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Evaluation of the Benefits of Open-Graded Friction Course (OGFC) on NDOT Category-3 Roadways

May 2018

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16. Abstract

Numerous agencies use Open Graded Friction Course (OGFC) mixtures as the final riding surface on their roadways because of the many benefits such as: reduced hydroplaning, reduced splash and spray, reduced headlight glare, improved visibility, reduced accidents, reduced noise, and surface friction properties. However, there have been some indications that OGFC performance is reduced over time due to the tendency of the surface pores to become clogged, so it was urgent that Nevada Department of Transportation (NDOT) conduct this research since OGFC mixtures cost about 25 percent more than dense-graded mixtures. NDOT constructed two projects for this study. The northern project was on state route 535 in Elko and the southern project was on I-15 east of Las Vegas. At each location a dense-graded mix was placed as a control mix to compare performance of the OGFC mix. A series of laboratory and field tests such as Cantabro stone loss, Hamburg Wheel Track Test for rutting susceptibility, retained tensile strength for moisture susceptibility, permeability, friction, texture, and tire-pavement noise were conducted with mixtures at both OGFC and dense-graded locations. Field testing showed the I-15 OGFC mixture exhibited benefits in permeability, friction, and noise reduction compared to the dense-graded mix and was cost-effective while the SR 535 OGFC applied in an urban setting was not. Based on this study, it is recommended that OGFC not be used in an urban environment or town area.

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Evaluation of the Benefits of Open Graded Friction Course (OGFC) on NDOT Category-3 Roadways

by

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May 2018

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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
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)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF
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)

(Source: FHWA)

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EXECUTIVE SUMMARY

This study evaluated the benefits of Open Graded Friction Course (OGFC) on NDOT Category-3 Roadways. Field projects constructed in Elko and Las Vegas, respectively were used for the research analysis. Each project included both the OGFC and Dense-Graded Hot Mix Asphalt (DGHMA) sections. The Elko project was a Category-3 project located on state route 535 in the town area of Elko while the Las Vegas project was a Category- 1 project constructed in a rural area on I-15 interstate highway. The I-15 Category-1 project was selected for this study because there were no Category-3 projects in southern Nevada during the time of this research study. Laboratory tests were performed to evaluate the durability, rutting and moisture-susceptibility of OGFC mixtures. The selected test methods included the Cantabro test, Tensile Strength Ratio (TSR) test, and Hamburg Wheel-Track Test (HWTT). The laboratory test results showed that the Las Vegas OGFC mixture passed all the performance criteria, but the Elko Mixture failed to satisfy the HWTT criterion.

The field performance tests were conducted to assess the permeability, friction, texture, and noise functionality over time. The selected test methods included the NCAT falling head permeameter test, locked-wheel skid trailer test, Circular Texture Meter (CTM), and On-Board Sound Intensity (OBSI) test. The field performance results demonstrated that the Las Vegas OGFC pavement exhibited benefits in permeability, friction, and noise reduction compared to the DGHMA pavement, while the Elko OGFC pavement showed comparable performance with the DGHMA pavement after 2-years of service.

Finally, a cost-benefit analysis was conducted to monetize the advantages and disadvantages of OGFC pavements. As demonstrated in the economic analysis, the OGFC pavement in Las Vegas reduced the net present value of project costs by 36%, while the OGFC pavement in Elko increased the net present value of project costs by 86%. This indicates that the implementation of OGFC is cost-effective in rural highways but impractical in urban or town areas. High speed traffic is generally needed to help keep the interconnected voids of an OGFC pavement from becoming clogged over time. As a result of the reduced speed on the Elko project, the permeability functionality was lost after one year and the noise reduction benefit was lost after thirty two months.

CHAPTER 1. LITERATURE REVIEW

INTRODUCTION

Open graded friction course (OGFC) is a gap-graded asphalt mixture that contains a high percentage of air voids (i.e., usually 15% - 22%) (Alvarez et al. 2006). It is also known as Permeable European Mix (PEM), Porous Friction Course (PFC), and Porous Asphalt (PA) that has been widely used in Europe (e.g., The Netherlands, France, and Germany), Asia (e.g., China, Japan, and Korea), and the United States for decades. The OGFCs are usually paved as the final riding surface on roadways because of the safety and environmental benefits associated with this mixture. Despite the benefits, the use of OGFC has diminished over the years due to durability and service life issues. The durability problems are generally evidenced by raveling, and once the distress begins, it progresses rapidly. A 1998 survey conducted by the National Center for Asphalt Technology (NCAT) showed that in 1998, 22 states had discontinued use of OGFC (Kandhal and Mallick 1998). A 2015 survey conducted by NCAT showed that only half of 41 responding agencies (40 states and Puerto Rico) were using OGFC mixes. Figure 1 depicts the results of the 2015 survey regarding OGFC usage. The survey revealed that agencies that did not use OGFC felt that their designs were not adequate to maintain the expected performance life of OGFC mixes. The primary distresses that reportedly caused premature failure were identified as raveling and top-down cracking. Figure 2 shows the examples of raveling and cracking in an OGFC mix. In this chapter, a thorough review of existing OGFC studies was conducted to summarize the benefits and disbenefits of OGFC mixes, and their mix design methods and construction and maintenance issues.

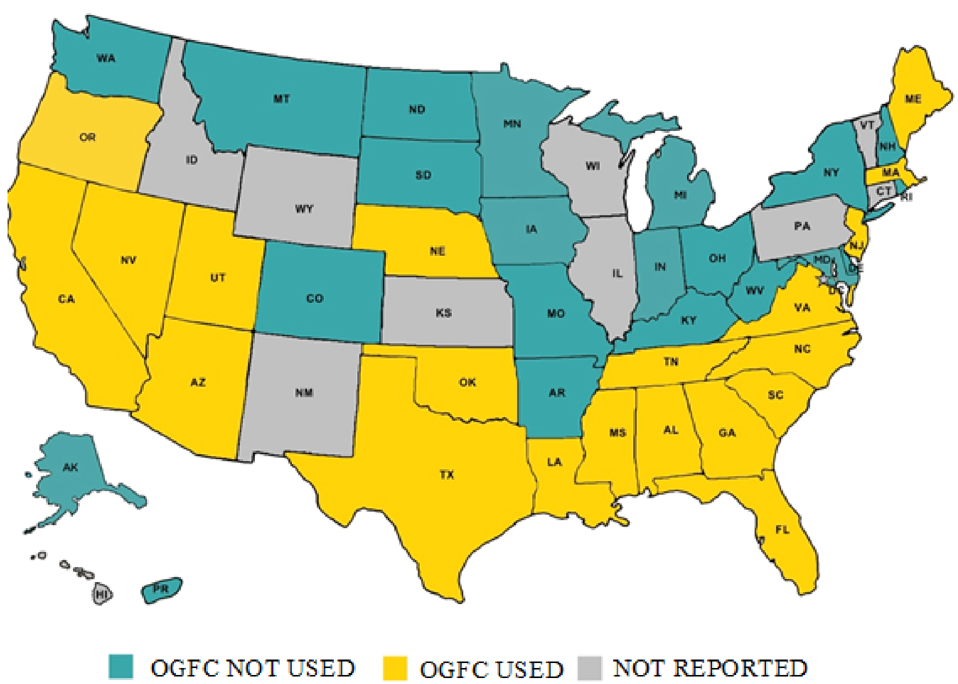


Figure 1 Use of OGFC Mixtures by State Highway Agencies in 2015.

(a) **(b)**

Figure 2 Primary distresses observed in OGFC mixes of (a) top-down cracking and (b) raveling.

BENEFITS AND DISBENEFITS OF OGFC MIX

The safety and environmental benefits of OGFC mix have been documented in many studies. In regard to safety, one of the obvious abilities of OGFC mixtures is to channel water through the pavement structure. The reduction in water standing or flowing across the pavement surface during wet weather is a significant improvement over the performance of dense-graded hot mix asphalt (DGHMA) layers. Thereby, the use of OGFC mixture as a surface layer is effective in improving the friction resistance of pavement in wet weather, reducing splash and spray from surrounding vehicles, reducing glare from on-coming headlights during rainy conditions, and enhancing the visibility of pavement markings. Figure 3 compares the driver's view on the surfaces of OGFC and DGHMA in rainy days. It is shown that the backsplash and spray from vehicles dramatically diminish a driver's view of the paint striping and surrounding vehicles.

(a) **(b)**

Figure 3 Comparison of driver's view on rainy days on (a) dense-graded mix and (b) OGFC surface.

Because of these safety benefits, the OGFC treatment has been shown to lower wet weather vehicle crashes or accident rates and reduce the economic costs of accidents. Figure 4 shows a traffic study conducted by Japanese researchers in 2010 (Shimento and Tanaka 2010). As presented, the OGFC significantly reduced the number of fatalities during rainy weather in Japan when compared to standard DGHMA. Hernandez-Saenz et al. (2016) asserted that these safety-related benefits were the main reason for using OGFC mixtures in the United States. However, some studies challenged that the safety effectiveness of OGFC was limited and inconclusive (Elvik and Greibe 2005; Buddhavarupu et al. 2015). They claimed that the road user usually drives faster on OGFC surfaced pavements, which might result in a higher accident rate as compared to the conventional pavements. Thus, there is an urgent need to thoroughly review these studies in order to evaluate the safety effectiveness of OGFC pavements.

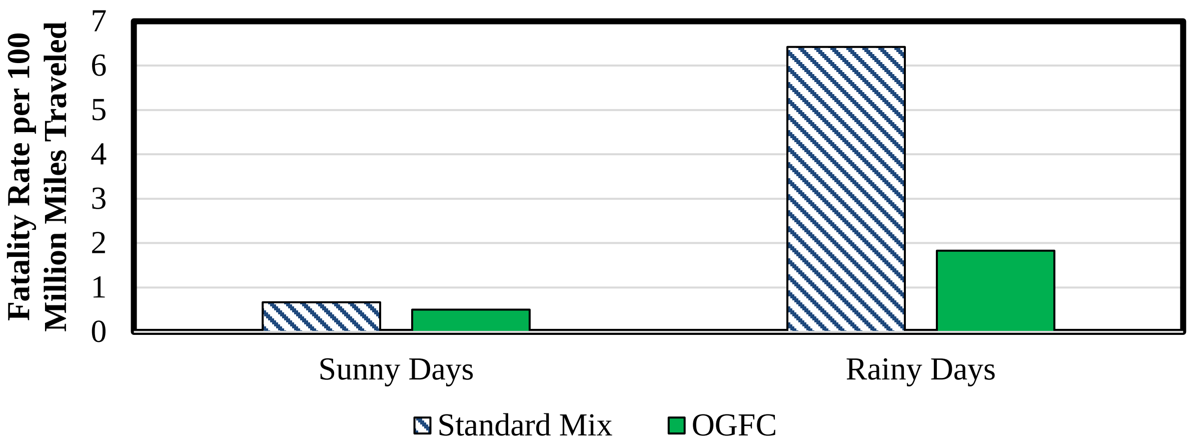


Figure 4 Fatality reduction on rainy days.

In terms of environmental benefits, OGFC is effective in reducing the tire/pavement noise and improving the water runoff quality. The majority of highway noise comes from the pavement-tire interaction, especially when the traffic speed is above 45 miles per hour. The noise can become an annoyance to human beings, which leads to negative impacts on the quality of life. It can also have an economic impact on real estate by keeping properties from being developed or sold (Donavan 2007). Because of its high interconnected air void content, the OGFC mix acts as a resonant cavity structure that efficiently absorbs sound energy generated from the tire-pavement interface. The existing studies indicate that the use of OGFC reduces the tire/pavement noise by 3 to 6 dBA, which is equivalent to diminishing the traffic volume by 50 percent or comparable to the construction of a noise wall (Bernhard and Wayson 2004). Due to its considerable noise reduction, OGFC has been used as a strategic means of meeting environmental noise regulations in Europe.

In addition, a few studies also pointed out the water runoff generated from OGFC surface was of better quality than that from conventional DGHMA surfaces. It was found that water runoff from OGFC layers had a significant lower concentration of total suspended solids, total metals, and phosphorus. This benefit of OGFC was attributed to the reduction of splash and spray that reduced the amount of pollutants derived from the bottoms of vehicles, and a large amount of pores in the surface layer that were able to retain these pollutants.

Although these safety and environmental benefits are attractive, the use of OGFCs is also associated with several shortcomings. One great shortcoming is its high material cost. The material cost of OGFC is usually 20%-40% higher than that of conventional mixes used in highway construction. Winter maintenance is another serious problem for OGFC pavement. Compared to the conventional pavement, OGFC pavement has earlier and more frequent frost and ice formation due to its low thermal conductivity caused by a porous void structure. To maintain a desirable ride quality in winter, OGFC pavement requires more deicing agents and more frequent maintenance activities, which means OGFC pavement has higher maintenance costs than the conventional pavement. In addition, OGFC mixture is often associated with poor long-term performance or durability. The OGFC mixture normally has a higher potential for raveling when compared to conventional mix. This results in a shorter service life for OGFC pavements (e.g., typically 7-10 years for OGFCs and 12-15 years for conventional mix). Apparently, the durability and service life issues diminish the use of OGFC treatment in asphalt pavements. As shown in Figure 1, only 20 state highway agencies were using OGFC mixtures. Based on the survey feedback, the primary reason agencies did not use OGFC was that their mix designs were not adequate to ensure the expected service life of OGFC mixtures. Therefore, a performance-based mix design is needed to produce long-lasting OGFC mixtures with adequate functionality.

MIX DESIGN METHODS

An OGFC pavement must be permeable enough to drain the water away from the surface and off the roadway, and meanwhile it must provide acceptable performance with a long service life. Current design of OGFC mixtures requires three major components, including: a) suitable materials; b) a well-designed gradation; and c) optimum binder content. In this section, the existing mix designs of OGFC mixture are reviewed on the basis of these three components.

Selection of Materials

The OGFC mixtures usually consist of aggregates, asphalt binders, stabilizing agents, and fillers or anti-stripping agent. A detailed description of the selection of these materials is presented as follows.

Aggregates

In the United States, the most commonly used aggregate types are granite, limestone, gravel and sandstone. Some state highway agencies also consider traprock and blast furnace slag for the mix design of OGFC mixtures. Figure 5 presents a survey result of aggregate type specified by agencies. To ensure the aggregates with high quality, the aggregate characteristics that are considered for the mix design include durability, polish resistance, angularity, shape, cleanliness, abrasion resistance, and absorption. Table 1summarizes the requirements of these aggregate characteristics in the existing mix designs in terms of importance level, test method, test indicator, and typical values. The importance level is ranked according to a survey from National Cooperative Highway Research Program (NCHRP) Report 640 (Cooley et al. 2009). The typical values are summarized from the existing OGFC specifications in different countries.

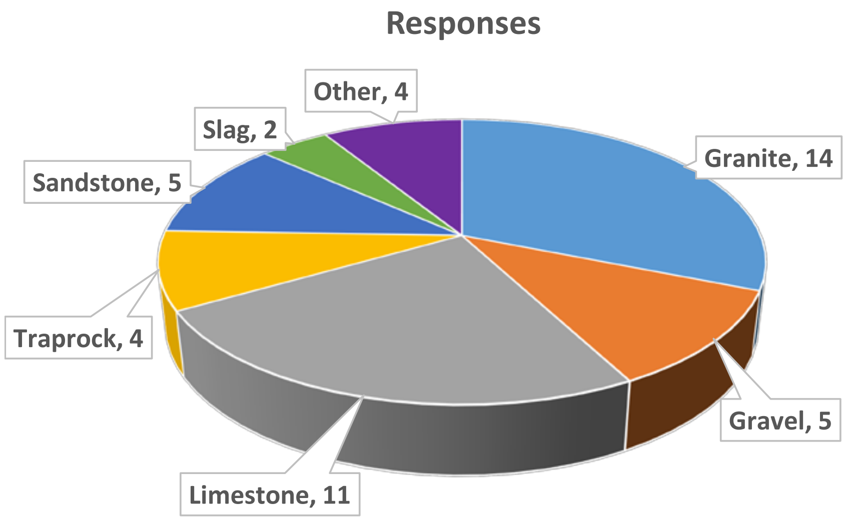


Figure 5 Aggregate type specified by agencies.

Table 1 Requirements of aggregate characteristics in OGFC mix design

Characteristic	Importance Level	Test Method	Test Indicator	Typical Values
Polish resistance	1	AASHTO T278, T279	Polished Stone Value	45-60 (min)
Durability	2	AASHTO T104	Soundness loss	12-20 % (max)
Angularity	3	ASTM D7064	Fractured face count	2 or more fractured faces: 75-95% (min)
Abrasion resistance	4	ASTM C131, AASHTO T96	Abrasion loss	12-50% (max)
Shape	5	ASTM D4791	Percentage of flat and elongated particle	5:1 ratio: 5-10% (max) 3:1 ratio: 20% (max)
Cleanliness	6	ASTM D2419, AASHTO T176	Sand Equivalency	45-55% (min)
Absorption	7	ASTM C127	Water absorption	2-4% (max)

Asphalt Binders

OGFC mixes have been successfully used with both modified and unmodified binders. The use of modified binders becomes more prevalent since the modified binders are effective in increasing the service life of OGFC pavements and preventing the draindown of OGFC mixtures. In the United States, the most common modifiers for OGFC mixtures are SBS polymer and rubber (e.g., crumb rubber modifier and ground tire rubber). These modifiers can provide a stiffer asphalt binder for OGFC mixtures, which leads to the increase of cohesion in aggregate stone skeleton. For this reason, the OGFC mixes with the modified asphalt binders usually have higher resistances to rutting, cracking, and raveling damage, which exhibit better durability in the field. Table 2 presents the requirements of highway agencies for the use of modified and unmodified asphalt binders in OGFC mixtures. Note that the binders are graded by the Superpave Performance Grading (PG) system in the United States, and graded by the penetration grading system in European countries.

Table 2 Requirements of asphalt binders used in OGFC mixtures

Agency	Binder Requirement
UK	100 pen
Italy	80/100 pen
Spain	80/100 pen
Alabama	PG 76-22
Florida	PG 76-22, PG 76-22 HP, ARM-5, ARB-12
Mississippi	PG 76-22
North Carolina	PG 76-22, PG 64-22
Texas	PG 76-XX
Virginia	PG 70-28

Stabilizing Agents

Stabilizing additives are used to improve the durability of OGFC mixtures by preventing draindown and by increasing their tensile strength. When draindown occurs during production and transportation of the OGFC mixture, a significant amount of the asphalt binder is lost from the mix. This loss of binder can cause decreased durability, which may lead to premature raveling or cracking. Figure 6 shows a survey response to stabilizing additives used in OGFC mixes. The most commonly used stabilizers are cellulose and mineral fiber. They are typically added to the mix at a rate of 0.2-0.5 percent by total weight of the mixture (Cooley et al., 2009). Cellulose fibers are flora-based and made in either pellet or loose form. The cellulose fiber has high absorption so that it enables to maintain high binder content and reinforced asphalt film. Mineral fibers exist in two forms: manufactured and naturally-occurring. Asbestos, the only naturally-occurring fiber used in asphalt, was used as mineral filler in the 1960’s until its negative impact on human health was discovered. The most common manufactured mineral fibers are mineral wool or rock wool. They are not as absorbent as cellulose fiber and sometimes create harsh mixtures that are hard to compact.

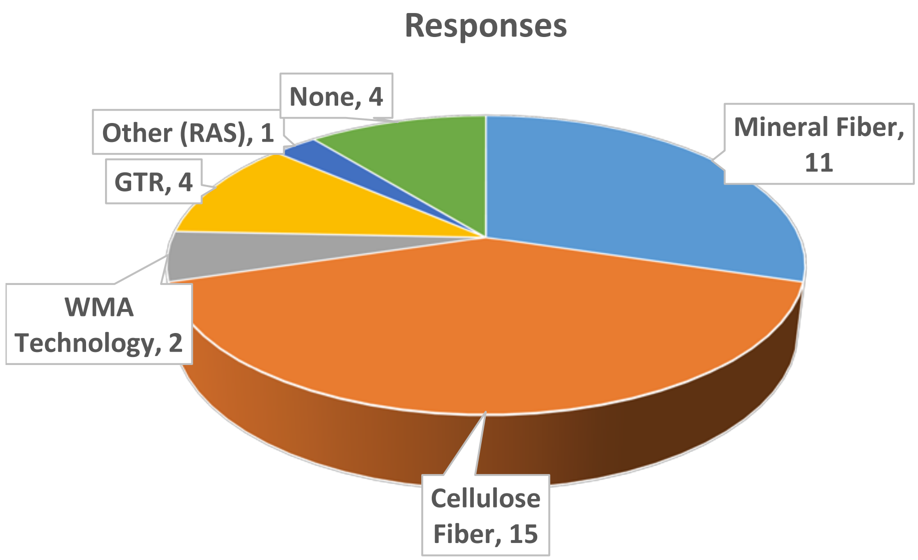


Figure 6 Survey response to stabilizing additives used in OGFC mixes.

Fillers/Anti-stripping Agents

Fillers or antistripping agents are recommended in OGFC mixtures to improve the bond between aggregates and asphalt binders, and to prevent moisture damage of the mixtures. The fillers or anti-stripping materials that are commonly used in OGFC mixtures include hydrated lime, limestone dust, and liquid anti-stripping agent.

