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LABORATORY EVALUATION OF THIN ASPHALT CONCRETE OVERLAYS FOR PAVEMENT PRESERVATION

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16. Abstract

A significant percentage of the existing lane miles of roadways in the United States, and in particular in Nevada, consists of rural roads. Thus, using a cost-effective pavement surface treatment becomes critical and essential in reducing maintenance and preservation costs on rural and low volume roads. The overall objective of this study was to assess the use of locally available materials in Nevada for the development of a durable fine-graded thin hot-mix asphalt (HMA) overlay mixture for pavement preservation. Accordingly, a comprehensive laboratory evaluation was conducted. The investigation considered establishing two mix designs using typical local materials for the northern and southern part of the state. For each mixture, the determined optimal binder content based on volumetric properties was varied within the allowable tolerances to simulate the potential variation in asphalt binder content during plant production. The performance of the two thin HMA mixtures were then evaluated at the various asphalt binder contents in terms of their resistance to moisture damage, resistance to surface raveling and abrasion, dynamic modulus property, resistance to rutting, and resistance to reflective cracking. Furthermore, the workability of the designed thin HMA overlay mixtures using the locking point concept in addition to the developed interlayer bond strength using the Louisiana Interlayer Shear Strength Tester were evaluated. Overall, both designed fine-graded mixtures showed a very good performance and are expected to perform well when used as a thin HMA overlay in Nevada. In particular, good stability, very good resistance to surface raveling and abrasion, and excellent resistance to reflective cracking were observed for both thin HMA overlay mixtures at all evaluated asphalt binder contents. A cost analysis was also conducted between the thin HMA overlay and a typically used pavement surface treatment. Based on the findings from this study, it was recommended to construct field test sections in various parts of the state to evaluate the field performance of the developed thin HMA overlay mixtures in Nevada.

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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 oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: 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 or (F-32)/1.8	Celsius	°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 inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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CHAPTER I: INTRODUCTION

Over the last 35 years, the United States Departments of Transportation and highway agencies changed their emphasis from the construction of new roads to maintenance and rehabilitation of existing infrastructure by using several pavement preservation techniques *(1)*. These techniques are defined as a set of cost-effective practices designated to extend pavement life, improve safety, and save public tax dollars. Table 1 shows the different possible preservation treatments typically used for flexible and rigid pavements.

Table 1. Preservation Techniques for Flexible and Rigid Pavements.

Flexible pavement treatments	Rigid pavement treatments
Asphalt Rejuvenators	Crack Sealing
Asphalt Sealers	Joint Resealing
Crack Sealing	Spall Repair
Crack Filling	Dowel Bar Retrofit
Scrub Seals	Cross Stitching (longitudinal cracks & joints)
Chip Seals	Partial Depth Repair
Cape Seals	Full Depth Repair (limited number of repairs)
Slurry Seals	Ultra-Thin White Topping
Micro-surfacing	Undersealing
Ultra-thin Overlays	Slab Lifting
Bonded Wearing Course	Diamond Grooving
Profile Milling	Diamond Grinding
Thin Overlays (non-structural, generally ≤ 1½ inch)	CPR (concrete pavement restoration)
Mill & Resurface (non-structural, generally ≤ 1½ inch)	-
Hot In-place Recycling	-
Cold In-place Recycling	-

The Nevada Department of Transportation (NDOT) uses various maintenance and rehabilitation repair strategies to improve the overall states' pavement network condition *(2, 3)*. The maintenance repair strategies for flexible pavements include work such as chip seals, filling potholes, and patching. The rehabilitation repair strategies include work such as asphalt overlays and recycling methods. The cost and construction timing for the various repair strategies are significantly different and depend on the pavement condition at the time of the repair *(3)*. For instance, some treatments are applied on a schedule basis such as the proactive treatments. A significant cost saving is anticipated when a pavement is proactively rehabilitated in fair to good condition as compared to reactively reconstructed in very poor condition. For example, a proactive asphalt overlay prevents the pavement from deteriorating to a point when more expensive major rehabilitation or reconstruction strategies are required.

Recently, NDOT expressed interest in using thin hot-mix asphalt overlays as a mean to extend the available funds for pavement maintenance and preservation and for essentially delaying future need for pavement rehabilitation. As a routine maintenance and pavement preservation tool, thin asphalt overlays were classified as extremely useful for asphalt and composite pavements according to an American Association of State Highway and Transportation Officials (AASHTO) survey done by the Lead States Team on Pavement Preservation in 1999 *(1, 4)*. These overlays are defined as surface courses typically placed no more than 1.5 in. (38 mm) thick on a well prepared surface *(5)*. Used as simple surface lifts or part of mill-and-fill strategies, their essential function is not to strengthen the pavement but to address functional problems *(5)*. Thin asphalt overlays are used to protect the pavement structure, slow the rate of deterioration, correct many surface deficiencies, improve ride quality, and add a minor amount of enhancement to the existing pavement *(1)*.

In 2014, a study was sponsored by the SOLARIS institute (Tier 1 University Transportation Center) and NDOT to assess the use of locally available materials in the state of Nevada for the development of a durable fine-graded thin hot-mix asphalt overlay mixture for pavement preservation *(6)*.

The first task of this study consisted of a review of literature to compile information on the available research, overall characteristics and properties (e.g., benefits, applications, factors affecting the application, functional and structural characteristics, and treatment life), materials and mix design (e.g., aggregate gradations and optimal laboratory compaction), and construction of thin asphalt concrete (AC) overlay (e.g., surface treatment and preparation, placement and in-place compaction, quality control, and performance).

The second task consisted of identifying the properties of the designed thin hot-mix asphalt concrete mixtures through a comprehensive laboratory evaluation. The designed mixtures were evaluated in terms of their resistance to moisture damage (i.e., Tensile strength ratio), surface raveling (i.e., raveling test), surface abrasion (i.e., Cantabro loss test), rutting (i.e., unconfined flow number test), and reflective cracking (i.e., Texas Overlay test). The workability and compactability of the thin hot-mix asphalt designed mixtures were evaluated using the pressure distribution analyzer (PDA) mounted recently as a permanent part in the Superpave Gyratory Compaction machine (SGC). The bond strength between the thin hot-mix asphalt overlay and the existing asphalt layer was also evaluated using the Louisiana Interlayer Shear Strength tester (LISST).

The third task of the study consisted of providing recommendations for the use of thin AC overlays in Nevada relative to design, materials, mix design criteria, and acceptance testing.

This report is the final product of this SOLARIS research project. The report has been divided into chapters covering the various efforts of the study: background and general overall view, mix design and testing, performance analysis, and summary and conclusions.

I.1 Problem Statement

Regardless of the anticipated benefits, the historical success of thin AC overlays varied among the various state highway agencies (SHAs). A 2008 AASHTO questionnaire study revealed that out of the twenty five states that have used thin AC overlays before, eleven reported less than satisfactory results *(7)*. The reported problems with thin AC overlays included delamination, reflective cracking, poor friction, low durability, excessive permeability, and maintenance problems once failure occurs. A high resistance to reflective cracking and moisture damage along with a good bond to the existing asphalt layer are deemed necessary in order to guarantee an extended performance life for a thin AC overlay. Furthermore, past experiences revealed that thin AC overlays can be in some cases susceptible to early rutting problems due to mix instability under heavy traffic.

Based on the varying success of using thin AC overlays by SHAs, the challenge of this study was to develop a stable and durable fine-graded asphalt mixture using locally available materials in Nevada to fulfill the function of a thin overlay. The developed thin AC overlay should be able to resist the various environmental and traffic conditions encountered throughout the State of Nevada.

I.2 Objective

This study was conducted to provide NDOT with a comprehensive evaluation of the material characteristics and design of thin hot-mix AC overlays for the State of Nevada. For this purpose, the major tasks carried out in this research were:

- Establish a review of literature by compiling information about thin AC overlays and their performance all around the United States.
- Establish a mix design for two thin hot-mix asphalt (HMA) overlay mixtures following NDOT Hveem design specifications using typically used local materials from the northern and southern part of the state.
- Evaluate the performance properties of the designed thin HMA overlay mixtures at different asphalt binder contents within allowable tolerances.
- Conduct a statistical data analysis to evaluate the variation in performance properties for each mixture at different asphalt binder contents.
- Generate conclusions and recommendations for the use of thin HMA overlay in Nevada.

CHAPTER II: REVIEW OF LITTERATURE

The objective of this chapter is to provide an overall background of thin AC overlays in the United States by summarizing the benefits, limitations and factors affecting the application of thin AC overlays; functional and structural characteristics of thin AC overlays; and treatment life and construction practices for thin AC overlays.

II.1 General Overview

Referring to a survey conducted by the National Cooperative Highway Research Program (NCHRP, synthesis 464), several limitations for the thin asphalt overlay thickness were given by several state highway agencies as shown in Table 2 and illustrated in Figure 1 *(4)*.

Table 2. State Survey for Thin Asphalt Overlay Thicknesses.

Thickness Limit (in inches)	Percentage of answer
more than 2.0	3 %
Between 1.5 and 2.0	11 %
Between 1.0 and 1.5	24 %
Between 0.75 and 1.5	25 %
Between 0.75 and 1.0	28 %
Less than 0.75	9 %

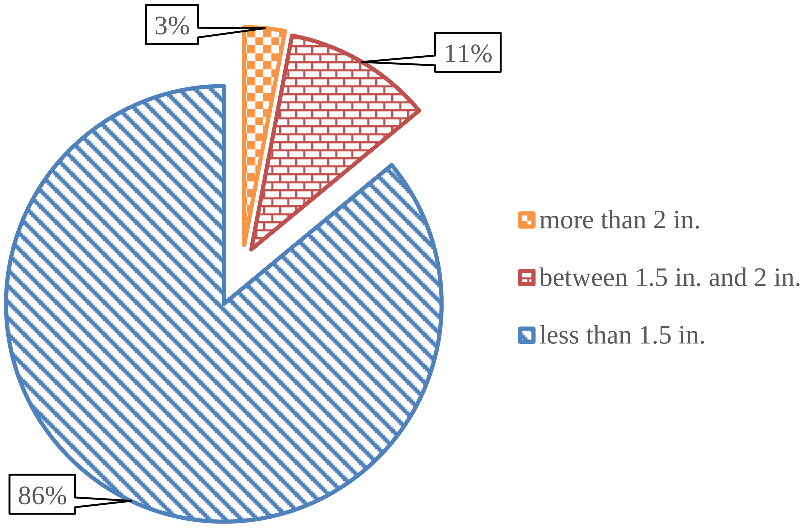


Figure 1. Summary of states responses for thin AC overlay thickness.

A thin AC overlay was defined as a surface course typically placed no more than 1.5 inch (38 mm) for more than 86% of the surveyed States' participants. Thus, because of this limitation on thickness, a smaller nominal maximum aggregate size (NMAS) is necessary for a thin AC overlay mixture. The following relationship between NMAS and the AC pavement layer thickness is typically used.

$$t = n * S \qquad \text{(Eq. 1)}$$

Where, t is the thin AC overlay thickness, S is the nominal maximum aggregate size (NMAS), and n is an integer scaling factor. Previous studies provided an integer scaling factor (n) between 1 and 3 as an acceptable range.

II.2 Benefits

Several agencies use thin AC overlays as a standard practice for pavement preservation and rehabilitation. A review of the literature revealed several benefits for thin AC overlays and are summarized as follow *(5)*:

- Long service life and reduced life cycle cost;
- Ability to preserve the road grade and slope in residential areas with minimal impact to drainage system, particularly with a small NMAS mixture;
- Ability to withstand heavy traffic and sustain high shear stresses;
- Assure a smoother surface and maintain surface geometrics;
- Prevent stones loss after initial construction and minimize dust;
- Minimize traffic delays and reduce the tire-pavement noise generation;
- Neglect the curing time and the binder runoff;
- Recycle and save a considerable amount of energy products;
- Ability to be easily maintained and used during the construction stage;
- Ability to restore the skid resistance;
- Ability to use the roadway while reconstruction is in progress;
- Saving on the construction time (i.e., an old road can be usually improved and put into full service more rapidly than building a new road).

Not all of the benefits mentioned above are present at the same time. They have a relative importance according to location of the project, climate, and existing traffic. Furthermore, an AASHTO questionnaire of twenty five different states showed that these overlays can present some limitations *(7)*. Several problems were reported such as delamination, reflective cracking, poor friction, low durability, early severe rutting and mix instability under heavy traffic, excessive permeability, and maintenance problems once failure occurs *(7)*.

II.3 Application

It is well recognized that the proper preservation technique should be applied at the right time and at the right pavement condition. The existing pavement condition, the expected traffic level, and the environmental condition can widely affect the application of these thin AC overlays *(1, 8)*.

II.3.1 Existing Pavement Conditions

Applying a thin AC overlay on the top of an existing pavement surface is usually influenced by the pavement condition and the need of performing a structural rehabilitation. If the existing pavement conditions fit to the requirements, a thin AC overlay is certain to be a suitable treatment.

The existing pavement should exhibit a good base condition and a uniform cross section. The visible surface distress may include moderate to severe raveling, longitudinal and transverse cracks with the first sign of raveling and secondary cracking, first sign of edge cracking, block cracking, extensive to sever bleeding or polishing, and some patching in good condition. The pavement may also have some minor base failures and depressions *(1, 8)*. However, some limitations can prevent the use of thin AC overlays such as a weak base or a delaminated surface for a rutted pavement.

According to the Maintenance Division at the California Department of Transportation (Caltrans), the primary failure modes of thin AC overlays are as follow: delamination, raveling, cracking due to poor compaction, fast cooling, and less cohesion *(9)*.

II.3.2 Traffic Level

Thin AC overlays were originally considered as a part of the standard pavement preservation techniques used for low-volume roads. However, latest studies indicated that this technique can also be effective and well workable for high-volume roads *(1, 8)*.

II.3.3 Existing Environment

According to Liu and Gharaibeh *(8)*, the climate constitutes an important factor for the performance of a thin AC overlay. A shorter performance life is expected in dry- and wet-freeze environments. In addition, moisture may have a low impact leading to a variation in the service life time of a thin AC overlay.

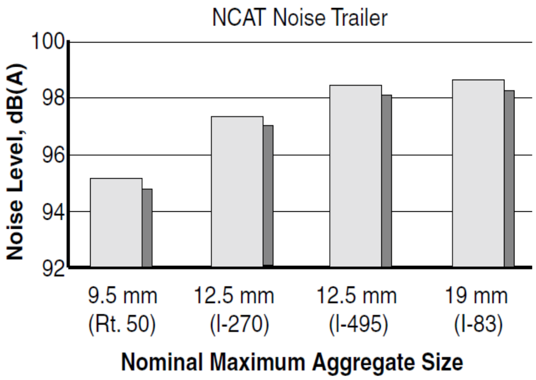
II.4 Characteristics

The thin AC overlay presents some functional and structural characteristics which are summarized as follows.

II.4.1 Functional Characteristics

The following functional characteristics can be provided with the use of a thin AC overlay *(1, 5)*: (a) improved ride quality by smoothening of the pavement surface; (b) improved skid resistance using polish-resistant aggregates; and (c) reduced tire-pavement noise level using smaller NMAS.

- Ride Quality Improvement: the possibility to improve the ride quality with a thin AC overlay improves appreciably when a milling process precedes the overlay placement. Milling is recommended to improve smoothness because it provides an initial surface leveling, removes surface distresses, and assures a uniform surface for the overlay construction. The ride quality improvement on flexible pavements can lasts over a dozen years before reverting to the same ride quality prior to the thin AC overlay application. On the other hand, the duration of the ride quality improvement decreases to seven years in the case of composite pavements.
- *Skid Resistance Improvement*: the skid resistance can be widely improved by the use of a thin AC overlay. If an existing pavement surface was constructed with polishing aggregates, or has been subjected to bleeding, it can be a good candidate for improved friction. Friction can be improved with a thin AC overlay by using skid-resistant aggregates with a specific gradation.
- *Noise Level Reduction*: It is well-known that the pavement-tire noise generation is largely affected by the pavement surface macro-texture (increase noise level with coarser macro-texture of the pavement surface). Figure 2 shows the reduction in the generated noise level with the decrease in the NMAS.



After NAPA Study IS 135

Figure 2. Noise level variation as a function of NMAS. *(1)*

II.4.2 Structural Characteristics

In general, the essential function of a preventive maintenance technique (e.g., slurry seal, chip seal, micro-surfacing) is not to strengthen the existing pavement capacity but primarily to address issues related to pavement functional performance. However, a 0.5 to 1.0 inch (12.5 mm to 25.0 mm) AC overlay can add to the structural capacity of the existing pavement **Error! Reference source not found.**. For instance, the tensile strain at the bottom of the existing AC layer decreases and the fatigue life repetitions to failure increases when additional inches of AC are added on top of the existing pavement (Figure 3). This reduction in fatigue life can be significant even within the typical thicknesses of 1 to 2 inches for the thin AC overlay.

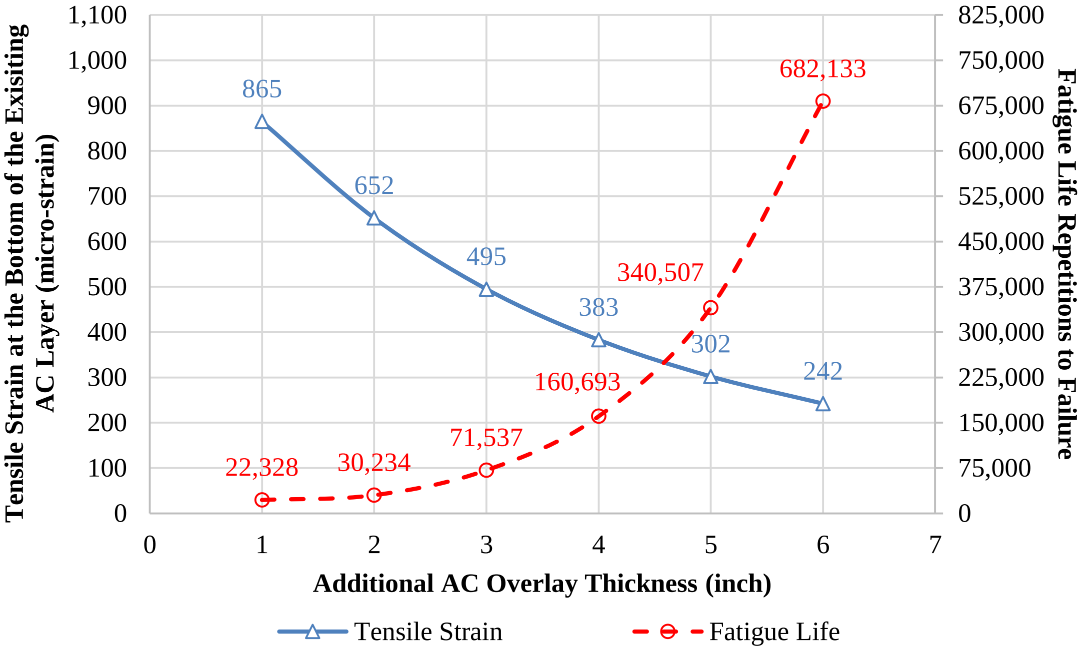


Figure 3. Example for tensile strain and fatigue life repetitions variations as a function of the overlay thickness increment. Error! Reference source not found.

