	26.786	2171.61	46.875
12.5 mm	1909	35.556	1874.93	28.571	2313.78	50
12.5 mm	2006.85	37.778	1913.27	30.357	2373.16	53.125
12.5 mm	2013.17	40	1952.47	32.143	2558.06	56.25
12.5 mm	2030.94	42.222	1957.62	33.929	2612.46	59.375
12.5 mm	2062.6	44.444	2010.4	35.714	2619.55	62.5
12.5 mm	2084.52	46.667	2013.63	37.5	2884.9	65.625
12.5 mm	2159.55	48.889	2036.49	39.286	2987.02	68.75
12.5 mm	2197.71	51.111	2048.24	41.071	3267.82	71.875
12.5 mm	2285.68	53.333	2078.84	42.857	3524.34	75
12.5 mm	2395.94	55.556	2082.02	44.643	3528.36	78.125
12.5 mm	2433.68	57.778	2105.64	46.429	4566	81.25
12.5 mm	2455.49	60	2108.35	48.214	5042.84	84.375
12.5 mm	2458.28	62.222	2120.89	50	5212.91	87.5
12.5 mm	2524.72	64.444	2123.47	51.786	6115.3	90.625
12.5 mm	2630.31	66.667	2130.98	53.571	6597.46	93.75
12.5 mm	2742.33	68.889	2188.83	55.357	7471.57	96.875
12.5 mm	2956.45	71.111	2218.18	57.143	9295.44	100
12.5 mm	2980.43	73.333	2276.74	58.929		
12.5 mm	3028.65	75.556	2354.32	60.714		
12.5 mm	3251.95	77.778	2368.15	62.5		
12.5 mm	3258.57	80	2416.51	64.286		
12.5 mm	3283.19	82.222	2434.05	66.071		
12.5 mm	3701.58	84.444	2450.17	67.857		

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	4794.7	86.667	2501.39	69.643		
12.5 mm	5232.57	88.889	2514.88	71.429		
12.5 mm	5330.6	91.111	2573.17	73.214		
12.5 mm	5880.53	93.333	2581.1	75		
12.5 mm	5944.68	95.556	2582.88	76.786		
12.5 mm	7072.53	97.778	2584.92	78.571		
12.5 mm	8051.37	100	2651.8	80.357		
12.5 mm			2658.07	82.143		
12.5 mm			2745.33	83.929		
12.5 mm			2800.41	85.714		
12.5 mm			2854.14	87.5		
12.5 mm			2887.16	89.286		
12.5 mm			2969.28	91.071		
12.5 mm			3060.13	92.857		
12.5 mm			3199.88	94.643		
12.5 mm			3286.25	96.429		
12.5 mm			3535.24	98.214		
12.5 mm			5784.57	100		

Limestone: Angularity 12.5 mm, Treated, Post-Micro-Deval

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	661.01	2.041	800.19	2.128	773.3	2.564
12.5 mm	679.78	4.082	899.52	4.255	1354.72	5.128
12.5 mm	1101.7	6.122	1066.62	6.383	1385.59	7.692
12.5 mm	1304.27	8.163	1401.83	8.511	1435.11	10.256
12.5 mm	1338.7	10.204	1438.19	10.638	1519.74	12.821

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	1529.53	12.245	1560.16	12.766	1538.15	15.385
12.5 mm	1563.7	14.286	1578.37	14.894	1548.99	17.949
12.5 mm	1724.52	16.327	1645.07	17.021	1584.14	20.513
12.5 mm	1735.09	18.367	1697.74	19.149	1604.56	23.077
12.5 mm	1737.22	20.408	1748.99	21.277	1615.04	25.641
12.5 mm	1766.95	22.449	1766.79	23.404	1648.89	28.205
12.5 mm	1794.05	24.49	1850.82	25.532	1652.71	30.769
12.5 mm	1835.86	26.531	1861.61	27.66	1657.62	33.333
12.5 mm	1844.75	28.571	1874.74	29.787	1700.46	35.897
12.5 mm	1886.96	30.612	1896.87	34.043	1758.01	38.462
12.5 mm	1909.16	32.653	1950.31	36.17	1828.3	41.026
12.5 mm	1931.48	34.694	1981.76	38.298	1876.19	43.59
12.5 mm	2011.4	36.735	1996.06	40.426	1882.5	46.154
12.5 mm	2029.72	38.776	2032.88	42.553	1888.04	48.718
12.5 mm	2039.13	40.816	2052.6	44.681	1915.87	51.282
12.5 mm	2065.34	42.857	2085.76	46.809	2057.36	53.846
12.5 mm	2086.94	44.898	2166.38	48.936	2082.06	56.41
12.5 mm	2278.22	46.939	2167.09	51.064	2110.3	58.974
12.5 mm	2308.43	48.98	2193.84	53.191	2159.17	61.538
12.5 mm	2357.13	51.02	2202.61	55.319	2288.59	64.103
12.5 mm	2390.13	53.061	2235.37	57.447	2295.78	66.667
12.5 mm	2425.99	55.102	2277.32	59.574	2536.39	69.231
12.5 mm	2455.13	57.143	2347.82	61.702	2864.12	71.795
12.5 mm	2494.77	59.184	2382.06	63.83	2947.23	74.359
12.5 mm	2506.63	61.224	2568.11	65.957	3132.25	76.923
12.5 mm	2512.62	63.265	2583.24	68.085	3417.82	79.487

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	2513.87	65.306	2603.03	70.213	4000.61	82.051
12.5 mm	2573.87	67.347	2797.44	72.34	4437.26	84.615
12.5 mm	2614.11	69.388	2868.58	74.468	4470.7	87.179
12.5 mm	2648.17	71.429	3048.87	76.596	5374.32	89.744
12.5 mm	2682.71	73.469	3139.13	78.723	5463.15	92.308
12.5 mm	2741.06	75.51	3322.55	80.851	7735.9	94.872
12.5 mm	2803.83	77.551	3744.9	82.979	8680.61	97.436
12.5 mm	2805.05	79.592	4618.09	85.106	9392.3	100
12.5 mm	2813.89	81.633	4619.19	87.234		
12.5 mm	3114.29	83.673	5699.8	89.362		
12.5 mm	3256.58	85.714	5850.02	91.489		
12.5 mm	4184.14	87.755	6289.16	93.617		
12.5 mm	5595.84	89.796	6788.69	95.745		
12.5 mm	6463.33	91.837	8008.79	97.872		
12.5 mm	6498.97	93.878	9685.56	100		
12.5 mm	8294.07	95.918				
12.5 mm	9134.92	97.959				
12.5 mm	9828.37	100				

Limestone: Angularity 16 mm, Not Treated (Baseline), Pre-Micro-Deval

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
16 mm	1434.32	1.961	1644.98	2.857	1245.49	2.083
16 mm	1957.72	3.922	1686.79	5.714	1576.72	4.167
16 mm	1961.25	5.882	1792.47	8.571	1792.45	6.25
16 mm	2038.09	7.843	1832.13	11.429	1891.35	8.333
16 mm	2156.76	9.804	2026.58	14.286	1919.22	10.417

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
16 mm	2200.48	11.765	2042.44	17.143	1997.92	12.5
16 mm	2239.18	13.725	2046.19	20	2069.97	14.583
16 mm	2245.88	15.686	2068.65	22.857	2167.1	16.667
16 mm	2250.06	17.647	2205.63	25.714	2220.63	18.75
16 mm	2338.68	19.608	2283.2	28.571	2238.5	20.833
16 mm	2358.98	21.569	2316.27	31.429	2250.72	22.917
16 mm	2405.6	23.529	2330.9	34.286	2259.36	25
16 mm	2415.66	25.49	2434.8	37.143	2259.53	27.083
16 mm	2416.17	27.451	2596.73	40	2282.82	29.167
16 mm	2449.99	29.412	2617.11	42.857	2287.96	31.25
16 mm	2469.85	31.373	2639.57	45.714	2306.47	33.333
16 mm	2505.54	33.333	2700.7	48.571	2319.46	35.417
16 mm	2616.29	35.294	2701.31	51.429	2387.03	37.5
16 mm	2705.01	37.255	2710.88	54.286	2484.54	39.583
16 mm	2729.61	39.216	2750.91	57.143	2521.62	41.667
16 mm	2765.93	41.176	2821.84	60	2535	43.75
16 mm	2770.03	43.137	3076.26	62.857	2576.03	45.833
16 mm	2773.27	45.098	3442.57	65.714	2594.88	47.917
16 mm	2796.17	47.059	3450.63	68.571	2606.17	50
16 mm	2797.85	49.02	3655.05	71.429	2606.79	52.083
16 mm	2822.57	50.98	3714.76	74.286	2613.97	54.167
16 mm	2933.3	52.941	3817.96	77.143	2649.78	56.25
16 mm	3034.58	54.902	4272	80	2652.79	58.333
16 mm	3063.03	56.863	5033.88	82.857	2660.09	60.417
16 mm	3064.82	58.824	6247.65	85.714	2816.5	62.5
16 mm	3072.81	60.784	7009.04	88.571	2833.95	64.583