Selection of Design Gradation

With suitable materials selected, trial gradations with initial asphalt contents should be established. The rules of thumb for the gradation design are a) to establish coarse aggregate skeleton that develops stone-on-stone contact; and b) to guarantee high interconnected air voids content. Three trial gradations are usually evaluated, which include the coarse limit, fine limit and the middle of the recommended gradation band. Currently, there is no nationally accepted gradation band for OGFC mixtures in the United States. Table 3 lists the aggregate gradations for OGFC mixtures that are specified by highway agencies. As can be seen from Table 3, U.S. agencies primarily use a 19.0 mm maximum aggregate size design and the majority of them are gapped between the 9.5 mm sieve and the 4.75 mm sieve. In addition, the OGFC mixtures use much less fine aggregates as compared to the conventional DGHMAs. The gradations for Alabama, Georgia, Louisiana and South Carolina are almost identical. These similarities in the specifications are attributed to the studies from Watson et al. (1998) conducted on OGFCs in Georgia. Table 3 also shows the aggregate gradation recommended by the National Center for Asphalt Technology (NCAT). The NCAT-recommended gradation band gaps at sieves 9.5mm and 4.75mm with the ranges from 35 to 60 percent passing the 9.5 mm sieve and 10 to 25 percent passing the 4.75 mm sieve. This gradation is also documented in ASTM D7064, entitled "Standard practice for open-graded friction course mix design".

Cooley et al. (2009) provided an empirical relationship to estimate the initial asphalt content for trial gradation, which is based on the combined aggregate bulk specific gravity. Specimens are compacted for each of the trial gradation, and the corresponding air void content of mixture and voids in the coarse aggregate (VCA) are used to select the design gradation.

Table 3 Aggregate gradations for OGFC mixtures specified by highway agencies

State Mix	19mm (3/4")	12.5mm (1/2")	9.5mm (3/8")	4.75mm (No. 4)	2.36mm (No. 8)	1.18mm (No. 16)	0.6mm (No. 30)	0.075mm (No. 200)
AL	100	85-100	55-65	10-25	5-10			2-4
AZ 1			100	30-45	4-8			0-2
AZ 2			100	31-46	5-9			0-3
CA 1			78-89	28-37	7-18			
CA 2		99-100		29-36	7-18			
FL	100	85-100	55-75	15-25	5-10			2-4
GA 1		100	85-100	20-40	5-10			2-4
GA 2	100	85-100	55-75	15-25	5-10			2-4
GA 3	100	80-100	35-60	10-25	5-10			1-4
LA 1		100	90-100	25-50	5-15			2-5
LA 2	100	85-100	55-75	10-25	5-10			2-4
MS		100	80-100	15-30	10-20			2-5
NC 1		100	75-100	25-45	5-15			1-3
NC 2		100	75-100	25-45	5-15			1-3
NC 3	100	85-100	55-75	15-25	5-15			2-4
NE	100	95-100	40-80	15-35	5-12			0-3
NJ 1		100	89-100	30-50	5-15			2-5
NJ 2	100	85-100	35-60	10-25	5-10			2-5
NJ 3		100	85-100	20-40	5-10			2-4
NM		100	90-100	25-55	0-12		0-8	0-4
NV 1		100	90-100	35-55		5-18		0-4
NV 2		100	95-100	40-65		12-22		0-5
OR 1		99-100	90-100	22-40	5-15			1-5
OR 2	99-100	90-98		18-32	3-15			1-5
SC	100	85-100	55-75	15-25	5-10			0-4
TN	100	85-100	55-75	10-25	5-10			2-4
TX 1	100	80-100	35-60	1-20	1-10			1-4
TX 2	100	95-100	50-80	0-8	0-4			0-4
NCAT	100	85-100	35-60	10-25	5-10			2-4

Determination of Optimum Binder Content

Once the design gradation is selected, the optimum binder content (OBC) needs to be determined. In this step, there are usually 3 or 4 trial asphalt contents with a 0.5 percent increment above and below the initial asphalt content. The methods to determine the OBC are generally categorized as three groups: 1) absorption calculation; 2) visual determination; and compacted specimen evaluation.

The absorption calculation method utilizes the oil absorption capacity and the apparent specific gravity of aggregates to empirically estimate the OBC of OGFC mixture. This method ignores the influence of binder type and aggregate type on the OBC of asphalt mixture. Meanwhile this method cannot ensure that OGFC mixture with designed OBC has satisfied field performance.

The visual determination method refers to Pie-plate or Pyrex bowl test. In this method, approximately 1000 grams uncompacted OGFC mix placed in a glass pie plate is oven-heated at 160°C for 1 hour. After that, the pie plate with OGFC mix is removed from the oven to cool down to room temperature, and then the plate is inverted for the visual determination whether the trial binder content is the OBC. The visual determination is extremely subjective, which requires experienced technician to judge the results. To overcome this issue, Pernia et al. (2016) employed an image analysis technique to quantitatively determine the OBC of OGFC mix. This approach is similar to the draindown test, which can evaluate the stability of OGFC mix.
The compacted specimen evaluation method directly targets the performance of OGFC mixture to determine its OBC. The specimens are compacted either at a level of 50 gyrations using Superpave Gyratory Compactor (SGC) or at a level of 50 blows per each side using a Marshall Compactor. The following engineering properties of compacted specimen are evaluated:

1) Air voids, which are related to the permeability of pavement;
2) VCA of the dry-rodded aggregate (VCA_{DRC}) and VCA of the mix (VCA_{MIX}), which is to ensure the stone-on-stone contact;
3) Cantabro loss, which is related to durability;
4) Draindown, which is related to stability;
5) Permeability; and
6) Tensile strength ratio (TSR), which is related to the moisture susceptibility.

Table 4 summarizes three national compacted specimen evaluation criteria to determine the OBC of OGFC mixture. In general, these three mix design criteria are in good agreement with each other. Compared to the other two methods above, the compacted specimen evaluation method is more desirable to reflect the field performance of OGFC mixture. However, the use of compacted specimen-based methods still cannot ensure the designed OGFC mixture possesses satisfactory field performance. For example, the existing studies reported that some premature distresses including raveling, shoving, and excessive rutting, were found in OGFC pavements. This is because other important engineering properties (e.g., cracking and rutting resistance) should also be considered in OGFC mix design.

Table 4 Optimum asphalt content properties for OGFC mixes

Mix Property	NCHRP 640	ASTM D7064	NAPA Series 115
Air Voids (%)	18 – 22	≥18	≥18
Unaged Cantabro Loss (%)	≤15.0	≤20.0	≤20.0
VCA_{MIX} (%)	<VCA_{DRC}	≤VCA_{DRC}	≤VCA_{DRC}
Tensile Strength Ratio	≥0.70	≥0.80	≥0.80
Draindown at Production Temperature (%)	≤0.30	≤0.30	≤0.30
Permeability (m/day), min.	100	100	100

CONSTRUCTION AND MAINTENANCE

The main issues with OGFC mixes that can be related to construction are raveling and delamination. The following factors are the main influences that lead to issues with OGFC pavements during production and construction:

- Homogenous mix gradation and temperature
- Asphalt content
- Tack bond strength, rate and quality of application
- Layer thickness
- Mixing temperature during placement

According to Bennert et al. (2014), production and construction issues may be more responsible for raveling than mix design properties. Inconsistent temperatures in the mix during construction can lead to both delamination and raveling. Delamination occurs when the bond between the underlying surface and the OGFC is inadequate and causes a slip plane. A tack application is placed on the surface of the underlying layer so that the OGFC can adhere. If the underlying layer is too cold or covered in dust the tack material may not adhere, causing the pavement to delaminate. The amount and type of tack material is also important. Since OGFC mixtures are coarse-graded, there is less contact area between aggregate particles in the OGFC and the underlying layer than for a DGHMA. It would therefore seem logical that the tack rate should be increased so that the contact area has the same tack bond strength as a DGHMA.

Several studies have been conducted on the interface bond strength. An NCAT study in 2005 recommends a bond strength of 100 psi, when tested at 77°F, for newly constructed overlays (West et al. 2005). This study was primarily for DGHMA overlays but did include porous overlay data in the bond strength recommendation. By improving the bond of the two layers, the risk of delamination is diminished.

The rate at which the tack is applied is also a critical component. Figure 7 shows tack rates provided by agencies that responded to the 2014 NCAT survey. Most tack material is an emulsion. Emulsions consist of asphalt binder particles that are suspended in water. This allows the tack to be spread more evenly and allows it to be applied at lower temperatures for safety reasons. The percent of asphalt binder in the emulsion is known as the residual. Most application rates are based on the residual. There is a wide range of tack rates provided in the responses

(0.02 – 0.15 gal/sy) depending on the type of tack material used. One example of the "Other" category shown in Figure 7 is from South Carolina which provided a range of 0.05-0.15 gal/sy.

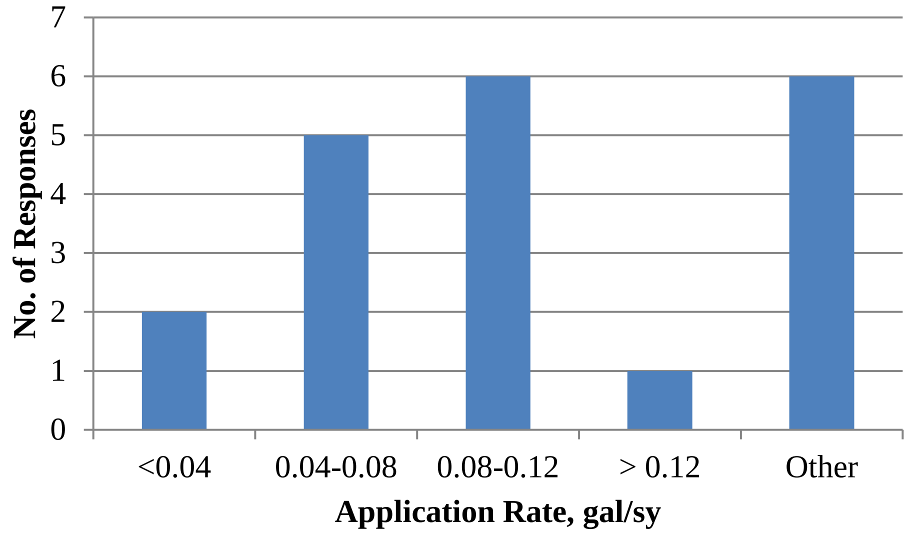


Figure 7 Agency response for tack application rate.

While raveling can be linked to the interface bond, it is also a durability issue that begins at the top of the pavement. Mix temperature is one of the biggest concerns when constructing OGFC mixtures. Consistent mix temperatures and short haul times are critical for adequate placement. Due to the open structure, an OGFC will cool faster than a standard DGHMA. This can be mitigated somewhat with the use of insulated truck beds and tarpaulins during transport to resist crusting of the outer surface of the mix on the haul truck. However, initial production temperature, haul time, and the ambient/pavement surface temperature are more critical. Great Britain specifies that from production until the mix is placed on the ground, no more than 3 hours can elapse (Alvarez et al. 2006). The FHWA Technical Advisory recommended a maximum haul distance of 40 miles and a travel time of less than 1 hour (FHWA 1990). In order to mitigate the loss of heat in OGFC mixtures during construction the following items have be considered:

1. Provide an adequate number of haul trucks so that there is no pause in construction. When the paver is required to wait on haul trucks due to a lack of mix, a cold transverse joint is created (Figure 8a).
2. Preheat the screed before the initial start-up at a transverse joint. A cold screed will pull some of the mix particles at the start-up transverse joint and will cause a lack of mix homogeneity. In DGHMA, the material can be raked to correct this issue; but raking an OGFC, especially with modified binder is somewhat difficult.
3. Use a material transfer vehicle (MTV). A MTV is used to remix the asphalt mixture after it has been transported to the job site. This remixing should result in a homogenous mix temperature that will help eliminate cold spots in the asphalt mat.
4. Ensure adequate screed crown and temperature. Most pavers use multiple burners to heat the screed. These burners can go out during production and cause a cold spot in one section of the screed. It is important to provide proper adjustment of screed crown and screed

extensions in order to obtain a smooth finish. Due to the relatively thin layer thickness and high proportion of coarse aggregate, failure to properly adjust the screed will cause the mix to pull and results in streaks in the mat (Figure 8b).

(a) **(b)**

Figure 8 Raveling of OGFC mixture due to poor construction practices (a) cold transverse joint and (b) center of paver streak.

CHAPTER 2. OGFC FIELD CONSTRUCTION PROJECTS

INTRODUCTION

NDOT constructed two projects for evaluation during this research: one project each in northern and southern Nevada as shown in Figure 9. The northern Category-3 OGFC section was constructed in Elko on a two lane section of SR 535 which extends from I-80 eastward to Fifth Street (3.8 miles). The focus of the research testing for this project was from milepost 0.0-1.0 for the dense-graded control section and from 1.0-2.0 for the OGFC section. The southern Nevada project was built on Interstate 15 (I-15), a four lane roadway with divided median, east of Las Vegas. This project is a Category 1 project, but was selected for this research study because there were no Category-3 projects in southern Nevada available at the time this study was conducted. The project extends for 25 miles from 2.4 miles north of U.S. 93 to the Nevada/Arizona state line. The focus of the research was from milepost 85-89 in the northbound direction with the dense-graded mix being placed from milepost 86.8 to 87.6. From the magnified map shown in Figure 9, it is seen that the Elko OGFC mix was paved in an urban area, while the OGFC mix placed near Las Vegas was paved in a rural area.

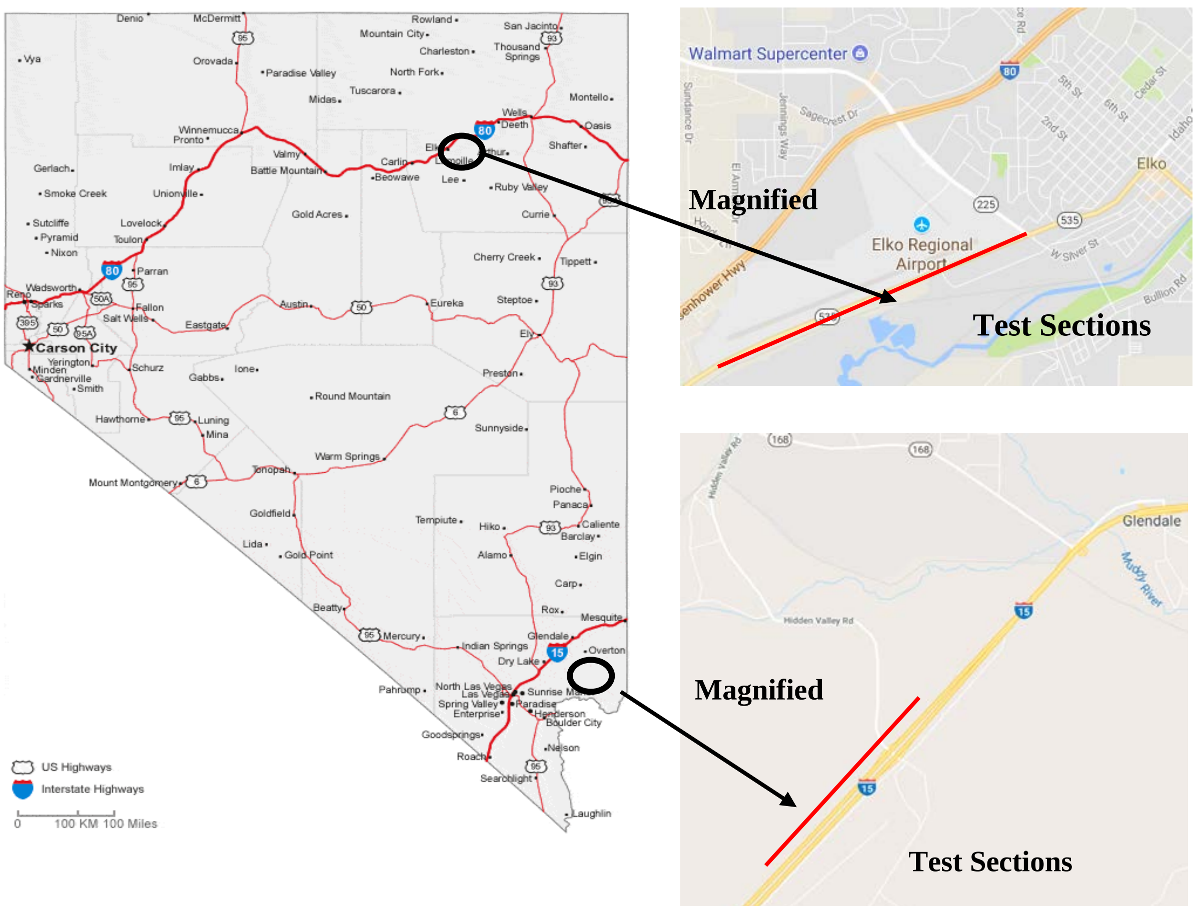


Figure 9 Locations of identified construction projects.

CONSTRUCTION INFORMATION

In the Elko project, the existing asphalt concrete was milled 2 inches and then 2-inch dense-graded hot mix asphalt (DGHMA), Type 2, was placed as the surface for the control section. For the OGFC section, 2¾-inch existing asphalt concrete was milled, and then 2-inch DGHMA and ¾-inch OGFC mix was placed as the final riding surface. The dense-graded mix also contained 15% RAP which contributed 0.8% of the total binder. PG 64-28 NV virgin binder was added at a rate of 4.2% for a total binder content of 5.0%. The same binder at an optimum rate of 6.7% was used for OGFC. It is important to note that NDOT bases asphalt content on the total weight of aggregate instead of total weight of mix. Hydrated lime was used as an anti-stripping agent in both mixes to improve the resistance to moisture damage. The lime was added to the virgin aggregate in slurry form at a rate of 1.5% of the virgin aggregate rate. The treated aggregated is required to marinate for 48 hours before using in mix production.

The aggregate gradations of the two SR 535 mixes are presented in Table 5. The unit cost of DGHMA was $70/ton, and the unit cost of OGFC was $130/ton. Figure 10 shows SR 535 OGFC construction.

Table 5 Aggregate gradations of DGHMA and OGFC mixes for the Elko project

Sieve Size	DGHMA		OGFC	
	% Passing	Spec. Range	% Passing	Spec. Range
1”	100	100		
3/4”	91	90-100		
1/2”	72		100	100
3/8”	64	63-85	97	95-100
No. 4	47	45-63	49	40-65
No. 10	31	30-44		
No.16			18	12-22
No. 40	14	12-22		
No.200	5	3-8	4	0-5

Figure 10 OGFC construction on SR 535.

In the I-15 project, 3-inch to 5-inch existing asphalt concrete was milled. The control section was resurfaced with 3-inch DGHMA, and the OGFC section was resurfaced with 3-inch plant mix DGHMA and ¾-inch OGFC. The I-15 project also incorporated 15% RAP in the dense-graded mix with a RAP binder contribution of 0.6%. PG 76-22NV binder was added at 3.2% for a total binder content of 3.8%. The same binder with a ratio of 5.7% of total aggregate was used for OGFC. Lime slurry was used as anti-strip for this project as well and was based on 1% of the coarse aggregate portion and 2% of the fine aggregate portion for a combined treatment rate of 1.29% for the dense mix and 1.7% for the OGFC mix. In both cases, the treated aggregate was required to marinate 48 hours before incorporating into plant mixture.

The aggregate gradations of these two I-15 mixes are shown in Table 6. The unit cost of DGHMA was $63.5/ton, and the unit cost of OGFC was $87/ton. As described, the cost of Elko OGFC mix is much higher than that of the Las Vegas mix. This is because the Elko OGFC mix had a higher binder content and higher transportation fees. Figure 11 shows OGFC construction on the I-15 project.

Table 6 Aggregate gradations of DGHMA and OGFC mixes for the I-15 project

Sieve Size	DGHMA		OGFC	
	% Passing	Spec. Range	% Passing	Spec. Range
1”	100	100		
3/4”	91	88-95		
1/2”	74	70-85	100	100
3/8”	68	60-78	93	90-100
No. 4	53	43-60	43	35-55
No. 10	36	30-44		
No.16			7	5-18
No. 40	21	12-22		
No.200	8	3-8	3	0-4

Figure 11 OGFC construction on I-15.

CHAPTER 3. LABORATORY TEST RESULTS

INTRODUCTION

The objective of this chapter was to evaluate the laboratory performance of the OGFC and DGHMA mixtures that were received from the identified field projects. The selected test methods included the Cantabro test, tensile strength ratio (TSR) test, and Hamburg wheel-track test (HWTT). The test methods and the corresponding results are detailed in the following sections.

CANTABRO TEST

The Cantabro test was used to determine the durability of an OGFC. The test method AASHTO TP 108-14, Standard Method of Test for Determining the Abrasion Loss of Asphalt Mixture Specimens was followed for this test. The Cantabro tests were performed on the three groups of OGFC mixtures, which were: (1) unconditioned mixtures; (2) long-term oven aged mixtures; and (3) vacuum saturated with one freeze/thaw cycle conditioned mixtures. The long-term oven aging procedure followed the AASHTO R30, Standard Practice for Mixture Conditioning of Hot Mix Asphalt. The vacuum saturation with one freeze/thaw cycle conditioning procedure followed AASHTO T283, Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. The OGFC specimens were individually placed in the Los Angeles Abrasion machine and were tested for 300 revolutions at a rate of 30 to 33 revolutions per minute. The loose material was discarded and the final specimen weight was recorded. The percent loss was calculated for each specimen according to Equation 1.

$$CL = \frac{A-B}{A} * 100 \qquad (1)$$

Where:
CL = Cantabro Loss, %
A = Initial weight of test specimen
B = Final weight of test specimen

Figure 12 shows the Cantabro loss results of the two OGFC mixtures and DGHMA mixtures with various conditioning procedures: none, long-term aging per AASHTO R30, and vacuum-saturated with one freeze-thaw cycle. As shown in Figure 12, both Elko and Las Vegas OGFC mixtures had lower Cantabro loss values compared to the DGHMA mixtures. Both the long-term oven aging and freeze-thaw conditioning increased the Cantabro loss values of OGFC mixtures. Compared with the Las Vegas OGFC mixtures, the Elko OGFC mixtures had less Cantabro loss values no matter the conditioning of the mixtures. According to ASTM D7064, an acceptable amount of loss is less than 20% for unaged specimens and 30% for aged specimens. Therefore, both Elko and Las Vegas OGFC mixtures met the minimum requirements for the durability performance of asphalt mixtures.