II.5 Treatment Life

Thin AC overlays have been shown as one of the most cost-effective methods used as a pavement preservation technique. Table 3 summarizes the treatment lives for commonly used preventive maintenance treatments as well as cost estimates per lane mile from two national studies. It should be noted that the presented average treatment lives from the NCHRP Synthesis 464 were based on some qualitative perceptions rather than well-designed quantitative experimental analyses. Newcomb *(1)* showed that the thin AC overlay can have a performance life of ten years or more when applied to a flexible pavement, and six to ten years when placed on the top of a rigid pavement surface. Table 3 clearly show a higher expected life for the thin AC overlay when compared to other commonly used pavement preservation treatments. Given the prolonged treatment life, there has been interest by highway agencies in using thin AC overlays to extend the available funds for maintenance and preservation and increase the number of lane-miles to be resurfaced annually.

Table 3. Treatment Life of and Cost Estimate for Selected Preventive Maintenance Treatments.

Reference	Treatment Type	Average Treatment Life (years)	Cost Estimate per Lane Mile (U.S. Dollars)
NCHRP Synthesis 464, 2014 *(5)*	Thin Asphalt Concrete Overlay	8.4	14,600
	Double chip seal	7.3	12,600
	Micro-surfacing	7.4	12,600
	Slurry Seal	4.8	6,600
NAPA, Information series 135, 2009 *(1)*	Thin Asphalt Concrete Overlay • FHWA *(11)* • Florida • Minnesota • New York • Ohio	 8 – 11 10 – 12 5 – 8 8 8 – 12	Not Provided

II.6 Mixture Properties

The success of the pavement is essentially based, among others, on the proper selection of the raw materials. This section of the report provides some information from the literature on thin AC overlay mix designs and requirements to assure a good field performance.

II.6.1 Aggregate Gradation and Properties

The use of a smaller NMAS in thin AC overlay mixtures is essential in order to be able to reach the desired thin layer thickness without crushing the aggregates under the induced high stresses from the compaction effort and the traffic loading. The smaller size of aggregates when compared to typical dense-graded surface mixtures implies a high specific area which could lead to a higher asphalt binder content for the thin AC overlay mixture.

Table 4 shows typical gradations for thin AC overlay based on a national survey conducted by NAPA in 2009 *(1)*. Accordingly, it was recommended to use a maximum NMAS of 0.5 inch (12.5 mm) for thin AC overlay mixtures. Table 5 presents the revised NDOT gradation for thin AC overlays with a NMAS of 12.5 mm (compared to the previous gradation with a 9.5 mm NMAS). Figure 4 compares the NDOT gradation limits for thin AC overlay to limits from other selected states.

Table 6 summarizes the aggregate qualifications and properties for selected state agencies according to the NAPA 2009 study *(1)*. The requirements for coarse and fine aggregates varied according to locally available materials as well as traffic levels.

Table 4. Typical Aggregate Gradations for Thin AC Overlay Mixtures from Various State Agencies. *(1)*

Sieve Size	Percent Passing by Weight							
	NMAS							
	1/2 inch 12.5 mm		3/8 inch 9.5 mm				No. 4 4.75 mm	
	Alabama	N. Carolina	Utah	Nevada	Georgia	Ohio	New York	Maryland
3/4 inch 19 mm	100	100						
1/2 inch 12.5 mm	90 – 100	85 – 100	100	100	100	100		
3/8 inch 9.5 mm	< 90	60 – 80	90 – 100	85 – 100	90 – 100	95 – 100	100	100
No. 4 4.75 mm		28 – 38	< 90	50 – 75	75 – 95	85 – 95	90 – 100	80 – 100
No. 8 2.36 mm	28 – 58	19 – 32	32 – 67		60 – 65	53 – 63	30 – 70	36 – 76
No. 50 0.300 mm		8 – 13			20 – 50	4 – 19		
No. 200 0.075 mm	2 – 10	4 – 7	2 – 10	3 – 8	4 – 12	3 – 8	2 – 10	2 – 12

Table 5. NDOT Gradation Limits for Thin AC Overlay Mixtures (2014).

Sieve Size	Percent Passing by Weight
3/4 inch 19 mm	100
1/2 inch 12.5 mm	90 – 100
3/8 inch 9.5 mm	70 – 90
No. 4 4.75 mm	50 – 70
No. 8 2.36 mm	
No. 10 2.00 mm	30 – 50
No. 40 0.425 mm	12 – 24
No. 50 0.300 mm	
No. 200 0.075 mm	3 – 8

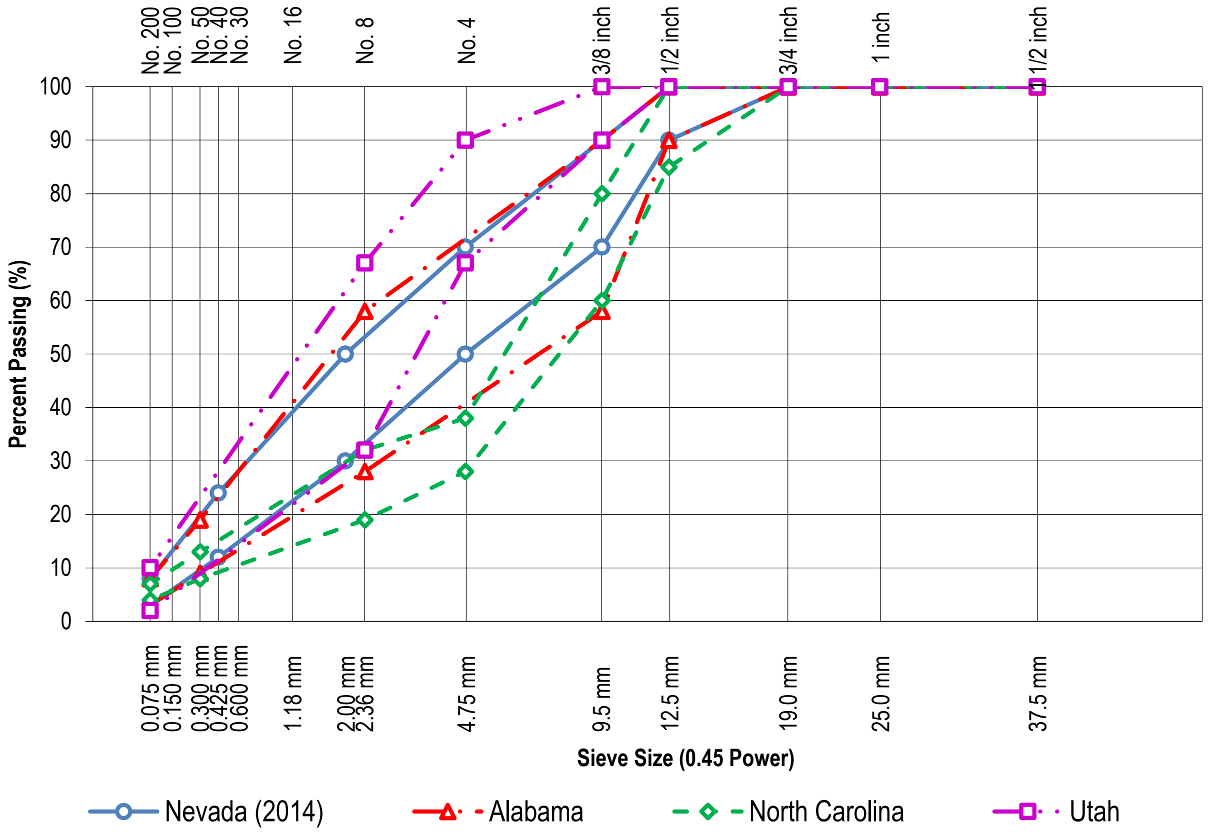


Figure 4. Comparison of gradation limits from selected State Agencies.

Table 6. Aggregate Qualifications and Properties for Thin AC Overlay Mixtures from Selected State Agencies.

Aggregate Properties	State Agency					
	Alabama	**Nevada**	**New York**	**N. Carolina**	**Ohio**	**Utah**
LA Abrasion (% Loss)	48 Max	37 Max		35 Max	40 Max	40 Max
Sodium Sulfate Soundness (% Loss)	10 Max	12 Max		15 Max	12 Max	16 Max
Fractured Faces • % 2 or more • % 1 or more		80 Min		85 Min 100	100	90 95
Sand Equivalent			45 Min	45 Min		45 Min
Un-Compacted Void Content	43 Min		43 Min	40 Min		

II.6.2 Asphalt Binders

In general, two factors, the climate and the traffic level, influence the selection and specification of the asphalt binder performance grade (PG). Some state agencies use modified asphalt binders for their mixes as shown in Table 7.

Table 7. Asphalt Binder Types Used for Thin AC Overlay Mixtures in Selected State Agencies. *(4)*

State Agency	Asphalt Binder Type
Minnesota	Straight asphalt binder
New Jersey	Polymer-modified PG76-22
New York (downstate region)	Polymer-modified PG76-22
New York (upstate region)	Polymer-modified PG64-22
North Carolina (ESAL level: highest)	Polymer-modified PG76-22
North Carolina (ESAL level: lowest)	Polymer-modified PG64-22
Ohio	Polymer-modified PG64-22 or PG76-22

II.6.3 Mix Design

Table 8 summarizes, for selected state agencies, the mix design characteristics for the thin AC overlay. Some agencies (e.g., Georgia, Illinois, North Carolina, Ohio, Texas, and Washington) includes other performance criteria like a rutting failure limit using either the Asphalt Pavement Analyzer (APA) or the Hamburg Wheel-Tracking Device (HWTD) to evaluate mixture's resistance to rutting. In Texas, the Texas Overlay Tester is used to evaluate the resistance of the thin AC overlay mixture to reflective cracking. The design number of gyrations (N_{design}) has also been adjusted based on the traffic level and NMAS of the thin AC overlay mixture. It has been recommended that each agency determines N_{design} based on the optimum locking point of the aggregate structure in the thin AC overlay mixture **Error! Reference source not found.**.

Table 8. Mix Design Characteristics for Thin AC Overlay in Selected State Agencies *(1)*

Property	State Agency							
	Alabama	Georgia	Maryland	Nevada	New York	North Carolina	Ohio	Utah
Design Number of gyrations, N_{design} – based on traffic level	60	50	50 – 65	N/A	75		50 – 75	50 – 125
Design Air Voids (%)		4 – 7	4	3 - 6	4		3.5	3.5
VMA (%)	15.5 min			12 - 22	16 min		15 min	
VFA (%)		50 – 80			70 - 78			70 - 80
Asphalt Content (%)	5.5 min	6.0 – 7.5	5.0 – 8.0			4.6 – 5.6	6.4 min	

II.7 Construction Practice

II.7.1 Surface Preparation

It is well recognized than properly treating the pavement surface before adding any overlay is essential for achieving a better in-service life of the overlay. The pavement surface treatment varies from a project to another and depends on the existing pavement condition and distress severities. It has been recommended that the surface of the existing pavement should be prepared as follows before the application of the thin AC overlay **Error! Reference source not found.**.

- All the dirt and silt should be cleaned and removed from the existing surface, especially after milling the pavement surface.
- A geotextile fabric can be applied above the milled surface to increase the tensile strength of the overlaid surface; thus, leading to a potential reduction in reflective cracking.

- A tack coat can be used to ensure a sufficient bond between the succeeding layers of a pavement because the interface is close to the additional shearing forces caused by breaking and turning traffic. A good bond prevents delamination and ensures long-term performance and lasting ride quality.

II.7.2 Placement and Compaction

Many agencies in the United States require the use of a materials transfer vehicle (MTV) to maintain a continuous paving operation *(12, 13, 14).* In some cases, the MTV may also contribute to improved road smoothness. To optimize the paver performance, steady state conditions have to be defined for the operation. The ability to adjust changes and to quickly bring the paver back to a steady state is a distinct advantage. The paver should directly deal with the environment changes: either those reactive to the environment or those being induced changes at the operator's discretion. The synchronization should be well controlled. The number of rollers is fixed in a way to keep up with the paver and to control a steady state operation. In general the thinner the lift, the faster the paver travel speed *(12, 13, 14).* Vibratory rollers are not typically used to compact thin AC overlays to avoid the fracture of the aggregate particles. Reaching compaction with thin AC overlay is generally more difficult because of the low accuracy of measuring the density and verifying the required adequate compaction. In addition, several factors make a thin AC overlay more difficult to compact such as the boundary effect of the underlying layer and the maximum effective particle size and its influence on the concentration of the coarse aggregate. For layers thicker than 1 inch (25.4 mm), the density is usually compared to the theoretical void less density. Some agencies use nuclear or nonnuclear density gauges to evaluate roadway density. In other cases, the contractor can monitor the compaction during the construction to accept the required density.

In general, because the thin AC layers cool faster than thick layers, the time window for compaction is reduced. In addition, if the targeted air voids is not reached during compaction, the thin AC layer will be less cohesive and ravel or delaminate faster *(12, 13, 14).* All these issues can be resolved by the correct selection of the asphalt binder grade, adjustments to the gradation not limited only to the NMAS and the grain size distribution, and the optimal compaction during construction.

II.7.2 Quality Control

Three main stages are considered as essential for the quality control (QC) of the thin asphalt overlay mixtures **Error! Reference source not found.**: the materials before entering the plant, the mixtures after production, and the paving process. Aggregate gradations and moisture measurements should be checked in the plant. At each step of production, a mixture sample is checked and all its volumetric properties and characteristics are measured. The asphalt content, voids in mineral aggregates (VMA), and air voids (AV) can be tracked with time and a control chart should be developed showing warning limits and action limits. The density in the final mat is so important and especially for mats that are so thin (1 inch or less). It is often best to use density gauges on this type of pavement construction to monitor the consistency in density because it is difficult to drill and trim cores and obtain an accurate in-situ density measurement *(1, 5)*.

CHAPTER III: EXPERIMENTAL PROGRAM

This chapter provides some detailed information about the materials used in this study and presents the experimental program followed to complete this research. In addition, a description of the test methods used as part of this study is provided.

III.1 Materials

III.1.1 Aggregates

Two commonly used aggregate sources in asphalt mixtures were evaluated in this study: the Lockwood pit from Northern Nevada, and the Lone Mountain pit from southern Nevada. Figure 5Figure 5. Map showing the approximate locations for the two selected aggregate sources. shows the approximate locations of the two selected pits in this study. The Lockwood aggregates are best characterized as a complex volcanic sequence consisting of Basalt, Andesite, and Rhyolite while the Lone Mountain aggregates are a combination of Limestone and Dolomite. The aggregate gradations for the laboratory evaluation were selected in accordance with the 2014 NDOT gradation limits for thin AC overlays (Table 5). Aggregate stockpiles were obtained from each source and were blended using appropriate proportions to meet target gradation. The gradations of the individual stockpiles are shown in Table 9 and Table 10 for the Lockwood and Lone Mountain sources, respectively. Figure 6 and Figure 7 illustrate the aggregate gradation curve of the blend for the northern (Lockwood) and southern (Lone Mountain) mixtures, respectively.

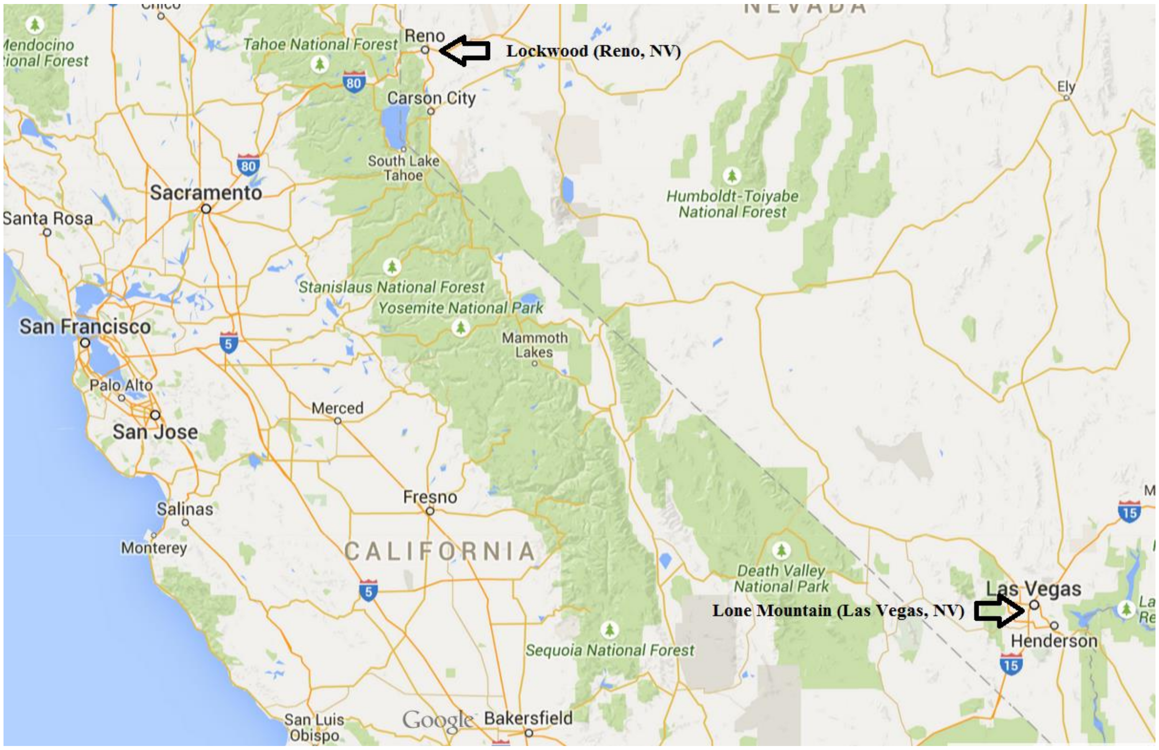


Figure 5. Map showing the approximate locations for the two selected aggregate sources.

Table 9. Aggregate Gradations for Selected Stockpiles from Lockwood Pit.

Sieve Size	**Percent Passing by Weight**				
	3/4" AGG.	1/2" AGG.	3/8" AGG.	Crushed Fines	Natural Fines
25.0 mm (1")	100.0	100.0	100.0	100.0	100.0
19.0 mm (3/4")	100.0	100.0	100.0	100.0	100.0
12.5 mm (1/2")	38.2	99.7	100.0	100.0	100.0
9.5 mm (3/8")	4.2	48.4	99.6	100.0	100.0
4.75 mm (No. 4)	0.3	0.7	18.7	97.9	99.2
2.36 mm (No. 8)	0.3	0.5	0.8	72.0	97.9
2.00 mm (No. 10)	0.3	0.5	0.7	64.8	97.4
1.18 mm (No. 16)	0.3	0.4	0.6	45.7	94.5
0.6 mm (No. 30)	0.3	0.4	0.6	29.9	78.4
0.425 mm (No. 40)	0.2	0.4	0.6	25.3	60.0
0.3 mm (No. 50)	0.2	0.3	0.5	21.5	36.6
0.15 mm (No. 100)	0.2	0.3	0.5	16.6	9.8
0.075 mm (No. 200)	0.2	0.3	0.4	12.8	2.7

Table 10. Aggregate Gradations for Selected Stockpiles from Lone Mountain Pit.