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
16 mm	3106.01	62.745	7441.92	91.429	2843.33	66.667
16 mm	3133.38	64.706	7679.71	94.286	2857.71	68.75
16 mm	3145.38	66.667	7745.35	97.143	2874.18	70.833
16 mm	3288.04	68.627	8583.46	100	2927.74	72.917
16 mm	3325.9	70.588			2957.61	75
16 mm	3409.87	72.549			3052.66	77.083
16 mm	3610.9	74.51			3157.45	79.167
16 mm	3614.36	76.471			3161.53	81.25
16 mm	3892.58	78.431			3389.94	83.333
16 mm	3906.62	80.392			3463.37	85.417
16 mm	3942.23	82.353			3486.54	87.5
16 mm	3953.64	84.314			3612.63	89.583
16 mm	4038.86	86.275			4937.43	91.667
16 mm	4305.45	88.235			5206.36	93.75
16 mm	4506.1	90.196			5598.24	95.833
16 mm	4518.01	92.157			5757.86	97.917
16 mm	4764.87	94.118			9968.74	100
16 mm	5120.09	96.078				
16 mm	6217.63	98.039				
16 mm	6867.01	100				

Limestone: Angularity 16 mm, Not Treated, Post-Micro-Deval

Size	Sample 1	Percentage	Sample 2	Percentage
16 mm	1098.94	1.786	1194.86	2.041
16 mm	1161.51	3.571	1220.23	4.082
16 mm	1228.41	5.357	1240.04	6.122

Size	Sample 1	Percentage	Sample 2	Percentage
16 mm	1353.98	7.143	1319.48	8.163
16 mm	1371.62	8.929	1386.83	10.204
16 mm	1374.22	10.714	1388.82	12.245
16 mm	1417.44	12.5	1419.6	14.286
16 mm	1442.8	14.286	1496.44	16.327
16 mm	1498.05	16.071	1522.1	18.367
16 mm	1508.5	17.857	1684.17	20.408
16 mm	1517.13	19.643	1716.92	22.449
16 mm	1598.16	21.429	1732.25	24.49
16 mm	1605.34	23.214	1781.1	26.531
16 mm	1616.54	25	1820.4	28.571
16 mm	1625.65	26.786	1841.93	30.612
16 mm	1779.13	28.571	1926.69	32.653
16 mm	1789.38	30.357	1931.55	34.694
16 mm	1810.15	32.143	1959.96	36.735
16 mm	1882.19	33.929	2000.09	38.776
16 mm	1900.05	35.714	2000.31	40.816
16 mm	1932.82	37.5	2025.02	42.857
16 mm	1980.86	39.286	2083.18	44.898
16 mm	1982.43	41.071	2116.83	46.939
16 mm	1986.14	42.857	2145.82	48.98
16 mm	2014.65	44.643	2160.96	51.02
16 mm	2016.66	46.429	2181.85	53.061
16 mm	2078.64	48.214	2199.79	55.102
16 mm	2087.69	50	2267.09	57.143
16 mm	2092.18	51.786	2273.48	59.184

Size	Sample 1	Percentage	Sample 2	Percentage
16 mm	2119.37	53.571	2347.23	61.224
16 mm	2127.86	55.357	2381.31	63.265
16 mm	2140.17	57.143	2451.7	65.306
16 mm	2146.3	58.929	2461.12	67.347
16 mm	2159.61	60.714	2464.61	69.388
16 mm	2191.44	62.5	2490.28	71.429
16 mm	2193.59	64.286	2509.44	73.469
16 mm	2279.03	66.071	2530.4	75.51
16 mm	2296.97	67.857	2553.26	77.551
16 mm	2303.24	69.643	2605.65	79.592
16 mm	2324.79	71.429	2689.17	81.633
16 mm	2333.89	73.214	2767.71	83.673
16 mm	2364.66	75	3490.79	85.714
16 mm	2389.48	76.786	4997.52	87.755
16 mm	2501.44	78.571	5885.94	89.796
16 mm	2508.74	80.357	6613.39	91.837
16 mm	2558.26	82.143	6942.33	93.878
16 mm	2579.1	83.929	7068.42	95.918
16 mm	2637.34	85.714	7969.72	97.959
16 mm	2662.4	87.5	9511.02	100
16 mm	2709.1	89.286		
16 mm	2733.38	91.071		
16 mm	2783.98	92.857		
16 mm	2970.06	94.643		
16 mm	3151.83	96.429		
16 mm	3296.1	98.214		

Size	Sample 1	Percentage	Sample 2	Percentage
16 mm	3351.99	100		

Limestone: Angularity 16 mm, Treated, Post-Micro-Deval

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
16 mm	1256.55	1.961	1120	1.961	274.78	2.5
16 mm	1319.44	3.922	1329.28	3.922	1110.15	5.0
16 mm	1328.37	5.882	1658.04	5.882	1242.13	7.5
16 mm	1433.42	7.843	1660.05	7.843	1300.24	10.0
16 mm	1464.61	9.804	1783.98	9.804	1478.61	12.5
16 mm	1500.93	11.765	1805.85	11.765	1577.02	15.0
16 mm	1541.41	13.725	1820.8	13.725	1669.94	17.5
16 mm	1567.13	15.686	1826.71	15.686	1688.39	20.0
16 mm	1569.29	17.647	1839.41	17.647	1694.63	22.5
16 mm	1570.21	19.608	1991.72	19.608	1730.2	25.0
16 mm	1571.15	21.569	1996.42	21.569	1735.93	27.5
16 mm	1672.21	23.529	2008.83	23.529	1743.54	30.0
16 mm	1694.85	25.49	2023.32	25.49	1785.66	32.5
16 mm	1779.16	27.451	2045.81	27.451	1966.87	35.0
16 mm	1809.77	29.412	2075.17	29.412	1988.22	37.5
16 mm	1845.77	31.373	2075.18	31.373	2035.9	40.0
16 mm	1875.59	33.333	2085.15	33.333	2089.43	42.5
16 mm	1930.57	35.294	2106.35	35.294	2089.91	45.0
16 mm	1970.39	37.255	2135.21	37.255	2128.26	47.5
16 mm	1973.92	39.216	2158.6	39.216	2278.89	50.0
16 mm	2004.47	41.176	2332.04	41.176	2311.47	52.5

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
16 mm	2050.95	43.137	2369.86	43.137	2343.66	55.0
16 mm	2108.51	45.098	2396.79	45.098	2379.73	57.5
16 mm	2128.75	47.059	2429.43	47.059	2477.01	60.0
16 mm	2141.38	49.02	2439.97	49.02	2493.62	62.5
16 mm	2259.67	50.98	2454.21	50.98	2602.3	65.0
16 mm	2271.42	52.941	2505.3	52.941	2637.88	67.5
16 mm	2286.02	54.902	2537	54.902	2656.53	70.0
16 mm	2287.81	56.863	2546.53	56.863	2729.51	72.5
16 mm	2384.11	58.824	2561.66	58.824	2871.36	75.0
16 mm	2487.91	60.784	2592.12	60.784	3007.41	77.5
16 mm	2575.4	62.745	2595.21	62.745	3565.96	80.0
16 mm	2583.69	64.706	2658.8	64.706	4243.25	82.5
16 mm	2603.38	66.667	2746.94	66.667	5361.73	85.0
16 mm	2637.97	68.627	2830.81	68.627	5388.83	87.5
16 mm	2708.15	70.588	2846.64	70.588	5919.93	90.0
16 mm	2787.08	72.549	2881.07	72.549	7620.84	92.5
16 mm	2884.92	74.51	2986.21	74.51	8294.43	95.0
16 mm	3093.7	76.471	3004.78	76.471	8532.55	97.5
16 mm	3236.88	78.431	3014.58	78.431	9211.4	100.0
16 mm	3428.82	80.392	3048.25	80.392		
16 mm	3756.45	82.353	3061.69	82.353		
16 mm	3958.69	84.314	3158.62	84.314		
16 mm	4280.4	86.275	3410.89	86.275		
16 mm	4416.27	88.235	3952.78	88.235		
16 mm	5015.78	90.196	4555.35	90.196		

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
16 mm	5870.9	92.157	4957.54	92.157		
16 mm	7075.68	94.118	5727.76	94.118		
16 mm	7098.76	96.078	8451.18	96.078		
16 mm	9242.78	98.039	8469.27	98.039		
16 mm	9492.97	100	9147.97	100		