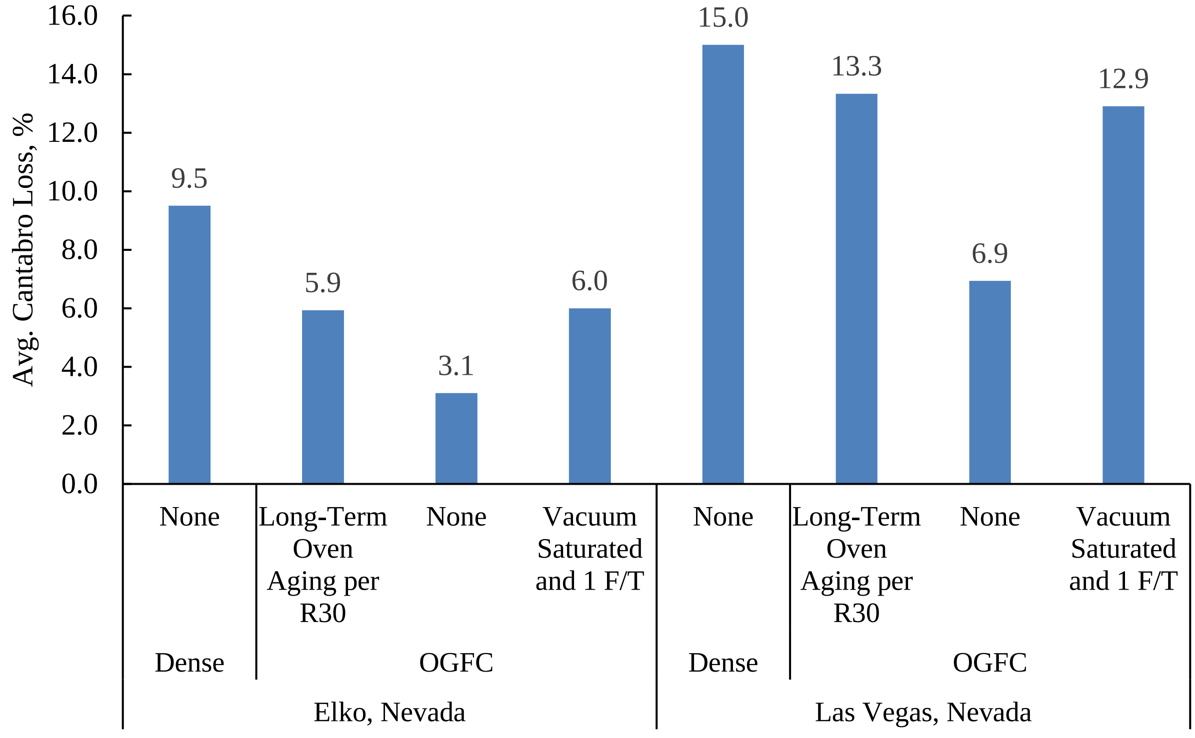


Figure 12 Cantabro loss results for DGHMA and OGFC mixtures.

TENSILE STRENGTH RATIO

The tensile strength ratio (TSR) is defined as the ratio of the tensile strength of water conditioned specimens to the tensile strength of unconditioned specimens, which is shown in Equation 2.

$$TSR = \frac{S_2}{S_1} * 100 \qquad (2)$$

Where:
S_1 = the average tensile strength of unconditioned specimen
S_2 = the average tensile strength of conditioned specimen

The TSR test was conducted on each mix design and performed according to AASHTO T 283, *Resistance of Compacted Bituminous Mixture to Moisture Induced Damage,* with slight modifications to accommodate OGFC mixes. The modifications are recommended in the ASTM D7064 test procedure. The specimens were compacted to the design gyration level and height instead of the target height in the procedure of 95 mm. While this differed from the specification, the height of the specimens was included in the final calculations so this change was accounted for in the final results. The weight of the design specimens was altered slightly for these specimens to target a height of 110 to 115 mm in order to ensure that the specimens fit inside the breaking head. The specimens were saturated at 26 in Hg (660.4 mm Hg) below atmospheric pressure for 10 minutes and then the saturated specimens were frozen in plastic concrete cylinder molds. The specimens were kept submerged under water while freezing to keep the interior voids filled with water. Specimens were then conditioned in a hot water bath at 140°F for 24 hours and put in a 77°F water bath according to AASHTO T 283 prior to breaking. The specimens were tested for indirect tensile strength on a Marshall Stability press at a rate of 2 inches per minute. The tensile strength of the mixes was determined by using the peak load recorded on the device and the specimen dimensions.

Figure 13 presents the TSR test results for DGHMA and OGFC mixtures. It is shown that the OGFC mixtures had lower conditioned tensile strength and TSR than the DGHMA mixtures. Compared to the Elko OGFC mixtures, the Las Vegas OGFC mixtures had higher conditioned tensile strength. However, the TSR values between Elko and Las Vegas OGFC mixtures were comparable with each other. The ASTM D7064 standard suggests that the TSR should be at least 80% for OGFC mix. Accordingly, neither the Elko nor the Las Vegas OGFC mixtures met this requirement. Watson et al. (2018) developed a performance-based mix design for OGFC mixtures. They recommended that the TSR should be at least 70% for OGFC mix, meanwhile the conditioned tensile strength should be greater than 50 psi. Based on this criterion, both the Elko and the Las Vegas OGFC mixtures passed the requirement.

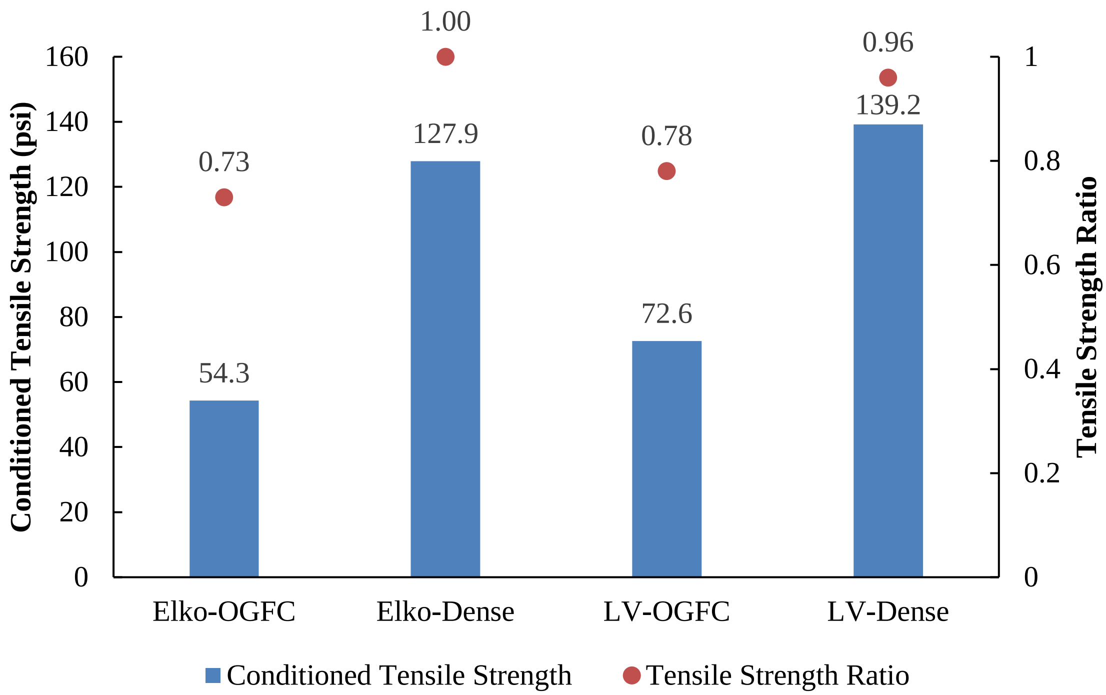


Figure 13 Tensile strength ratio test results for DGHMA and OGFC mixtures.

HAMBURG WHEEL TRACKING TEST

The Hamburg wheel tracking test (HWTT) determines the susceptibility of asphalt mixtures to stripping and rutting. All specimens were fabricated and tested according to AASHTO T 324, *Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)*. Six specimens were fabricated for each design so that statistical analysis could be performed on all of the mixtures. The specimens were subjected to a load of 158 ± 1 lbs. The specimens were submerged and conditioned in a 50°C water bath for 30 minutes prior to testing. The water bath maintained the 50°C temperature for the duration of the testing (20,000 passes). All data output of the linear variable differential transformer (LVDT) attached to each arm was recorded by a computer and analyzed to determine the stripping inflection point (SIP) and moisture susceptibility of the mix. The SIP of the mix was determined by incorporating tangents to the secondary and tertiary stages. The SIP is the number of loaded wheel passes where the tangents intersect. An example of calculating the SIP was shown in Figure 14.

There is currently no nationally accepted criterion for the maximum allowable rutting depth with the HWTT device. Watson et al. (2018) recommended the following criteria based on asphalt binder grade:

i. PG 64 or lower ≥ 10,000 passes before reaching 12.5 mm rut
ii. PG 70 ≥ 15,000 passes before reaching 12.5 mm rut
iii. PG 76 or higher ≥ 20,000 passes before reaching 12.5 mm rut

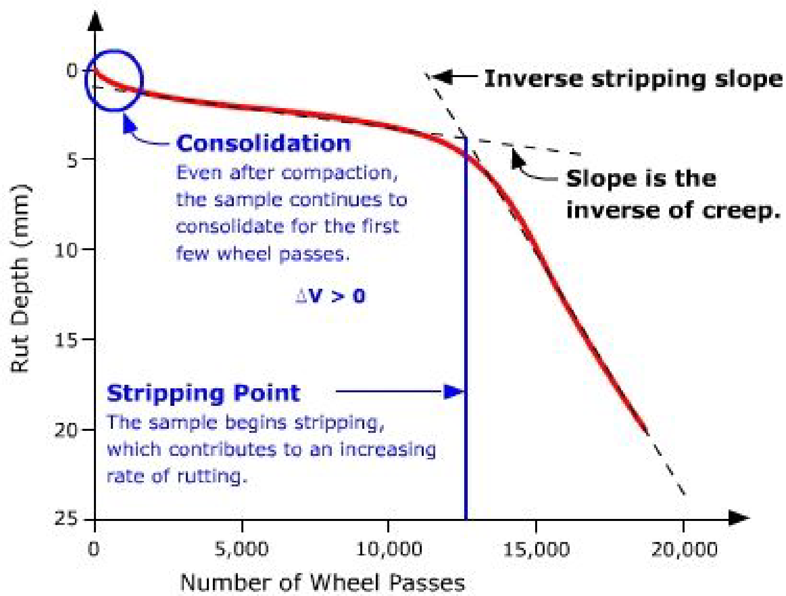


Figure 14 Determination of stripping inflection point from HWTT.

As mentioned in Chapter 2, the Elko project used PG 64-28 NV asphalt binder, while the Las Vegas project used the PG 76-22 NV asphalt binder. According to Watson (2018), the Elko mixtures should have more than 10,000 passes prior to reaching 12.5 mm rut, while the Las Vegas mixtures should have more than 20,000 passes before reaching 12.5 mm rut. Table 7 shows the HWTT results for the Elko and Las Vegas asphalt mixtures. It is indicated that most of the asphalt mixtures passed the requirements except the Elko OGFC mixture. It is also shown that the Elko DGHMA mixture had less rut depth than the Las Vegas DGHMA mixture. This indicated that the Elko DGHMA mixture had a higher rutting resistance and less moisture susceptibility.

Table 7 Hamburg wheel tracking test results for DGHMA and OGFC mixtures

Mixture ID	Rut Depth @ 10,000 passes (mm)	Rut Depth @ 20,000 passes (mm)	Passes to 12.5 mm Rut	Stripping Inflection Point (passes)
Elko OGFC	14.08	>12.5	8950	20,000+
Elko DGHMA	1.70	2.20	20000+	20,000+
Las Vegas OGFC	5.05	8.12	20,000+	20,000+
Las Vegas DGHMA	1.90	2.82	20,000+	20,000+

CHAPTER 4. FIELD PERFORMANCE TEST RESULTS

INTRODUCTION

The objective of this chapter was to evaluate the field performance of the OGFC and DGHMA mixes, which included permeability, friction, texture, and noise. The selected test methods included the NCAT falling head permeameter test, locked-wheel skid trailer test, Circular Texture Meter (CTM), and On-Board Sound Intensity (OBSI) test. The test methods and the corresponding results are detailed in the following sections.

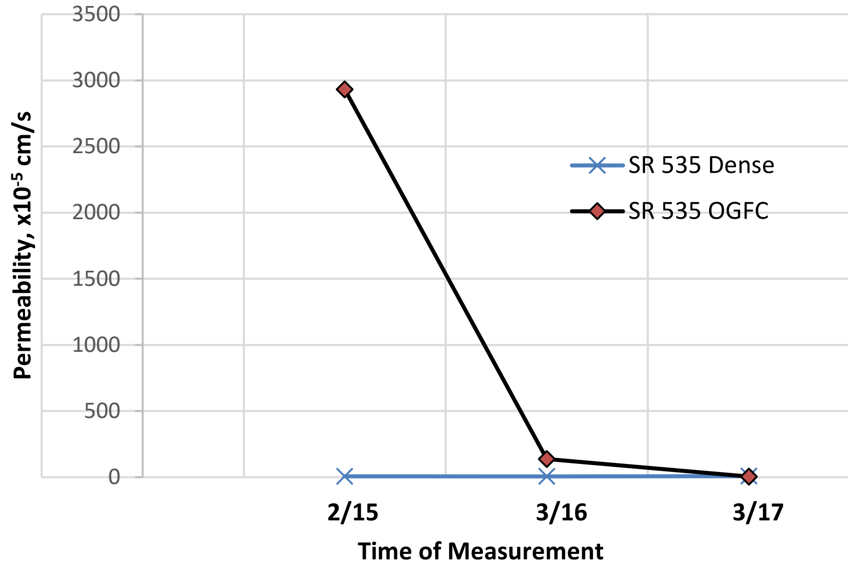
FIELD PERMEABILITY TEST

The NCAT Field Permeameter is a falling head permeameter that uses Darcy's Law to determine the rate of water flow through asphalt pavement. In the field, a clean, representative spot is selected to place the permeameter. A wax ring is placed at the base of the permeameter to prevent water leakage. Water is poured inside the tube and allowed to flow for a few minutes to saturate the pavement. Equation 3 was used to determine the field permeability.

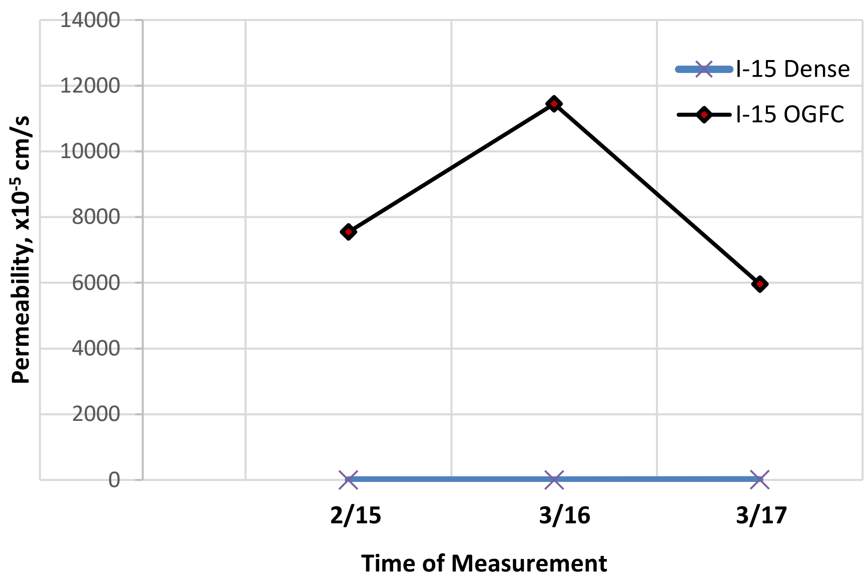
$$k = \frac{aL}{At} ln\left(\frac{h_1}{h_2}\right) \quad (3)$$

Where:
k = coefficient of permeability (cm/s)
a = inside cross-sectional area of the standpipe (cm^2)
L = lift thickness of asphalt mixture
A = base area of the permeameter (cm^2)
t = elapsed time between h_1 and h_2 (s)
h_1 = initial head (cm)
h_2 = final head (cm)

Figure 15 presents the field permeability values of the DGHMA and OGFC pavement sections at different service times. The measurements in February 2015 represented the initial permeability of pavement sections. The measurements in March 2016 and March 2017 reflected the permeability of pavement sections after 1- and 2-years service, respectively. As shown in Figure 15 both the Elko and Las Vegas OGFC sections had much greater initial permeability values than the DGHMA sections. This was because the OGFC mixture had a higher interconnected air void content that was effective in channeling the water to the underlying lifts. For the Elko sections, the permeability of OGFC reduced dramatically after 1-year service, and became comparable to that of DGHMA section after 2-years of service. For the Las Vegas sections, the OGFC pavement still exhibited a satisfactory permeable function after 2-years of service. The Elko sections were located in a town area with low speed limits and frequent stops, while the Las Vegas sections were located on an interstate highway with high speed limits and continuously moving traffic. This infers that the low speed limit and frequent stops were prone to clog the interconnected air voids of OGFC, which thereby diminished the permeability of the OGFC pavements.



(a) Elko Sections



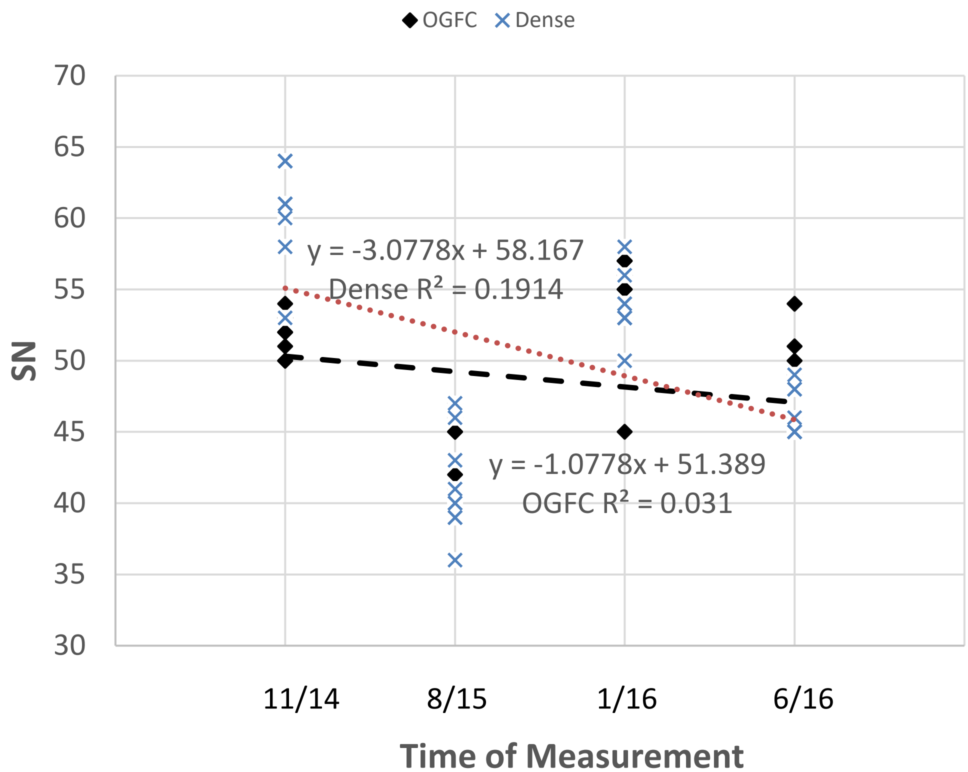
(b) Las Vegas Sections

Figure 15 Field permeability test results of (a) Elko and (b) Las Vegas sections.

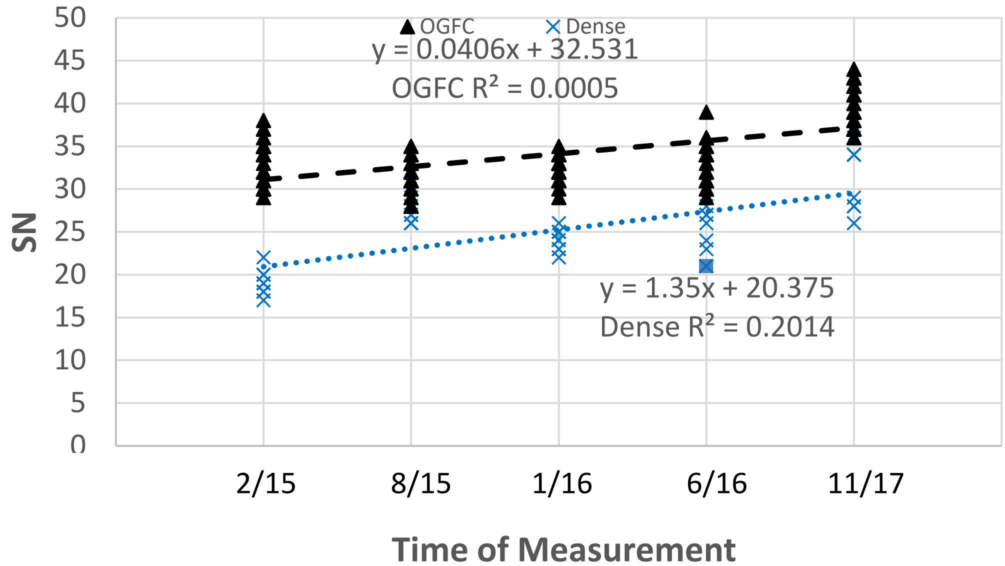
FIELD FRICTION TEST

The locked-wheel skid trailer measures the steady-state friction force on a locked test wheel as it is dragged under a constant load and at a constant speed over a wet pavement surface. In this test, water is sprayed on the pavement surface to simulate wet conditions. The test procedures are documented in ASTM E274. The skid number (SN) is used to characterize the friction of pavement surface, which is determined from the resulting force or torque. A higher SN indicates greater frictional resistance.