Sieve Size	**Percent Passing by Weight**		
	1/2" AGG.	Crushed Fines	Rinker Sand
25.0 mm (1")	100.0	100.0	100.0
19.0 mm (3/4")	100.0	100.0	100.0
12.5 mm (1/2")	100.0	100.0	100.0
9.5 mm (3/8")	74.6	100.0	100.0
4.75 mm (No. 4)	4.6	97.4	99.9
2.36 mm (No. 8)	1.9	69.5	97.9
2.00 mm (No. 10)	2.3	63.7	97.2
1.18 mm (No. 16)	1.5	46.9	94.9
0.6 mm (No. 30)	1.1	33.9	90.4
0.425 mm (No. 40)	0.9	28.2	84.5
0.3 mm (No. 50)	0.9	25.4	71.7
0.15 mm (No. 100)	1.2	19.9	26.6
0.075 mm (No. 200)	1.0	15.0	6.5

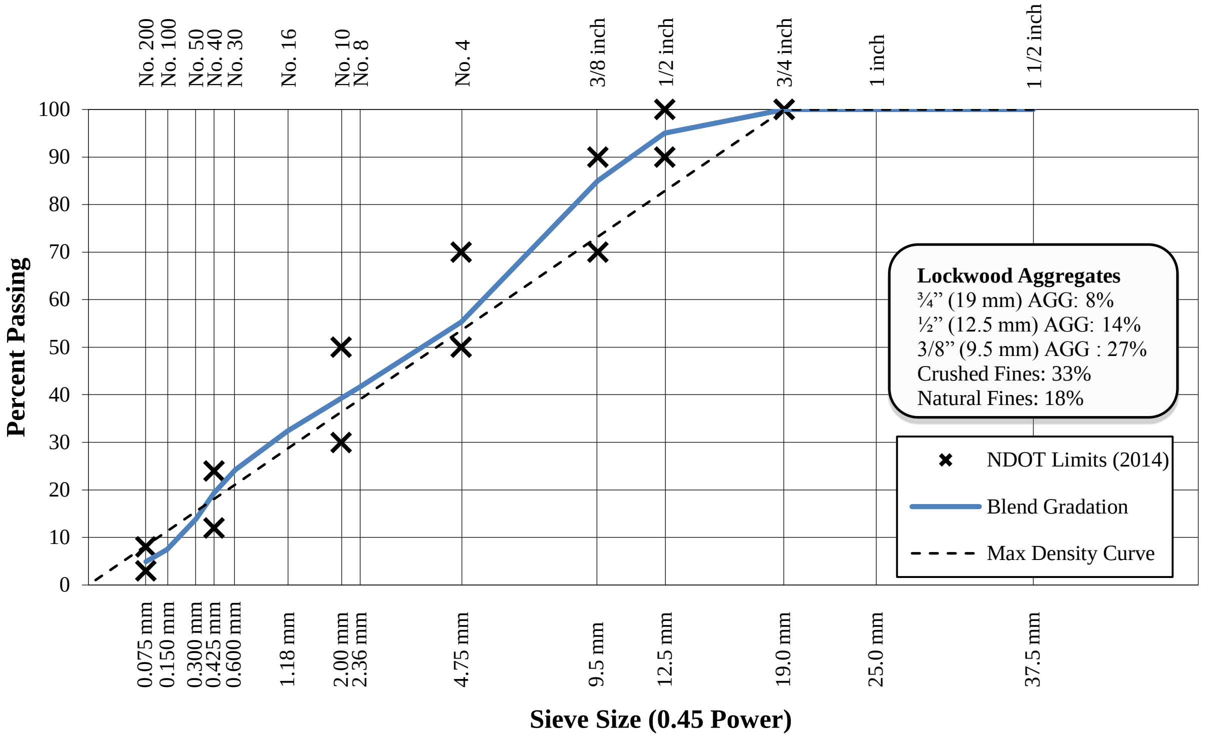


Figure 6. Aggregate blend gradation for the Lockwood mixture.

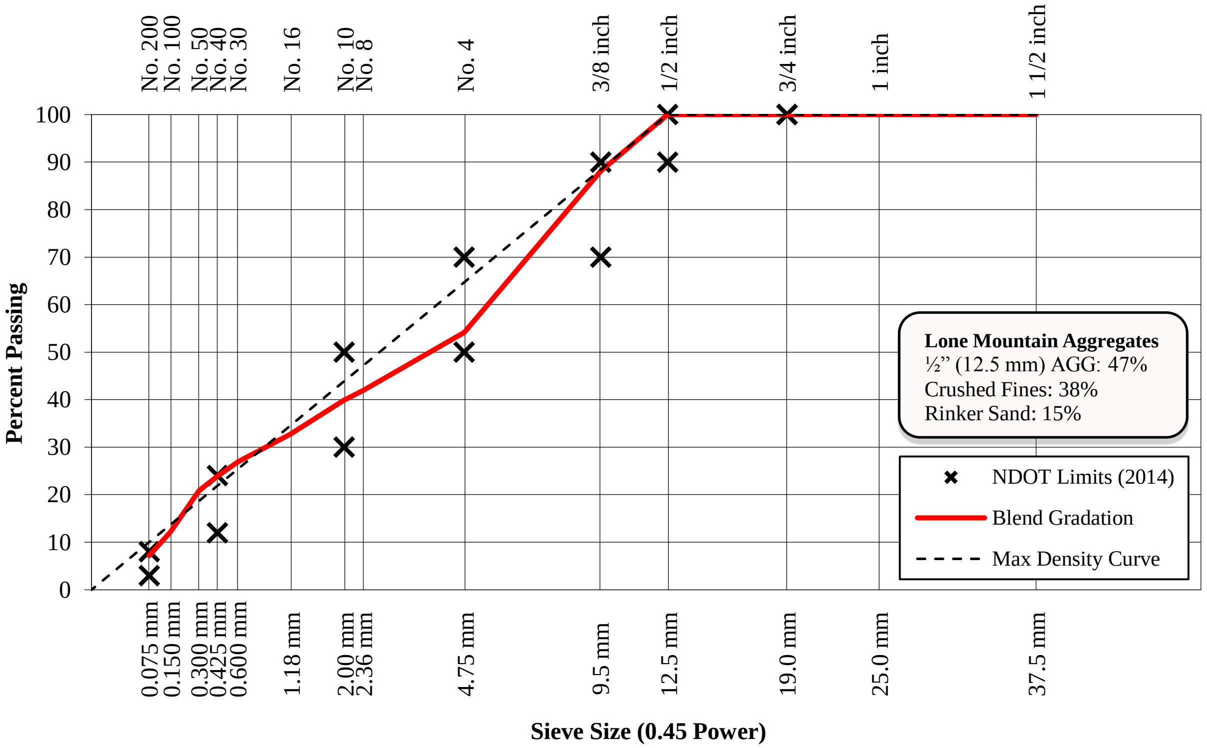


Figure 7. Aggregate blend gradation for the Lone Mountain mixture.

III.1.2 Asphalt Binders

Typical PG64-28NV and PG76-22NV polymer-modified asphalt binders, supplied by Paramount Petroleum Company and Ergon Asphalt Products, were used with the northern and southern aggregate sources, respectively. The Superpave Performance Grading (PG) binder system (AASHTO M320 *(15)*) was used to verify the grades of the sampled asphalt binders. The "*NV*" extension indicates that the asphalt binders have been graded with the PG-plus system which includes the Superpave PG binder system plus the following properties:

- For PG64-28NV: ductility at 39°F (4°C) for original and rolling thin film oven (RTFO) residue binder, and toughness and tenacity at 77°F (25°C) for original binder.
- For PG76-22NV: ductility at 39°F (4°C) for original binder, and non-recoverable creep compliance and creep recovery for RTFO binder.

Table 11 and Table 12 show that both asphalt binders met the NDOT PG-plus specifications and requirements.

Table 11. Properties of the PG64-28NV Asphalt Binder.

Property	**Test Results**	**Specifications**	**Test Method**
Test on Original Binder			
Flash Point, °C	298	230 min.	AASHTO T48
Viscosity at 135°C, Pa.s	0.715	3.00 max.	AASHTO T316
Dynamic Shear, G*/sinδ , Test Temp 64°C at 10 rad/s, kPa	1.63	1.00 min.	AASHTO T315
Ductility at 4°C, 5 cm/min, cm	77	50 min.	Nev. T746
Toughness at 25°C, Inch.lb	138	110 min.	Nev. T745
Tenacity at 25°C, Inch.lb	122	75 min.	Nev. T745
Solubility, %	Not Tested	99.0 min.	AASHTO T44
Sieve, Particulates Retained	Not Tested	0	Nev. T730
Tests on Rolling Thin Film Oven (RTFO) Residue, AASHTO T240			
Mass Loss, %	0.46	1.00 max.	AASHTO T240
Dynamic Shear, G*/sinδ , Test Temp 64°C at 10 rad/s, kPa	3.43	2.20 min.	AASHTO T315
Ductility at 4°C, 5 cm/min, cm	46	25 min.	Nev. T746
Tests on Residue from Pressure Aging Vessel Residue, AASHTO R28 @ 100 ˚C			
Dynamic Shear, G*.sinδ , Test Temp 22°C at 10 rad/s, kPa	1,674	5,000 max.	AASHTO T315
Creep Stiffness, S, Test Temp -18°C at 60 s, MPa	140	300 max.	AASHTO T313
Creep Stiffness, m-Value, Test Temp -18°C at 60 sec	0.330	0.300 min.	AASHTO T313

Table 12. Properties of the PG76-22NV Asphalt Binder.

Property	Test Results	Specifications	Test Method
Test on Original Binder			
Flash Point, °C	304	230 min.	AASHTO T48
Viscosity at 135°C, Pa.s	1.540	3.00 max.	AASHTO T316
Dynamic Shear, G*/sinδ , Test Temp 76°C at 10 rad/s, kPa	1.49	1.30 min.	AASHTO T315
Ductility at 4°C, 5 cm/min, cm	36	20 min.	Nev. T746
Solubility, %	Not Tested	99.0 min.	AASHTO T44
Sieve, Particulates Retained	Not Tested	0	Nev. T730
Polymer Content, % by mass	Not Tested	3.0 min	AASHTO T302
Tests on Rolling Thin Film Oven (RTFO) Residue, AASHTO T240			
Mass Loss, %	0.06	1.00 max.	AASHTO T240
Creep Recovery, $R_{3.2}$, Test Temp 76°C at 3.2 kPa, %	60.9	30.0 min.	AASHTO T350
Non-Recoverable Creep Compliance, $J_{nr\ 3.2}$, Test Temp at 76˚C at 3.2 kPa, kPa^{-1}	0.8	2.0 max.	AASHTO T350
Non-Recoverable Creep Compliance Difference, $J_{nr\ diff}$, %	88.0	--	AASHTO T350
Tests on Residue from Pressure Aging Vessel Residue, AASHTO R28 @ 110 ˚C			
Dynamic Shear, G*.sinδ , Test Temp 31°C at 10 rad/s, kPa	925	5,000 max.	AASHTO T315
Creep Stiffness, S, Test Temp -12°C at 60 s, MPa	60	300 max.	AASHTO T313
Creep Stiffness, m-value, Test Temp -12°C at 60 sec	0.346	0.300 min.	AASHTO T313

III.1.3 Hydrated Lime

Lime at a rate of 1.5% by dry weight of aggregate (DWA), was added to the mixtures in the form of dry hydrated lime on wet aggregate (3% moisture above the saturated surface dry condition) in accordance with NDOT specifications *(16)*. The dried aggregates were first mixed with water for two minutes, and then dry hydrated lime was added and remixed with moistened wet aggregates for three additional minutes. The lime-treated aggregates were then marinated in a sealed plastic container for 48 hours prior to their use in the mixing process. After marination, the samples were dried at 230˚F (110˚C) for overnight and then mixed with the asphalt binder following the correspondent mixing procedure for HMA mixtures.

III.2 Experimental Program

As mentioned before, two aggregate sources were used in this study: Lockwood from the north and Lone Mountain from the south. Typical polymer-modified asphalt binders (i.e., PG64-28NV and PG76-22NV) were used with each aggregate source from common suppliers in the north and the south. Once the stockpiles were blended and the targeted aggregate gradations were obtained, the aggregates were lime-treated following the marination process mandated by NDOT. The Hveem mix design method was adopted to establish two mix designs, one for the northern part and one for the southern part of the state of Nevada. Based on NDOT volumetric requirements *(16)*, an optimal asphalt binder content was selected for each of the developed mixtures.

The performance of the designed mixtures was evaluated in terms of their resistance to moisture damage by determining the tensile strength ratio (TSR); resistance to surface raveling and abrasion; mechanical dynamic modulus property (|E*|); resistance to rutting by conducting the unconfined flow number (FN) test; resistance to reflective cracking using the Texas overlay advanced jig; workability using the pressure distribution analyzer (PDA) incorporated in the Superpave gyratory compacter (SGC); and the developed interlayer bond strength using the Louisiana Interlayer Shear Strength Tester (LISST). Table 13 presents the experimental program adopted for this study. All testing, except for the bond test, were performed at three asphalt binder contents for each mixture: selected optimal asphalt binder content, selected optimal asphalt binder content plus allowable tolerance, and selected optimal asphalt binder content minus allowable tolerance. The purpose of the evaluation at different binder contents is to ensure that the properties of the evaluated thin AC overlay mixtures are still acceptable if any changes in the asphalt binder contents occurred during plant production within the allowable tolerances.

All mixtures were evaluated at the short-term aging condition following the Superpave recommendations since raveling, abrasion, reflective cracking, rutting and delamination are considered to be short-term distresses. The loose mixtures were subjected to 275˚F (135˚C) in a forced-draft laboratory oven for four hours prior to compaction in accordance with AASHTO R30 *(17)*. In the case of the bond test, the conditioning duration was reduced to two hours in accordance with the LISST draft AASHTO procedure.

Table 13. Summary of the Experimental Testing Program.

Property	Test Method	Number of Replicates per Mix
Tensile Strength Ratio (part of mix design)	AASHTO T283	6[b]
Resistance to Surface Raveling (percent of mass loss): • Unconditioned. • Moisture-conditioned, 3 Freeze-Thaw (F-T) cycles.	ASTM D7196	2[a] 2[a]
Resistance to Surface Abrasion (percent of mass Loss)	Tex-245-F	2[a]
Dynamic Modulus Master Curve	AASHTO TP79 / PP61	3[a]
Resistance to Reflective Cracking • Test temperature of 50°F (10°C) and Maximum Displacement Opening of 0.018” (0.457 mm).	Tex-248-F	6[a]
Resistance to Rutting using Flow Number (FN) Test: • Unconfined FN at a Single Temperature.	AASHTO TP79	3[a]
Workability and Compactability	NA[c]	2[a]
Interlayer Shear Bond Strength	Draft AASHTO	2[b]

[a] Test conducted at optimal binder content and optimal binder content ± selected allowable tolerance.
[b] Test conducted at only the selected optimal binder content.
[c] NA denotes “Not Available”

III.3 Description of Laboratory Tests

III.3.1 Raveling Test

The raveling test is conducted on the thin AC overlay mixtures to simulate the surface raveling and abrasion under traffic and weather damage. Initially, this test is typically used to measure the resistance to raveling characteristics of emulsified asphalt mixed with field aggregates, recycled asphalt pavement (RAP) mixtures, cold-in-place recycled (CIR), and cold mix asphalt (CMA) mixtures. The reduced thickness of the thin AC overlay in particular, and the dry mixture usually used in the southern part of the state make the thin AC overlay mixture potentially more susceptible to surface raveling. The test specimens, 6.0 inch (150 mm) in diameter and 2.8 inch (70 mm) in height, are placed on a raveling test adapter and allowed to abrade for 15 minutes at the room temperature according to the ASTM D7196 *(18)*. Figure 8 below shows the raveling test setup along with a thin HMA overlay specimen.

Figure 8. Installed raveling test adapter with a specimen ready for testing.

The resistance to raveling is evaluated in terms of mass loss of the specimen at the end of the test. Initially, the specimen is weighted prior to the testing and once the test is done, the sample is well cleaned from fines with a smooth brush and weighted again. The percent of difference between the two masses (prior and after test) are considered to be the percent in mass loss as shown in Equation 2 (the percent of mass loss is reported to the nearest 0.1% as an average of at least two tested replicates); where A is the specimen mass prior to test and B is the mass of the abraded specimen at the end of the test.

$$\%\,Mass\ Loss = 100 \times \left(\frac{A-B}{A}\right) \qquad \text{(Eq. 2)}$$

For this study, two sets of samples were prepared. The first set of specimens consisted of testing the compacted thin HMA overlay mixtures, once cooled down to the room temperature, without subjecting them to any additional moisture conditioning. The second set of the thin HMA overlay specimens were evaluated after moisture conditioning which consisted of subjecting the compacted mixtures to three freeze-thaw (3 F-T) cycles following the conditioning procedure outlined in AASHTO T283 *(19)* for one freeze-thaw cycle. Moisture conditioning was done to evaluate and assess the susceptibility of the evaluated mixtures to the combined effect of moisture and raveling damage.

III.3.2 Cantabro Loss Test

Another desired property to be evaluated for thin AC overlay mixtures is its ability to resist surface abrasion. Abrasion wear occurs due to rubbing, scraping, skidding, or sliding of tires on the asphalt pavement surface. The resistance of a mixture to surface abrasion is influenced by several factors such as stiffness of the asphalt mixtures, aggregate properties, surface finishing, compaction procedure, and type of toppings (i.e. Open-Graded-Friction-Coarse OGFC).

The Cantabro Loss test was used to measure the resistance of the mixtures to surface abrasion. The test measures the breakdown of the compacted specimens utilizing the Los Angeles abrasion machine in accordance with Tex-245-F *(20)*. The specimens are prepared in accordance with Tex-241-F *(21)*. The test is conducted at the room temperature on a 6.0 inch (150 mm) diameter and 4.5 inch (115 mm) height specimen compacted to a 93±1% relative density. The resistance to abrasion is evaluated by rolling the asphalt specimens in the Los Angeles machine drum at a speed of 30 revolutions per minutes, for 300 successive revolutions without including any steel ball (Figure 9).

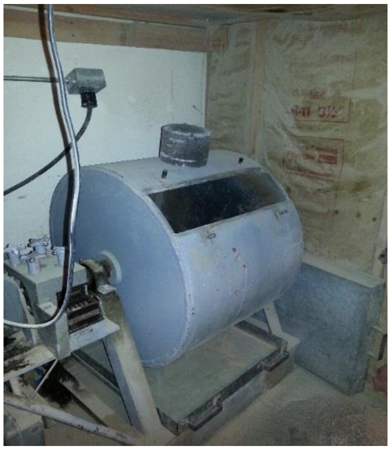


Figure 9. Los Angeles abrasion machine with a thin AC overlay specimen after testing.

The percent of loss by mass due to abrasion is called "Cantabro loss" and is related to the quantity and quality of the asphalt binder being used. The specimen is weighted prior to testing and when the test is completed after cleaning the evaluated sample from fines with a smooth brush. The percent of difference between the mass before and after the test is considered to be the percent in mass loss as shown in Equation 3 (the percent of mass loss is reported to the nearest tenth as an average of at least two tested replicates); where *CL* is the Cantabro Loss (percent of loss by mass due to abrasion), *A* is the specimen mass prior to testing, and *B* is the specimen mass at the end of the 300 revolutions.

$$CL = 100 * \left(\frac{A-B}{A}\right) \qquad \text{(Eq. 3)}$$

III.3.3 Dynamic Modulus Test

The AASHTO Pavement Mechanistic-Empirical (ME) software uses the dynamic modulus (E*) master curve to evaluate the structural response of the asphalt pavement under various combinations of traffic loads, speed, and environmental conditions. To be able to achieve and complete these simulations, the E* property of an asphalt mixture is evaluated under various combinations of loading frequency and temperatures. Sample preparation, testing and the development of the master curve were completed following AASHTO TP79 *(22)* and AASHTO PP61 *(23)*. The test was conducted using the Asphalt Mixture Performance Tester (AMPT) at frequencies of 10, 1 and 0.1 Hz (the 0.01 Hz is additionally selected only for the highest temperature) and at temperatures of 39, 68 and 104 or 113°F (4, 20 and 40 or 45°C) depending on the asphalt binder performance grade. The 104°F (40°C) was considered for the northern mixture with PG64-28NV while 113°F (45°C) was used for the southern mixture with PG76-22NV.