Limestone: Texture 12.5 mm, Not Treated (Baseline), Pre-Micro-Deval

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	61.5	1.786	92.5	1.786	55	1.786
12.5 mm	68.5	3.571	125.5	3.571	55.5	3.571
12.5 mm	120	5.357	144.5	5.357	88.5	5.357
12.5 mm	133	7.143	149	7.143	91.5	7.143
12.5 mm	151.5	8.929	153.5	8.929	144.5	8.929
12.5 mm	155	10.714	154.5	10.714	180.5	10.714
12.5 mm	155.5	12.5	168.5	12.5	183	12.5
12.5 mm	157	16.071	195	14.286	187.5	14.286
12.5 mm	167.5	17.857	197	16.071	190	16.071
12.5 mm	176	19.643	209.5	17.857	201	17.857
12.5 mm	188.5	21.429	215.5	19.643	209.5	19.643
12.5 mm	191.5	23.214	216	21.429	211	21.429
12.5 mm	196.5	25	217.5	23.214	221.5	23.214
12.5 mm	218.5	26.786	218.5	25	222.5	25
12.5 mm	232	28.571	221.5	26.786	230.5	26.786
12.5 mm	239.5	30.357	226.5	30.357	232	28.571
12.5 mm	240.5	32.143	246.5	32.143	234.5	30.357

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	243	33.929	247.5	33.929	240.5	32.143
12.5 mm	245.5	37.5	253.5	35.714	245	33.929
12.5 mm	251	39.286	258	37.5	247	35.714
12.5 mm	253	41.071	268	39.286	265	37.5
12.5 mm	254.5	42.857	279	41.071	265.5	39.286
12.5 mm	257.5	44.643	283.5	42.857	270	42.857
12.5 mm	269.5	48.214	284.5	44.643	271.5	44.643
12.5 mm	276	50	296	46.429	275.5	46.429
12.5 mm	277.5	51.786	320	48.214	277	48.214
12.5 mm	297	53.571	328	50	280.5	50
12.5 mm	299	55.357	328.5	53.571	283	51.786
12.5 mm	309.5	57.143	329.5	55.357	285	53.571
12.5 mm	317	58.929	335	57.143	286	55.357
12.5 mm	318	60.714	336	58.929	289.5	57.143
12.5 mm	318.5	62.5	338	60.714	292.5	58.929
12.5 mm	322.5	64.286	347	62.5	293	60.714
12.5 mm	327.5	66.071	355.5	64.286	306	62.5
12.5 mm	334	67.857	364	66.071	316	64.286
12.5 mm	335	69.643	364.5	67.857	318.5	66.071
12.5 mm	348.5	71.429	366	69.643	319	67.857
12.5 mm	355	73.214	375.5	71.429	337.5	69.643
12.5 mm	356	75	378.5	73.214	341.5	71.429
12.5 mm	357	76.786	391	75	348.5	73.214
12.5 mm	362	78.571	404	76.786	356.5	75
12.5 mm	378	80.357	405	78.571	366.5	76.786
12.5 mm	386.5	82.143	406	80.357	368	78.571

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	395	83.929	411.5	82.143	377	80.357
12.5 mm	397	85.714	421.5	83.929	388	82.143
12.5 mm	401.5	87.5	436	85.714	394	83.929
12.5 mm	407.5	89.286	437	87.5	397	87.5
12.5 mm	411	91.071	449	89.286	417	91.071
12.5 mm	429.5	92.857	454.5	91.071	429	92.857
12.5 mm	440.5	94.643	460	92.857	429.5	94.643
12.5 mm	506	96.429	475.5	94.643	439	96.429
12.5 mm	580.5	98.214	499	96.429	439.5	98.214
12.5 mm	691	100	574.5	98.214	469	100
12.5 mm			635.5	100		

Limestone: Texture 12.5 mm, Not Treated, Post-Micro-Deval

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	25	1.786	39.5	1.786	31.5	1.887
12.5 mm	31.5	3.571	42.5	3.571	36	3.774
12.5 mm	53.5	5.357	43	5.357	37.5	5.66
12.5 mm	59.5	7.143	47	7.143	41	7.547
12.5 mm	64.5	8.929	56.5	8.929	43	9.434
12.5 mm	66	10.714	59.5	10.714	44	11.321
12.5 mm	68.5	12.5	71	12.5	50.5	13.208
12.5 mm	71	14.286	77	14.286	54	15.094
12.5 mm	72	16.071	82	16.071	58	16.981
12.5 mm	79.5	17.857	82.5	17.857	59.5	18.868
12.5 mm	95	19.643	86	19.643	71.5	20.755

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	98.5	21.429	87.5	21.429	81.5	22.642
12.5 mm	99.5	23.214	92	23.214	84	24.528
12.5 mm	100.5	25	94	25	84.5	26.415
12.5 mm	101.5	28.571	95.5	26.786	85	28.302
12.5 mm	104.5	30.357	100.5	28.571	89	30.189
12.5 mm	105	32.143	102	30.357	91	32.075
12.5 mm	112.5	33.929	106.5	32.143	92.5	33.962
12.5 mm	115	39.286	107.5	33.929	95	35.849
12.5 mm	117	41.071	110.5	35.714	95.5	37.736
12.5 mm	119.5	42.857	117	37.5	97	39.623
12.5 mm	122	44.643	118	39.286	104	41.509
12.5 mm	124	46.429	118.5	41.071	104.5	43.396
12.5 mm	126.5	48.214	121.5	42.857	112.5	45.283
12.5 mm	128.5	50	122	44.643	116.5	47.17
12.5 mm	130.5	51.786	124	46.429	117	49.057
12.5 mm	131.5	53.571	124.5	48.214	119	50.943
12.5 mm	134	55.357	130.5	50	119.5	52.83
12.5 mm	135.5	57.143	131	51.786	122.5	54.717
12.5 mm	138.5	58.929	135	53.571	127	56.604
12.5 mm	141.5	60.714	140	55.357	129	58.491
12.5 mm	146	62.5	140.5	57.143	130	60.377
12.5 mm	147.5	64.286	144	58.929	134	62.264
12.5 mm	148.5	66.071	146	60.714	137.5	67.925
12.5 mm	153	67.857	146.5	62.5	149	69.811
12.5 mm	158	69.643	150	64.286	149.5	71.698
12.5 mm	160	71.429	150.5	66.071	154.5	73.585

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	162	73.214	160	67.857	159.5	75.472
12.5 mm	162.5	75	164.5	69.643	160.5	77.358
12.5 mm	163.5	76.786	167	71.429	163.5	79.245
12.5 mm	171.5	78.571	167.5	73.214	171.5	81.132
12.5 mm	172	80.357	168.5	75	177.5	83.019
12.5 mm	178	82.143	170.5	76.786	203.5	84.906
12.5 mm	178.5	83.929	173	78.571	204.5	86.792
12.5 mm	184.5	85.714	175	80.357	208.5	88.679
12.5 mm	188	87.5	175.5	82.143	218	90.566
12.5 mm	198	89.286	180.5	83.929	222.5	94.34
12.5 mm	208	91.071	182	85.714	224.5	96.226
12.5 mm	212	92.857	186	87.5	241	98.113
12.5 mm	218.5	94.643	195	89.286	261.5	100
12.5 mm	256.5	96.429	200	91.071		
12.5 mm	260	98.214	204	92.857		
12.5 mm	307.5	100	208	94.643		
12.5 mm			212	96.429		
12.5 mm			256	100		

Limestone: Texture 12.5 mm, Treated, Post-Micro-Deval

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	27	1.786	35	1.786	28	3.571
12.5 mm	35	3.571	35.5	3.571	32	5.357
12.5 mm	49.5	5.357	37.5	5.357	35	7.143
12.5 mm	56	7.143	51.5	7.143	56	8.929
12.5 mm	64	8.929	58.5	8.929	75	10.714

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	80	10.714	59.5	10.714	80.5	12.5
12.5 mm	97	12.5	64.5	12.5	90.5	14.286
12.5 mm	108	14.286	68.5	14.286	91	16.071
12.5 mm	109.5	17.857	85.5	16.071	93.5	17.857
12.5 mm	112.5	19.643	87	17.857	94.5	19.643
12.5 mm	115	21.429	89.5	19.643	99	21.429
12.5 mm	116.5	23.214	90.5	21.429	100	23.214
12.5 mm	118.5	25	95.5	23.214	106.5	25
12.5 mm	122.5	26.786	100	25	107	26.786
12.5 mm	125.5	28.571	102	26.786	107.5	28.571
12.5 mm	135	30.357	102.5	28.571	109	30.357
12.5 mm	136.5	32.143	107	30.357	110.5	32.143
12.5 mm	144	33.929	108	32.143	111	33.929
12.5 mm	145	35.714	109.5	33.929	116	35.714
12.5 mm	147.5	37.5	110	35.714	119.5	37.5
12.5 mm	149.5	39.286	110.5	37.5	122.5	39.286
12.5 mm	150.5	41.071	114	39.286	124.5	42.857
12.5 mm	151.5	44.643	120.5	41.071	127	44.643
12.5 mm	153.5	46.429	122	42.857	128	46.429
12.5 mm	157	48.214	128	44.643	131.5	48.214
12.5 mm	158	50	132.5	46.429	132.5	50
12.5 mm	161	51.786	133	48.214	133	51.786
12.5 mm	165	53.571	136.5	50	136	53.571
12.5 mm	165.5	55.357	137.5	53.571	137.5	55.357
12.5 mm	167.5	57.143	145.5	55.357	139	60.714
12.5 mm	169	58.929	146	57.143	141	64.286