Figure 16 shows the friction test results of OGFC and DGHMA pavements in Elko and Las Vegas. For the Elko sections, the OGFC pavement had a lower skid number than the DGHMA pavement at the beginning of service, but had a comparable skid number to the DGHMA pavement after 1.5-year service. For the Las Vegas sections, the OGFC pavement showed higher skid numbers than the DGHMA pavement within 1.5-year service. However, this difference reduced with the increase of service time.



(a) Elko Sections



(b) Las Vegas Sections

Figure 16 Surface friction test results of (a) Elko and (b) Las Vegas sections.

For comparison, NDOT conducted friction tests on a variety of other projects involving both OGFC and dense-graded mixtures. A summary of those results is provided in Table 8.

Table 8 Friction resistance on various NDOT projects

Contract	Location	Pavement Surface Type	Direction	Test No.	Average OG Friction No. (Test Date)	Average DG Friction No. (Test Date)
3550	SR535 (Cum. Mile from EL 0.000 to EL 2.408)	DG is Type 2 mix, OGFC is 3/8" mix	EB	1	51 (11/19/2014)	61 (11/19/2014)
				2	41 (8/18/2015)	41 (8/18/2015)
				3	55 (1/20/2016)	52 (1/20/2016)
				4	49 (6/8/2016)	47 (6/8/2016)
				5	Not tested	Not tested
				6	Not tested	Not tested
				7	Not tested	Not tested
			WB	1	53 (11/19/2014)	60 (11/19/2014)
				2	46 (8/18/2015)	41 (8/18/2015)
				3	54 (1/20/2016)	55 (1/20/2016)
				4	42 (6/8/2016)	45 (6/8/2016)
				5	Not tested	Not tested
				6	Not tested	Not tested
				7	Not tested	Not tested

Table 8 Friction resistance on various NDOT projects

Contract	Location	Pavement Surface Type	Direction	Test No.	Average OG Friction No. (Test Date)	Average DG Friction No. (Test Date)
3561	US050 (Cum. Mile from CC 14.761 to LY 2.597)	DG is Type 2 mix, OGFC is 3/8" mix	EB	1	44 (11/04/2014)	58 (10/01/2014)
				2	36 (7/23/2015)	
				3	53 (1/28/2016)	
				4	54 (7/21/2016)	
				5	49 (12/13/2016)	
				6	46 (7/25/2017)	
				7	56 (12/07/2017)	
			WB	1	44 (11/04/2014)	55 (10/01/2014)
				2	36 (7/23/2015)	
				3	53 (1/28/2016)	
				4	54 (7/21/2016)	
				5	48 (12/13/2016)	
				6	50 (7/25/2017)	
				7	57 (12/07/2017)	
3564	SR207 (Cum. Mile from DO 0.000 to DO 3.760)	DG is Type 2 mix.	EB	1	No OGFC surface	66 (11/4/2014)
				2		43 (7/23/2015)
				3		52 (1/28/2016)
				4		42 (7/27/2016)
				5		Not tested
				6		46 (7/26/2017)
				7		48 (12/07/2017)
			WB	1	No OGFC surface	62 (11/4/2014)
				2		45 (7/23/2015)
				3		49 (1/28/2016)
				4		45 (7/27/2016)
				5		Not tested
				6		45 (7/26/2017)
				7		49 (12/07/2017)

Table 8 Friction resistance on various NDOT projects

Contract	Location	Pavement Surface Type	Direction	Test No.	Average OG Friction No. (Test Date)	Average DG Friction No. (Test Date)
3558	SR431 (Cum. Mile from WA 8.130 to WA 24.413)	DG is Type 2 mix, OGFC is 3/8" mix	EB	1	41 (3/11/2015)	59 (Oct 01, 2014)
				2	45 (7/28/2015)	
				3	42(1/28/2016)	
				4	54 (7/21/2016)	
				5	55 (12/12/2016)	
				6	57 (07/26/2017)	
				7	60 (12/07/2017)	
			WB	1	42 (3/11/2015)	62 (10/01/2014)
				2	46 (7/28/2015)	
				3	42(1/28/2016)	
				4	52 (7/21/2016)	
				5	56 (12/12/2016)	
				6	57 (07/26/2017)	
				7	62 (12/07/2017)	
3546	IR015 (Cum. Mile from CL 85.0 to CL 89.0)	DG is Type 2C mix, OGFC is 1/2" mix	NB	1	33 (2/10/2015)	19 (2/10/2015)
				2	32 (8/18/2015)	27 (8/18/2015)
				3	32 (1/20/2016)	24 (1/20/2016)
				4	33 (6/8/2016)	25 (6/8/2016)
				5	Not tested	Not tested
				6	Not tested	Not tested
				7	40 (11/09/2017)	31 (11/9/2017)
3533	IR080 (Cum. Mile from EU 15.736 to EU 25.704)	DG is Type 2C mix, OGFC is 3/8" mix	EB	1	53	45
			WB	1	53	44
3524	IR080 (Cum. Mile from HU 0.112 to HU 12.011)	DG is Type 2C mix, OGFC is 3/8" mix	EB	1	50	53
			WB	1	51	52

SURFACE TEXTURE TEST

The Circular Texture Meter (CTM) is a texture measuring device equipped with a Charged Couple Device laser displacement sensor mounted on an arm above the surface. According to ASTM E2157, the CTM measures the profile of a circle that is 284 mm in diameter or 892 mm in circumference. The profile is divided into eight segments of 111.5 mm. The mean profile depth (MPD) of each segment or arc of the circle is calculated according to ASTM E1845.

Figure 17 presents the measured surface texture results of DGHMA and OGFC sections at different times. It is shown that the OGFC surface had consistently higher MPD values than the DGHMA surface in the Las Vegas sections, but had comparable MPD values to the DGHMA surface in the Elko sections. The existing studies found that the pavement surface with a greater MPD value generally has a higher skid number. Thus, the surface texture results were in good agreement with the surface friction results.

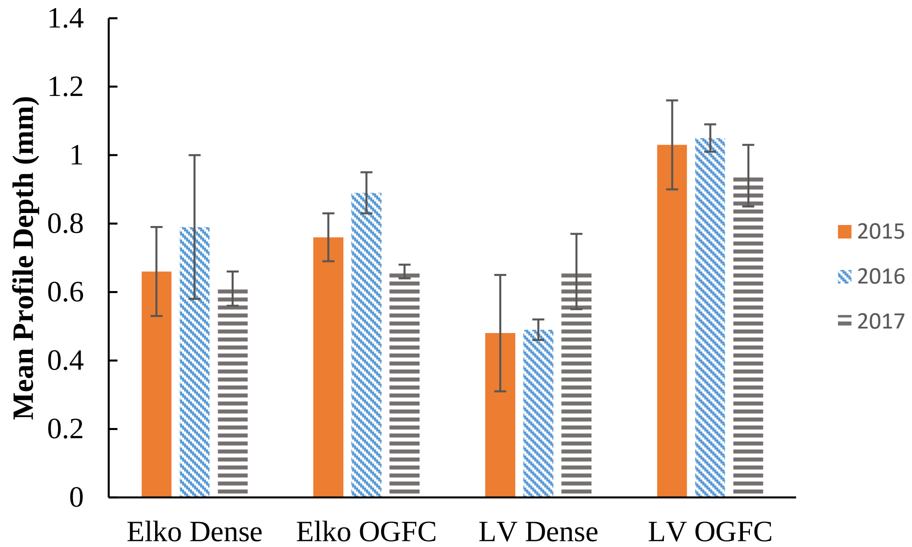


Figure 17 Surface texture results of Elko and Las Vegas sections.

TIRE-PAVEMENT NOISE TEST

The on-board sound intensity (OBSI) is used to measure noise levels at the tire/pavement interface. The sound intensity probe consists of two microphones with 12.5 mm diameter and preamplifiers in a side-by-side configuration spaced 16 mm apart and protected with a custom foam windscreen. The sound intensity is measured at 100 mm away from the plane of the tire sidewall, 70-80 mm away from the pavement surface, and opposite the leading and trailing edges of the tire/pavement contact. Because of the nature of sound intensity, there is no need for an acoustical chamber. Thus, the equipment can be mounted on the wheel of a passenger car.

Figure 18 presents the sound intensity results of OGFC and DGHMA sections in Elko and Las Vegas. At the beginning, both OGFC sections exhibited a noise reduction benefit when compared to the DGHMA sections. For the Elko sections, the reduction of sound intensity for

OGFC significantly reduced with the increasing service time. After 32-months service time, the OGFC section showed a similar sound intensity level to the DGHMA section. For the Las Vegas sections, the OGFC pavement consistently showed a noise reduction by approximately 2dB(A) within the 32-month service time.

When the final OBSI testing was performed in September, 2017 it was requested by NDOT that a recently placed OGFC section on US 93 near McGill, NV (Milepost 66.99 to 76.34 in White Pine County) be tested for information purposes. That project averaged 97.7 dB(A) which is similar to the I-15 results after construction.

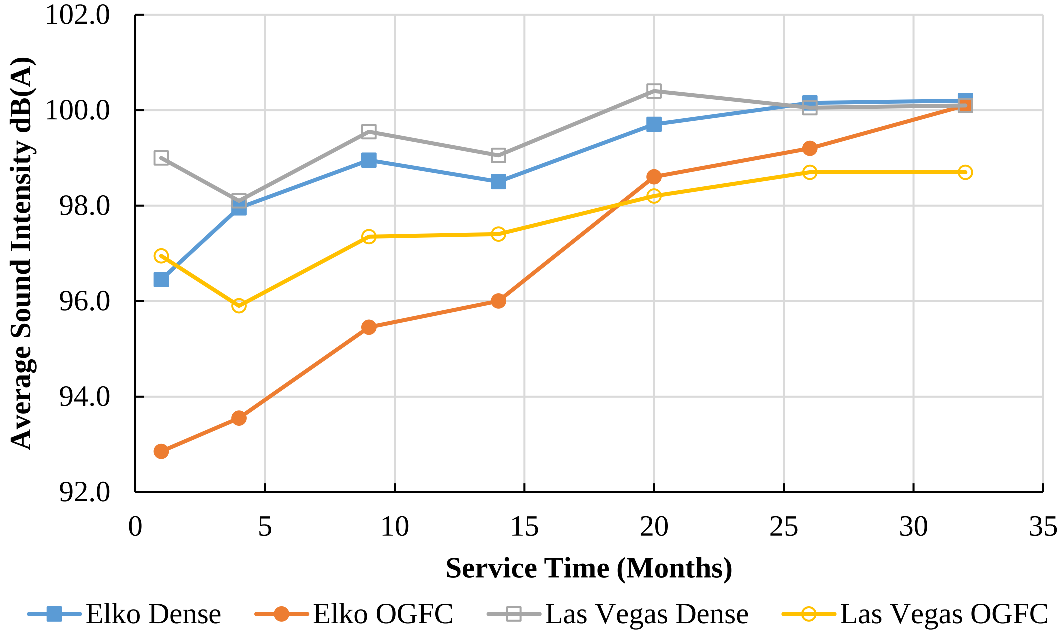


Figure 18 Sound intensity results of Elko and Las Vegas sections.

CHAPTER 5. COST-BENEFIT ANALYSIS OF OGFC PROJECTS

INTRODUCTION

The cost-benefit analysis was conducted on the identified OGFC projects and the corresponding DGHMA projects. To unify the analysis, both OGFC pavements and DGHMA pavements were assumed to be 1.0 mile long. The cost-benefit of OGFC pavement was analyzed by investigating the initial construction and maintenance costs, the durability, and the functionality, such as permeability, friction, and tire/pavement noise. Compared to DGHMA pavements, the OGFC pavements have the following advantages and disadvantages:

- Advantages: significantly improves pavement permeability, enhances pavement friction, and reduces tire/pavement noise.
- Disadvantages: increased initial construction cost, increased maintenance cost, and reduced serviceable life.

To conduct the economic analysis, these advantages and disadvantages were monetized as follows.

- Increasing initial construction cost is due to the increased material cost;
- Increasing maintenance cost is attributed to the increased road salt usage;
- Reduced serviceable life is equivalent to the decreased salvage value of existing pavement;
- Improved pavement permeability raises the driver visibility and reduces the hydroplaning in wet-weather condition, which decreases the accident rate and cost;
- Enhanced surface friction also reduces the accident rate and cost; and
- Reduced tire/pavement noise raises the value of houses that are near the highway and saves on the costs of noise barriers.

It has been noted that OGFC pavement also improves the quality of storm water runoff, but it was not assessed in this study. In addition, the permeability improvement enhanced the ride quality especially in the wet-weather condition, but the improvement of ride quality was difficult to assess monetarily. Therefore, this study considered the increase of ride quality (quantified by the increase of permeability) as an additional benefit for OGFC pavements. Figure 19 illustrates the factors considered in the cost-benefit analysis, which are elaborated in the following sections.

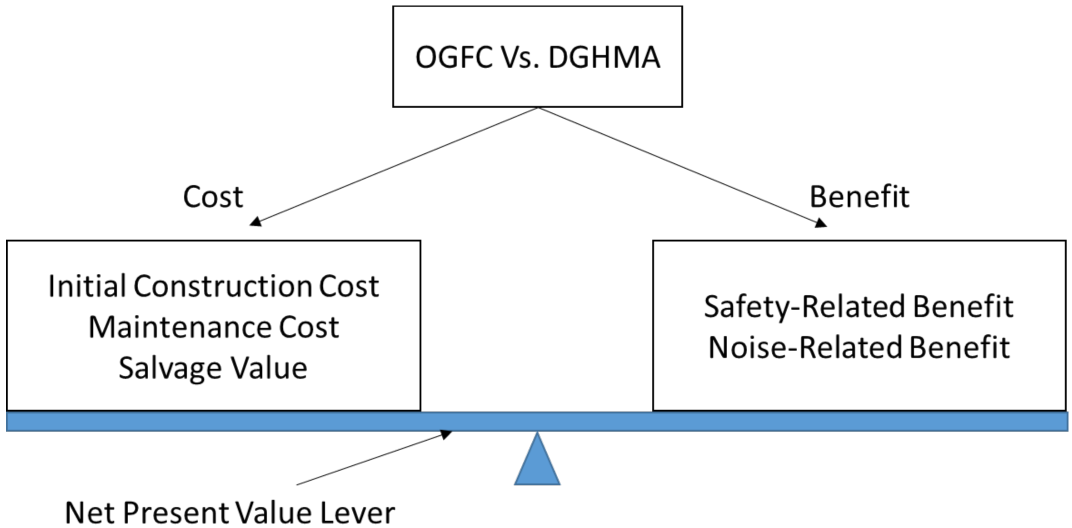


Figure 19 Illustration of cost-benefit analysis for OGFC pavements.

INITIAL CONSTRUCTION COST

The cost-benefit analysis only considered differential costs or benefits between pavement alternatives. In regard to the initial construction cost, the major difference between OGFC and DGHMA pavements was that OGFC mix had a higher material price than DGHMA mix due to higher asphalt contents. Thus, this study only took into account the material cost, which was calculated by Equations 4 and 5.

$$\text{Initial Construction Cost} = \text{Material Unit Price} \times \text{Weight of Material} \quad (4)$$

$$\text{Weight of Material} = \text{Section Length} \times \text{Section Width} \times \text{Layer Thickness} \times \text{Density} \quad (5)$$

The detailed calculation of initial construction cost is presented in Table 99.

Table 8 Calculation of initial construction cost

Project Name	Material Unit Price ($/ton)	Section Length (mile)	Section Width (ft)	Layer Thickness (inch)	Density (lb/ft^3)	Initial Construction Cost ($)
Elko DGHMA	70	1	24	0.75	143.5	39,553
Elko OGFC	130	1	24	0.75	130.7	66,906
Las Vegas DGHMA	63.5	1	24	0.75	154.1	38,518
Las Vegas OGFC	87	1	24	0.75	126.9	43,471

MAINTENANCE COST

The maintenance of OGFC pavement usually includes the general maintenance and winter maintenance. The general maintenance focuses on recovering the permeability of the OGFC layer, which utilizes water washing or vacuum cleaning methods to remove debris from clogged pores. The winter maintenance is to apply the liquid chemicals or road salt to melt the ice and snow on the surface and interior of OGFC pavement. In the United States, the general maintenance is not conducted on a routine basis, but the winter maintenance is mandatory if the OGFC pavement has snow or ice on the surface. For the Elko sections, the pavements usually have snow or ice in winter, but for the Las Vegas sections, no snow or ice is expected. Thus, this study only considered the winter maintenance cost for the OGFC and DGHMA pavements in Elko.

Regarding the chemical deicers, salt (sodium chloride) is very effective when the temperature is above 25°F, fairly effective when temperature is between 25°F and 15°F, and marginally effective when temperature is between 10°F and 15°F. In Elko, the average minimum temperature is 15°F. While in Las Vegas, the average minimum temperature is 39°F. Therefore, salt is only applicable for deicing the OGFC and DGHMA sections in Elko. NDOT recommends the optimum application rate of salt for winter maintenance is 300 pounds per lane mile for DGHMA. Generally, the salt usage for OGFC pavement is higher than that for DGHMA pavement by 20 to 30 percent. This study assumed that the salt application rate is 375 pounds per lane mile for OGFC pavement. The details of the calculation of winter maintenance costs are presented in Table 10.

Table 9 Calculation of Winter Maintenance Cost

Project Name[1]	Salt Unit Price ($/ton)	Section Length (mile)	Number of Traffic Lanes	Salt Application Rate (ton/lane mile)	Maintenance Frequency Per Year	Maintenance Cost Per Year ($)
Elko DGHMA	41.72	1	2	300	30	375
Elko OGFC	41.72	1	2	375	30	469

[1] No winter maintenance activity was needed for pavements in the Las Vegas sections.

SALVAGE VALUE

Salvage value represents the expected worth of a pavement alternative at the end of the analysis period. It is comprised of two components: serviceable life and residual value. Serviceable life represents the value of the remaining life of a pavement alternative at the end of the analysis period. A recent survey showed that the service life of DGHMA pavements in Nevada is usually 10 years, while that of OGFC pavement in Nevada is only 7 years (Jackson et al. 2008). Thus, this study assumed the service lives of OGFC and DGHMA pavements to be 7 and 10 years, respectively. For the sake of simplicity, the analysis period was assigned as 7 years, which excluded the rehabilitation activity from the analysis. Note that this study did not take into account the influence of mix design on pavement service life, although an appropriate mix design could significantly extend the service life of OGFC pavement. Residual value is defined as the asset value of in-place materials of a pavement alternative at the end of the service life. Until now, no studies have been found to investigate the differential asset values between OGFC and DGHMA pavements. Therefore, the residual value was not taken into account by this study. The salvage value is calculated using Equation 6.

$$Salvage\ Value = C_{Last\ Activity} \times \frac{N_{RL}}{N_{SL}} \qquad (6)$$

where $C_{Last\ Activity}$ is the cost of last rehabilitation or reconstruction activity, herein it refers to the initial construction cost; N_{RL} is the remaining service life of pavement alternative; and N_{SL} is the total service life of pavement alternative. Table 11 shows the salvage values of the identified OGFC and DGHMA pavements.

Table 10 Salvage values of OGFC and DGHMA pavements

Project Name	Initial Construction Cost ($)	N_{SL} (Years)	N_{RL} (Years)	Salvage Value ($)
Elko DGHMA	39,553	10	3	11,866
Elko OGFC	66,906	7	0	0
Las Vegas DGHMA	38,518	10	3	11,555
Las Vegas OGFC	43,471	7	0	0

SAFETY-RELATED BENEFIT

OGFC is typically applied to improve driving safety by means of increasing pavement surface friction and reducing the hydroplaning of vehicles in wet-weather conditions. There are numerous studies investigating the safety improvement by OGFC treatment. For example, Shimeno and Tanaka (2010) reported that OGFC reduced the wet weather fatality accident rate from 3.9 percent to 1.1 percent in Japan. Kabir et al. (2012) compared the accident rates of four pavement sections before and after OGFC treatment in Louisiana. They concluded that the OGFC treatment was effective in reducing the fatalities and total accidents regardless of the weather conditions. Chen et al. (2017) assessed the effect of OGFC treatment on accident rate reduction of 12 pavement sections in Tennessee. They found that the OGFC is significantly effective in reducing the accident rate in wet weather conditions.

Buddhavarapu et al. (2015) analyzed the accident data of 43 OGFC pavements and 83 non-OGFC pavements in Texas. Based on their statistical analysis, the hypothesis that OGFC is effective in reducing wet weather crashes was not accepted. They claimed that the road user usually drives faster on OGFC surfaced pavements, which might result in a higher accident rate as compared to the non-OGFC pavements.

Due to the inconclusiveness of these safety studies, Lyon et al. (2018) conducted a large-scale study to quantify the safety effect of OGFC treatment. They collected the accident data of the OGFC and non-OGFC pavements from California, Minnesota, North Carolina and Pennsylvania, and estimated the crash modification factors (CMFs) for OGFC treatment, which are presented in Table 12. Herein, the CMF refers to the ratio of expected number of crashes after treatment to that before treatment. A CMF less than 1.0 indicates that the treatment reduces the number of crashes on that pavement site. As shown in Table 12 the OGFC treatment was only effective in decreasing the accident rate in wet-conditions of the freeway, but meanwhile increased the accident rate in dry-conditions of roads. In summary, the OGFC treatment only reduced the total accident rate on freeways. In this study, the Las Vegas sections were classified as freeway, and the Elko sections were considered as multilane road. Thus, the OGFC pavement on the Las Vegas section reduced the accident rate by 5.5 percent, while the OGFC pavement on the Elko section increased the accident rate by 9.2 percent.