All the mixtures were evaluated at the short-term aging condition which consisted of subjecting loose mixture to 275˚F (135°C) in a forced-draft laboratory oven for four hours prior to compaction in accordance with AASHTO R30 *(17)*. The E* test specimen consisted of a 4.0 inch (100 mm) diameter by 6.0 inch (150 mm) height cylinder that is cored from the center of a Superpave gyratory compacted (SGC) sample of 6.0 inch (150 mm) diameter by 7.0 inch (175 mm) height. All test specimens were compacted to 7.0 ± 0.5% air voids. The dynamic modulus setup and a specimen ready for testing are shown in Figure 10.

Figure 10. Dynamic modulus testing setup.

The time-temperature superposition is used to mainly construct the master curve. The data at various temperatures are shifted with respect to time until the curves merge into a single smooth function at a single temperature known as "*reference temperature*." The time-temperature superposition is only applicable within the linear viscoelastic region on thermo-rheologically simple materials such as bituminous materials. The general form of the dynamic modulus master curve equation is shown in a sigmoidal model as follows:

$$\log E^* = \delta + \frac{E_{max} - \delta}{1+e^{\beta+\gamma \log fr}} \quad \text{(Eq. 4)}$$

where:
E^* = dynamic modulus, ksi or kPa;
δ, β, and γ = fitting parameters;
f_r = reduced frequency, Hz;
E_{max} = maximum value of the dynamic modulus, ksi or kPa.

III.3.4 Unconfined Flow Number Test

Permanent deformation can either be in the form of rutting or shoving and is most critical at the early stages of a pavement life. Rutting is caused by progressive movement of materials under repeated loads. The rutting resistance was evaluated by measuring the flow number (FN) of the evaluated thin HMA overlay mixtures in accordance with AASHTO TP79 *(22)*. The test is conducted unconfined with a repeated deviator stress of 87 psi (600 kPa) and a contact deviator stress of 4.35 psi (30 kPa). Each loading cycle consisted of a 0.1 second loading followed by a rest period of 0.9 second. The specimen for the FN test is a cylinder with 4.0 inch (100 mm) diameter and 6.0 inch (150 mm) height that is cored from the center of a SGC sample having 6.0 inch (150 mm) diameter and 7.0 inch (175 mm) height. The test specimens were compacted to 7.0 ± 0.5 percent air voids. The test temperature was selected as the design high pavement temperature at 50% reliability as determined using the Long-Term Pavement Performance Binder (LTPPBind) software Version 3.1. The temperature is computed at a depth of 0.80 in. (20 mm) below the pavement surface. The testing temperatures were determined to be 129°F (54°C) and 147°F (64°C) for the northern and southern Nevada mixtures, respectively.

The axial deformation after each pulse is measured and the cumulative permanent axial strain is calculated and plotted with respect to the number of loading cycles. This relationship covers three stages: primary, secondary, and tertiary. The FN is defined as the number of cycles at which tertiary flow begins. The Francken mathematical model is used to compute the FN value. This well suited mathematical model combines both a power model which characterizes the primary and secondary stages, and an exponential model which fits the tertiary stage *(**Error! Reference source not found.**)*. A regression mathematical analysis is conducted in order to obtain the Francken model parameters shown in Equation 5.

$$\xi_p(N) = A * N^B + C * (e^{D*N} - 1) \qquad \text{(Eq. 5)}$$

where:
ξ_p = permanent axial strain;
N = number of loading cycles;
$A, B, C,$ and D = regression constants.

III.3.5 Texas Overlay Test

Reflective cracking is one of the primary forms of distresses in asphalt overlays of flexible and rigid pavements. It may affects ride quality and allows the penetration of water and debris into these cracks which would accelerate the deterioration of the overlay and the underlying pavement, thus leading to a reduction in pavement serviceability *(25)*. The Texas overlay test was used in this study to evaluate the mixtures' resistance to reflective cracking in accordance with Tex-248-F procedure *(26)*. The horizontal opening and closing of joints and cracks that exist underneath a new asphalt overlay are specifically simulated using the Overlay jig. The Overlay test jig was recently designed to increase the functionality of the Asphalt Mixture Performance Tester AMPT machine by enabling it to determine the susceptibility of asphalt mixtures to reflective cracking.

The overlay test specimen consists of a 6 inch (150 mm) long by 3 inch (75 mm) wide and 1.5 inch (37.5 mm) thick sample that is trimmed from a 6 inch (150 mm) diameter by 4.5 inch (115 mm) height SGC sample. The trimmed test specimens are compacted to 7.0 ± 0.5 percent air voids. Once prepared, each sample is glued on two metallic plates, well fixed on a mounting wide plate using epoxy. Once dried, the samples glued to the plates are mounted in the jig making the setup ready to start the test. A photo of the overlay test set up and a specimen ready for testing is shown in Figure 11.

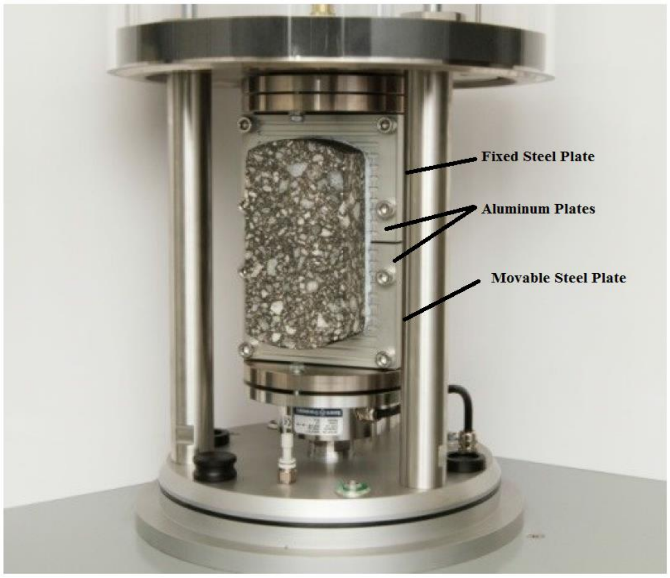


Figure 11. AMPT overlay test setup.

The test was conducted in a controlled displacement mode until the failure occurs at a loading rate of one cycle per 10 seconds with a maximum displacement of 0.018 inch (0.457 mm) at 50°F ± 1°F (10 ± 0.5°C) *(2)*. Each cycle consisted of 5 seconds of loading and 5 seconds of unloading. The number of cycles to failure was defined as the number of cycles to reach a 93% drop in initial load which is measured from the first opening cycle. If a 93% reduction in initial load was not reached within a certain specified maximum number of cycles, the test will stop automatically. A minimum value of 1,200 cycles is typically required by NDOT for a stress relief course (SRC) layer. For this study, a total of 2,500 loading cycles were first selected as a maximum number of cycles for stopping the test; but then it was increased to 5,000 cycles since no failures were observed for the evaluated thin HMA overlay mixtures. At the end of the test, the trimmed specimen density, starting load, final load, percent reduction in load, number of cycles to failure and, the number of observed cracks were reported.

III.3.6 Workability and Compactability Test

The term workability has been used to describe several properties related to the ease with which an asphalt mixture can be placed, worked by hand, and compacted. Satisfactory workability is important in obtaining the desired asphalt mixture smoothness and density within a compacted pavement. It is more difficult to construct smooth pavements with mixtures having a low workability. Pavements that are under-compacted may experience significant performance problems due to high voids. If not properly compacted, the potential for permeability problems, as well as the rate of oxidative aging of the binder increase considerably thereby reducing pavement life.

The Gyratory Pressure Distribution Analyzer (GPDA) was utilized in this study to investigate the compaction and the workability aspects of the evaluated thin HMA overlay mixtures. The GPDA was newly developed and incorporated to increase the functionality of the Superpave Gyratory Compaction (SGC) machine by enabling it to measure the pressure, moment, resistive effort and shear in addition to the height, density and angle of the sample at each gyration during the compaction process. Once mixed, the samples are conditioned for two hours at the compaction temperature according to AASHTO R30 *(17)* and then compacted to the maximum number of gyration (function of the expected traffic) using the SGC machine according to AASHTO R35 *(27)*. A typically used NDOT dense-graded Type 2C HMA mixture from each the northern and southern part of the state were used as a reference mixture *(28)*; therefore a better comparison among the workability and compactability of the mixtures can be established.

The primary objective of this test is to estimate the number of gyrations required to provide an optimum aggregate interlock, in other terms sufficient workability and best compactability. The data generated from the SGC are generally used to compute the volumetric properties such as density or air voids contents function of the number of the applied gyrations. The densification curves represent the density ($\%G_{mm}$) of the evaluated mixture sample at each applied gyration. These curves are used to evaluate the tested mixture resistance to compaction energy applied by the compaction machine. Previous studies *(29)*, suggest evaluating the mixtures' compaction characteristics based on the locking point. The locking point describes the point at which the mixture exhibits a marked increase in resistance to densification *(29)*.

The GPDA is a simple accessory that measures the force applied to the mixture using three load-cells equally spaced at angle of 120°. The variation of forces during each gyration is measured and the eccentricity of the resultant force is reported. Thus, the frictional shear resistance (FR) of each evaluated mixture can be calculated using Equation 6. The locking point corresponds to the number of gyrations at which the rate of change in the frictional resistance is less than 0.01.

$$FR = \frac{Re}{AH} \qquad \text{(Eq. 6)}$$

where,
FR = frictional resistance;
R = resultant force;
e = eccentricity;
A = cross-section area;
H = sample height at any gyration cycle.

III.3.7 Interlayer Bond Strength Test

Usually tack coats are applied on a well prepared surface before the placement of the overlay to ensure adequate bond strength between the old and the new AC layer. Shear failure may occur at the interface when the surface of the old pavement cannot provide enough strength to resist stresses due to traffic and environmental loadings. A poor interface bond strength can result in slippage, shoving and surface cracks. The Louisiana Interlayer Shear Strength Tester (LISST) was used to characterize the interface shear strength between the layers of the compacted specimens. The test was conducted in accordance with the draft AASHTO procedure that was developed as part of the NCHRP Project 9-40 *(300)*.

The test specimen consisted of a thin HMA overlay mixture compacted on top of a typical dense-graded HMA layer. A cylindrical base specimen (i.e., dense-graded Type 2C HMA) of 6.0 inch (150 mm) in diameter and 2 inch (50 mm) in height was compacted first until it reached approximately 4% air voids simulating the existing asphalt pavement layer. The base specimen is then allowed to cool down in the mold to room temperature *(300, 301)*. Three sets of samples were prepared.

- The first set of specimens consisted of placing the thin HMA overlay mixture at the compaction temperature directly on top of the cooled base part of the specimen without applying any tack coat.
- The second set of specimens consisted of applying a slow setting (SS) asphalt emulsion (70/30) 50% diluted with water at a rate of 0.09 to 0.12 gallon per square yards on top of the base specimen and then compact the thin HMA overlay on top.
- The third set of specimens consisted of applying a High Performance Seal (HPS) at a temperature of 350°F (177°C) on the top of the base specimen and then compact the HMA overlay mixture.

In all cases, the thin HMA overlay was compacted to 2 inch (50 mm) height and to a target air voids level of 7 ± 1 percent simulating the initial in-place air voids level. Figure 12 shows the test setup as well as a typical test specimen before and after testing. Final specimens were maintained for 24 hours at room temperature prior to testing.

Figure 12. LISST test setup with a Specimen before and after Testing.

The specimens were loaded in the LISST frame in such a manner that the interlayer surface (i.e., interface) is located directly in the middle of the gap between the fix reaction frame and the mobile loading one. The displacement was applied continuously at a constant displacement rate of 0.1 inch/min (2.54 mm/min) until failure. The peak ultimate load was recorded. The interlayer shear strength was calculated using Equation 7.

$$ISS = \frac{P_{ult}}{\frac{\pi D^2}{4}} \qquad \text{(Eq. 7)}$$

where,
ISS = interlayer shear strength, Pa or psi;
P_{ult} = ultimate load applied to specimen, N or lbs;
D = diameter of test specimen, m or in.

CHAPTER IV: MIX DESIGNS AND TEST RESULTS

This section of the report presents in detail the mix designs for the thin AC overlay mixtures as well as the results from the experimental program that was completed as part of this study.

IV.1 Mix Designs

The thin HMA overlay mixtures were designed following the NDOT Hveem Mix Design Method *(16)*. The heated aggregates were mixed with various amount of asphalt so that at least two were above and at least two were below the expected optimum binder content for each mixture. The samples, once mixed and conditioned for 16 hours at 140°F (60°C), were compacted with the kneading compactor at 230°F (135°C). The optimum binder content was determined by identifying the maximum asphalt content which provides 4-5% air voids, a minimum VMA of 12% (range of 12 to 22%) and a minimum Hveem stability of 37. Following NDOT specifications, the thin AC overlay mixtures were designed with a minimum dry tensile strength (TS) at 77°F (25°C) of 65 psi (448 kPa) and a minimum retained Tensile Strength Ratio (TSR) of 70%. Figure 13 and Figure 14 summarize the mix design information for the northern and southern mixtures, respectively. Each figure summarizes pertinent mix design data, NDOT requirements, and information on aggregate specific gravities and gradation. The optimum binder content was varied with respect to the allowable tolerances to simulate any variations in the binder content during production while still meeting the volumetric and stability requirements for plant produced mixtures. Values of ±0.4% and ±0.3% were selected for the northern and southern thin HMA overlay mixtures, respectively. Table 14 summarizes the volumetric and aggregate properties of the evaluated mixtures at the optimum binder content and at the optimum plus or minus the selected allowable tolerances.

Table 14. Summary of Volumetric Properties at Different Asphalt Binder Contents.

Property	Thin AC Overlay Mixture					
	Northern Mixture (Lockwood+PG64-28NV)			Southern Mixture (Lone Mountain+PG76-22NV)		
Binder Content by DWA, %	5.90	6.30[1]	6.70	4.20	4.50[1]	4.80
Binder Content by TWM, %	5.57	5.93	6.28	4.03	4.31	4.58
Air Voids (AV), %	5.9	4.9	4.2	5.2	4.2	3.2
Voids in Mineral Aggregate (VMA), %	19.6	19.5	19.6	14.3	14.0	13.7
Voids Filled with Asphalt (VFA), %	70.0	74.8	79.0	63.8	70.3	76.7
Hveem Stability	46	45	42	53	50	44
Aggregate Water Absorption, %			2.0	1.0		
Bulk Specific Gravity (G_{sb})			2.622	2.719		
Effective Specific Gravity (G_{se})			2.654	2.788		
Specific Gravity of Asphalt binder (G_b)			1.015	1.015		
Effective Binder Content (P_{be}), % by Weight	5.13	5.49	5.84	3.14	3.42	3.70
Effective Binder Content (V_{be}), % by Volume	11.6	12.5	13.3	7.7	8.4	9.1

[1] Optimum asphalt binder content.

Mix Design		
Nominal Maximum Aggregate Size, inch		1/2
Property	**Value**	**Requirement**
Hydrated Lime, %	1.5	1.5
Mixing Temperature, °F	320	319-329
Compaction Temperature, °F	305	295-310
Coarse Aggregate Bulk Gravity, G_{sb}	2.607	2.85 Max.
Fine Aggr. Apparent Gravity, G_{sa}	2.765	2.85 Max.
Optimum Binder (OBC), % DWA	6.3	--
Optimum Binder (OBC), % TWM	5.9	--
Air Voids in Total Mix	4.9	3-6
VMA, %	19.5	--
Hveem Stability	45	37 Min.
Max. specific gravity at OBC, G_{mm}	2.422	--
Unconditioned Tensile Strength, psi	70	65 Min.
Conditioned Tensile Strength, psi	71.5	--
Tensile Strength Ratio, %	100	70 Min.

Aggregate Gradation (Lockwood)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1.5")	100.0	--	--
25.0 mm (1")	100.0	--	--
19.0 mm (3/4")	100.0	100	100
12.5 mm (1/2")	95.0	90	100
9.5 mm (3/8")	85.0	70	90
4.75 mm (No. 4)	55.3	50	70
2.36 mm (No. 8)	41.7	--	--
2.00 mm (No. 10)	39.2	30	50
1.18 mm (No. 16)	32.3	--	--
0.6 mm (No. 30)	24.2	--	--
0.425 mm (No. 40)	19.4	12	24
0.3 mm (No. 50)	13.9	--	--
0.15 mm (No. 100)	7.4	--	--
0.075 mm (No. 200)	4.9	3	8

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	3/4" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Nat. Fines	--
Bin Proportions	8%	14%	27%	33%	18%	--

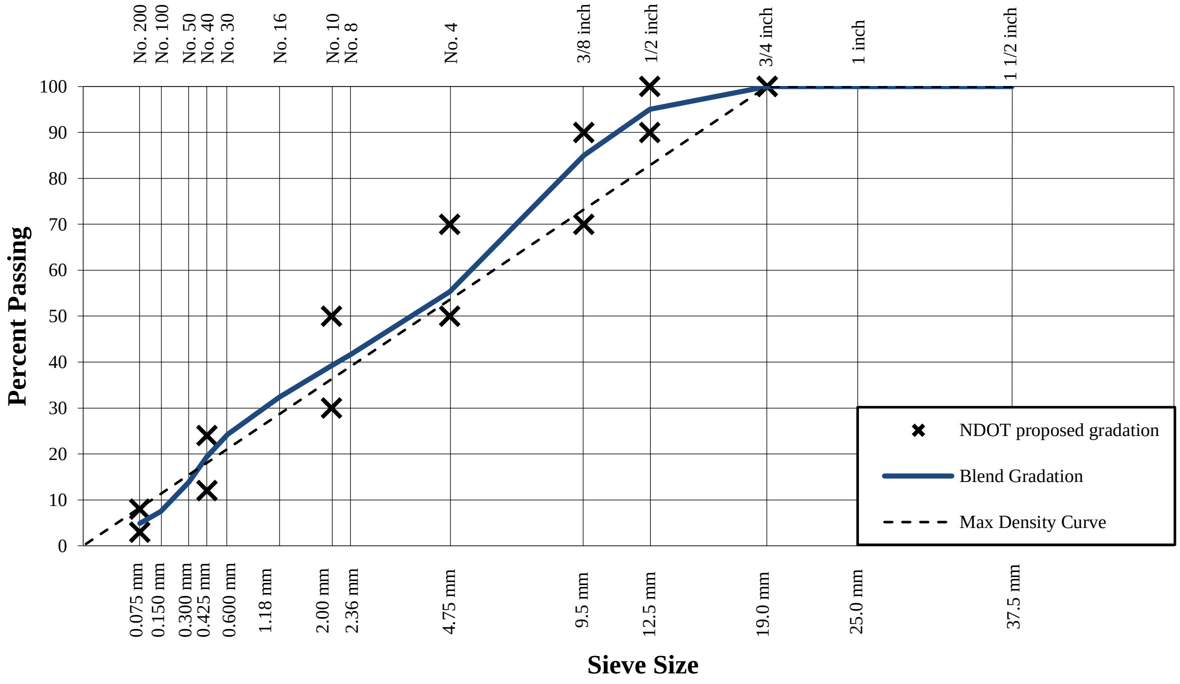


Figure 13. Thin AC overlay mix design for Lockwood aggregates and PG64-28NV.