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
12.5 mm	172	60.714	148.5	58.929	145	66.071
12.5 mm	173	62.5	149.5	62.5	146	67.857
12.5 mm	179	64.286	152	64.286	150	69.643
12.5 mm	183	66.071	153.5	66.071	151.5	71.429
12.5 mm	189.5	67.857	158	67.857	160	73.214
12.5 mm	194	69.643	158.5	69.643	165.5	75
12.5 mm	195	71.429	162	71.429	178	76.786
12.5 mm	196.5	73.214	165	73.214	179	78.571
12.5 mm	197.5	75	172	75	182	80.357
12.5 mm	201.5	76.786	176.5	76.786	185.5	82.143
12.5 mm	204	78.571	177	78.571	188.5	83.929
12.5 mm	212	80.357	178.5	80.357	190.5	85.714
12.5 mm	213.5	82.143	183.5	82.143	191.5	87.5
12.5 mm	224.5	83.929	185	83.929	194	89.286
12.5 mm	227	85.714	196	87.5	198.5	91.071
12.5 mm	228.5	87.5	216.5	89.286	210.5	92.857
12.5 mm	240	89.286	220.5	91.071	227.5	94.643
12.5 mm	252.5	91.071	224.5	92.857	243.5	96.429
12.5 mm	259	92.857	245.5	94.643	261	98.214
12.5 mm	262	94.643	257	96.429	297	100
12.5 mm	284.5	96.429	289	98.214		
12.5 mm	294.5	98.214	302.5	100		
12.5 mm	329	100				

Limestone: Texture 16 mm, Not Treated (Baseline), Pre-Micro-Deval

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
16 mm	79.5	1.786	74.5	1.887	116	1.786
16 mm	108.5	3.571	83	3.774	123.5	3.571
16 mm	139.5	5.357	104.5	5.66	126.5	5.357
16 mm	162.5	7.143	108	7.547	167.5	7.143
16 mm	165.5	8.929	150.5	11.321	173.5	8.929
16 mm	183.5	10.714	164	13.208	175	10.714
16 mm	184.5	12.5	165.5	15.094	200	12.5
16 mm	196.5	14.286	188	16.981	201	14.286
16 mm	202	16.071	190	18.868	221	16.071
16 mm	203	17.857	193.5	20.755	229.5	17.857
16 mm	205.5	19.643	200	22.642	230	19.643
16 mm	209	21.429	211.5	24.528	233	21.429
16 mm	218	25	218	26.415	236.5	23.214
16 mm	228.5	26.786	230.5	28.302	237.5	25
16 mm	233	28.571	232.5	30.189	239	26.786
16 mm	234.5	32.143	234.5	32.075	239.5	28.571
16 mm	242	33.929	235.5	33.962	240	30.357
16 mm	245.5	35.714	241.5	35.849	248	32.143
16 mm	256.5	37.5	244.5	37.736	249	35.714
16 mm	261.5	39.286	246	39.623	254	37.5
16 mm	270	41.071	248	41.509	255	39.286
16 mm	278.5	42.857	255	43.396	275.5	41.071
16 mm	282	44.643	257.5	45.283	276	44.643
16 mm	286	46.429	258	47.17	277	46.429
16 mm	287	48.214	263.5	49.057	281	48.214
16 mm	294.5	50	265	50.943	282.5	50

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
16 mm	295.5	51.786	269	52.83	284	51.786
16 mm	296	53.571	271.5	54.717	299	53.571
16 mm	297	57.143	273.5	56.604	299.5	55.357
16 mm	299	58.929	287	58.491	305	57.143
16 mm	304.5	60.714	289	60.377	307	58.929
16 mm	305	62.5	294.5	62.264	310	60.714
16 mm	316.5	64.286	309	64.151	317	62.5
16 mm	336	66.071	316	66.038	323.5	64.286
16 mm	341.5	67.857	317.5	67.925	326.5	66.071
16 mm	344.5	69.643	318	69.811	329	69.643
16 mm	347.5	71.429	320	71.698	335	71.429
16 mm	354.5	73.214	321	75.472	345	73.214
16 mm	355.5	75	329	77.358	346	75
16 mm	359	76.786	336.5	79.245	348.5	76.786
16 mm	359.5	78.571	353	81.132	350	78.571
16 mm	368	80.357	360.5	83.019	361	80.357
16 mm	368.5	82.143	362.5	84.906	366	82.143
16 mm	384.5	83.929	388.5	86.792	377	83.929
16 mm	394	85.714	393.5	88.679	378	85.714
16 mm	400.5	87.5	396.5	90.566	381.5	89.286
16 mm	401.5	91.071	402	92.453	384.5	91.071
16 mm	404.5	92.857	430.5	94.34	385.5	92.857
16 mm	407	94.643	441.5	96.226	394.5	94.643
16 mm	424	96.429	445	98.113	397.5	96.429
16 mm	441	98.214	512.5	100	429.5	98.214
16 mm	488.5	100			474	100

Limestone: Texture 16 mm, Not Treated, Post-Micro-Deval

Size	Sample 1	Percentage	Sample 2	Percentage
16 mm	34.5	1.786	36	1.818
16 mm	47.5	3.571	48	3.636
16 mm	56	5.357	48.5	5.455
16 mm	62.5	7.143	54	7.273
16 mm	70.5	8.929	59	9.091
16 mm	74.5	10.714	84.5	10.909
16 mm	93	12.5	85	12.727
16 mm	93.5	14.286	89	14.545
16 mm	96	16.071	90	16.364
16 mm	98	17.857	90.5	18.182
16 mm	105.5	19.643	95.5	21.818
16 mm	107	21.429	103	23.636
16 mm	116	23.214	109.5	27.273
16 mm	123.5	25	113.5	29.091
16 mm	124.5	26.786	115	30.909
16 mm	129	28.571	116	32.727
16 mm	132.5	30.357	117	34.545
16 mm	135.5	32.143	125	36.364
16 mm	138	33.929	126.5	38.182
16 mm	141.5	35.714	127	40
16 mm	142	37.5	128	41.818
16 mm	142.5	39.286	130	43.636
16 mm	143.5	41.071	131.5	45.455
16 mm	147	42.857	133.5	47.273

Size	Sample 1	Percentage	Sample 2	Percentage
16 mm	148.5	44.643	134.5	49.091
16 mm	149	46.429	136.5	50.909
16 mm	152.5	48.214	137	52.727
16 mm	153	53.571	139.5	54.545
16 mm	154	55.357	140	56.364
16 mm	154.5	57.143	141.5	58.182
16 mm	157	58.929	142.5	60
16 mm	159	62.5	144.5	61.818
16 mm	165.5	64.286	147.5	63.636
16 mm	167	66.071	151	65.455
16 mm	167.5	67.857	154	67.273
16 mm	175	69.643	155	69.091
16 mm	180.5	71.429	171	70.909
16 mm	185.5	73.214	174.5	74.545
16 mm	190	75	178	76.364
16 mm	197.5	76.786	178.5	78.182
16 mm	207.5	78.571	179	80
16 mm	208	80.357	183.5	81.818
16 mm	209.5	82.143	184	83.636
16 mm	222.5	83.929	191	85.455
16 mm	233	85.714	207.5	87.273
16 mm	240	87.5	230.5	89.091
16 mm	242	89.286	232.5	90.909
16 mm	243.5	91.071	236.5	92.727
16 mm	247	92.857	253	94.545
16 mm	248	94.643	260	96.364

Size	Sample 1	Percentage	Sample 2	Percentage
16 mm	263.5	96.429	267.5	98.182
16 mm	276.5	98.214	288.5	100
16 mm	277.5	100		

Limestone: Texture 16 mm, Treated, Post-Micro-Deval

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
16 mm	52.5	1.786	12.5	1.786	29	2.041
16 mm	69	3.571	29.5	3.571	36.5	4.082
16 mm	72	5.357	56	5.357	43	6.122
16 mm	80.5	7.143	71.5	7.143	49.5	10.204
16 mm	84	8.929	77	10.714	67	12.245
16 mm	86.5	10.714	78	12.5	68	14.286
16 mm	90.5	12.5	80.5	14.286	70	16.327
16 mm	97	14.286	88	17.857	79.5	18.367
16 mm	101.5	16.071	88.5	19.643	83	20.408
16 mm	102.5	17.857	90	21.429	85	22.449
16 mm	104.5	19.643	94.5	23.214	89	24.49
16 mm	107.5	21.429	107	25	93	26.531
16 mm	109	23.214	108.5	26.786	94.5	28.571
16 mm	111	25	111.5	28.571	97.5	30.612
16 mm	115	26.786	115.5	30.357	99.5	34.694
16 mm	120.5	28.571	116	32.143	104	36.735
16 mm	121	30.357	117	33.929	105	38.776
16 mm	121.5	32.143	120	35.714	110	40.816
16 mm	122	33.929	125	37.5	116	42.857
16 mm	125	35.714	125.5	39.286	126.5	44.898