Table 11 Estimation of Crash Modification Factors for OGFC treatment (Lyon et al. 2018)

Group	Miles	Estimated CMF		
		Total	Wet-Condition	Dry-Condition
Freeway	165	0.945	0.668	1.008
Multilane	61	1.092	0.981	1.108

For the conventional pavement, the accident cost was calculated by,

$$C_{acc} = \sum_{i=1}^{3} C_f p_f + C_h p_h + C_d p_d \tag{7}$$

where C_{acc} is the total accident cost per year (dollars/year), C_f is the unit cost of a fatal accident per crash (dollars), C_h is the unit cost of an injury accident per crash (dollars), C_d is the unit cost of a property damage accident per crash (dollars), and p_f, p_h, and p_d are the number of fatal accidents, injury accidents, and property damage accidents, respectively. Table 13 lists the unit costs of these accident types (i.e., values of C_f, C_h, and C_d), which were converted from the data source in Ozbay et al. (2001) to year 2017 using the discount rate of 4 percent.

Table 12 Unit costs of various accident types (Ozbay et al., 2001)

Accident Type	Cost Per Crash (Dollars)
Fatality	8,013,577
Injury	281,065
Property Damage	13,213

The expected number of accidents per year (i.e., values of p_f, p_h, and p_d) were estimated using Equation 8.

$$p = \alpha_1 M^{\alpha_2} Q^{\alpha_3} \quad (8)$$

where M is the length of roadway, Q is the annual average daily traffic, and α_1, α_2, and α_3 are model coefficients that are shown in Table 14. In this study, the roadway length was assumed as 1.0 mile for all the sections. The annual average daily traffic was 3700 for the Elko sections, and 41600 for the Las Vegas sections. The safety-related savings or costs for OGFC pavements are presented in **Table 15 Safety-related savings (or costs) for OGFC pavements**Table 15.

Table 13 Model coefficients for estimation of expected number of accidents per year

Pavement Section	Coefficient	Accident Type		
		Fatality	Injury	Property damage
Elko	α1	4.15E-05	5.95E-09	4.70E-07
	α2	8.95E-01	7.37E-01	4.59E-01
	α3	7.36E-01	2.51E+00	2.19E+00
Las Vegas	α1	7.79E-05	3.11E-10	3.23E-05
	α2	3.32E-01	9.77E-01	9.04E-01
	α3	8.07E-01	2.10E+00	1.09E+00

Table 14 Safety-related savings (or costs) for OGFC pavements

Project Name	Safety-related Savings Per Year (Dollars)
Las Vegas Section	2,084
Elko Section	-1,886[1]

[1] Negative value represented the safety-related costs for OGFC pavement.

NOISE-RELATED BENEFIT

Noise reduction is another well-recognized benefit for OGFC pavement. This study related the tire/pavement noise to the affected house value of nearby residents. For the same house, generally, the higher outside noise represents a lower selling value. The noise depreciation sensitivity index (NDSI) is usually used to calculate the noise costs, which is defined as the ratio of the percentage reduction in the house value and the change in the noise level. There are many studies estimating the local NDSI values, which were presented in Table 16.

Table 15 NDSI values from existing studies

Existing Study	Location	NSDI (%)
Vaughan and Huckins (1975)	USA	0.65
Holsman and Bradley (1982)	Australia	0.7-1.8
Itenand Maggi (1990)	Switherland	0.9
Nelson (2004)	USA	0.51-0.67
Blanco and Flindell (2011)	UK	1.15-4.50
Andersson et al. (2013)	Sweden	1.35-2.90
Szczepanska et al. (2015)	Poland	0.7-0.94

As shown in Table 16 the NDSI value varied from region to region. Overall, this value slightly increased with time. In this study, the NDSI value was assigned as 0.8% for both Las Vegas and Elko sections. Accordingly, the noise cost was calculated by,

$$Noise\ \mathrm{Cos}\,t = N_h \times \Delta L \times NDSI \times W_{avg} \tag{9}$$

where N_h is the number of houses affected by noise that was calculated by multiplying the average residential density by the tire/pavement noise affected area, ΔL is the change of noise due to OGFC, and W_{avg} is the average of house value. The detailed calculation of noise cost is shown in Table 17.

Table 16 Calculation of noise costs for OGFC pavements

Model Parameters	Identified Projects	
	Elko OGFC	Las Vegas OGFC
Residential Density (number of houses per square mile)	417.3	110.5
Noise Affected Area (square mile)	0.03	0.03
Change of Noise, ΔL (dB)[1]	0.9	2.1
NDSI (%)	0.8	0.8
Average House Value, W_{avg} ($)	223,100	216,500
Noise Costs ($)	20,110	12,057

[1] Change of noise between OGFC and DGHMA pavements was an average value in the analysis period.

NET PRESENT VALUE OF COSTS OF IDENTIFIED PAVEMENTS

To enable a fair comparison among competing pavement alternatives, all future anticipated costs, such as maintenance and rehabilitation costs and user costs, are first "discounted" to the present to take into account the time value of money. If an alternative has any value remaining at the end of the analysis period, a salvage value is also discounted back to its present value. The net present value (NPV) of initial construction and discounted future costs and salvage value is then determined for each alternative using the common economics formula shown in Equation 10. Finally, the alternative with the lowest NPV of life cycle costs calculated by Equation 10 is considered to be the most economical choice.

$$NPV\ of\ Life\ Cycle\ Costs = Initial\ Const.Cost + \sum_{k=1}^{N} Maintenance\ Cost_k \left[\frac{1}{(1+i)^{n_k}}\right] - Salvage\ Value \left[\frac{1}{(1+i)^{n_e}}\right] - \sum_{k=1}^{N} Safety\ Benefit_k \left[\frac{1}{(1+i)^{n_k}}\right] - Noise\ related\ Benefit \left[\frac{1}{(1+i)^{n_e}}\right] \quad (10)$$

where i is the discount rate (4% used in this study), and N is the analysis period (7 years used in this study).

Table 18 summarizes the monetary items of identified OGFC and DGHMA pavements, and their calculated NPVs. The values shown as maintenance costs per year are used in Equation 10 to calculate the NPV of life cycle costs. The present value of life cycle costs of the OGFC section in Elko was 86 percent higher than the DGHMA section, while the present value of life cycle costs of the OGFC section in Las Vegas was 36 percent lower than that of DGHMA section. This indicates that the implementation of OGFC is cost-effective in rural highways while the use of OGFC in a town area significantly increased the life cycle cost of pavement.

Table 17 Calculation of NPVs for identified OGFC and DGHMA pavement costs

Monetary Item	Elko Sections		Las Vegas Sections	
	OGFC	DGHMA	OGFC	DGHMA
Initial construction cost ($)	66,906	39,553	43,471	38,518
Maintenance cost ($/year)	469	375	0	0
Salvage value ($)	0	11,866	0	11,555
Safety benefits ($)	-1,886	0	2,084	0
Noise benefits ($)	20,110	0	12,057	0
NPV of life cycle costs ($)	60,933	32,790	18,905	29,737
NPV of costs per lane mile ($/mile)	30,466	16,395	9,453	14,868

CONCLUSIONS

This project identified two OGFC projects and two DGHMA projects (i.e., control projects) from Nevada. A Category-3 roadway in Elko and Category-1 roadway near Las Vegas were analyzed to determine the benefits of OGFC pavements. Specifically, the laboratory tests were conducted to comprehensively assess the durability, cracking, rutting and moisture-susceptibility of OGFC and DGHMA mixtures. The field performance tests were performed to evaluate the functional characteristics of OGFC and DGHMA pavements, including the permeability, friction, texture, and tire-pavement noise over time. This project summarizes the advantages and disadvantages of OGFC, and these advantages and disadvantages were monetized for cost-benefit analysis. The major findings of this project are summarized as follows.

- The Cantabro test results indicated that both Elko and Las Vegas OGFC mixtures met the minimum requirements for the durability performance of asphalt mixtures. Compared to the Las Vegas OGFC mixtures, the Elko OGFC mixtures had less Cantabro loss values regardless of the conditioning the mixtures experienced.
- The TSR test results showed that both the Elko and Las Vegas OGFC mixtures passed the recommended TSR criteria of a minimum 70% TSR. Compared to the Elko OGFC mixtures, the Las Vegas OGFC mixtures have higher conditioned tensile strength. This may be attributed to the higher grade modified binder used in the Las Vegas project (PG 76-22) compared to the PG 64-28 used in the Elko project.
- The HWTT results demonstrated that the Las Vegas OGFC mixture passed the HWTT requirement, but Elko OGFC mixture failed to satisfy the criteria.
- The field performance results demonstrated that the Las Vegas OGFC pavement exhibited benefits in permeability, friction, and noise reduction compared to the DGHMA pavement, while the Elko OGFC pavement showed comparable performance with the DGHMA pavement after 2-years of service.
- A cost-benefit analysis conducted on the identified OGFC and DGHMA projects shows the OGFC pavement in Las Vegas reduced the net present value of life cycle costs by 36%, while the OGFC pavement in Elko increased the net present life cycle cost value by 86%. This indicates that the implementation of OGFC is cost-effective in rural highways, but impractical in urban or town areas.

Limitations

This project had several limitations that prevented the analysis from being as thorough as planned. There was not a Category-3 OGFC project in the southern part of the state at the time research began, so a Category-1 project was selected by NDOT instead. During the course of the project, the friction trailer needed repairs and resulted in some of the data not being available for the time increments scheduled. Finally, the Elko section was covered with a chip seal in 2017 due to cracking concerns so that final field testing could not be conducted.

Future Research

There is a need to develop an OGFC mix design procedure for NDOT that addresses the distresses such as raveling, cracking, and stripping observed in the performance of OGFC. The design procedure should include a method of optimizing the combined aggregate gradation to obtain best performance in regard to resistance to raveling, minimum permeability, and noise reduction. There is a need to evaluate the effect of the two different asphalt PG binders of these two projects because the northern part of the state may benefit from the modified binder used in the southern part of the state.

This research was performed in cooperation with the Nevada Department of Transportation (NDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or NDOT. This report does not constitute a standard, specification, or regulation.

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APPENDIX A
Asphalt Mix Designs

APR 1 2014

STATE OF NEVADA
DEPARTMENT OF TRANSPORTATION
MATERIALS DIVISION
1263 S. STEWART ST. CARSON CITY, NV 89712

OPEN GRADED BITUMINOUS MIX DESIGN

LAB NUMBER:	BF14-18	*BITUMEN RATIO:*	6.7 PG 64-28NV
CONTRACT NUMBER:	3550		
COUNTY:	ELKO		
PRIMARY CONTRACTOR:	ROAD & HIGHWAY BUILDERS		
DATE AGG. SAMPLED:	03/19/14		
DATE AGG. RECEIVED:	03/26/14		
REPORT DATE:	04/11/14		
SAMPLED BY:	ELWELL & MILLER		
CHECKED BY:	DT & RP		
TYPE MATERIAL:	3/8" OPEN GRADED PLANTMIX AGGREGATE		
SOURCE OF SAMPLE(S):	FRAZIER PIT		
MINERAL FILLER:	1.5% HYDRATED LIME WET-CURED (MARINATED) 48 HOURS		
TYPE ASPHALT:	PG 64-28NV (CCAC14-26)		
ASPHALT PRODUCER:	CALUMET		

JOB DESCRIPTION:

SR 227 FROM IDAHO STREET TO 0.15 MILES SOUTH OF JIGGS ROAD; SR 535 FROM THE SOUTH CATTLE GUARD AT THE WEST ELKO INTERCHANGE TO 5TH STREET; ON SR 225 IDAHO STREET TO CATTLE DRIVE.

		SPECIFICATIONS:
MAX. DENSITY, Mg/m³ (PCF):	2.370 (147.9)	
SURFACE AREA m²/kg (ft²/lb):	4.03 (19.7)	
SAND EQUIVALENT:	76	
CALIF. SPECIFIC GRAVITY:	2.61	
COARSE AGG. BULK SPECIFIC GRAVITY:	2.55	*2.85 MAX*
FINE AGG. BULK SPECIFIC GRAVITY:	2.55	*2.85 MAX*
+#4 WATER ABSORPTION:	1/2": 1.0; 3/8": 1.2	*4% MAX*
SS SOUNDNESS COARSE:	2	*12% MAX*
SS SOUNDNESS FINES:	2	*15% MAX*
LIQUID LIMIT (BEFORE MARINATION):	1/2": N/A; 3/8": N/A: CRUSHER FINES: N/A	*35 MAX*
PLASTICITY INDEX (BEFORE MARINATION):	1/2": NP; 3/8": NP: CRUSHER FINES: NP	*10 MAX*
LA ABRASION:	22.9	*37% MAX*
FRACTURE FACE COUNT:	1/2": 100; 3/8": 100	*90% MIN*

REMARKS:

FOR THE MATERIAL REPRESENTED BY THE SUBMITTED SAMPLES WITH THE ATTACHED GRADINGS, LABORATORY TESTS INDICATE A BITUMEN RATIO OF 6.7 PG 64-28NV FOR 3/8" OPEN GRADED PLANTMIX AGGREGATE TREATED WITH 1.5% HYDRATED LIME WET-CURED (MARINATED) 48 HOURS.

DISTRIBUTION:

- 1 *DISTRICT ENGINEER*
- 1 *RESIDENT ENGINEER*
- 2 *CONSTRUCTION ENGINEER*
- 1 *LAB FILES*
- 1 *BITUMINOUS LAB*
- 1 *ASPHALT LAB*
- 1 *BITUMINOUS OPERATIONS*
- 1 *LAS VEGAS LAB*
- 1 *AGGREGATE LAB*

BIN PERCENTAGES:
08% 1/2" AGG
64% 3/8" AGG
28% CRUSHER FINES

NOTE: CHANGES FROM THE RECOMMENDED BITUMEN RATIO SHALL BE DISCUSSED WITH THE MATERIALS DIVISION. THE RECOMMENDED BITUMEN RATIO IS BASED UPON DRY WEIGHT OF AGGREGATE.

APR 1 2014

STATE OF NEVADA
DEPARTMENT OF TRANSPORTATION
MATERIALS DIVISION
1263 S. STEWART ST. CARSON CITY, NV 89712

OPEN GRADED BITUMINOUS MIX DESIGN

BF14-18

3550

SIEVE ANALYSIS RESULTS:
(PERCENT PASSING)

BIN PERCENTAGES:	8	64	28	100	PROJECT
			CRUSHER	*AS	SPECS:
SIEVE SIZE:	1/2" AGG:	3/8" AGG:	FINES:	COMBINED:	3/8" OG
19 mm (3/4"):					
12.5 mm (1/2"):	99.6	100.0	100.0	100.0	100
9.5 mm (3/8"):	59.8	99.9	100.0	96.7	95 - 100
4.75 mm (NO. 4):	3.2	33.1	99.0	49.2	40 - 65
2.36 mm (NO. 8):	2.0	5.4	78.8	25.7	
2.00 mm (NO. 10):	1.9	4.1	72.4	23.0	
1.18 mm (NO. 16):	1.7	2.8	55.7	17.5	12 - 22
600 µm (NO. 30):	1.5	2.3	39.2	12.6	
425 µm (NO. 40):	1.4	2.1	32.6	10.6	
300 µm (NO. 50):	1.3	1.9	26.4	8.7	
150 µm (NO. 100):	1.1	1.6	16.7	5.8	
75 µm (NO. 200):	0.9	1.3	10.9	4.0	0 - 5

** AGGREGATE COMBINED PER TRANSMITTALS.*

Elko OGFC Mix Design

APR 15 2014

STATE OF NEVADA

DEPARTMENT OF TRANSPORTATION
MATERIALS DIVISION
1263 S. STEWART ST. CARSON CITY, NV 89712

DENSE GRADE BITUMINOUS MIX DESIGN

LAB NUMBER:	BF14-16	*BITUMEN RATIO ADDED:*	4.2 PG 64-28NV
CONTRACT NUMBER:	3550	*BITUMEN RATIO FROM RAP:*	0.8
COUNTY:	ELKO	*BITUMEN RATIO TOTAL:*	5.0
PRIMARY CONTRACTOR:	ROAD & HIGHWAY BUILDERS		
DATE AGG. SAMPLED:	03/19-20/14		
DATE AGG. RECEIVED:	03/26/14		
REPORT DATE:	04/11/14		
SAMPLED BY:	ELWELL, MILLER & NUNEZ		
CHECKED BY:	DT & RP		
TYPE MATERIAL:	TYPE 2 PLANTMIX AGGREGATE WITH RAP		
SOURCE OF SAMPLE(S):	FRAZIER PIT		
MINERAL FILLER:	1.5% HYDRATED LIME WET-CURED (MARINATED) 48 HOURS		
TYPE ASPHALT:	PG 64-28NV (CCAC14-26)		
ASPHALT PRODUCER:	CALUMET		

JOB DESCRIPTION:

SR 227 FROM IDAHO STREET TO 0.15 MILES SOUTH OF JIGGS ROAD; SR 535 FROM THE SOUTH CATTLE GUARD AT THE WEST ELKO INTERCHANGE TO 5TH STREET; ON SR 225 IDAHO STREET TO CATTLE DRIVE.

		SPECIFICATIONS:
SURFACE AREA m²/kg (ft²/lb):	5.14 (25.1)	
SAND EQUIVALENT:	75	
CALIF. SPECIFIC GRAVITY:	2.54	
COARSE AGG. BULK SPECIFIC GRAVITY:	2.54	*2.85 MAX*
FINE AGG. BULK SPECIFIC GRAVITY:	2.46	*2.85 MAX*
+#4 WATER ABSORPTION:	1": 0.9; 3/4": 1.1; 1/2": 1.0; 3/8": 1.2	*4% MAX*
SS SOUNDNESS COARSE:	2	*12% MAX*
SS SOUNDNESS FINES:	2	*15% MAX*
LIQUID LIMIT (BEFORE MARINATION):	1": INSUFF; 3/4": N/A; 1/2": N/A; 3/8": N/A: CRUSHER FINES: N/A	*35 MAX*
PLASTICITY INDEX (BEFORE MARINATION):	1": INSUFF; 3/4": NP; 1/2": NP; 3/8": NP: CRUSHER FINES: NP	*10 MAX*
LA ABRASION:	22.9	*37% MAX*
FRACTURE FACE COUNT:	1": 100; 3/4": 100; 1/2": 100; 3/8": 100	*80% MIN*
VMA (BASED UPON CALIF. SP. GR.):	12.9 @ 5.0	*12 - 22*
ORIGINAL TENSILE STRENGTH (PSI):	118.0	*65 PSI MIN*
% RETAINED STRENGTH:	102	*70% MINIMUM*

REMARKS:

FOR THE MATERIAL REPRESENTED BY THE SUBMITTED SAMPLES WITH THE ATTACHED GRADINGS, LABORATORY TESTS INDICATE A BITUMEN RATIO OF 4.2 PG 64-28NV FOR TYPE 2 PLANTMIX AGGREGATE WITH RAP TREATED WITH 1.5% HYDRATED LIME AND WET CURED (MARINATED) 48 HOURS.

DISTRIBUTION:

1 DISTRICT ENGINEER
1 RESIDENT ENGINEER
2 CONSTRUCTION ENGINEER
1 LAB FILES
1 BITUMINOUS LAB
1 ASPHALT LAB
1 BITUMINOUS OPERATIONS
1 LAS VEGAS LAB
1 AGGREGATE LAB

BIN PERCENTAGES:

23%	1" AGG
10%	3/4" AGG
10%	1/2" AGG
09%	3/8" AGG
33%	CRUSHER FINES
15%	RAP

NOTE: CHANGES FROM THE RECOMMENDED BITUMEN RATIO SHALL BE DISCUSSED WITH THE MATERIALS DIVISION. THE RECOMMENDED BITUMEN RATIO IS BASED UPON DRY WEIGHT OF AGGREGATE AND RAP.