Mix Design		
Nominal Maximum Aggregate Size, inch		3/8
Property	**Value**	**Requirement**
Hydrated Lime, %	1.5	1.5
Mixing Temperature, °F	350	345-360
Compaction Temperature, °F	320	315-325
Coarse Aggregate Bulk Gravity, G_{sb}	2.762	2.85 Max.
Fine Aggr. Apparent Gravity, G_{sa}	2.765	2.85 Max.
Optimum Binder (OBC), % DWA	4.5	--
Optimum Binder (OBC), % TWM	4.3	--
Air Voids in Total Mix	4.2	3-6
VMA, %	14.0	--
Hveem Stability	50	37 Min.
Max. specific gravity at OBC, G_{mm}	2.593	--
Unconditioned Tensile Strength, psi	93	65 Min.
Conditioned Tensile Strength, psi	85	--
Tensile Strength Ratio, %	91	70 Min.

Aggregate Gradation (Lone Mountain)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1.5")	100.0	--	--
25.0 mm (1")	100.0	--	--
19.0 mm (3/4")	100.0	100	100
12.5 mm (1/2")	100.0	90	100
9.5 mm (3/8")	88.1	70	90
4.75 mm (No. 4)	54.1	50	70
2.36 mm (No. 8)	42.0	--	--
2.00 mm (No. 10)	39.9	30	50
1.18 mm (No. 16)	32.8	--	--
0.6 mm (No. 30)	26.9	--	--
0.425 mm (No. 40)	23.8	12	24
0.3 mm (No. 50)	20.8	--	--
0.15 mm (No. 100)	12.1	--	--
0.075 mm (No. 200)	7.2	3	8

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1/2" AGG	Cr. Fines	Rinker Sand	--	--	--
Bin Proportions	47%	38%	15%	--	--	--

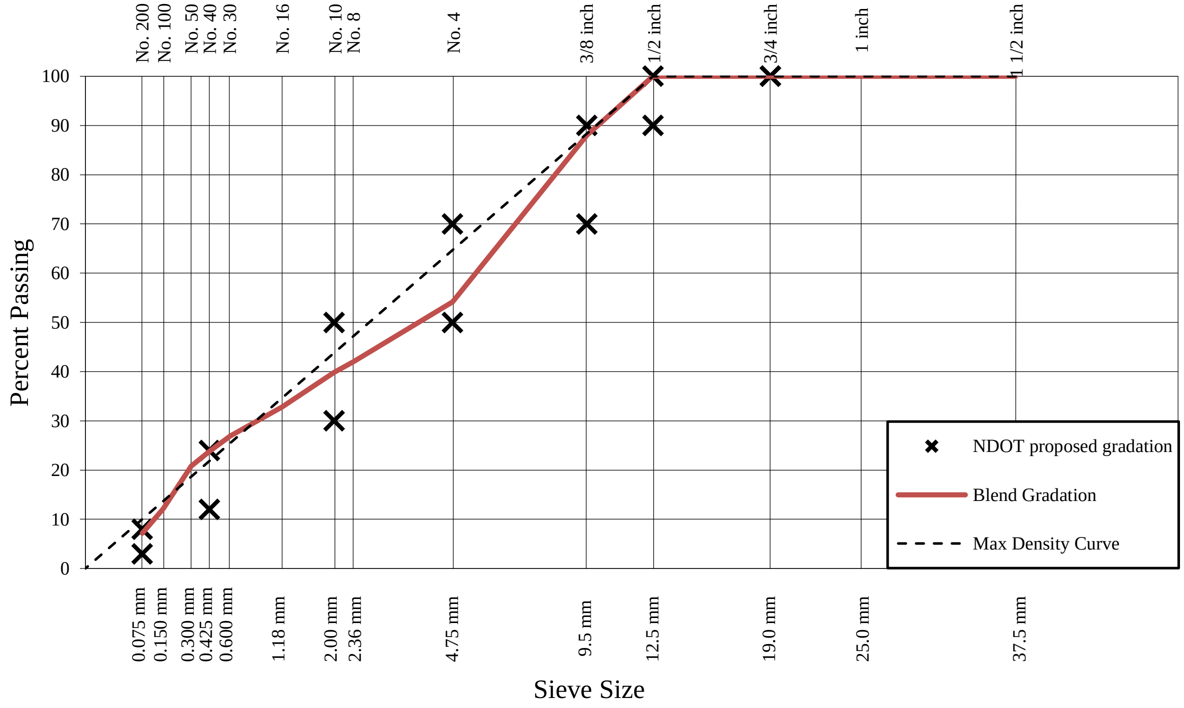


Figure 14. Thin AC overlay mix design for Lone Mountain aggregates and PG76-22NV.

IV.2 Test Results and Data Analysis

As mentioned before, the experimental plan included tests to evaluate the thin HMA overlay resistance to surface raveling and abrasion, reflective cracking, rutting, and moisture damage. In addition, the interlayer shear strength capacity was determined using the Louisiana Interlayer Shear Strength Tester (LISST). The workability of the thin HMA overlay mixtures was also evaluated using the pressure distribution analyzer (PDA). All testing, except for the interlayer bond test, were performed at three asphalt binder contents: selected optimal asphalt binder content (*OBC*), optimal asphalt binder content plus allowable tolerance (*OBC + tolerance*), and optimal asphalt binder content minus allowable tolerance (*OBC - tolerance*). The purpose of the evaluation at different asphalt binder contents is to ensure that mixtures with acceptable properties are still achieved if any changes in the design asphalt binder content occurred during plant production.

All mixtures were evaluated at the short-term aging condition where loose mixtures were subjected to 275°F (135°C) in a forced-draft laboratory oven for four hours prior to compaction in accordance with AASHTO R30 *(17)*. In the case of the bond test, the conditioning duration was reduced to two hours in accordance with the LISST draft AASHTO procedure *(30)*. This section presents the results and the analysis of the data generated from the various laboratory tests. Various statistical tools were used including F- and t-tests to compare the performance data reported at the optimal binder content and the optimal binder content plus or minus selected tolerances for each mixture. A significance level of 5% was adopted for this statistical analysis. The following nomenclatures were used in this study.

- **L6428_OBC, L6428_OBC+ and L6428_OBC-:** Northern mixture (L6428) manufactured with Lockwood aggregates and PG64-28NV asphalt binder at OBC, OBC plus 0.4%, and OBC minus 0.4%, respectively.
- **LM7622_OBC, LM7622_OBC+ and LM7622_OBC-:** Southern mixtures (LM7622) manufactured with Lone Mountain aggregates and PG76-22NV asphalt binder at OBC, OBC plus 0.3%, and OBC minus 0.3%, respectively.

IV.2.1 Resistance to Surface Raveling

The mass loss of the specimen after testing was used to evaluate the resistance of the evaluated mixture to raveling. While no standard criterion has been implemented for dense-graded asphalt mixtures, a maximum percent of mass loss of 20% for un-aged specimens has been typically used for open-graded mixtures *(30)*. Figure 15 and Figure 16 show selected samples before and after the surface raveling test for the un-conditioned and moisture-conditioned state, respectively. A review of the percent of mass loss by raveling data (Figure 17) reveals the following observations:

- Regardless of the asphalt binder content and moisture conditioning state, both evaluated thin HMA overlay mixtures exhibited an extremely low percent of mass loss by raveling (less than 0.4%) indicating a very high resistance to surface raveling.
- The LM7622 mixture exhibited a higher mass loss than the L6428 mixture. This may be attributed to the lower asphalt binder content for the LM7622 mixture when compared to the L6428 mixture.

Figure 15. Pictures of unconditioned samples before and after the raveling testing.

Figure 16. Pictures of moisture-conditioned samples before and after the raveling testing.

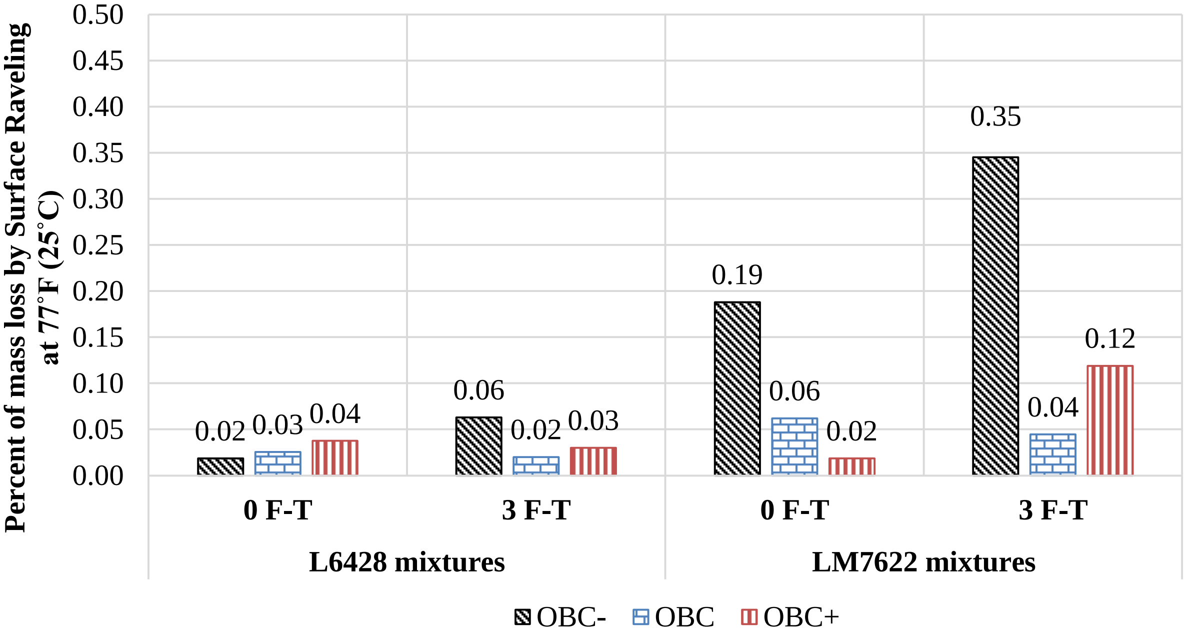


Figure 17. Percent of mass loss by raveling for unconditioned and moisture-conditioned samples.

It has been reported in previous studies *(302)*, that the use of polymer-modified asphalt binders in general can help to improve durability and resistance to surface raveling. It has also been reported that lime treatment of asphalt mixtures, a mandated procedure by NDOT for all designed asphalt mixtures, can significantly improve their resistance to raveling and moisture damage.

IV.2.2 Resistance to Surface Abrasion

The "Cantabro loss," as defined by the mass loss of the specimen after testing, was used to evaluate the resistance of the evaluated mixture to abrasion. A good resistance to surface abrasion is considered for un-aged mixtures whose maximum percent of Cantabro loss does not exceed 20% *(30)*. Figure 18 and Figure 19 show L6428 and LM7622 samples after testing for surface abrasion, respectively. The following observations can be made based on the data presented in Figure 20 and Figure 21.

- Both thin HMA overlay mixtures exhibited a Cantabro loss less than 20% at all evaluated asphalt binder contents (i.e., at OBC and OBC ± selected tolerances) indicating a good resistance to surface abrasion.
- A decrease in the Cantabro loss was observed for both mixtures with the increase in asphalt binder content. However, no statistical significant difference at the 5% significance level was observed between the mixtures at OBC+ and OBC- when compared to the respective mixture at OBC.
- Higher Cantabro loss values (5 to 8 times) were observed for the LM7622 mixture when compared to the L6428 mixture at all evaluated asphalt binder contents. The higher susceptibility to surface abrasion for the LM7622 mixture can be attributed to the lower asphalt binder content.

Figure 18. Picture of L6428 samples after testing for surface abrasion.

Figure 19. Picture of LM7622 samples before and after testing for surface abrasion.

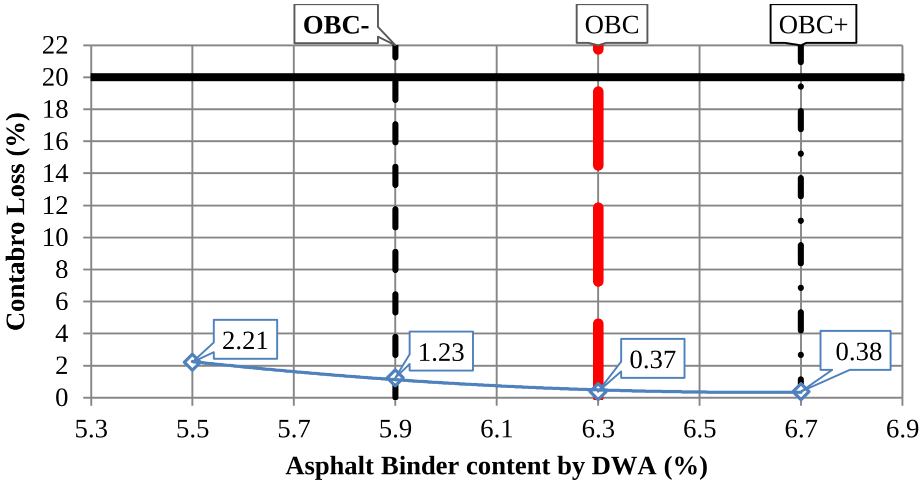


Figure 20. Percent of mass loss by abrasion for L6428 Samples.

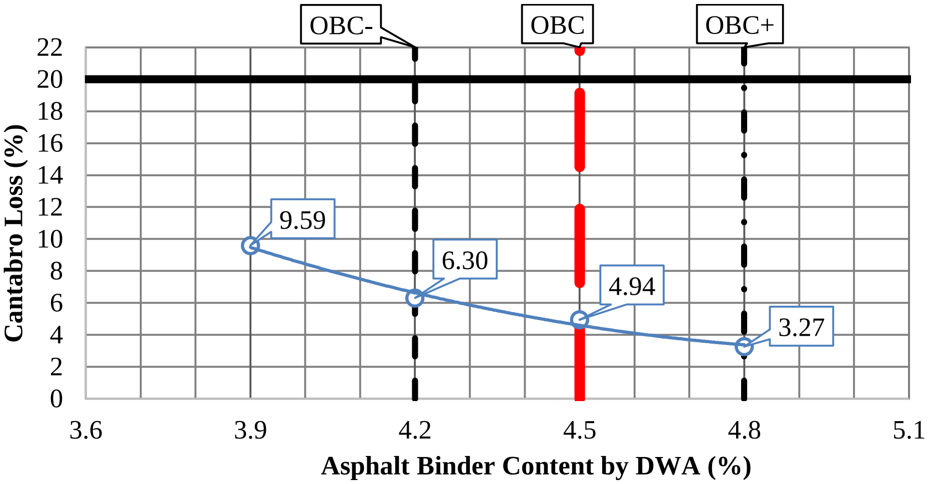


Figure 21. Percent of mass loss by abrasion for LM7622 Samples.

IV.2.3 Dynamic Modulus Property

The E* property provides an indication on the overall quality of the asphalt mixture. The magnitude of the E* property depends on several properties of the mixture including aggregate properties, gradation, asphalt binder grade, volumetrics, and age. In addition, the magnitude of E* also depends on temperature and rate of loading (i.e., frequency). A temperature of 68°F (20°C) and a loading frequency of 10 Hz were selected to represent an intermediate effective pavement temperature and a standard highway loading speed for the analysis, respectively. In general, an E* property above 300 ksi (2,068 MPa) at 68°F (20°C) and 10 Hz indicates a good stable asphalt mixture. On the other hand an E* Property at 68°F (20°C) and 10 Hz above 1,500 ksi (10,342 MPa) indicates a mixture susceptible to cracking. In addition, a temperature of 104°F (40°C) and 113°F (45°C) were also selected for the L6428 and LM7622 mixtures, respectively, representing an effective high pavement temperature at which the mixture might be susceptible to rutting. Figure 22 and Figure 23 show the E* master curves of the L6428 and LM7622 mixtures at OBC-, OBC and OBC+, respectively. Figure 24 compares the E* property at 10 Hz and at the intermediate and high pavement temperatures for the different evaluated asphalt binder contents. Overlapping of the confidence intervals implies the similarity in the measured dynamic modulus of the mixtures. A review of the data reveals the following observations:

- In general, both evaluated thin HMA overlay mixtures exhibited a dynamic modulus property similar to the ones observed for the corresponding dense-graded HMA mixtures in Nevada indicating a good stability under traffic loading.
- In the case of the L6428 mixture, a decrease in the E* property was observed with the increase in asphalt binder content. On the other hand, no statistical significant difference was observed between the E* property of the LM7622 mixture at the various asphalt binder contents.
- The combination of aggregate source and asphalt binder grade had a significant impact on the magnitude of the E* property. Higher E* values were observed for the LM7622 mixture when compared to the L6428 mixture regardless of the asphalt binder content. However, all mixtures had E* values at 68°F and 10 Hz that are above 300 ksi and well below 1,500 ksi; indicating a stable behavior under traffic loading without any apparent susceptibility to cracking.

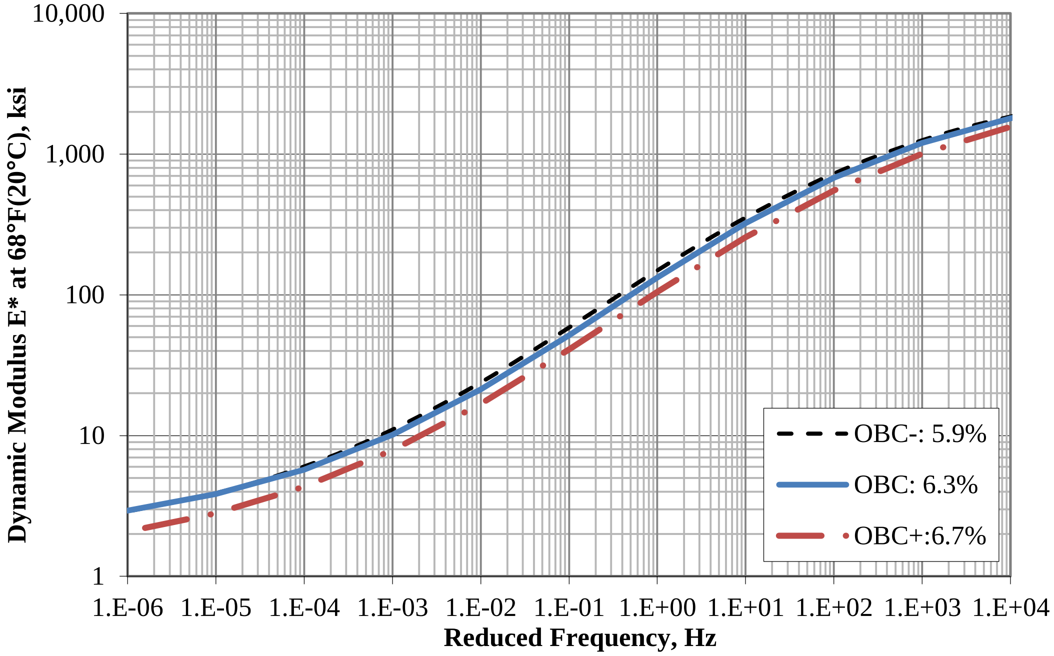


Figure 22. Dynamic modulus of L6428 mixture at 68°F.