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
16 mm	138	37.5	127.5	41.071	131	46.939
16 mm	138.5	39.286	129	42.857	137	48.98
16 mm	140.5	41.071	135.5	44.643	138	51.02
16 mm	141	42.857	136	46.429	142	53.061
16 mm	143	46.429	137	48.214	146	55.102
16 mm	150	50	144	50	146.5	57.143
16 mm	150.5	51.786	145.5	51.786	151.5	59.184
16 mm	153.5	53.571	150	53.571	153.5	61.224
16 mm	155	55.357	152.5	57.143	157	65.306
16 mm	158.5	57.143	156	60.714	161	67.347
16 mm	162.5	58.929	159	62.5	161.5	69.388
16 mm	170	60.714	159.5	64.286	164	71.429
16 mm	172.5	62.5	160.5	66.071	169	73.469
16 mm	173	64.286	162	67.857	171.5	75.51
16 mm	175.5	66.071	164.5	69.643	180	77.551
16 mm	177	69.643	167	71.429	180.5	79.592
16 mm	180	73.214	172.5	73.214	189	81.633
16 mm	182	75	179.5	75	200.5	83.673
16 mm	189	76.786	183	76.786	204.5	85.714
16 mm	190	78.571	186	78.571	205	87.755
16 mm	194	80.357	187	80.357	213	89.796
16 mm	196.5	82.143	190	82.143	223.5	91.837
16 mm	198.5	83.929	191	83.929	234.5	93.878
16 mm	199	85.714	198	85.714	240.5	95.918
16 mm	202.5	87.5	199.5	87.5	241	97.959
16 mm	207	89.286	201	89.286	328	100

Size	Sample 1	Percentage	Sample 2	Percentage	Sample 3	Percentage
16 mm	210	91.071	204.5	91.071		
16 mm	217.5	92.857	249	92.857		
16 mm	226	94.643	263.5	94.643		
16 mm	236.5	96.429	287.5	96.429		
16 mm	278	98.214	296.5	98.214		
16 mm	364	100	312	100		

Appendix C: DRAFT DOS Specifications

DRAFT SPECIFICATION FOR
DENSIFIER OVER SHOTBLASTING (DOS)

DESCRIPTION

This work consists of treating an existing bituminous or concrete surface with shotblasting and silicon reactive lithium densifier material (DOS).

> **Shotblasting**: a mechanical technique applied to a bituminous or concrete surface by a machine that blasts small steel balls or pellets at high velocity to enhance surface texture.
> **Silicon Reactive Lithium Densifier**: a chemical agent that hardens a bituminous or concrete surface.

MATERIALS

Requirements for Silicon Reactive Lithium Densifier
[No ASTM specifications currently for Silicon Reactive Lithium Densifier]
Abrasion Resistance: ASTM D 4060, H-22, 1000g, 1000 cyc
Adhesion: ASTM D 4541
Compressive Strength: ASTM C 805

EQUIPMENT

A. Shotblasting Equipment

Provide shotblasting equipment capable of collecting used shot and waste material. The Department will allow the use of recycled shot. Dispose of materials removed in the cleaning operation in accordance with Subsection 104.09, "Removal and Disposal of Salvaged Materials, Structures and Obstructions".

B. Spraying Equipment

Provide fully atomizing equipment to apply the silicon reactive lithium densifier. Ensure the Resident Engineer can verify the application rate based on tank capacity.

CONSTRUCTION METHODS

A. General

Clean the existing roadbed surface before applying the DOS treatment. Ensure that application minimizes damage and inconvenience to traffic and allow one-way traffic to have no contact with the silicon reactive lithium densifier.

Do not apply shotblasting during wet weather or to damp surfaces.

Do not apply the silicon reactive lithium densifier during wet or cold weather, or in windy conditions that would cause the densifier to drift. Do not apply the densifier to damp surfaces.

Before application, the Resident Engineer must approve of the following:

- quantity,
- rate of application,
- temperature and
- areas to be treated.

B. Densifier over Shotblasting (DOS)

Apply shotblasting to yield surface profiles ranging from a CSP3 and CSP9 (between 32 and 210mils), based upon the required texture, per the International Concrete Repair Institute (ICRI) published guidelines for Concrete Surface Profiles (CSP), ICRI title no. 310.2R-2013.

Apply silicon reactive lithium densifier at a rate of 0.06 gal/yd^2 [0.27 L/m^2].

Ensure that the chemical cures for at least 4 hours before opening to traffic.

C. Weather Limitations

Place DOS on a dry surface. Ensure that the pavement surface is at least 50 degrees Fahrenheit [10 C] measured away from artificial heat sources. Ensure weather conditions allow for proper application and curing of DOS.

METHOD OF MEASUREMENT

The Resident Engineer will measure the volume of silicon reactive lithium densifier for *DENSIFIER OVER SHOTBLASTING (DOS)*, as delivered.

BASIS OF PAYMENT

The Department will pay for the pay item at the contract unit price per the specified pay unit as follows:

Pay Items:	**Pay Unit:**
SILICON REACTIVE LITHIUM DENSIFIER	Gallon [Liter]
SHOTBLASTING	Square Yard [Square Meter]

Appendix D: DRAFT DOS Inspector’s Guide

[DRAFT]

June 2016

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Acknowledgments

This guidebook is the result of a robust partnership between the University of Oklahoma (OU), the Oklahoma Department of Transportation (ODOT), and members of the pavement preservation industry. Our sincere appreciation is extended to all persons who contributed information for the use in this guide.

Densifier-over-Shotblasting (DOS) for Pavement Surface Texture Maintenance

This guidebook is the result of an ODOT research project entitled, “Evaluate Densifier-over-Shotblasting (DOS) Treatment Performance for Pavements and Bridge Decks”, and can be referenced for a more in-depth understanding of the concepts discussed in this guide. This guide should be supplemented with other sources of information, regarding items such as standard testing procedures and software products.

INTRODUCTION

Pavement skid resistance is perhaps the most important engineering component of the road from a safety standpoint. Slippery pavements are the result of several causes, chief of which is the loss of pavement surface micro and macrotexture. As a result, pavement managers must not only manage the structural condition of their roads but also their skid resistance (Gee 2007, NCHRP 1989). In fact, it is possible for a structurally sound pavement to be rendered unsafe from a loss of skid resistance due to polishing of the surface aggregate, or in the case of chip seals, flushing of the binder in the wheel paths (Patrick et al. 2000). Engineers must use every possible tool during design, construction and operations to make the road as safe as possible. The design/construction engineer has control over the geometry of the road, both in horizontal and vertical alignments, the speed of travel, the signage of the roadway system and the material properties of the surface course. As the pavement deteriorates over time, the maintenance engineer can also control the characteristics of the pavement surface by selecting various pavement preservation and maintenance treatments. Ultimately, the physics of the moving vehicle will determine if the engineers who have been involved in the road's service life will determine whether or not the road can be safely traveled. Once the road is built, the only facet of the road that is truly controllable is its surface. No other factor of the complex three-dimensional equation that determines whether a moving vehicle will be able to safely remain on the surface of the road can be changed without a large relative commitment of resources to affect the desired change. As a result, the maintenance engineer's mission must be to preserve the road's structural capacity and to ensure that its surface frictional characteristics are sufficient to safely pass traffic for which it was originally designed.

This results in a safety requirement to modify the pavement surface to restore skid resistance. *Silicon Reactive Lithium Densifier and Shotblasting* (or generally, densifier over shotblasting, DOS) is a new pavement preservation treatment that has been investigated for its ability to harden pavement surfaces against abrasion, enhance macrotexture, retain microtexture (surface friction) and inhibit rutting and polishing, hence extending pavement service life (Gransberg and Pittenger, 2012).

BACKGROUND

Pavement Preservation

Preserving the public investment in the pavement network is the purpose of a state agency's preservation program. An effective program will "extend pavement life, enhance pavement performance, ensure cost effectiveness and reduce user delays" (Galehouse et al 2003). Highway programs are becoming more centered on pavement preservation, with emphasis placed on developing effective preservation and preventative maintenance concepts and programs (FHWA, 1998; FHWA, 1999; Peshkin et al. 2004). Developing an effective pavement preservation plan is critical for the state of Oklahoma due to its relatively small transportation budget (Gransberg et al. 2012). This is emphasized in the states 2010 Asset Preservation Plan which states, "the preservation of our existing transportation system is an absolutely critical part of the Department's Mission" (ODOT 2010).