APR , , 2014

STATE OF NEVADA

DEPARTMENT OF TRANSPORTATION

MATERIALS DIVISION

1263 S. STEWART ST. CARSON CITY, NV 89712

DENSE GRADE BITUMINOUS MIX DESIGN

BF14-16

3550

						PROJECT SPECS: (TYPE 2)
MAX. DENSITY, Mg/m³:			2.427	2.410		
MAX. DENSITY, PCF:			151.4	150.4		
DENSITY, Mg/m³ :	2.256	2.280	2.316	2.330	2.344	
DENSITY, PCF:	140.7	142.3	144.5	145.4	146.3	
BITUMEN RATIO:	3.0	3.5	4.0	4.5	5.0	
HVEEM VALUE:	55	53	47	45	41	35 MIN
% AIR VOIDS:	8.3	6.7	4.5	3.3	2.0	3 - 6

SIEVE ANALYSIS RESULTS:

(PERCENT PASSING)

BIN PERCENTAGES:	23	10	10	9	33	15	100	*PROJECT SPECS: (TYPE 2)*
SIEVE SIZE:	1" AGG:	3/4" AGG:	1/2" AGG:	3/8" AGG:	CRUSHER FINES:	RAP:	*AS COMBINED & TESTED:	
37.5 mm (1½"):								
25 mm (1"):	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100
19 mm (3/4"):	60.7	100.0	100.0	100.0	100.0	100.0	91.0	90 - 100
12.5 mm (1/2"):	2.5	43.8	99.6	100.0	100.0	100.0	71.9	
9.5 mm (3/8"):	1.2	7.0	59.8	99.9	100.0	98.3	63.7	63 - 85
4.75 mm (NO. 4):	0.8	1.3	3.2	33.1	99.0	73.5	47.3	45 - 63
2.36 mm (NO. 8):	0.7	1.1	2.0	5.4	7.8	48.1	10.7	
2.00 mm (NO. 10):	0.7	1.1	1.9	4.1	72.4	43.7	31.3	30 - 44
1.18 mm (NO. 16):	0.7	1.0	1.7	2.8	55.7	33.4	24.1	
600 µm (NO. 30):	0.7	0.9	1.5	2.3	39.2	23.9	17.1	
425 µm (NO. 40):	0.7	0.9	1.4	2.1	32.6	19.8	14.3	12 - 22
300 µm (NO. 50):	0.7	0.8	1.3	1.9	26.4	16.4	11.7	
150 µm (NO. 100):	0.6	0.7	1.1	1.6	16.7	11.2	7.7	
75 µm (NO. 200):	0.5	0.6	0.9	1.3	10.9	8.1	5.2	3 - 8

** AGGREGATE COMBINED PER TRANSMITTALS.*

Elko Dense-Graded Mix

APR 2014

STATE OF NEVADA

DEPARTMENT OF TRANSPORTATION

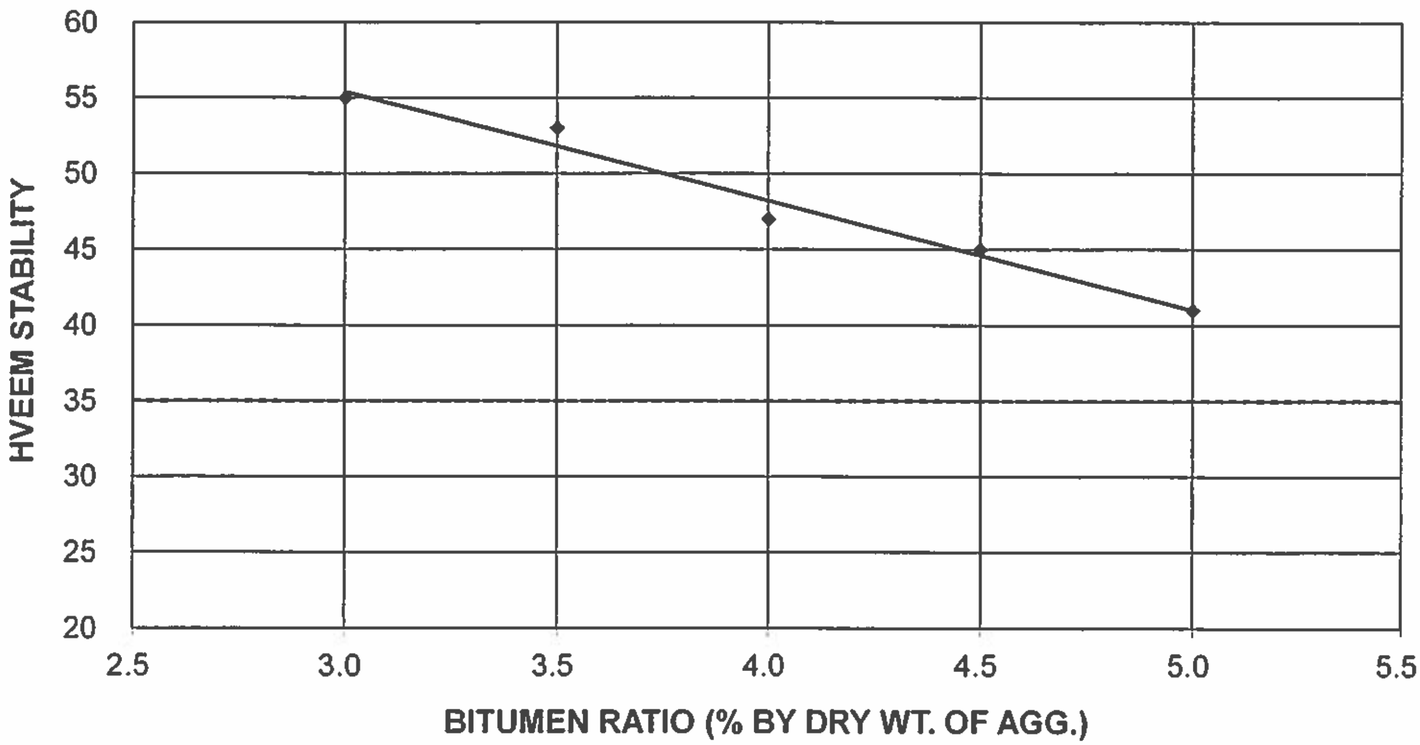
MATERIALS DIVISION

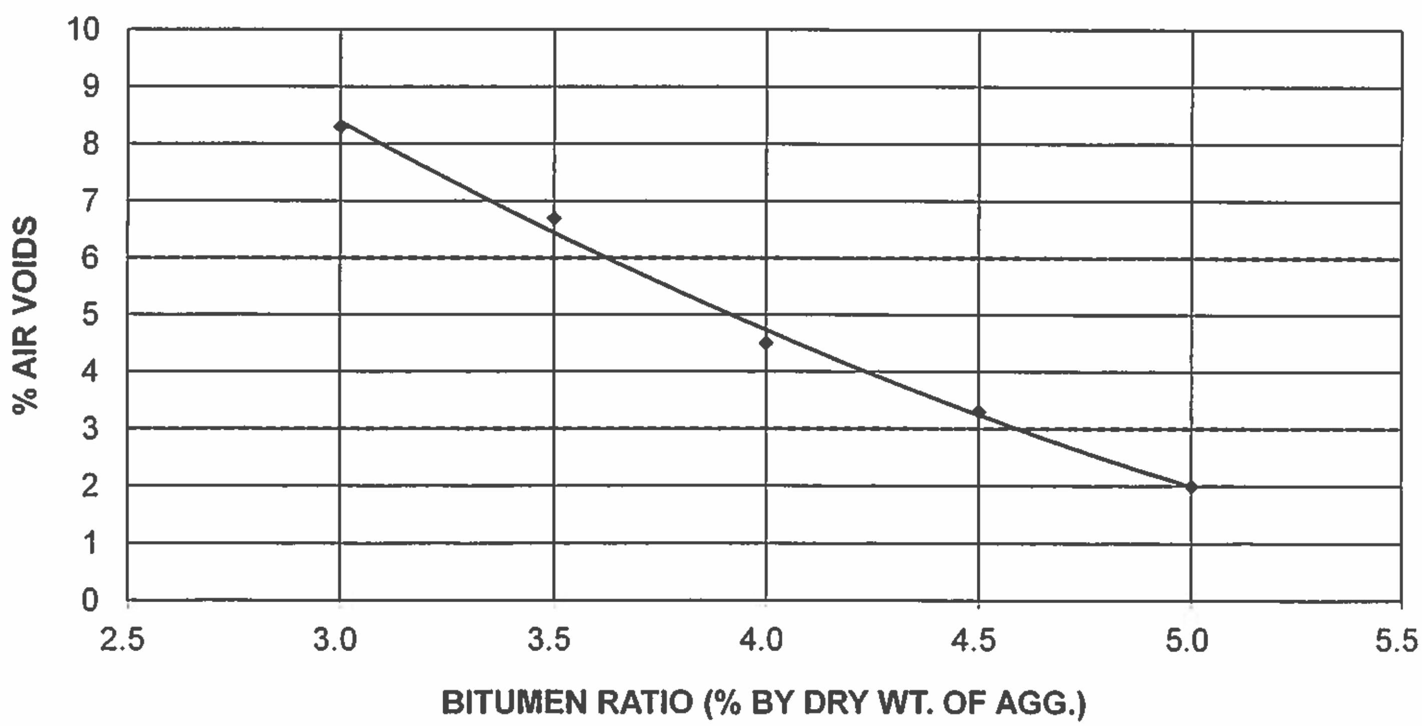
1263 S. STEWART ST. CARSON CITY, NV 89712

DENSE GRADE BITUMINOUS MIX DESIGN

BF14-16

3550





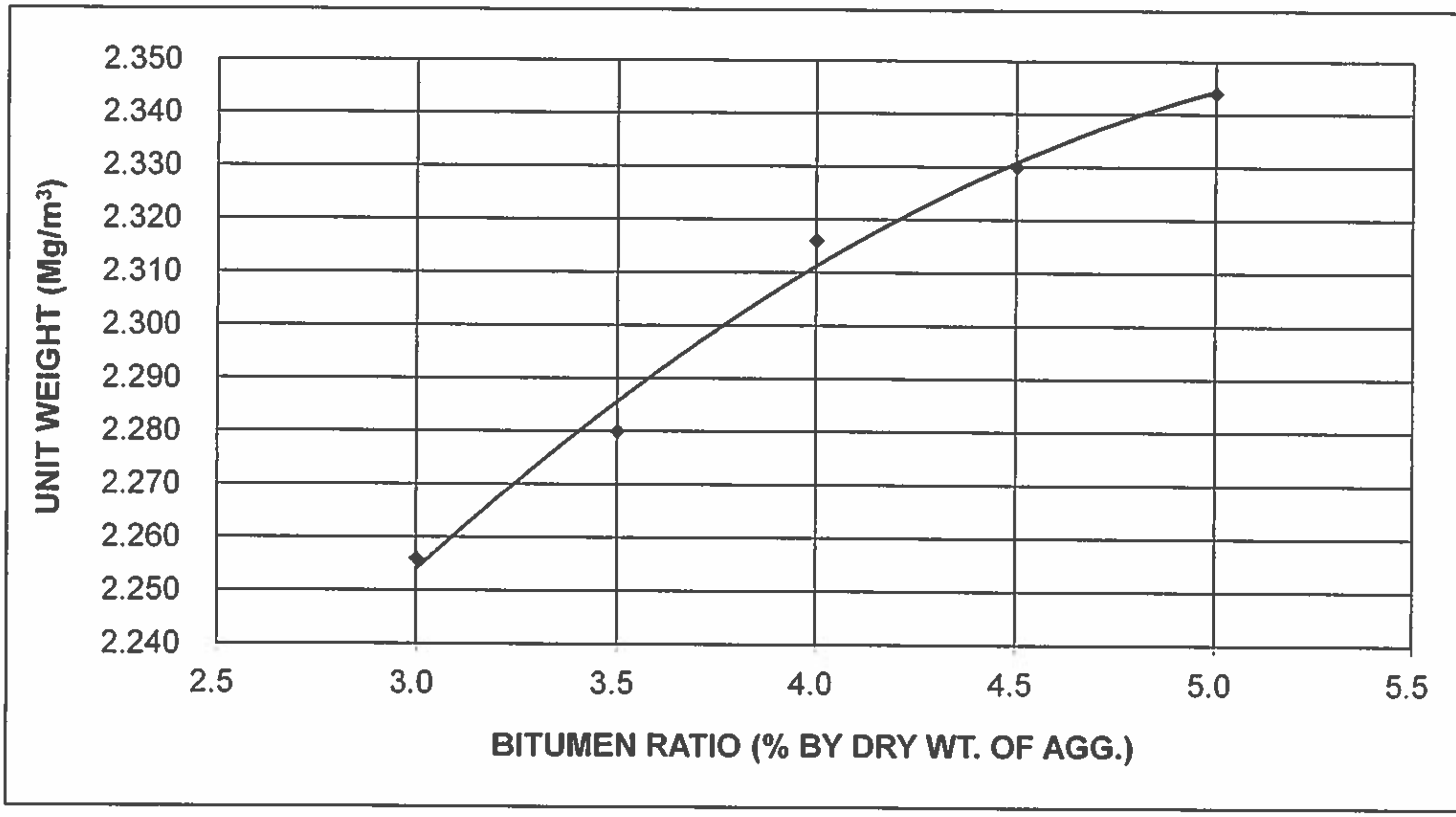
APR 1 2014

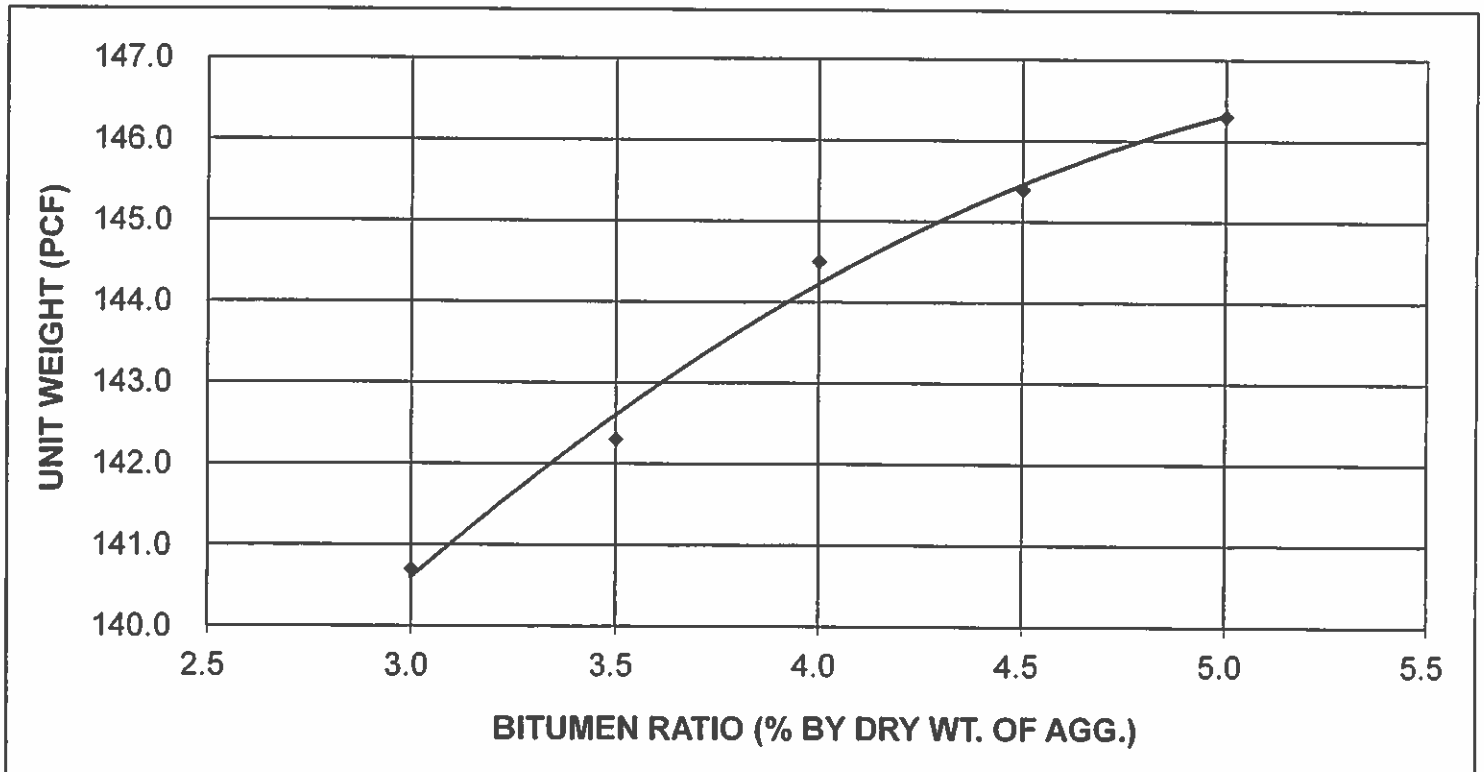
STATE OF NEVADA
DEPARTMENT OF TRANSPORTATION
MATERIALS DIVISION
1263 S. STEWART ST. CARSON CITY, NV 89712

DENSE GRADE BITUMINOUS MIX DESIGN

BF14-16

3550





STATE OF NEVADA
DEPARTMENT OF TRANSPORTATION
1263 S. Stewart Street
Carson City, Nevada 89712

BRIAN SANDOVAL
Governor

RUDY MALFABON, P.E., Director

In Reply Refer to

February 11, 2014

Las Vegas Paving Corp.
3401 N. 5th Street
N. Las Vegas, Nevada 89032

Contract No. 3546
Project No. IM-015-2(042)
& SPI-015-2(015)
Open Grade
Mix Design BF13-43(101NO14)
Job-mix Formula No. 1

Attention: Jared Wagstaff, Project Manager

Dear Sir:

The following job-mix formula is for Open Grade mix design to be used on Contract 3546. The hotplant is owned and operated by Las Vegas Paving Corp. and is located at the Valley of Fire interchange at the Moapa River Indian Reservation. The Open Grade mix design represents aggregates sampled on 12/06/13 at Apex Pit, using PG 76-22NV supplied by Ergon. Aggregate bin percentages are 30% - 1/2" rock, 60% - 3/8" rock, and 10% crushed fines. Any modifications to this job-mix formula must be approved by the Engineer.

Sieve Size	% Passing	Job-Mix Range	Specification Range
1/2 in. (12.5mm)	100	100	100
3/8 in. (9.5mm)	93	90-100	90-100
No.4 (4.75 mm)	43	39-53	35-55
No.16 (1.18mm)	7	5-13	5-18
No.200 (75um)	3	0-4	0-4

The bitumen ratio to be added shall be 5.7% (± 0.4% operational tolerance, Subsection 401.02.02) PG 76-22NV, Ergon. Do not use the ± 0.4% operational tolerance as a means to alter the bitumen ratio target value.

All aggregates shall be marinated in accordance with subsection 401.03.08 (Marination Method) of the specifications, using 1% lime for coarse aggregates and 2% lime for fine aggregates. The combined lime for the above bin percentages shall be 1.7 %.

Baghouse fines will be introduced at a rate not to exceed 2% (Subsection 401.03.01).

Target temperature of the mixture leaving the plant shall be 330 °F (± 20 °F operational tolerance, Subsection 401.02.02).

Minimum temperature of the mixture in the hopper of the paver shall not drop below 310 °F (Subsection 401.02.02).

The temperature drop between the mixture leaving the plant and arriving at the hopper of the paver cannot be more than 20 °F (subsection 4014.02.02).

Should you have any questions, comments or concerns, please contact me at (702) 486-7930.

Sincerely,

Jason R. Voigt, P.E.
Resident Engineer C903

cc: Mario Gomez, Assistant District Engineer
Jeff Shapiro, Chief Construction Engineer
Reid Kaiser, Chief Materials Engineer
District I QA Staff
File

Las Vegas OGFC Mix for I-15

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www.lasvegaspaving.com

January 8, 2014

Jason Voigt, PE, Resident Engineer
Nevada Department of Transportation
123 E. Washington Avenue
Las Vegas, NV 89101

Subject: NDOT Contract No. 3546, Project No. IM-015-2(042) & SPI-015-2(015)
On I-15, Dry Lake to Overton Interchange
Job-Mix Formula #1 for LVP Open Grade Mix Design No. **101NO-14**

Mr. Voigt,

Las Vegas Paving Corporation submits the following job-mix formula #1 for plantmix bituminous surface (Open Grade) (NDOT Lab No. BF13-43) on the subject project:

Sieve Size		Percent Passing	Job – Mix Range	Specifications
12.5 mm	(1/2")	100	100	100
9.5 mm	(3/8")	93	90 – 100	90 – 100
4.75 mm	(No. 4)	*46	39 – 53	35 – 55
1.18 mm	(No. 16)	*9	5 – 13	5 – 18
75 um	(No. 200)	*2	0 – 4	0 – 4

Mineral Filler method: Hydrated Lime, Wet-Cured Marinated 48 Hrs. (401.03.08 method b)
Mineral Filler content: 1.7% Combined
Asphalt Content, by dry wt.: **5.7 % PG76-22NV, Ergon**
Max Temperature at the Plant: 350°F
Min Temperature at Paver. 300°F

Bin Percentages:

Apex Landfill Pit	30% 1/2" Coarse Aggregate
Apex Landfill Pit	60% 3/8" Intermediate Aggregate
Lhoist, Apex NV	10% Crushed Fines

*Please note our request to change some of the target values in the JMF. These targets are expected to match values during production paving and are based on historical process control testing. Should you have any questions please contact me.

Sincerely,

LAS VEGAS PAVING CORPORATION

Lawrence E. Sharp

cc: Ryan Mendenhall
Andy Kimball
Jared Wagstaff
File

STATE OF NEVADA
DEPARTMENT OF TRANSPORTATION
MATERIALS DIVISION
1263 S. STEWART ST. CARSON CITY, NV 89712

OPEN GRADED BITUMINOUS MIX DESIGN

LAB NUMBER:	BF13-43	*BITUMEN RATIO:*	5.7 PG 76-22NV
CONTRACT NUMBER:	3546		
COUNTY:	CLARK		
PRIMARY CONTRACTOR:	LAS VEGAS PAVING		
DATE AGG. SAMPLED:	12/06/13		
DATE AGG. RECEIVED:	12/17/13		
REPORT DATE:	01/08/14		
SAMPLED BY:	SAM ANDALES		
CHECKED BY:	SJH & RP		
TYPE MATERIAL:	1/2" OPEN GRADED PLANTMIX AGGREGATE		
SOURCE OF SAMPLE(S):	APEX PIT		
MINERAL FILLER:	1.5% HYDRATED LIME WET-CURED (MARINATED) 48 HOURS		
TYPE ASPHALT:	PG 76-22NV (CCAC13-1288)		
ASPHALT PRODUCER:	ERGON		

JOB DESCRIPTION:

ON I-15 0.103 MI N. DRY LK REST AREA TO 1.602 MI N. LOGANDALE/OVERTON INTCHG; FRCL10 W. OF HDN VLY INTCHG FROM W. CATTLEGUARD TO 0.081 MILES W.; FR-CL11 MOAPA VLY INTCHG W. OF I-15 TO 0.460 MI S. OF SR 168; FR-CL17 1-15/CRYSTAL INTCHG TO 0.338 MI. W

		SPECIFICATIONS:
MAX. DENSITY, Mg/m³ (PCF):	2.410 (150.4)	
SURFACE AREA m²/kg (ft²/lb):	2.52 (12.3)	
SAND EQUIVALENT:	100	
CALIF. SPECIFIC GRAVITY:	2.66	
COARSE AGG. BULK SPECIFIC GRAVITY:	2.62	*2.85 MAX*
FINE AGG. BULK SPECIFIC GRAVITY:	2.56	*2.85 MAX*
+#4 WATER ABSORPTION:	1/2": 1.2; 3/8": 1.4	*4% MAX*
SS SOUNDNESS COARSE:	2	*12% MAX*
SS SOUNDNESS FINES:	4	*15% MAX*
LIQUID LIMIT (BEFORE MARINATION):	1/2": 23; 3/8": 20; CRUSHED FINES: 13	*35 MAX*
PLASTICITY INDEX (BEFORE MARINATION):	1/2": 4; 3/8": 4; CRUSHED FINES: 2	*10 MAX*
LA ABRASION:	16.5	*37% MAX*
FRACTURE FACE COUNT:	1/2": 100; 3/8": 100	*90% MIN*

REMARKS:

FOR THE MATERIAL REPRESENTED BY THE SUBMITTED SAMPLES WITH THE ATTACHED GRADINGS, LABORATORY TESTS INDICATE A BITUMEN RATIO OF 5.7 PG 76-22NV FOR 1/2" OPEN GRADED PLANTMIX AGGREGATE TREATED WITH 1.5% HYDRATED LIME WET-CURED (MARINATED) 48 HOURS.