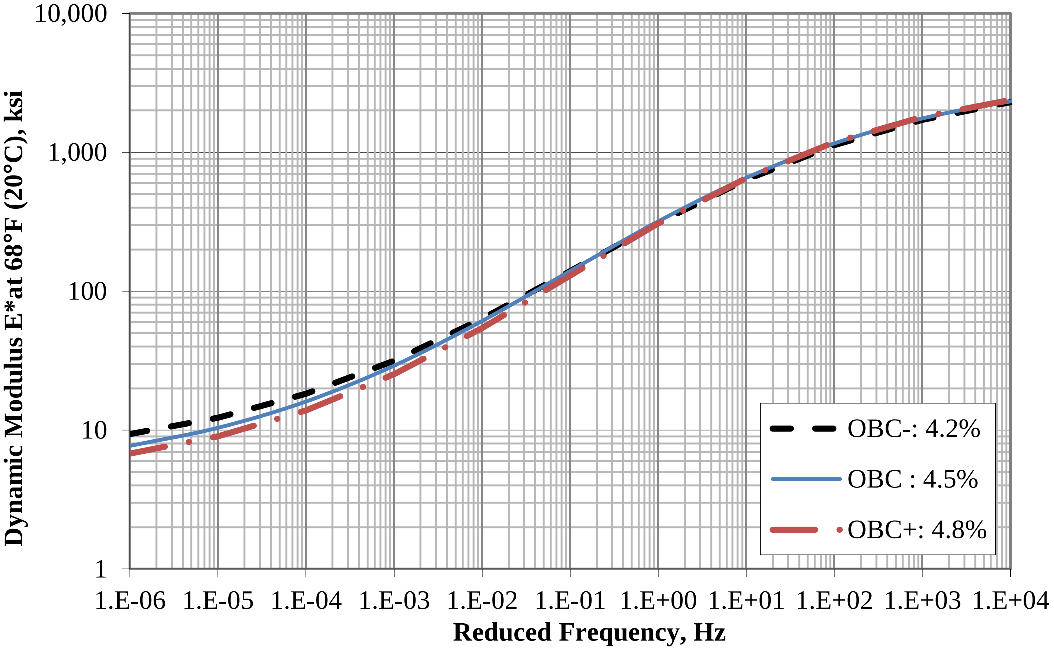


Figure 23. Dynamic modulus of LM7622 mixture at 68°F.

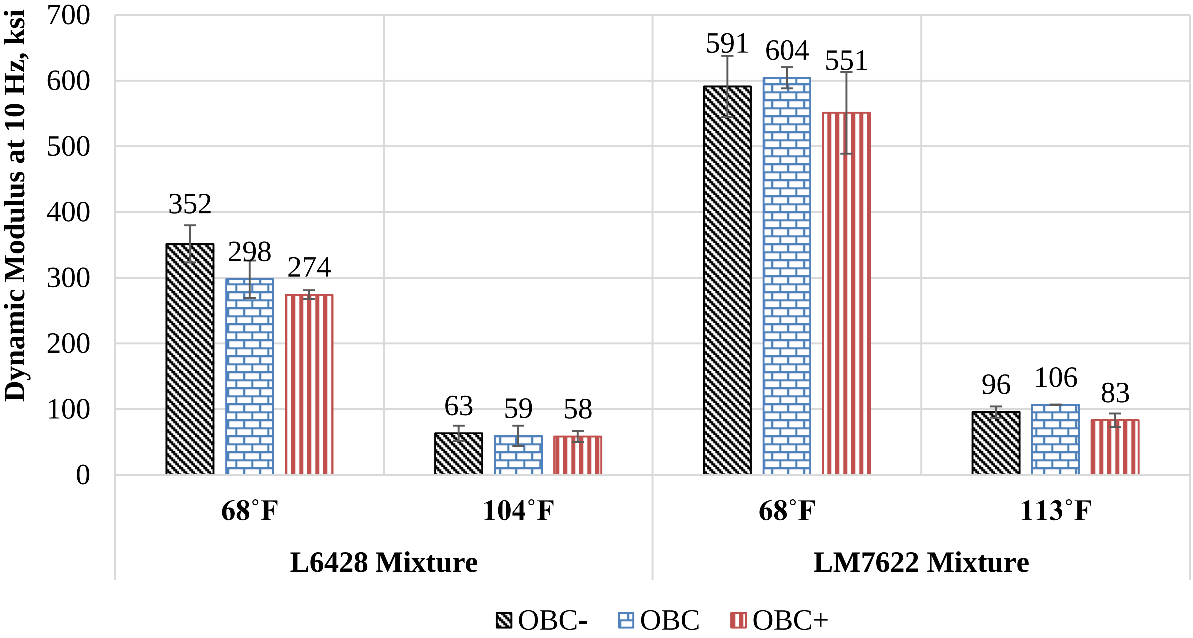


Figure 24. Comparison of dynamic modulus values at 10 Hz (Error bars represent the mean values plus or minus 95% confidence interval).

IV.2.4 Flow Number Test Results

According to AASHTO TP79 *(302)*, the thin HMA overlay mixture should meet the following FN criteria at the representative testing temperature based on the expected traffic level during the design period:

- No minimum FN value is required for a traffic level less than 3 million equivalent single axle loads (MESALs).
- A minimum FN value of 53 is required for a traffic level between 3 and 10 MESALs.
- A minimum FN value of 190 is required for a traffic level between 10 and 30 MESALs.
- A minimum FN value of 740 is required for a traffic level greater than 30 MESALs.

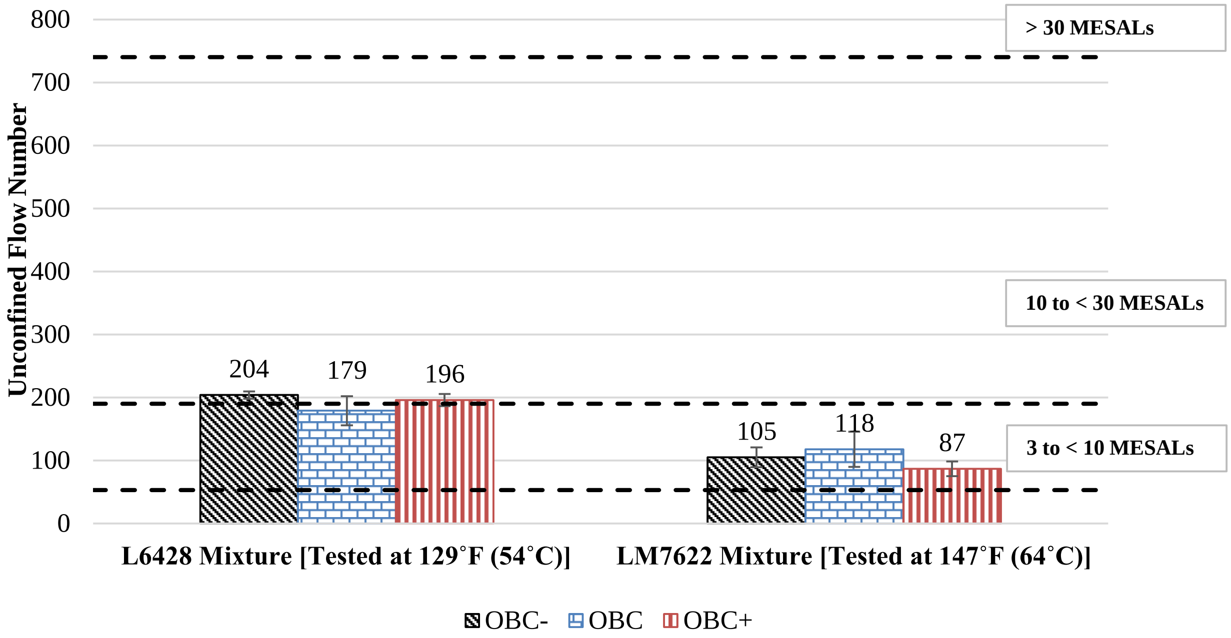


Figure 25 shows the FN values for the evaluated thin HMA overlay mixtures at different asphalt binder contents and at the respective testing temperature according to the LTPP Bind software Version 3.1; i.e., 129°F (54°C) and 147°F (64°C) for the L6428 and LM7622 mixtures, respectively. Overlapping of the confidence intervals implies the similarity in the measured FN value of the mixtures. Based on the test results the following observations can be made.

- Overall, the L6428 mixture met the minimum FN value of 190 for a traffic level up to 30 MESALs with the L6428 at OBC being slightly lower than the criterion value. On the other hand, the LM7622 met the minimum FN value of 53 for a traffic level up to 10 MESALs regardless of the asphalt binder content.
- The L6428 mixture exhibited higher FN values than the LM7622 mixture regardless of the asphalt binder content. However, it should be noted that the L6428 was tested at a temperature that was 18°F (10°C) lower than the test temperature of the LM7622.

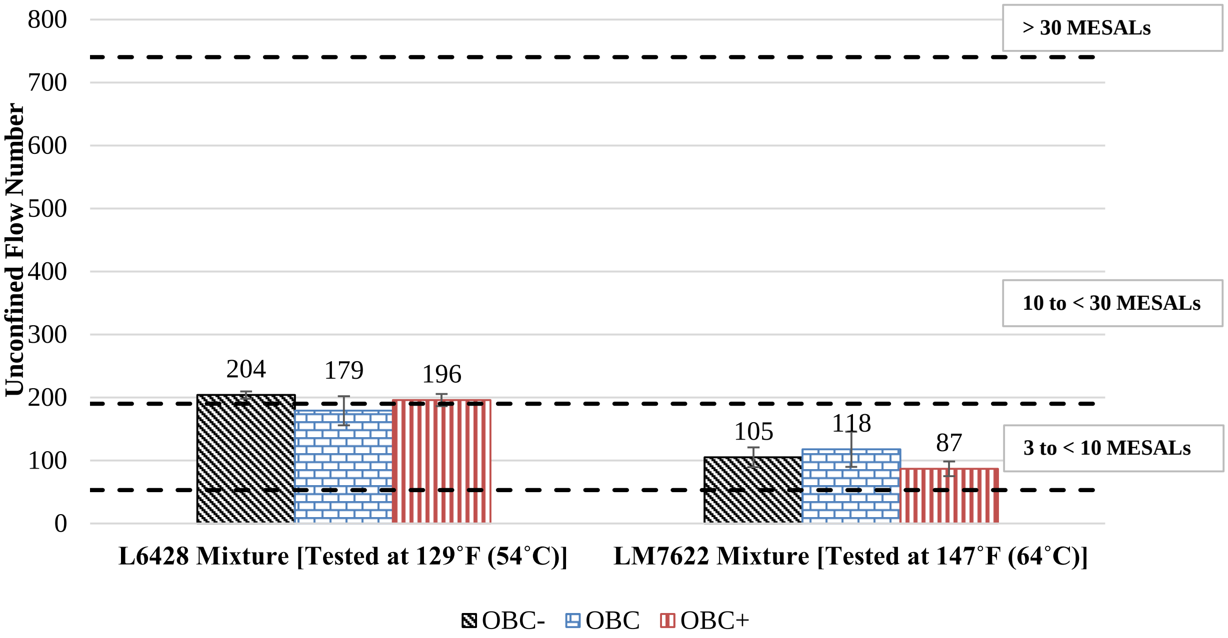


Figure 25. Flow Number results for the L6428 and LM7622 mixtures at different asphalt binder contents (Error bars represent the mean values plus or minus 95% confidence interval).

IV.2.5 Texas Overlay Test Results

None of the evaluated thin HMA overlay mixtures reached the 93% drop in initial load at 50°F (10°C) after 1,200 cycles indicating a very good resistance to reflective cracking. However, different percent of drops in initial load were observed at 2,500 and 5,000 cycles as shown in Figure 26 and Figure 27, respectively. Overlapping of the confidence intervals implies the similarity in the measured percent of drop in initial load for the evaluated mixtures. Based on the test results, the following observations can be made.

- Regardless of the asphalt binder content, both evaluated thin HMA overlay mixtures still showed a percent of drop in initial load lower than 93% even after 5,000 loading cycles indicating an excellent resistance to reflective cracking.
- For each mixture, the difference in the resistance to reflective cracking was not significantly different for different asphalt binder contents. In other words, the percent drops in the initial load were similar at OBC, OBC- and OBC+ for each of the thin HMA overlay mixtures.
- A significantly lower percent of drop in initial load was observed for the L6428 mixture when compared to the LM7622 mixture at all evaluated asphalt binder contents indicating a higher resistance to reflective cracking for the L6428 mixture. This observation can be attributed to the higher binder content for the L6428 mixture when compared to the LM7622 mixture.

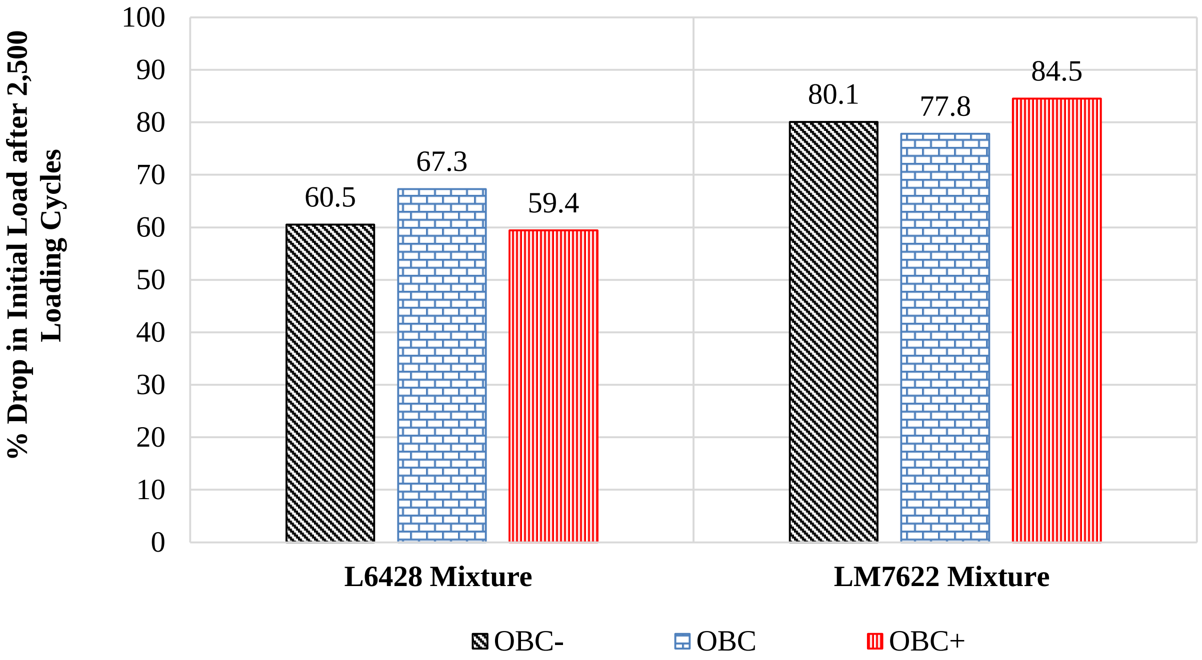


Figure 26. Percent drop in initial load after 2,500 Cycles in overlay tester.

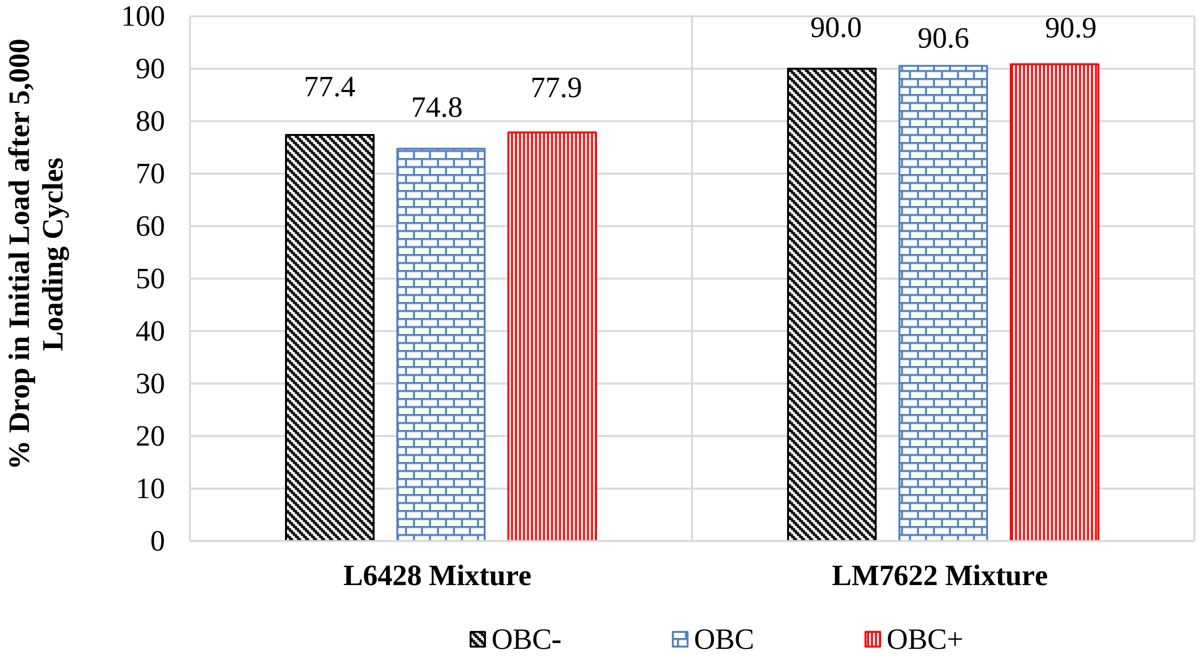


Figure 27. Percent drop in initial load after 5,000 Cycles in overlay tester.

IV.2.6 Workability and Compactability Test Results

As mentioned before, the Gyratory Pressure Distributor Analyzer (GPDA) results were used to determine the locking point of the evaluated mixtures. The L6428 and LM7622 mixtures were compacted in the SGC at 300°F (149°C) and 320°F (160°C), respectively. A typical NDOT dense-graded HMA mixture (Type 2C) from each the north and the south was used as a reference mixture for comparison purpose. Figure 28 and Figure 29 show, respectively, the frictional shear resistance (FR) curve for the L6428 and LM7622 mixtures at different asphalt binder contents along with the corresponding typical NDOT HMA mixture. The locking point corresponds to the number of gyrations at which the rate of change in the frictional resistance is less than 0.01.

While no standard criterion has been implemented for the locking point of dense-graded asphalt mixtures, this test was conducted on both mixtures at different asphalt binder contents only for comparison purposes. Figure 30 summarizes the locking point values for the evaluated mixtures defined as the point at which the mixture exhibits a marked increase in the resistance to densification. Accordingly, a higher locking point for a specific mixture indicates the need for additional energy to densify the mix to the appropriate air voids level. Based on the collected data the following observations can be made.

- In general, the dense-graded HMA mixture exhibited a higher locking point that the respective thin HMA overlay mixture. Hence, indicating that it takes less energy to densify the thin HMA overlay mixture when compared to the respective dense-graded HMA mixture. The reduction in the number of gyrations to reach the locking point was the highest at the optimum asphalt binder content.
- In general an increase in the locking point was observed with the increase in the asphalt binder content from OBC to OBC+ for the evaluated thin HMA overlay mixtures.
- At the optimum binder content, the L6428 mixture exhibited a higher locking point value than the LM7622 mixture. It should be noted that the L6428 was compacted at a temperature that was 20°F (11°C) lower the compaction temperature of the LM7622 while supposedly the viscosity was the same for both asphalt binders at the respective compaction temperatures.

In summary, the evaluated thin HMA overlay mixtures required less energy to density when compared to typically used dense-graded HMA mixtures. Thus, indicating a better workability and compactability for thin HMA overlay mixtures even when the asphalt binder content was maintained within the allowable tolerances.