Pavement preservation involves applying surface treatments to extend the functional service life of the underlying pavement, deferring expensive rehabilitation costs. "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" (Peshkin et al. 2004). Figure 1 illustrates the pavement preservation concept.

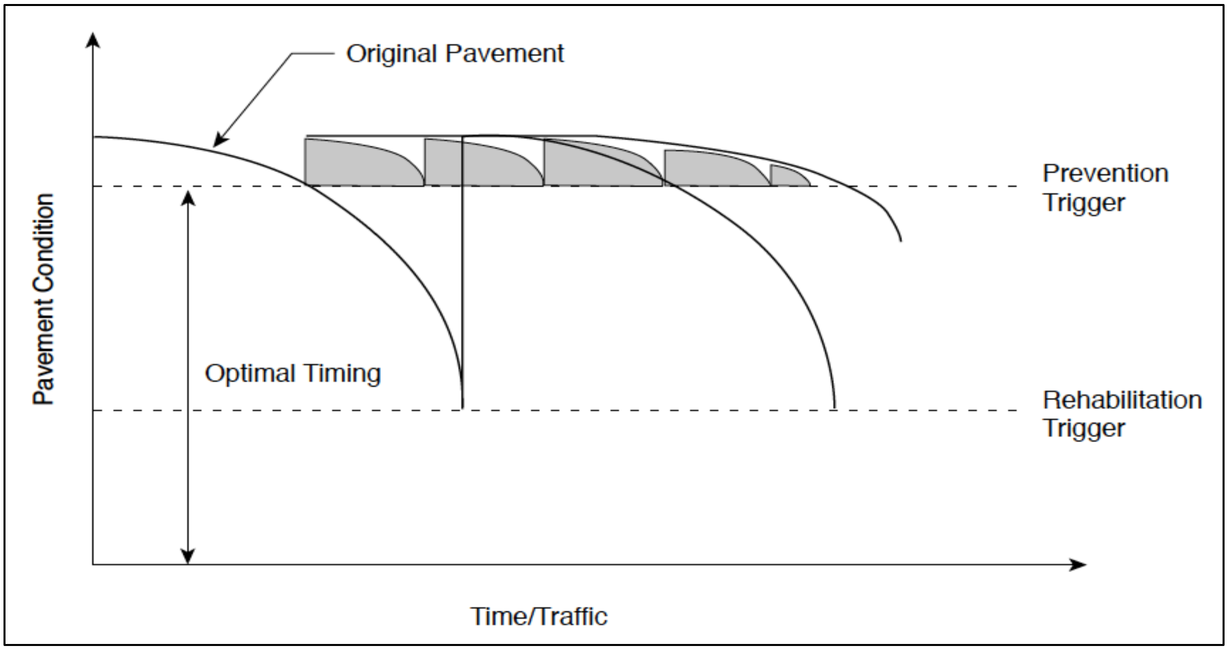

Figure 1 Proactive Approach versus Reactive Approach (Davies and Sorenson 2000)

A pavement preservation program consists of "preventative maintenance, minor rehabilitation (non-structural), and some routine maintenance", however does not include major rehabilitation to restore serviceability (FHWA 2005). The main goal of a preservation program is to extend pavement service life and is not expected to increase the strength or capacity like a major rehabilitation would (FHWA 2005). This is what delineates pavement preservation treatments, like DOS, from other interventions.

Economic benefits resulting from a pavement preservation program accrue over the long term (Galehouse et al. 2003). Essentially, an initial investment of $1 for preservation may save an agency $3 to $4 in future rehabilitation costs (AirTap 2005).

"Roads that receive preservation treatments are in better condition than those left without treatments" (Galehouse et al. 2003). The challenge of pavement preservation is determining what treatment to apply, when to apply it, and what measureable improvement the treatment will yield (Peshkin et al. 2004). Preventative maintenance treatments are a cost effective way to extend service life when applied to the "right pavement at the right time" (Peshkin et al. 2004). Applying the treatment to the pavement too soon will result in spending money for little or no benefit, and applying the treatment too late is ineffective and will result in costly rehabilitation of the pavement. A number of tools and procedures have been developed and used by state agencies to determine the optimum pavement preservation strategies.

Pavement Characteristics

The primary physical characteristic of a pavement that is measured after a traffic accident is surface texture, a key indicator of pavement performance in terms of skid resistance (Manion and Tighe 2007). Pavement skid resistance is one of “the most important engineering components of the road from a safety standpoint” (Gee 2007, NCHRP 1989). Therefore, pavement preservation treatments are commonly applied to rectify loss of skid resistance and enhance safety. Microtexture and macrotexture (illustrated in Figure 2) are physical properties of pavement that affect skid resistance, which is reduced by mechanical wear, polishing, and accumulation of surface contaminants (Neubert 2006).

Microtexture is a quantitative measure of aggregate surface friction properties and is a common indicator used to assess skid resistance (Abdul-Malak et al. 1993, Roque et al. 1991). Mechanical wear of aggregate by repetitive contact with vehicle tires causes the surface to polish and results in a loss of microtexture. 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. Macrotexture characterizes the resistant force given by the pavement surface’s overall roughness, which is reduced with the accumulation of contaminants.

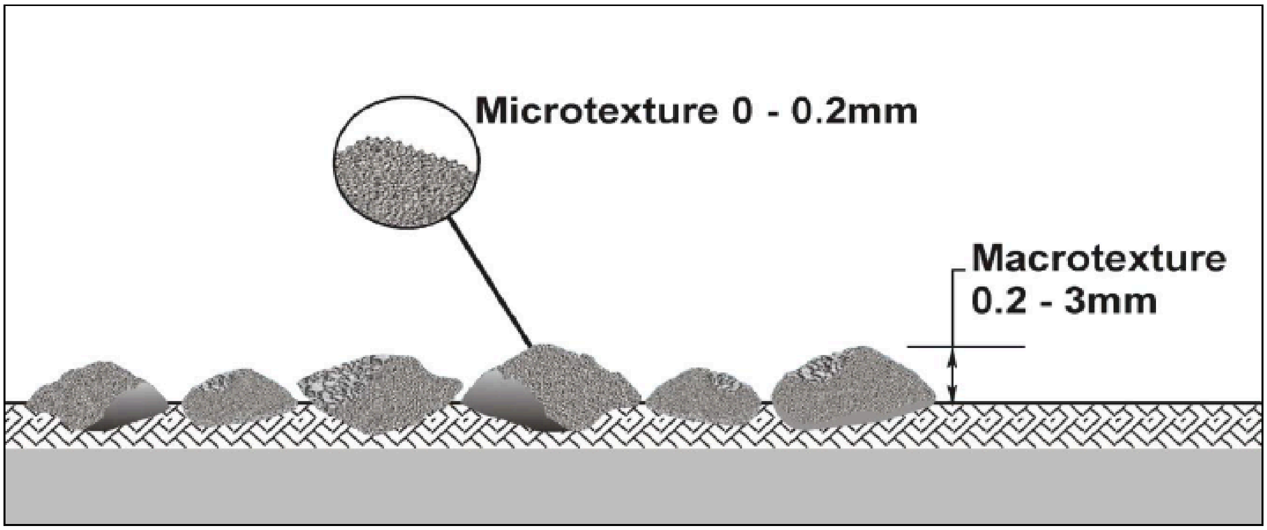

Figure 0 Pavement Surface Microtexture and Macrotexture (Pidwerbesky et al. 2006)

There are two major forces (Figure 3) contributing to the overall skid resistance force of pavement surfaces (NCHRP 2009). The adhesion force, F_A, and hysteresis force, F_H, are summed to determine the friction force, F, of the pavement surface, per the following equation:

$$F = F_A + F_H$$

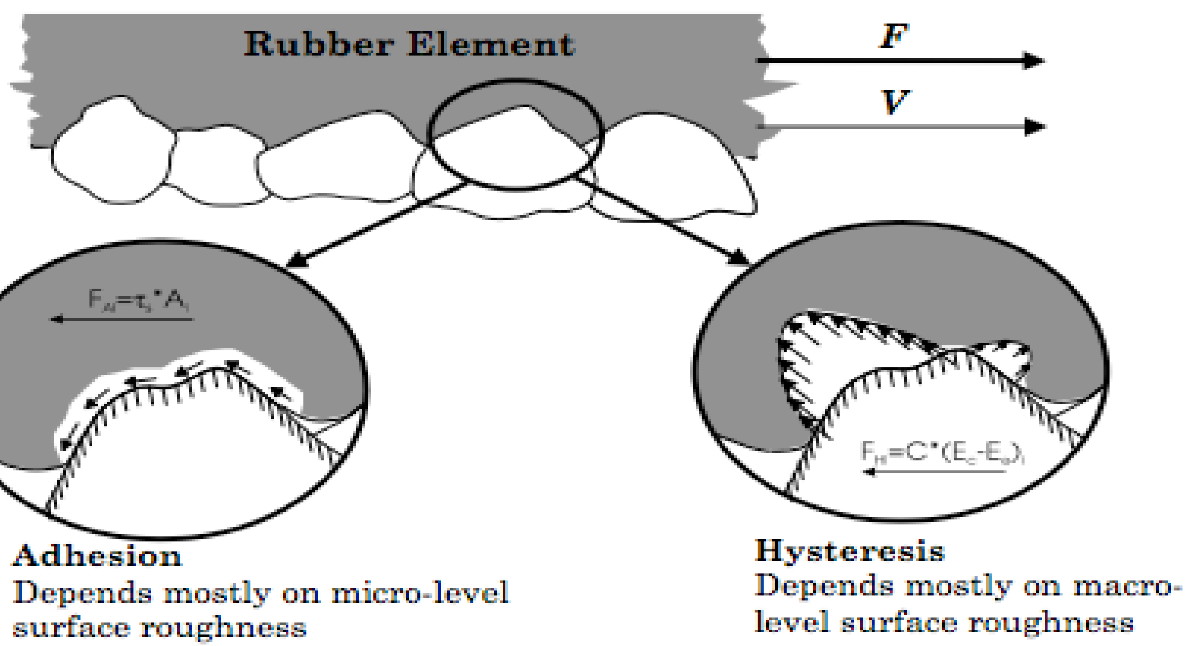

Figure 3 Pavement Friction Model (NCHRP 2009)

Figures 2 and 3 show the “adhesion force is proportional to the real area of adhesion between the tire and surface asperities” (NCHRP 2009), and the “hysteresis force is generated within the deflecting and viscoelastic tire tread material, and is a function of speed” (NCHRP 2009). Therefore macrotexture and microtexture are related to the hysteresis and adhesion forces respectively, both of which must be addressed to improve skid resistance.

Aggregate Characteristics

Aggregate particles consist of a number of distinguishable geometric aspects (Figure 4), including form, angularity, and surface texture, which due to the difference in size scales, can be used for the purposes of ordering (Masad 2005). “Any of the properties can vary widely without necessarily affecting the other two properties” (Masad 2005). Form relates to variations in the proportions of the particle, angularity is associated with the variations at the corners superimposed on shape, and surface texture describes the irregularity of the surface at a “scale that is too small to affect the overall shape” (Masad 2005). “For the case of coarse aggregate angularity, there is a distinct difference between angularity and texture, both of which have different effects on performance” (Fletcher et al. 2003).

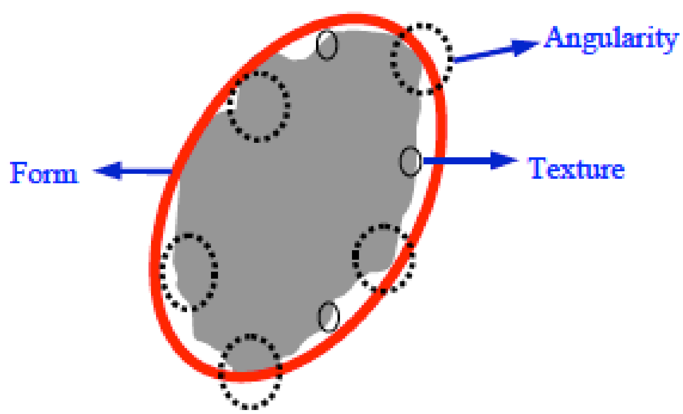

Figure 4 Components of an Aggregate Shape (Masad 2005)

Aggregate Quality

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 (Moaveni et al. 2014). Aggregate polishing and degradation have an adverse impact on these characteristics and result in accelerating the surface deterioration and increasing remediation frequency (Rezaei et al. 2009, Fowler and Rached 2012, Moaveni et al. 2014). Essentially, aggregate less prone to texture loss and abrasion will predictively have better skid resistance in the field (Lancieri et al. 2005).

Limestone has been the most commonly used aggregate type in US (and Oklahoma) road construction (Csathy et al. 1968). 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 (Fowler and Rached 2012, Csathy et al. 1968, Neaylon 2009, Smith et al. 2009). National Cooperative Highway Research Program (NCHRP) 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 (Smith et al. 2009). 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 (Smith et al. 2009). Essentially, harder and more durable aggregates retain higher friction values longer, contributing to adequate pavement safety and longer service life (Neaylon 2009, Smith et al. 2009).

Aggregate Polishing

Polished aggregate in a pavement surface is considered to be a surface defect that must be mitigated by pavement engineers to ensure safety (FHWA 2003). 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 (Lancieri et al. 2005). According to the US Department of Transportation (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 (NSP 2010).

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 (Komas 2011).

Most of the state of Oklahoma is comprised of soft aggregates (NSP 2010, Gransberg 2012). Table 1 shows statewide aggregate quality for Oklahoma, classified with polished stone value (PSV) based upon Neaylons' 2009 definitions of aggregate quality (Gransberg 2012). 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 (Gransberg 2012). 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 (Gransberg 2012).

Table 1 Oklahoma Aggregate Geology Based on Average PSV (after Gransberg 2012)

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%

Economic Analysis

Engineering economic analysis (i.e. LCCA) is used to “evaluate the over-all-long-term economic efficiency between [mutually exclusive] competing alternative investment options” (FHWA 2002). It is a vital component of pavement preservation and has long been promoted by the Federal Highway Administration (FHWA) for application to “highway project planning, design, construction, preservation, and operation” (FHWA 2003) for the evaluation of cost effectiveness and accountability (FHWA 2007). In the short-term (programming implementation level), economic analysis is used for evaluating projects and helps pavement managers facilitate the selection of pavement preservation treatments (FHWA 2007).

Environmental Analysis

Environmental protection measures have been largely associated with manufacturing products and processes, however methods are now being adopted by the pavement industry (Giustozzi et al. 2012). One method in particular, life cycle assessment (LCA), can be used to evaluate environmental impacts related to pavements (ISO 2006, Giustozzi et al. 2012). “LCA is a quantitative accounting of the cumulative environmental impacts of a product or process across all stages of the life cycle” (EPA 2013). Conducting a LCA comprises of four stages (ISO 2006), which are described by the EPA (2006) as:

1. “Goal Definition and Scoping - Define and describe the product, process or activity. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.
2. Inventory Analysis - Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).
3. Impact Assessment - Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.

4. Interpretation - Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results" (EPA 2006).

This type of analysis has been used to assess pavement preservation treatment performance (Giustozzi et al. 2012, Mosier et al. 2013).

In summary, pavement preservation is one way that transportation agencies are enhancing their programs' sustainability. Pavement preservation treatments are commonly applied to rectify loss of skid resistance and enhance safety while extending pavement service life and reducing costs. Oklahoma aggregate is prone to polishing, a condition for which few treatment options exist. However, analysis and proper treatment selection for a given project can contribute to an agency's goals of preserving the investment in the pavement network, enhancing sustainability performance and ensuring proper stewardship.

DENSIFIER-OVER-SHOTBLASTING (DOS)

Silicon Reactive Lithium Densifier and Shotblasting (or generally, densifier over shotblasting, DOS) consists of a mechanical process (shotblasting - high velocity impact method) and a chemical application (Silicon Reactive Lithium Densifier). The chemical application works to retain the surface texture and profile that the shotblasting restores. Application of the treatment is shown in Figure 8.

Figure 8 DOS Treated Pavement: Shotblasting (Left), Densifier Application (Right) (Convergent 2009)

The DOS process was developed to improve hardness, wear and polishing resistance properties of aggregates whereby reducing the rate at which friction values deteriorate making roads safer and extending the service lives of both asphalt and concrete pavements.

Chemical Densifier

Application of chemical densifiers, in particular lithium silicate, has proven to harden and extend the service life of industrial Portland Cement Concrete (PCC) floors subjected to low speed vehicular traffic (Nasvik 2008). Lithium silicate has the advantage over other hardening agents as it forms a dust rather than a crust when it dries, and it reacts with the calcium hydroxide, a by-product of cement hydration, to increase the concrete strength and resistance to traffic wear and abrasion. During the hydration process, calcium hydroxide dissolves in water and relocates to the surface, where it reacts with the lithium silicate. The calcium silicate hydrate then settles in the pores and voids of the concretes surface, creating a denser, harder surface than untreated concrete. In the process, lithium is used to “stabilize and solubilize the silicate so it can remain in solution until it penetrates the concrete and then can react with the abundant calcium hydroxide found in the concrete” (Nasvik 2008).

Recent developments have led to the use of the technique in the pavement industry, where it makes PCCP more rut resistant, and increases the ability to resist snowplow abrasion (Riemer et al. 2012, Nasvik 2008). Additionally, lithium silicate has been investigated for mitigating moisture intrusion and sealing concrete barrier walls exposed to chloride-based deicing salts to reduce chloride-induced corrosion of reinforcing steel in concrete structures and was found to reduce chloride concentration when compared to untreated walls (Guthrie et al 2015).