DISTRIBUTION:

1 DISTRICT ENGINEER
1 RESIDENT ENGINEER
2 CONSTRUCTION ENGINEER
1 LAB FILES
1 BITUMINOUS LAB
1 ASPHALT LAB
1 BITUMINOUS OPERATIONS
1 LAS VEGAS LAB
1 AGGREGATE LAB

BIN PERCENTAGES:

30%	1/2" AGG
60%	3/8" AGG
10%	CRUSHED FINES

NOTE: CHANGES FROM THE RECOMMENDED BITUMEN RATIO SHALL BE DISCUSSED WITH THE MATERIALS DIVISION. THE RECOMMENDED BITUMEN RATIO IS BASED UPON DRY WEIGHT OF AGGREGATE.

STATE OF NEVADA
DEPARTMENT OF TRANSPORTATION
MATERIALS DIVISION
1263 S. STEWART ST. CARSON CITY, NV 89712

OPEN GRADED BITUMINOUS MIX DESIGN

BF13-43

3546

SIEVE ANALYSIS RESULTS:
(PERCENT PASSING)

BIN PERCENTAGES:	30	60	10	100	*PROJECT*
SIEVE SIZE:	1/2" AGG:	3/8" AGG:	CRUSHED FINES:	*AS COMBINED:	*SPECS: 1/2" OG*
19 mm (3/4"):					
12.5 mm (1/2"):	99.7	100.0	100.0	99.9	*100*
9.5 mm (3/8"):	76.8	100.0	100.0	53.0	*90 - 100*
4.75 mm (NO. 4):	9.3	52.1	91.7	43.2	*35 - 55*
2.36 mm (NO. 8):	2.0	8.8	67.0	12.6	
2.00 mm (NO. 10):	1.8	6.4	60.1	10.4	
1.18 mm (NO. 16):	1.6	3.1	44.0	6.7	*5 - 18*
600 µm (NO. 30):	1.5	1.8	31.8	4.7	
425 µm (NO. 40):	1.5	1.6	27.9	4.2	
300 µm (NO. 50):	1.5	1.5	24.7	3.8	
150 µm (NO. 100):	1.4	1.4	20.4	3.3	
75 µm (NO. 200):	1.3	1.3	17.6	2.9	*0 - 4*

*** AGGREGATE COMBINED PER TRANSMITTALS.***

STATE OF NEVADA
DEPARTMENT OF TRANSPORTATION
1263 S. Stewart Street
Carson City, Nevada 89712

BRIAN SANDOVAL
Governor

RUDY MALFABON, P.E., *Director*

In Reply Refer to

February 11, 2014

Las Vegas Paving Corp.
3401 N. 5th Street
N. Las Vegas, Nevada 89032

Contract No. 3546
Project No. IM-015-2(042)
& SPI-015-2(015)
Type 2C Plantmix w/ RAP
Mix Design No.BF13-42(101N14)
Job-mix Formula No. 2

Attention: Jared Wagstaff, Project Manager

Dear Sir:

The following revised job-mix formula is for Type 2C Plantmix to be used on Contract 3546. This revised job-mix formula was adjusted utilizing test data for tests performed. The hotplant is owned and operated by Las Vegas Paving Corp. and is located at the Valley of Fire interchange at the Moapa River Indian Reservation. The mix design represents aggregates sampled on 12/06/13 at Apex Pit and Legacy Rock, using PG 76-22NV supplied by Ergon. Aggregate bin percentages are 29% - ¾" rock, 12% - ½" rock, 35% - crushed fines, 9% - blend sand, and 15% - ½" recycled asphalt pavement (RAP). Any modifications to this job-mix formula must be approved by the Engineer.

Sieve Size	% Passing	Job-Mix Range	Specification Range
1 in. (25 mm)	100	100	100
3/4 in. (19 mm)	91	88-95	88-95
1/2 in. (12.5 mm)	74	70-84	70-85
3/8 in. (9.5mm)	68	61-75	60-78
No. 4 (4.75 mm)	53	43-57	43-60
No. 10 (2.00 mm)	36	32-40	30-44
No. 40 (425 um)	21	14-22	12-22
No. 200 (75 um)	8	4-8	3-8

The bitumen ratio to be added shall be 3.2% (± 0.4% operational tolerance, Subsection 401.02.02) PG 76-22NV, Ergon. The bitumen ratio of the recycled asphalt pavement (RAP) will be 0.6%. The total bitumen ratio (after the ignition oven) shall be 3.8%. Do not use the ± 0.4% operational tolerance as a means to alter the bitumen ratio target value.

All aggregates with the exception of the recycled asphalt pavement (RAP) shall be marinated in accordance with subsection 401.03.08 (Marination Method) of the specifications, using 1% lime for coarse aggregates and 2% lime for fine aggregates. The combined lime for the above bin percentages shall be 1.29%.

Baghouse fines will be introduced at a rate not to exceed 2% (Subsection 401.03.01).

Target temperature of the mixture leaving the plant shall be 330 °F (± 20 °F operational tolerance, Subsection 401.02.02).

Minimum temperature of the mixture in the hopper of the paver shall not drop below 310 °F (Subsection 401.02.02).

The temperature drop between the mixture leaving the plant and arriving at the hopper of the paver cannot be more than 20 °F (subsection 4014.02.02).

All percentages are based on dry weight of aggregate and RAP.

Should you have any questions, comments or concerns, please contact me at (702) 486-7930.

Sincerely,

Jason R. Voigt, P.E.
Resident Engineer C903

cc: Mario Gomez, Assistant District Engineer
Jeff Shapiro, Chief Construction Engineer
Reid Kaiser, Chief Materials Engineer
District I QA Staff
File

Las Vegas Dense-Graded Mix for I-15

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January 8, 2014
REVISED: February 5, 2014

Jason Voigt, PE, Resident Engineer
Nevada Department of Transportation
123 E. Washington Avenue
Las Vegas, NV 89101

Subject: NDOT Contract No. 3546, Project No. IM-015-2(042) & SPI-015-2(015)
On I-15, Dry Lake to Overton Interchange
Job-Mix Formula #2 for LVP Dense Grade Mix Design No. **101N1-14**

Mr. Voigt,

Las Vegas Paving Corporation submits the following job-mix formula #2 for the plantmix bituminous surface (Type 2 – Coarse w/ RAP) (NDOT Lab No. BF 13-42) on the subject project:

Sieve Size		Percent Passing	Job – Mix Range	Type 2C Specifications
25 mm	(1")	100	100	100
19 mm	(3/4")	91	88 – 95	88 – 95
12.5 mm	(1/2")	77	70 – 84	70 – 85
9.5 mm	(3/8")	68	61 – 75	60 – 78
4.75 mm	(No. 4)	50	43 – 57	43 – 60
2.00 mm	(No. 10)	36	32 – 40	30 – 44
425 um	(No. 40)	18	14 – 22	12 – 22
75 um	(No. 200)	6	4 – 8	4 – 8

Mineral Filler method: Hydrated Lime, Wet-Cured Marinated 48 Hrs. (401.03.08 method b)
Mineral Filler content: 1.29% Combined
Asphalt Content, by dry wt.: **3.7% (TOTAL, PG76-22NV + RAP Residual)**
Asphalt Content, by dry wt.: 0.6% Residual from RAP
Asphalt Content, by dry wt.: 3.1% PG76-22NV, Ergon
Hot Plant Facility: On-site, I-15 Valley of Fire exit
Max Temperature at the Plant: 350°F
Min Temperature at Paver: 300°F

Bin Percentages:

Apex Landfill Pit	29% 3/4" Coarse Aggregate
Apex Landfill Pit	12% 1/2" Coarse Aggregate
Lhoist, Apex NV	35% Crushed Fines
Legacy Rock, Overton NV	09% Blend Sand
Las Vegas Paving	15% ½" RAP

The asphalt content is revised based upon the trial section results (attached). Should you have any questions please contact me.

Sincerely,

LAS VEGAS PAVING CORPORATION

Lawrence E. Sharp

cc: Ryan Mendenhall, Andy Kimball, Jared Wagstaff, File

STATE OF NEVADA
DEPARTMENT OF TRANSPORTATION
MATERIALS DIVISION

1263 S. STEWART ST. CARSON CITY, NV 89712

DENSE GRADE BITUMINOUS MIX DESIGN

LAB NUMBER	BF13-42	BITUMEN RATIO ADDED	3.8 PG 76-22NV
CONTRACT NUMBER	3515	BITUMEN RATIO FROM RAP	0.6
COUNTY:	CLARK	BITUMEN RATIO TOTAL:	4.4

PRIMARY CONTRACTOR	LAS VEGAS PAVING
DATE AGG. SAMPLED:	12/06/13
DATE AGG. RECEIVED	12/17/13
REPORT DATE:	01/06/14
SAMPLED BY:	SAM ANDALES
CHECKED BY:	SJH & RF
TYPE MATERIAL:	TYPE 2C PLANTMIX AGGREGATE WITH RAP
SOURCE OF SAMPLE(S)	APEX PIT & LEGACY ROCK OVERTON (BLEND SAND)
MINERAL FILLER:	1.5% HYDRATED LIME WET-CURED (MARINATED) 48 HOURS
TYPE ASPHALT:	PG 76-22NV (CCAC13 1228)
ASPHALT PRODUCER:	ERGON

JOB DESCRIPTION:

ON I-15 0.103 MI N. DRY LK REST AREA TO 1.002 MI N. LOGANDALE/OVERTON INTCHG; FRCL10 W. OF HDN VLY INTCHG FROM W. CATTLE GUARD TO 0.081 MILES W.; FR CL11 MOAPA VLY INTCHG W. OF I-15 TO 0.460 MI S. OF SR 168, FR CL17 1-15/CRYSTAL INTCHG TO 0.332 MI. W.

		SPECIFICATIONS
SURFACE AREA m²/kg (ft²/lb):	7.19 (35.1)	
SAND EQUIVALENT:	62	
CALIF. SPECIFIC GRAVITY:	2.66	
COARSE AGG. BULK SPECIFIC GRAVITY:	2.62	2.85 MAX
FINE AGG. BULK SPECIFIC GRAVITY:	2.64	2.85 MAX
+#4 WATER ABSORPTION:	3/4": 1.0, 1/2": 1.2	4% MAX
SS SOUNDNESS COARSE	APEX: 2	12% MAX
SS SOUNDNESS FINES:	APEX: 4, LEGACY ROCK OVERTON: 4	15% MAX
LIQUID LIMIT (BEFORE MARINATION):	3/4": INSUFF, 1/2": 23, CUSHED FINES: 13, BLEND SAND: N/A	35 MAX
PLASTICITY INDEX (BEFORE MARINATION):	3/4": INSUFF, 1/2": 4, CUSHED FINES: 2, BLEND SAND: NP	10 MAX
LA ABRASION	16.5	37% MAX
FRACTURE FACE COUNT:	3/4": 100, 1/2": 100	60% MIN
VMA (BASED UPON CALIF. SP. GR.)	13.9 @ 4.4	12 - 22
ORIGINAL TENSILE STRENGTH (PSI):	124.6	100 PSI MIN
% RETAINED STRENGTH:	101	70% MINIMUM

REMARKS:

FOR THE MATERIAL REPRESENTED BY THE SUBMITTED SAMPLES WITH THE ATTACHED GRADINGS LABORATORY TESTS INDICATE A BITUMEN RATIO OF 3.8 PG 76-22NV FOR TYPE 2C PLANTMIX AGGREGATE WITH RAP TREATED WITH 1.5% HYDRATED LIME AND WET CURED (MARINATED) 48 HOURS

DISTRIBUTION:

1 DISTRICT ENGINEER
1 RESIDENT ENGINEER
2 CONSTRUCTION ENGINEER
1 LAB FILES
1 BITUMINOUS LAB
1 ASPHALT LAB
1 BITUMINOUS OPERATIONS
1 [illegible]
1 AGGREGATE LAB

B.N PERCENTAGES

29% 3/4" AGG
12% 1/2" AGG
35% CRUSHED FINES
09% BLEND SAND
15% RAP

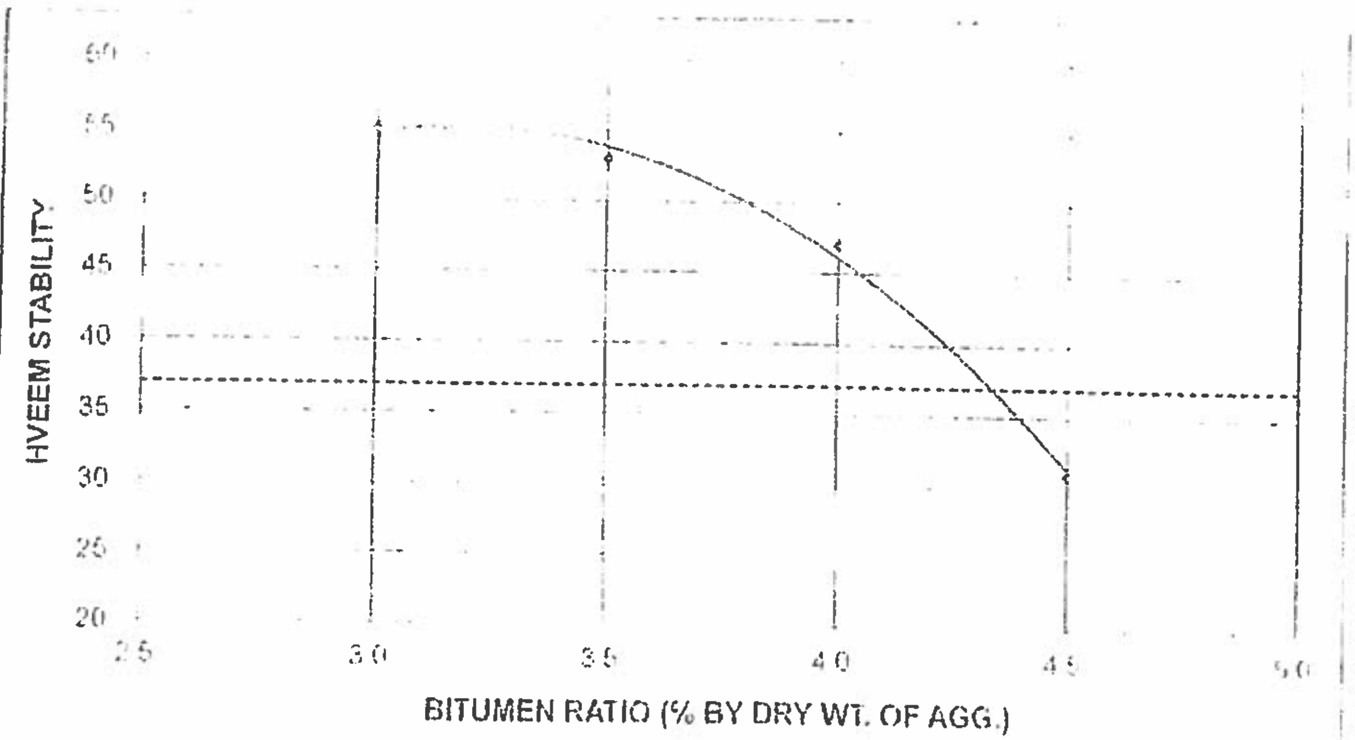
NOTE: CHANGES FROM THE RECOMMENDED BITUMEN RATIO SHALL BE DISCUSSED WITH THE MATERIALS DIVISION. THE RECOMMENDED BITUMEN RATIO IS BASED UPON DRY WEIGHT OF AGGREGATE AND RAP.

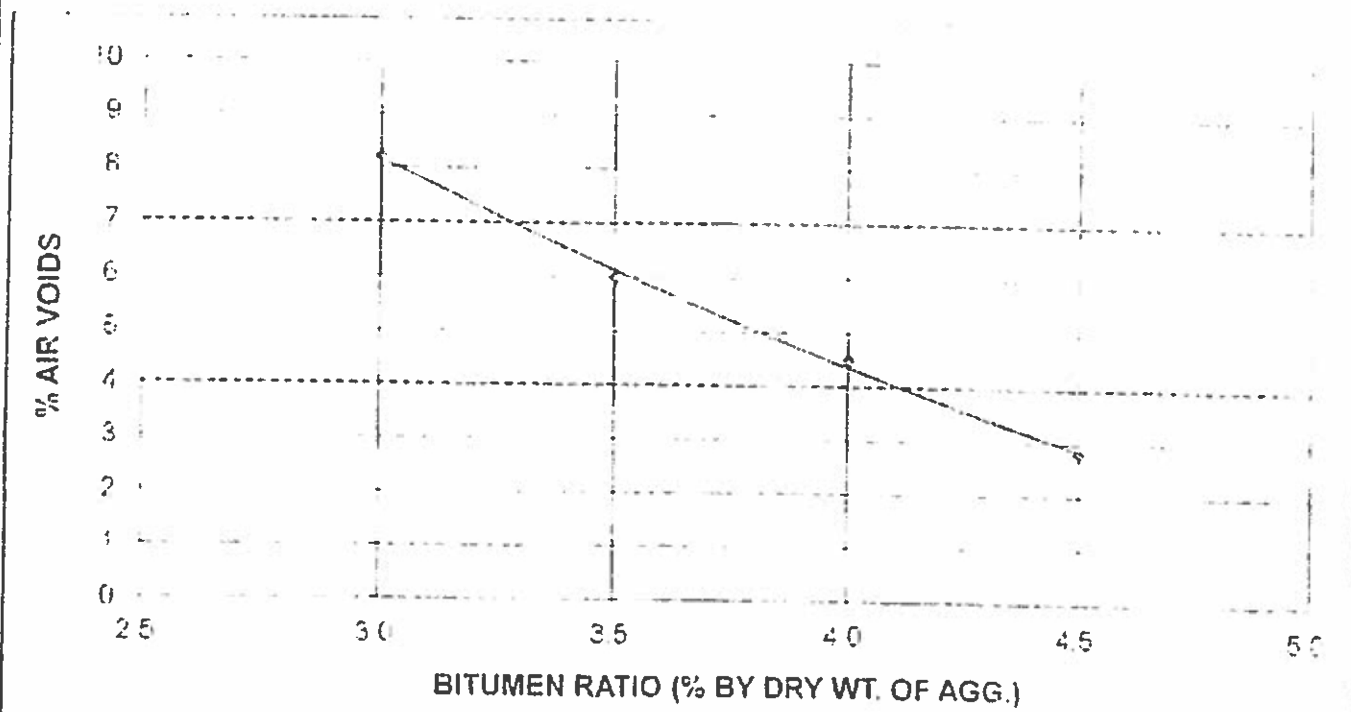
STATE OF NEVADA
DEPARTMENT OF TRANSPORTATION
MATERIALS DIVISION
1263 S. STEWART ST. CARSON CITY, NV 89712

DENSE GRADE BITUMINOUS MIX DESIGN

BF13-42

3515





APPENDIX B
Laboratory Test Results

Asphalt Content by Ignition Oven

Project ID	Mix ID	Bucket #	Ignition AC Replicate #1	Ignition AC Replicate #2	Uncorrected Ignition AC Average	Ignition Bitumen Ratio (excluding temp compensation) Replicate #1	Ignition Bitumen Ratio (excluding temp compensation) Replicate #2	Uncorrected Bitumen Ratio Average from Ignition
Elko, Nevada	OGFC	1	6.59	6.44	6.52	7.30	7.06	7.18
Las Vegas, Nevada	OGFC	1	4.83	4.83	4.83	5.23	5.23	5.23
Elko, Nevada	Dense	1	4.65	4.80	4.73	5.04	5.20	5.12
Las Vegas, Nevada	Dense	1	3.78	3.65	3.72	4.04	3.92	3.98
Las Vegas, Nevada	OGFC	2	4.83	4.83	4.83	5.18	5.19	5.19