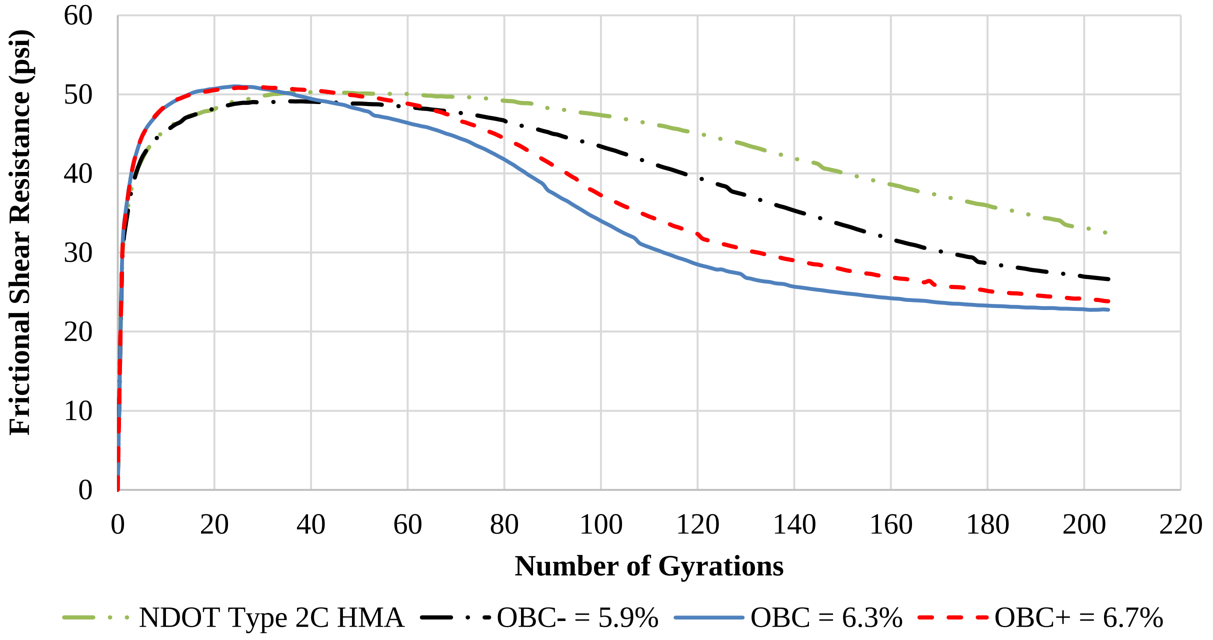


Figure 28. Frictional resistance (FR) as a function of the number of gyrations for the L6428 Mixture.

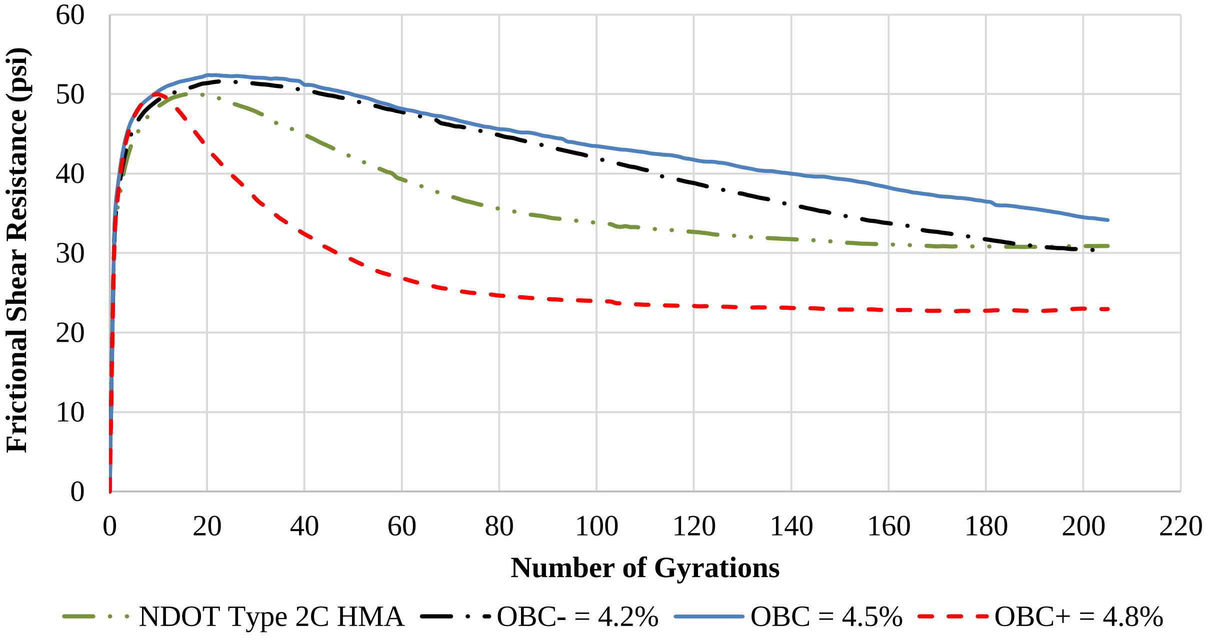


Figure 29.Frictional resistance (FR) as a function of the number of gyrations for the LM7622 Mixture.

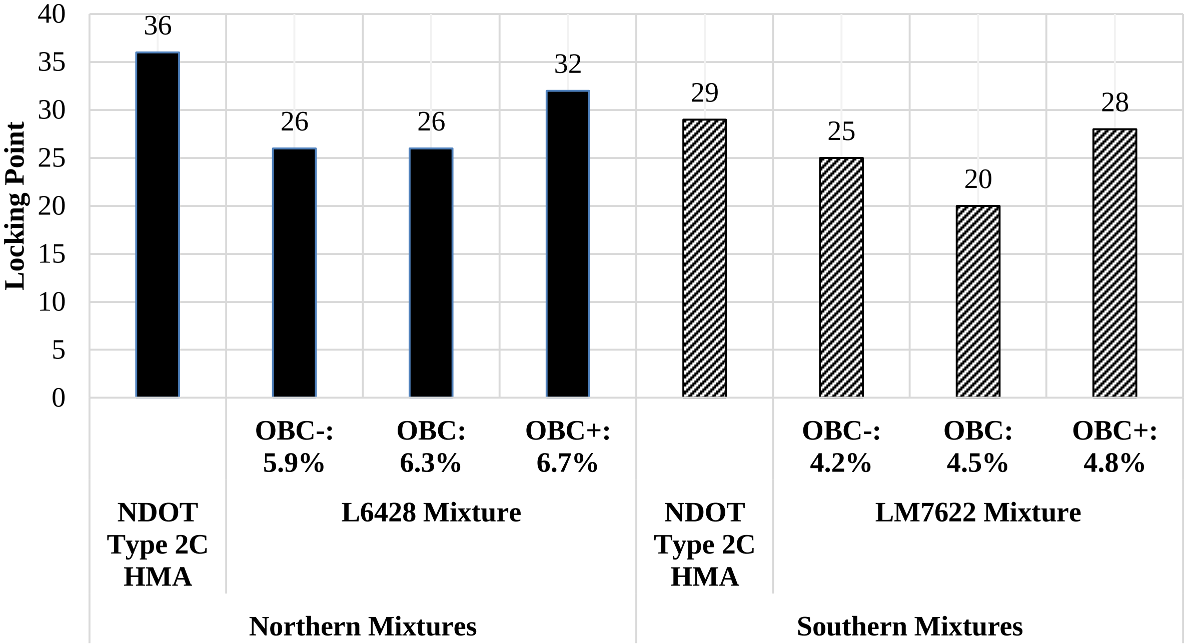


Figure 30. Locking point values for evaluated mixtures at different asphalt binder contents.

IV.2.7 Bond Strength Test Results

The test was conducted on thin HMA overlay specimens that were mixed and prepared at the selected optimal asphalt binder contents. Figure 31 shows a picture of the L6428 and LM7622 tested specimens with no tack coat being applied at the interface between the thin HMA overlay and the bottom dense-graded HMA mixture. While no standard criterion has been implemented for the developed interlayer shear strength *(ISS)* of dense-graded asphalt pavement layers, this test was conducted on both mixtures at the optimal asphalt binder content for the purpose of comparison only. Based on the LISST test results shown in Figure 32, the following observations can be made.

- In the case of the L6428 mixture, no significant difference was observed between the ISS developed when no tack coat was used and that developed when an asphalt emulsion SS tack coat was applied. On average, a significantly higher ISS value (about 1.8 times) was observed when the HPS tack coat was applied in comparison to the other two cases.
- In the case of the LM7622 mixture, significantly higher ISS values (1.6 and 2.3 times) were observed when a SS or a HPS tack coat was used in comparison to the case where no tack coat was applied.
- For both L6428 and LM7622 mixtures, the highest ISS value was observed for the HPS tack coat.
- The combination of aggregate source and asphalt binder grade had a significant impact on the magnitude of the developed interlayer shear strength. Significantly higher ISS values were observed for the LM7622 mixture when compared to the L6428 mixture. This can be attributed to the higher optimum asphalt binder content for the L6428 mixture when compared to the LM7622 mixture.

Applying the right tack coat at the appropriate rate is critical for the thin HMA overlay performance. Since the overlays are developed and designed primarily for functional and not structural purposes, a full stress transmission should be maintained between the new overlay and the old existing pavement to avoid shoving and delamination type of failures in the overlay mixture.

L6428 Mixture **LM7622 Mixture**

Figure 31. Picture of no tack coat specimens after testing in the LISST jig.

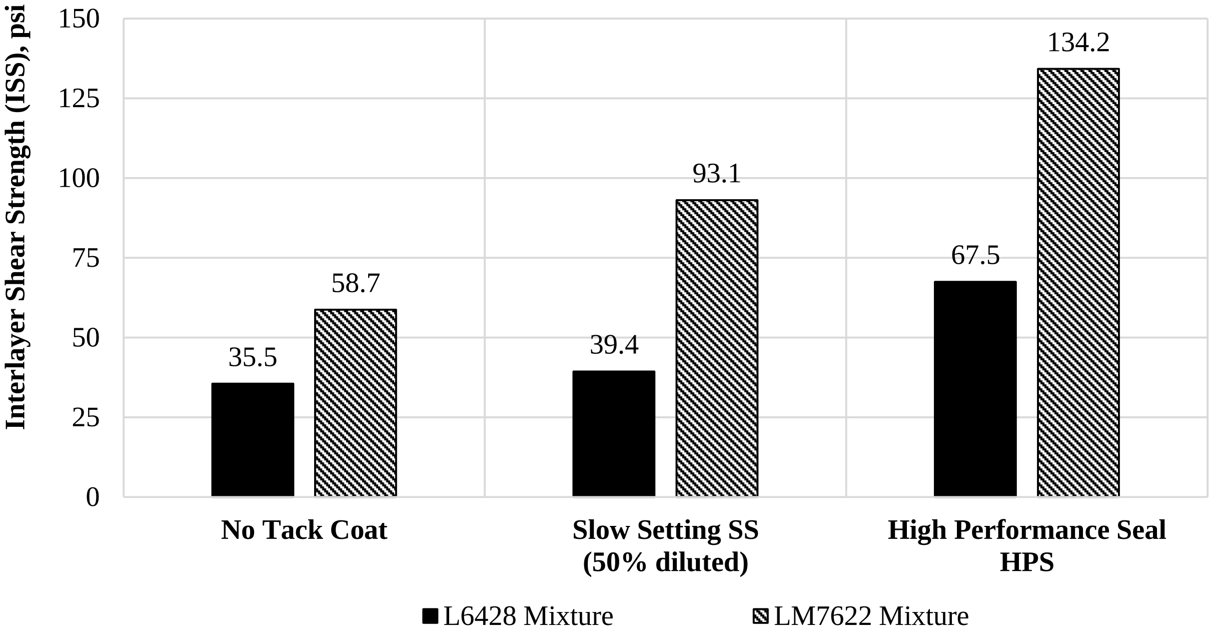


Figure 32. Measured interlayer shear strength for different type of tack coats.

CHAPTER V: COST ANALYSIS

As mentioned in Chapter 1, several preservation techniques can be applied and used as maintenance for flexible and rigid pavements. The review of literature (refer to Chapter 2) qualified the thin AC overlay as one of the most cost-effective preventive maintenance treatments that can be used to improve the functional capacity of a pavement. This chapter provides a hypothetical life cycle cost analysis (LCCA) study between the thin AC overlay and the chip seal pavement preservation treatment in an attempt to identify the minimum life necessary for the thin AC overlay to be considered as a cost-effective alternative in Nevada. The chip seal was selected for this cost comparison analysis for the following two main reasons: (1) the thin AC overlay is meant to be incorporated and implemented as part of the pavement preservation program for NDOT; and (2) chip seal is one of the mostly used techniques for preventive maintenance in the state of Nevada.

V.2 Pavement Maintenance Terminology

Providing a safe and comfortable ride for the road users requires several critical steps. The maintenance of highway facilities constitutes one of these critical steps. Slowing down the deterioration process to avoid significant failure is considered the fundamental purpose of maintenance. Typically, the cost of maintenance is 15 to 20% of the expected cost to repair the ultimate failure that will occur without the application of any maintenance activities. For example, national data indicate that every $1 spent on maintaining the pavement surface condition saves $5 on major rehabilitation that will be required if the maintenance activities are not conducted. This concept holds true for all highway maintenance activities *(313)*.

It is well known that the main objective of a pavement maintenance activity is to maintain the current condition of the pavement and/or slow down the rate of deterioration. In this respect, maintenance activities are not applied to strengthen the pavement capacity rather than fixing and improving the functional behavior *(313)*.

Defined as a proactive approach, a pavement preservation program has three primary components in accordance with the Federal Highway Administration (FHWA) guidelines: minor non-structural rehabilitation, preventive maintenance, and some routine maintenance activities *(334)*. Table 15 supports the idea that the main purpose of applying a pavement preservation activity is to restore the functionality of the existing pavement without the intention of adding structural support. Accordingly, pavement preservation is a set of cost-effective practices designated to extend the pavement life, improve the ride safety, and save some public dollar taxes under the concept of applying the right pavement preservation treatment on the right pavement condition at the right time *(353)*.

Table 15. FHWA Pavement Preservation Guidelines. ***(33)***

	Type of Activity	**Increase capacity**	**Increase strength**	**Reduce aging**	**Restore serviceability**
	New Construction	X	X	X	X
	Reconstruction	X	X	X	X
	Major (Heavy) Rehabilitation		X	X	X
	Structural Overlay		X	X	X
Pavement Preservation	Minor (Light) Rehabilitation			X	X
	Preventive Maintenance			X	X
	Routine Maintenance				X
	Corrective (Reactive) Maintenance				X
	Catastrophic Maintenance				X

V.3 Life Cycle Cost Analysis (LCCA)

V.3.1 Description of the LCCA Method

LCCA is defined as a tool to determine the most cost-effective alternative among different competing pavement preservation techniques when each one of them is equally appropriate to be used on an existing pavement section. Several parameters are necessary to undertake a life cycle cost analysis such as discount rate, analysis period, treatment unit cost, and estimated treatment life. Defined as the difference between the interest rate and the inflation rate, the discount rate has a significant effect on the LCCA; a $1 today is not worth $1 a year from now due to interest and inflation. Long historical trends are usually reflected by the discount rate concept.

Defined as the length time that agency would like to plan (e.g., 10, 15, 20 … years), the analysis period should be long enough to reflect the cost differences and force the use of each maintenance or rehabilitation alternative. An analysis period of 20 to 30 years is commonly used for flexible pavements while 30 to 40 years are adopted for rigid pavements. The analysis period is considered as the duration over which several preservation and rehabilitation techniques are compared. However, the design period remains to be the duration over which the pavement remains performing well with a pavement condition higher than the acceptable lower threshold value. The Present worth (PW) method was used to establish the LCCA of this study. The alternative which provides the least PW is usually selected. The PW value is calculated using Equation 8.

$$PW = \frac{F}{(1+i\,)^{n}} \qquad \text{(Eq. 8)}$$

where
F = future sum of money at the end of “N” years;
i = discount rate;
n = number of years (time in future when an alternative is applied).

Various alternatives will not end up at same level of serviceability. Thus, a salvage value for each alternative should be calculated relative to where it ends up at the end of the analysis period. The salvage value is presented as a percentage of the cost of the last applied treatment (Equation 9).

$$SV = \left(1 - \frac{L_A}{L_E}\right) * C \qquad \text{(Eq. 9)}$$

where,
SV = Salvage value;
L_A = actual life used out of the performance life;
L_E = Expected performance life;
C = cost of the treatment in today's dollars.

V.3.2 LCCA Results

NDOT commonly uses chip seals as a preventive maintenance technique for the state's flexible pavements. A study completed by University of Nevada, Reno (UNR) showed that the life expectancy for a chip seal in Nevada, on average, is 3.0 to 6.5 years when applied on state routes (SR) and 2.5 to 4.5 years when applied on interstate routes (IR) *(313)*. Recently, NDOT expressed some interest in making use of thin AC overlays as a preventive maintenance at early time of the pavement life to extend the available funds for pavement preservation techniques.

Hence, the main objective of this analysis was to explore the necessary minimum life for the thin AC overlay in order to be considered a cost-effective treatment in Nevada. This was achieved by conducting a comparison between the life cycle costs of using chip seal or thin AC overlay as a preventive maintenance. The chip seal was applied 3 years after the pavement construction while two scenarios were considered for the thin AC overlay: application at year 6 or year 8 after pavement construction. The time of application for the chip seal was selected based on the recent findings from a study completed at UNR *(363, 366)* which showed three years to be the optimal timing for the application of slurry seal in northern Nevada. The LCCA analysis was conducted for different performance lives of the chip seal and thin AC overlay pavement preservation treatments. The treatment life for the chip seal was varied between 3 and 6 years while that of the thin AC overlay was varied between 4 and 12 years in a 1 year increment. Table 16 shows the different alternatives considered in the LCCA based on the treatment life and the year of application. Table 17 summarizes the calculated present worth costs corresponding to each treatment as a function of the performance life and year of application. The following assumptions were used in the LCCA analysis.

- An analysis period of 20 years was used along with a discount rate of 3.1% for the selected analysis period based on information provided by the office of management and budget *(**Error! Reference source not found.**7)*.
- The life of the treatment for either chip seal or thin AC overlay is independent of the time of application. In other words, the treatment life is considered constant for all the sequential applications of the treatment during the analysis period.
- Only the material cost is being considered in this analysis. The user cost is not being considered as part of this analysis.
- A total of $11,334 per lane-mile was considered as an average initial cost for the chip seal based on the NDOT 2014 records (cost range: $1.61-2.80 \$/yd^2$; ($1.61 \$/yd^2$)×($1/9\ yd^2/ft^2$)× (12 ft Lane Width)×(5280 ft/mile)=11,334 $/lane-mile) *(**Error! Reference source not found.**8)*.
- Based on information compiled from the literature (Table 3), a total of $14,600 per lane mile was adopted as a typical cost for a thin AC overlay in 2006 which provides an approximate cost projection of $19,050 per lane-mile in 2015.

Figure 33 and Figure 34 compare the net present value (NPV) of the chip seal applied at year 3, the thin AC overlay applied at year 6, and the thin AC overlay applied at year 8 as a function of the treatment performance life. Cost savings or additions based on the difference in NPVs of the chip seal and thin AC overlay for the various performance lives of the treatments are shown in Figure 35 and Figure 36 (positive values indicate savings while negative values indicate additions in costs for thin AC overlays). Based on the LCCA the following observations can be made.