Shotblasting

The chemical densifier reaction is most advantageous when the chemical is applied to a porous surface, as this allows for greater penetration of the hardening agent, and results in a deeper hardened surface (Nasvik 2008, Gransberg and Pittenger 2012). Hence, shotblasting is an important factor in improving the concrete densification process. Shotblasting is a recent development being used by pavement managers as a preservation technique that retextures concrete and asphalt road surfaces. It has proved to be a cost effective method for restoring surface friction (MarylandDOT 2013). The technique involves a machine that blasts small steel balls or pellets onto the surface, which adds texture to each individual piece of aggregate in the surface, and therefore increases skid resistance (Blastrac 2013). A vacuum system is used to recover the shot along with the material removed from the surface, after which a magnet removes the shot for reuse. There are generally two types of shotblasting equipment, vehicular mounted and ground mounted.

Vehicular-mounted units consist of a shot propelling mechanism and magnetic retrieval system, with cutting widths that vary from approximately 6 to 12 feet, depending on the manufacturer and type. The ground-mounted type is smaller and is "capable of cutting six to twenty inches at a pass" (Speidel 2002). Two of the smaller shotblasters can be mounted over the wheel paths to shotblast the polished sections of the surface in order "to achieve a higher rate of production while reducing the overall unit cost per lineal unit" (Gransberg 2009). A typical shotblasting system includes:

- "Shot propelling apparatus,
- Vacuum system,
- Magnetic separator,

- Residue container, and
- Follow on magnetic brush and loom to pick up any debris" (Gransberg 2009).

A typical shotblasting setup is shown in Figure 9. The impellor propels the steel shot to abrade the surface, upon which the steel shot and abraded material are collected through a vacuum system. The material is then separated with the steel shot returned to the hopper and the debris sent to the dust collector. Shotblasting is considered sustainable, with vehicle fuel the only petroleum product consumed (Gransberg 2009).

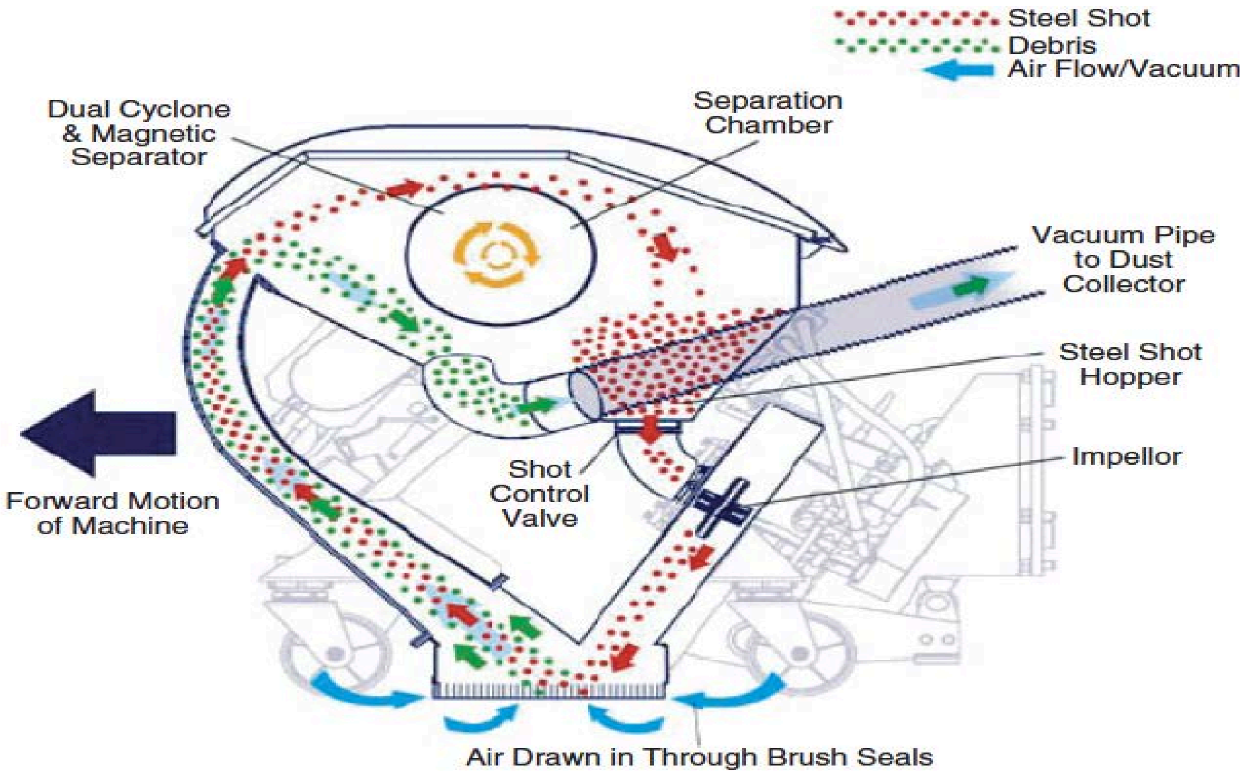

Figure 9 Typical Shotblasting Apparatus and Process (Jenman 2006)

The most in-depth study on road surface retexturing using the shotblasting technique was carried out in Australia (Bennett, 2007). The project included the retexturing of polished HMA surfaces. Bennett reported that

> "[The shotblasting] system has shown that it is a fast and efficient means of reinstating texture to road surfaces. At each trial site, the treatment increased texture depth by at least 0.2 to 0.8mm . . . The SCRIM [Sideway force Coefficient Routine Investigation Machine] data clearly shows that an increase in microtexture can also be achieved using this technology . . . the trial has proven that the shotblasting technology is very effective in reinstating both macro and microtexture to a wide variety of

road surfaces. The process has the added advantage in that it uniformly treats all areas of the road surface without excessively damaging surface integrity, and effectively improves both macro and microtexture. It is environmentally friendly in that it is a dust free process and recycles all materials used and generated by the process" (Bennett 2007, p. 23).

The major factor affecting the speed in which the shotblaster can operate is the relative hardness of the asphalt binder (Gransberg 2009). As temperature increases, asphalt binder becomes softer and is able to absorb more of the shots impact. This reduces the operating speed of the shotblaster and production rate decreases, which increases the cost per square yard. Aggregate hardness does not affect operation rate, however it does affect surface friction gain. Initially, softer aggregate gains a larger amount of microtexture than harder aggregate, however softer aggregate loses this microtexture faster than harder aggregate (Gransberg, 2009). This is where the application of the lithium silicate densifier can provide benefit (Gransberg and Pittenger, 2012).

Cost

Initial DOS treatment cost has been estimated to be $3.00 per square yard, on average, depending on project quantities. This equates to approximately $21,000 per lane-mile.

Life cycle cost analysis results indicate that DOS has a comparable life cycle cost related to the other surface treatments. In practice, commodity volatility could greatly impact the output (e.g. rise in lithium or crude oil prices). For example, hot mix asphalt and microsurfacing prices are driven by the volatile crude oil market, and therefore, DOS may yield lower initial and life cycle costs when binder prices rise.

Construction

DOS treatment should not be applied during wet or cold weather, or in windy conditions that would cause the densifier to drift. Treatment should not be applied to damp surfaces. The pavement surface should be at least 50 degrees Fahrenheit [10 C] measured away from artificial heat sources.

Before application, the quantity, rate of application, temperature and areas to be treated should be verified. The existing surface should be cleaned before applying the DOS treatment. Shotblasting equipment should be applied to the concrete or bituminous surface at light, medium or heavy rates, based upon required texture. It should also be capable of collecting used shot and waste material. Spraying equipment to apply the silicon reactive lithium densifier should be fully atomizing. The application rate of 0.06 gal/yd^2 [0.27 L/m^2] should be verifiable based on tank capacity.

Lastly, the treatment should be provided adequate curing time before opening to traffic. Based upon weather conditions, curing usually occurs from 30 minutes to 4 hours after application.

Application

The densifier-over-shotblasting (DOS) treatment has been found to address the issue of marginal aggregates commonly used in Oklahoma. The effectiveness of DOS has been evaluated related to increasing the overall durability and wear resistance of aggregate by improving resistance to polishing and abrasion through the application of a chemical treatment. The effectiveness of DOS to restore and maintain acceptable microtexture (skid) values and macrotexture for asphalt and concrete pavements and bridge decks has also been evaluated. It has been found that the chemical application or DOS treatment was able *to inhibit polishing and abrasion through the chemical hardening of aggregate* and *inhibit microtexture and macrotexture deterioration of road surfaces.* A multi-attribute analysis that evaluated the economic viability and environmental performance of the DOS technique indicates that it is a viable and sustainable alternative that can be included in the Oklahoma Department of Transportation (ODOT) *Pavement Preservation Treatment Toolbox*.

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