- *For the case of thin AC overlay applied after 6 years from construction:* a chip seal with a performance life of 3, 4, 5, and 6 years remains more cost-effective than the thin AC overlay with a performance life of or less than 4, 5.5, 7, and 8 years, respectively. In other words the performance life of a thin AC overlay should be at least 1 to 2 years more than that of a chip seal in order for the thin AC overlay to become a cost-effective treatment in comparison to the chip seal. Applying a thin AC overlay whose performance life is expected to be higher than 8 years shows significant cost savings in comparison to a chip seal application.
- *For the case of thin AC overlay applied after 8 years from construction:* regardless of the treatment life, a thin AC overlay was found to be cost-effective when compared to a chip seal with a performance life of 3 years. A chip seal with a performance life of 4, 5, and 6 years remains more cost-effective than the thin AC overlay with a performance life of or less than 4.5, 5.5, and 6.5 years, respectively. In other words the performance life of a thin AC overlay should be at least 0.5 years more than that of a chip seal in order for the thin AC overlay to become a cost-effective treatment in comparison to the chip seal. Applying a thin AC overlay whose performance life is expected to be higher than 8 years shows significant cost savings in comparison to a chip seal application.
- Additional savings are observed when the first application of the thin AC overlay is delayed to year 8 instead of year 6 while assuming that the thin AC overlay is always being applied on a structurally sound pavement. It should be noted that the traffic level remains as a very important factor affecting the chip seal and the thin AC overlay treatments’ lives.

Table 16. Pavement Preservation Program for Chip Seal and Thin AC Overlay.

Preservation Technique	Time of First Application After Pavement Construction (years)	Treatment Performance Life (years)	Sequential Time of Application of the ith Treatment (years)				
			2nd	3rd	4th	5th	6th
Chip Seal	3	3	6	9	12	15	18
		4	7	11	15	19	---
		5	8	13	18	---	---
		6	9	15	---	---	---
Thin AC Overlay	6	4	10	14	18	---	---
		5	11	16	---	---	---
		6	12	18	---	---	---
		7	13	---	---	---	---
		8	14	---	---	---	---
		9	15	---	---	---	---
		10	16	---	---	---	---
		11	17	---	---	---	---
		12	18	---	---	---	---
Thin AC Overlay	8	4	12	16	---	---	---
		5	13	18	---	---	---
		6	14	---	---	---	---
		7	15	---	---	---	---
		8	16	---	---	---	---
		9	17	---	---	---	---
		10	18	---	---	---	---
		11	19	---	---	---	---
		12	20	---	---	---	---

Table 17. Net Present Value (NPV) of Pavement Preservation Alternatives as a Function of the Treatment Performance Life.

Preservation Technique	Treatment Performance Life (years)	Cost of the i^{th} Treatment (US $/lane mile)						Salvage Value (US $)	Net Present Value (US $/lane mile)
		1st	2nd	3rd	4th	5th	6th		
Chip Seal	3	10,342	9,437	8,611	7,857	7,170	6,542	2,052	47,908
	4	10,342	9,153	8,101	7,170	6,346	---	4,616	36,495
	5	10,342	8,878	7,621	6,542	---	---	3,693	29,691
	6	10,342	8,611	7,170	---	---	---	1,026	25,097
Thin AC Overlay Applied at Year 6 After Construction	4	15,861	14,038	12,424	10,996	---	---	5,172	48,148
	5	15,861	13,616	11,688	---	---	---	2,069	39,097
	6	15,861	13,207	10,996	---	---	---	6,897	33,168
	7	15,861	12,810	---	---	---	---	0	28,671
	8	15,861	12,424	---	---	---	---	2,586	25,700
	9	15,861	12,051	---	---	---	---	4,598	23,315
	10	15,861	11,688	---	---	---	---	6,207	21,343
	11	15,861	11,337	---	---	---	---	7,523	19,675
	12	15,861	10,996	---	---	---	---	8,621	18,237
Thin AC Overlay Applied at Year 8 After Construction	4	14,922	13,207	11,688	---	---	---	0	39,817
	5	14,922	12,810	10,996	---	---	---	6,207	32,521
	6	14,922	12,424	---	---	---	---	0	27,346
	7	14,922	12,051	---	---	---	---	2,956	24,017
	8	14,922	11,688	---	---	---	---	5,172	21,438
	9	14,922	11,337	---	---	---	---	6,897	19,362
	10	14,922	10,996	---	---	---	---	8,276	17,642
	11	14,922	10,665	---	---	---	---	9,404	16,183
	12	14,922	---	---	---	---	---	0	14,922

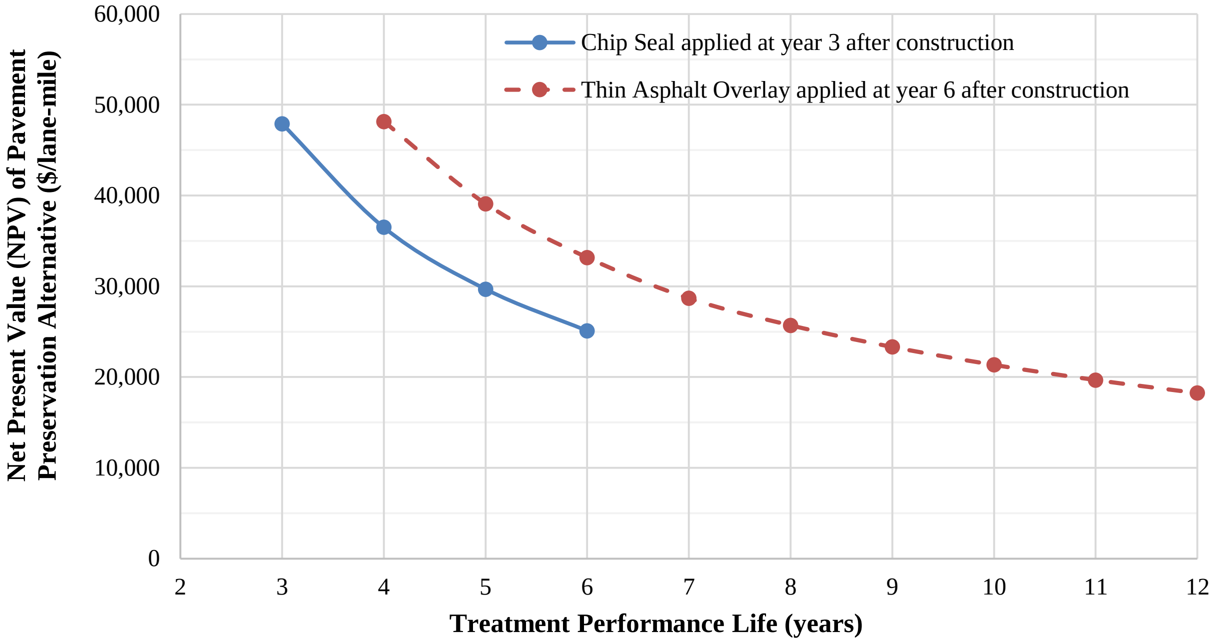


Figure 33. Net present value (NPV) of chip seal and thin AC overlay applied at year 6 as a function of treatment performance life.

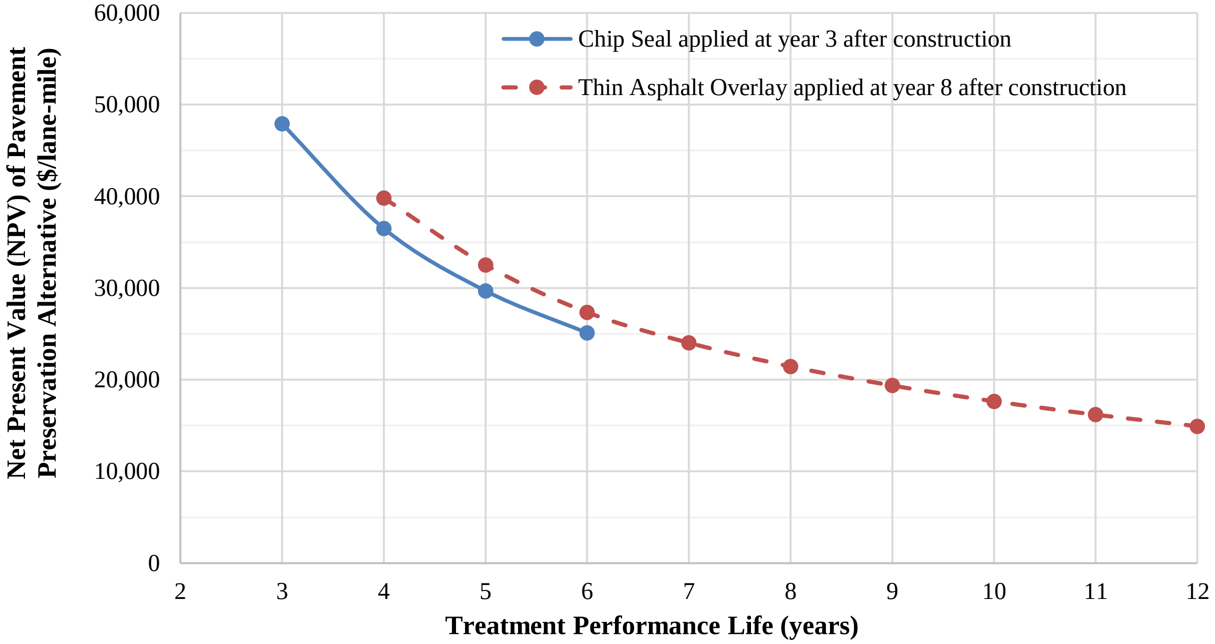


Figure 34. Net present value (NPV) of chip seal and thin AC overlay applied at year 8 as a function of treatment performance life.

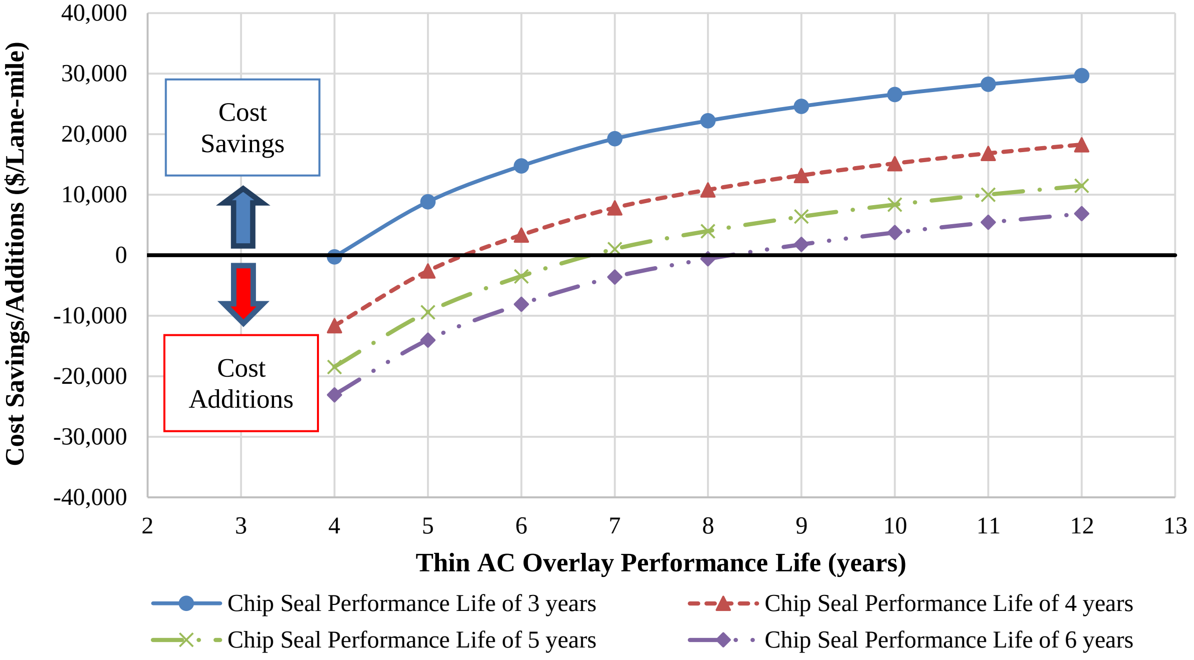


Figure 35. Cost Savings / Additions of Using Thin Asphalt Overlay Applied at Year 6 after Construction compared to Each Chip Seal Performance Life.

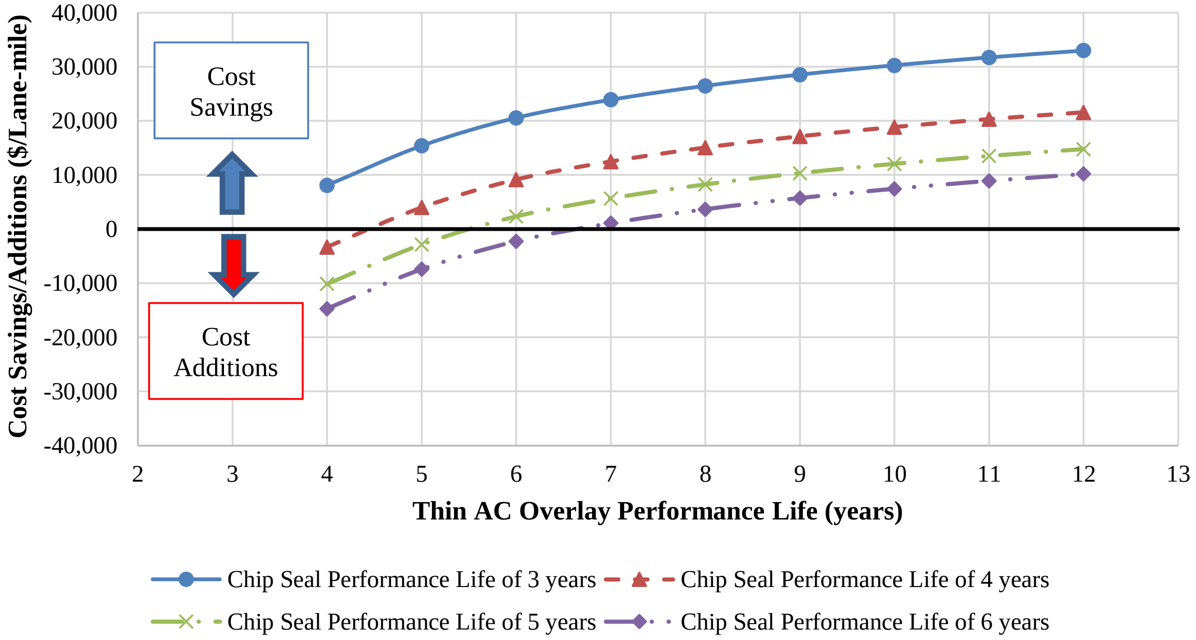


Figure 36.Cost Savings / Additions of Using Thin Asphalt Overlay Applied at Year 8 after Construction compared to Each Chip Seal Performance Life.

CHAPTER VI: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The overall objective of this study was to assess the use of locally available materials in Nevada for the development of durable fine-graded thin HMA overlay mixtures for use as a pavement preservation technique. Mix designs were conducted following the NDOT Hveem mix design method to determine the optimal asphalt binder content (OBC) for each of the two evaluated thin HMA overlay mixtures. Except for the interlayer bond strength test, the performance of each of the northern and southern Nevada thin AC overlay mixtures was evaluated at three asphalt binder contents: OBC and OBC ± selected tolerances. The purpose of the evaluation at different asphalt binder contents is to ensure that mixtures with acceptable properties are still achieved if minor changes in the design asphalt binder content occurred during plant production. The thin HMA overlay mixtures were evaluated in terms of their resistance to moisture damage, surface raveling and abrasion, dynamic modulus, rutting, reflective cracking, workability, and interlayer shear bond strength. The following summarizes the overall findings from this study.

- High stability values were observed for both northern and southern mixtures indicating a stable behavior under heavy traffic loading.
- Both mixtures met the NDOT criterion for moisture damage indicating a good resistance to moisture stripping.
- Very low values of mass loss were observed when mixtures were tested to surface raveling and abrasion. The excellent resistance to surface raveling and abrasion was observed at both, the unconditioned and moisture-conditioned (i.e., after 3 freeze-thaw cycles) states.
- Both evaluated thin HMA overlay mixtures showed dynamic modulus values similar to the corresponding dense-graded HMA mixtures typically used in Nevada indicating a potentially good field performance.
- Lower FN values were reported for the southern thin HMA overlay mixture in comparison to the northern mixture. The northern and southern mixtures were found to be applicable for a traffic level of up to 30 and 10 MESALs, respectively.
- An excellent resistance to reflective cracking was observed for both mixtures at all evaluated asphalt binder contents. A higher resistance to reflective cracking was observed for the northern mixture when compared to the southern mixture.
- In general, a higher interlayer shear bond strength was detected with the use of tack coat with the HPS tack coat resulting in a significantly higher bond strength. The type of the thin AC overlay mixture influenced the interlayer shear bond strength (a higher bond strength was observed for the southern mixture when compared to the northern mixture).

In summary, it was concluded that thin HMA overlay mixtures with acceptable laboratory performance can be designed for the state of Nevada using locally sourced materials. In addition, the designed mixtures will conserve their mechanical properties in case of a variation in the asphalt binder content within the allowable tolerances.

A hypothetical life cycle cost analysis (LCCA) was also conducted as part of this study in an attempt to estimate the minimum required performance life for the thin AC overlay mixture in order to become a cost-effective alternative. The analysis was based on a comparison between the LCCA of the thin AC overlay mixture and the chip seal surface treatment which is commonly used by NDOT throughout the state on flexible pavements. Depending on the time of application and the life of the treatment, it was demonstrated that a thin AC overlay mixture can be a cost-effective alternative under certain circumstances; thus justifying the additional initial cost for the thin AC overlay in comparison to other surface treatments such as chip seal.

Based on the findings from this study, preliminary draft specifications for thin AC overlay mixtures in Nevada were developed and are shown in Table 18 and Table 19. The aggregates shall still meet all other NDOT specifications for aggregates used in dense-graded asphalt mixtures.

It is recommended that field test sections be constructed to evaluate the field performance of the thin AC overlay mixtures in Nevada. At a minimum a test section in each of the northern and southern part of the state is recommended. The proper pavement candidates for the application of the thin AC overlay mixture should be selected based on the existing pavement condition and the expected traffic level. The test sections should be monitored for long-term field performance in order to allow for the development of a full specification for thin AC overlay mixtures. Field-produced asphalt mixtures as well as field cores should be sampled and tested in the laboratory for various properties. It is also recommended that falling weight deflectometer (FWD) testing be conducted on the field test sections before milling or placement of the thin AC overlay and periodically after placement of the overlay during the life of the treatment.

Table 18. Proposed Gradation Limits for Thin AC Overlay Mixtures.

Sieve Size	Percent Passing by Mass
19 mm (3/4 inch)	100
12.5 mm (1/2 inch)	90 – 100
9.5 mm (3/8 inch)	70 – 90
4.75 mm (No.4)	50 – 70
2.0 mm (No.10)	30 – 50
0.425 mm (No.40)	12 – 24
0.075 mm (No.200)	3 – 8

Table 19. Proposed Property Requirements for Thin AC Overlay Mixtures.

Test	Replicates	Criteria
Hveem stability @ 60°C (Nev. T303D), 100 mm mold[1]	3	37 min.
Cantabro Loss (Tex-245-F), 300 L.A revolutions (30 rpm), 7±1% air voids, 18 to 24°C	3	10% max.
Texas Overlay Test (Tex-248-F), 7±1% air voids, 10°C, 0.018 inch maximum displacement	6[2]	1,200 cycles min.

[1] Compact Hveem stability specimens to design air voids ± 0.5%.

[2] Discard the samples with the highest and lowest reflective cracking life, i.e., average the middle four results.

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