Sample Preparation by Gyratory Compactor

Project ID	Mix ID	Gyrations	Sample ID	Sample Mass, g	Height, mm	G_{mm}	G_{mb}	V_a ,%	Density, %	Test Used For
Elko, Nevada	OGFC	50	14	4206.2	115.7	2.374	2.082	12.3	87.7	Cantabro
Elko, Nevada	OGFC	50	15	4213.2	115.3	2.374	2.090	11.9	88.1	Cantabro
Elko, Nevada	OGFC	50	16	4186.2	115.8	2.374	2.062	13.1	86.9	Cantabro
Elko, Nevada	OGFC	50	17	4085.7	111.6	2.374	2.095	11.7	88.3	TSR
Elko, Nevada	OGFC	50	18	4099.8	112.2	2.374	2.095	11.7	88.3	TSR
Elko, Nevada	OGFC	50	19	4095.8	111.5	2.374	2.096	11.7	88.3	TSR
Elko, Nevada	OGFC	50	20	4098.9	112.0	2.374	2.096	11.7	88.3	TSR
Elko, Nevada	OGFC	50	21	4093.2	111.7	2.374	2.106	11.3	88.7	TSR
Elko, Nevada	OGFC	50	22	4099.4	112.0	2.374	2.092	11.9	88.1	TSR
Elko, Nevada	OGFC	50	23	4311.6	117.6	2.374	2.106	11.3	88.7	Hamburg
Elko, Nevada	OGFC	50	25	4366.7	119.5	2.374	2.101	11.5	88.5	Hamburg
Elko, Nevada	OGFC	50	26	4364.3	119.2	2.374	2.107	11.2	88.8	Hamburg
							Avg. Va =	11.8		
Las Vegas, Nevada	OGFC	50	114	4092.3	115.6	2.465	2.040	17.2	82.8	Cantabro
Las Vegas, Nevada	OGFC	50	115	4109.7	116.0	2.465	2.013	18.3	81.7	Cantabro
Las Vegas, Nevada	OGFC	50	116	4096.6	115.7	2.465	2.029	17.7	82.3	Cantabro
Las Vegas, Nevada	OGFC	50	117	3978.4	112.3	2.465	2.037	17.4	82.6	TSR
Las Vegas, Nevada	OGFC	50	118	3982	112.5	2.465	2.030	17.6	82.4	TSR
Las Vegas, Nevada	OGFC	50	119	3987.1	112.4	2.465	2.044	17.1	82.9	TSR
Las Vegas, Nevada	OGFC	50	120	3980.2	112.4	2.465	2.031	17.6	82.4	TSR
Las Vegas, Nevada	OGFC	50	121	3984.9	112.5	2.465	2.040	17.3	82.7	TSR
Las Vegas, Nevada	OGFC	50	127	3975.2	112.0	2.465	2.023	17.9	82.1	TSR
Las Vegas, Nevada	OGFC	50	124	4233.1	119.5	2.465	2.035	17.4	82.6	Hamburg
Las Vegas, Nevada	OGFC	50	125	4231.7	118.9	2.465	2.048	16.9	83.1	Hamburg
Las Vegas, Nevada	OGFC	50	126	4233.8	119.4	2.465	2.027	17.8	82.2	Hamburg
							Avg. Va =	17.5		
Elko, Nevada	Dense	75	203	4599.1	116.4	2.436	2.295	5.8	94.2	Design Verify
Elko, Nevada	Dense	75	204	4599.5	115.8	2.436	2.302	5.5	94.5	Design Verify
							Avg. Va =	5.7		
Las Vegas, Nevada	Dense	75	303	4803.7	112.8	2.534	2.463	2.8	97.2	Design Verify
Las Vegas, Nevada	Dense	75	304	4803.00	112.4	2.534	2.472	2.5	97.5	Design Verify
							Avg. Va =	2.7		

Hamburg Wheel Tracking Test

Project ID	Mix ID	Sample ID	Test Temperature, C	Sample 1 Air Voids (%)	Sample 2 Air Voids (%)	Average Air Voids (%)	Rut Depth @ 10,000 passes (mm)	Rut Depth @ 20,000 Passes (mm)	Passes to 12.5mm Rut	Stripping Inflection Point (passes)
Elko, Nevada	OGFC	23A and 23B	50	10.4	11.1	10.8	14.29	> 12.5	8,750	20,000+
Elko, Nevada	OGFC	25A and 25B	50	10.9	11.3	11.1	14.25	> 12.5	8,700	20,000+
Elko, Nevada	OGFC	26A and 26B	50	10.3	11.0	10.7	13.69	> 12.5	9,400	10,100
Las Vegas, Nevada	OGFC	124A and 124B	50	16.7	16.6	16.7	5.20	7.63	> 20,000	20,000+
Las Vegas, Nevada	OGFC	125A and 125B	50	16.5	16.3	16.4	3.83	7.52	> 20,000	20,000+
Las Vegas, Nevada	OGFC	126A and 126B	50	16.5	17.1	16.8	6.13	9.21	> 20,000	20,000+

Cantabro Stone Loss

Project ID	Mix ID	Sample ID	Conditioning	V_a ,%	Cantabro % Loss
Elko, Nevada	OGFC	14	None	12.3	2.1
Elko, Nevada	OGFC	15	None	11.9	3.7
Elko, Nevada	OGFC	16	None	13.1	3.5
Las Vegas, Nevada	OGFC	114	None	17.2	7.3
Las Vegas, Nevada	OGFC	115	None	18.3	6.3
Las Vegas, Nevada	OGFC	116	None	17.7	7.2
Elko, Nevada	OGFC	27	Vacuum Saturated and 1 F/T	12.4	5.4
Elko, Nevada	OGFC	29	Vacuum Saturated and 1 F/T	11.8	6.2
Elko, Nevada	OGFC	32	Vacuum Saturated and 1 F/T	12.3	6.4
Las Vegas, Nevada	OGFC	128	Vacuum Saturated and 1 F/T	17.6	13.4
Las Vegas, Nevada	OGFC	129	Vacuum Saturated and 1 F/T	17.8	12.7
Las Vegas, Nevada	OGFC	131	Vacuum Saturated and 1 F/T	17.5	12.6
Elko, Nevada	OGFC	28	Long-Term Oven Aging per R30	12.4	5.6
Elko, Nevada	OGFC	30	Long-Term Oven Aging per R30	11.9	6.9
Elko, Nevada	OGFC	31	Long-Term Oven Aging per R30	11.7	5.3
Las Vegas, Nevada	OGFC	130	Long-Term Oven Aging per R30	17.5	14.2
Las Vegas, Nevada	OGFC	132	Long-Term Oven Aging per R30	17.4	12.3
Las Vegas, Nevada	OGFC	133	Long-Term Oven Aging per R30	18.0	13.5
Elko, Nevada	Dense	230	None	6.5	10.8
Elko, Nevada	Dense	231	None	6.7	8.4
Elko, Nevada	Dense	232	None	7.3	9.3
Las Vegas, Nevada	Dense	330	None	6.8	13.7
Las Vegas, Nevada	Dense	331	None	6.5	13.6
Las Vegas, Nevada	Dense	332	None	6.7	17.7

Moisture Susceptibility Testing (Indirect Tensile Strength)

Project ID	Mix ID	Sample ID	V_a ,%	Conditioning Cycles	Tensile Strength (psi)	TSR
Elko, Nevada	OGFC	17	11.7	1	57.7	0.73
Elko, Nevada	OGFC	21	11.3	1	50.5	
Elko, Nevada	OGFC	22	11.9	1	54.8	
Elko, Nevada	OGFC	18	11.7	0	75.0	
Elko, Nevada	OGFC	19	11.7	0	76.5	
Elko, Nevada	OGFC	20	11.7	0	72.1	
Las Vegas, Nevada	OGFC	117	17.4	1	76.5	0.78
Las Vegas, Nevada	OGFC	119	17.1	1	70.7	
Las Vegas, Nevada	OGFC	127	17.9	1	70.7	
Las Vegas, Nevada	OGFC	118	17.6	0	88.0	
Las Vegas, Nevada	OGFC	120	17.6	0	96.6	
Las Vegas, Nevada	OGFC	121	17.3	0	95.2	

APPENDIX C
Roadway Test Results

Roadway Core Results Immediately after Construction

Roadway	Mix ID	Core ID	Average Height (in)	Average Diameter (in)	Gmm	Gmb	Air Voids (%)	Permeability (k), cm/s*10^-5
I-15	Dense	1	1.66	3.92	2.534	2.474	2.4	0
I-15	Dense	2	1.97	3.91	2.534	2.426	4.3	0
I-15	Dense	3	1.70	3.91	2.534	2.471	2.5	0
I-15	OGFC	4	0.92	3.91	2.465	1.991	19.2	8,514
I-15	OGFC	5	0.79	3.91	2.465	2.046	17.0	6,965
I-15	OGFC	6	0.87	3.92	2.465	1.999	18.9	8,687
SR 535	Dense	1	1.46	3.97	2.436	2.312	5.1	0.4
SR 535	Dense	2	1.23	3.99	2.436	2.322	4.7	0.0
SR 535	Dense	3	1.29	3.98	2.436	2.301	5.5	0.1
SR 535	OGFC	4	0.76	4.00	2.374	2.150	9.4	2.1
SR 535	OGFC	5	0.94	4.01	2.374	2.163	8.9	204.5
SR 535	OGFC	6	1.04	3.99	2.374	2.149	9.5	518.6

Field Permeability

SR 535 Elko Dense		SR 535 Elko OGFC		I-15 Las Vegas Dense		I-15 Las Vegas OGFC	
Date	Permeability	Date	Permeability	Date	Permeability	Date	Permeability
2/15	7	2/15	2932	2/15	1	2/15	7549
3/16	6	3/16	137	3/16	3	3/16	11447
3/17	8	3/17	5	3/17	5	3/17	5965

Nevada OBSI Summary

Location	Highway	Surface Type	Feb-15 dB(A) Avg.	May-15 dB(A) Avg.	Oct-15 dB(A) Avg.	Mar-16 dB(A) Avg.	Sep-16 dB(A) Avg.	Mar-17 dB(A) Avg.	Sep-17 dB(A) Avg.
Elko, NV	NV 535 EB	Dense Graded	96.45	97.95	98.95	98.50	99.14	100.15	100.2 a
Elko, NV	NV 535 EB	OGFC	92.85	93.55	95.45	96.00	98.21	99.20	100.1 a
Las Vegas, NV	I-15 NB	Dense Graded	99.00	98.10	99.55	99.05	100.10	100.05	100.10
Las Vegas, NV	I-15 NB	OGFC	96.95	95.90	97.35	97.40	98.02	98.70	98.70
McGill, NV	US 93 NB		-	-	-	-	-	-	97.70

Nevada Surface Texture by Circular Texture Meter

February, 2015		Site 1 Measurement #						Site 2 Measurement #						Site 3 Measurement #						Overall Average
		1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	
Elko, NV - Dense Graded	Mean Profile Depth (Average)	0.82	0.80	0.80	0.81	0.81	0.81	0.64	0.65	0.66	0.66	0.66	0.65	0.51	0.51	0.51	0.50	0.50	0.51	0.66
	% Dropouts (Average)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
	RMS (Average)	0.41	0.41	0.40	0.41	0.41	0.41	0.37	0.37	0.37	0.37	0.70	0.44	0.31	0.31	0.31	0.31	0.30	0.31	0.38
Elko, NV - OGFC	Mean Profile Depth (Average)	0.82	0.82	0.83	0.88	0.78	0.83	0.65	0.67	0.68	0.68	0.68	0.67	0.78	0.78	0.78	0.78	0.77	0.78	0.76
	% Dropouts (Average)	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0.01
	RMS (Average)	0.57	0.56	0.55	0.59	0.74	0.60	0.50	0.49	0.51	0.50	0.50	0.50	0.61	0.60	0.60	0.60	0.59	0.60	0.57
I-15 - Dense Graded MP 87.0 - 87.5	Mean Profile Depth (Average)	0.71	0.71	0.71	0.71	0.71	0.71	0.33	0.31	0.30	0.31	0.30	0.31	0.44	0.44	0.43	0.43	0.43	0.43	0.48
	% Dropouts (Average)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
	RMS (Average)	0.53	0.52	0.52	0.52	0.52	0.52	0.25	0.24	0.24	0.24	0.24	0.24	0.27	0.27	0.27	0.27	0.27	0.27	0.34
I-15 - OGFC MP 86.5 - 87.0	Mean Profile Depth (Average)	0.96	0.91	0.92	0.92	0.91	0.92	1.19	1.19	1.25	1.21	1.19	1.21	0.93	1.03	0.97	0.94	0.93	0.96	1.03
	% Dropouts (Average)	2%	3%	3%	2%	2%	2%	2%	2%	2%	2%	2%	2%	3%	3%	3%	3%	3%	3%	0.02
	RMS (Average)	0.89	0.74	0.76	0.74	0.76	0.78	0.80	0.79	1.01	0.79	0.78	0.83	0.64	0.94	0.80	0.63	0.63	0.73	0.78

March, 2016		Site 1 Measurement #						Site 2 Measurement #						Site 3 Measurement #						Overall Average
		1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	
Elko, NV - Dense Graded	Mean Profile Depth (Average)	0.85	0.93	0.92	0.93	0.92	0.91	0.52	0.51	0.51	0.51	0.51	0.51	0.96	0.95	0.96	0.96	0.96	0.96	0.79
	% Dropouts (Average)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
	RMS (Average)	0.50	0.52	0.51	0.53	0.50	0.51	0.25	0.25	0.25	0.25	0.25	0.25	0.49	0.50	0.50	0.50	0.50	0.50	0.42
Elko, NV - OGFC	Mean Profile Depth (Average)	0.89	0.88	0.88	0.88	0.88	0.88	0.96	0.95	0.97	0.97	0.97	0.96	0.82	0.82	0.82	0.81	0.82	0.82	0.89
	% Dropouts (Average)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0.00
	RMS (Average)	0.50	0.49	0.50	0.49	0.56	0.51	0.57	0.57	0.57	0.57	0.57	0.57	0.45	0.46	0.46	0.45	0.45	0.45	0.51
I-15 - Dense Graded MP 87.0 - 87.5	Mean Profile Depth (Average)	0.46	0.46	0.45	0.46	0.46	0.46	0.46	0.48	0.48	0.49	0.48	0.48	0.53	0.52	0.52	0.52	0.52	0.52	0.49
	% Dropouts (Average)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
	RMS (Average)	0.30	0.30	0.29	0.29	0.30	0.30	0.30	0.29	0.29	0.29	0.29	0.29	0.35	0.35	0.35	0.35	0.35	0.35	0.31
I-15 - OGFC MP 86.5 - 87.0	Mean Profile Depth (Average)	1.03	1.08	1.07	1.03	1.13	1.07	1.01	1.03	1.02	1.05	1.00	1.02	1.02	1.04	1.09	1.08	1.05	1.06	1.05
	% Dropouts (Average)	5%	5%	5%	5%	5%	5%	2%	2%	2%	2%	2%	2%	3%	3%	3%	3%	3%	3%	0.03
	RMS (Average)	0.74	1.01	1.00	0.72	1.09	0.91	0.70	0.76	0.70	0.89	0.70	0.75	0.65	0.66	0.72	0.92	0.69	0.73	0.80

March, 2017		Location 1 Measurement #						Location 2 Measurement #						Location 3 Measurement #						Overall Average
		1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average	
NV 535 East DGA Elko	Mean Profile Depth (Average)	0.77	0.70	0.69	0.69	0.70	0.71	0.65	0.65	0.67	0.66	0.66	0.66	0.61	0.61	0.62	0.61	0.61	0.61	0.66
	% Dropouts (Average)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
	RMS (Average)	0.38	0.37	0.37	0.37	0.37	0.37	0.31	0.31	0.31	0.31	0.31	0.31	0.29	0.29	0.29	0.29	0.29	0.29	0.32
NV 535 East OGFC Elko	Mean Profile Depth (Average)	0.60	0.65	0.66	0.66	0.66	0.65	0.64	0.62	0.63	0.63	0.63	0.63	0.65	0.66	0.67	0.66	0.66	0.66	0.65
	% Dropouts (Average)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
	RMS (Average)	0.34	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.32	0.33	0.33	0.33	0.33	0.33	0.34
I15 North DGA Las Vegas	Mean Profile Depth (Average)	0.56	0.56	0.56	0.56	0.56	0.56	0.39	0.40	0.40	0.41	0.40	0.40	0.65	0.66	0.66	0.66	0.66	0.66	0.54
	% Dropouts (Average)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
	RMS (Average)	0.29	0.29	0.29	0.29	0.29	0.29	0.20	0.21	0.21	0.21	0.21	0.21	0.37	0.38	0.38	0.37	0.38	0.38	0.29
I15 North OGFC Las Vegas	Mean Profile Depth (Average)	0.94	0.99	0.90	0.89	0.92	0.93	1.12	1.10	1.15	1.11	1.10	1.12	0.97	0.93	0.93	0.92	0.93	0.94	0.99
	% Dropouts (Average)	2%	2%	2%	3%	2%	2%	2%	2%	2%	2%	3%	2%	2%	1%	2%	2%	2%	2%	0.02
	RMS (Average)	0.60	0.92	0.73	0.59	0.81	0.73	0.85	0.72	0.97	0.72	0.71	0.79	0.69	0.58	0.79	0.58	0.58	0.64	0.72

Las Vegas I-15 Friction Tests

OGFC								Dense-Graded				
Route	Milepost	Direction	Mix Type	Lane	Date	Date	SN	Milepost	Lane	Date	Date	SN
I-15	85-89	N	OGFC	1	2/15	1	34	86.8-87.6	1	2/15	1	19
I-15	85-89	N	OGFC	1	2/15	1	31	86.8-87.6	1	2/15	1	20
I-15	85-89	N	OGFC	1	2/15	1	36	86.8-87.6	1	2/15	1	18
I-15	85-89	N	OGFC	1	2/15	1	34	86.8-87.6	1	2/15	1	18
I-15	85-89	N	OGFC	1	2/15	1	34	86.8-87.6	2	2/15	1	17
I-15	85-89	N	OGFC	1	2/15	1	32	86.8-87.6	2	2/15	1	20
I-15	85-89	N	OGFC	1	2/15	1	35	86.8-87.6	2	2/15	1	22
I-15	85-89	N	OGFC	1	2/15	1	34	86.8-87.6	2	2/15	1	19
I-15	85-89	N	OGFC	1	2/15	1	35	86.8-87.6	1	8/15	2	26
I-15	85-89	N	OGFC	1	2/15	1	35	86.8-87.6	1	8/15	2	27
I-15	85-89	N	OGFC	1	2/15	1	35	86.8-87.6	1	8/15	2	27
I-15	85-89	N	OGFC	1	2/15	1	34	86.8-87.6	1	8/15	2	29
I-15	85-89	N	OGFC	1	2/15	1	34	86.8-87.6	2	8/15	2	28
I-15	85-89	N	OGFC	1	2/15	1	37	86.8-87.6	2	8/15	2	26
I-15	85-89	N	OGFC	1	2/15	1	35	86.8-87.6	2	8/15	2	28
I-15	85-89	N	OGFC	1	2/15	1	35	86.8-87.6	2	8/15	2	26
I-15	85-89	N	OGFC	2	2/15	1	37	86.8-87.6	1	1/16	3	23
I-15	85-89	N	OGFC	2	2/15	1	38	86.8-87.6	1	1/16	3	25
I-15	85-89	N	OGFC	2	2/15	1	32	86.8-87.6	1	1/16	3	24
I-15	85-89	N	OGFC	2	2/15	1	32	86.8-87.6	1	1/16	3	26
I-15	85-89	N	OGFC	2	2/15	1	32	86.8-87.6	2	1/16	3	22
I-15	85-89	N	OGFC	2	2/15	1	31	86.8-87.6	2	1/16	3	25
I-15	85-89	N	OGFC	2	2/15	1	32	86.8-87.6	2	1/16	3	25
I-15	85-89	N	OGFC	2	2/15	1	29	86.8-87.6	2	1/16	3	23
I-15	85-89	N	OGFC	2	2/15	1	32	86.8-87.6	1	6/16	4	28
I-15	85-89	N	OGFC	2	2/15	1	32	86.8-87.6	1	6/16	4	27
I-15	85-89	N	OGFC	2	2/15	1	33	86.8-87.6	1	6/16	4	26
I-15	85-89	N	OGFC	2	2/15	1	30	86.8-87.6	1	6/16	4	27
I-15	85-89	N	OGFC	2	2/15	1	30	86.8-87.6	2	6/16	4	21
I-15	85-89	N	OGFC	2	2/15	1	30	86.8-87.6	2	6/16	4	24
I-15	85-89	N	OGFC	2	2/15	1	30	86.8-87.6	2	6/16	4	23
I-15	85-89	N	OGFC	2	2/15	1	30	86.8-87.6	2	6/16	4	21
I-15	85-89	N	OGFC	1	8/15	2	35	86.8-87.6	1	11/17	5	34
I-15	85-89	N	OGFC	1	8/15	2	32	86.8-87.6	1	11/17	5	34
I-15	85-89	N	OGFC	1	8/15	2	35	86.8-87.6	1	11/17	5	34
I-15	85-89	N	OGFC	1	8/15	2	34	86.8-87.6	1	11/17	5	36
I-15	85-89	N	OGFC	1	8/15	2	31	86.8-87.6	2	11/17	5	26
I-15	85-89	N	OGFC	1	8/15	2	28	86.8-87.6	2	11/17	5	28
I-15	85-89	N	OGFC	1	8/15	2	31	86.8-87.6	2	11/17	5	29
I-15	85-89	N	OGFC	1	8/15	2	29	86.8-87.6	2	11/17	5	28

Las Vegas I-15 Friction Tests *(Continued)*

OGFC							
Route	Milepost	Direction	Mix Type	Lane	Date	Date	SN
I-15	85-89	N	OGFC	1	8/15	2	34
I-15	85-89	N	OGFC	1	8/15	2	33
I-15	85-89	N	OGFC	1	8/15	2	33
I-15	85-89	N	OGFC	1	8/15	2	34
I-15	85-89	N	OGFC	1	8/15	2	32
I-15	85-89	N	OGFC	1	8/15	2	33
I-15	85-89	N	OGFC	1	8/15	2	31
I-15	85-89	N	OGFC	1	8/15	2	34
I-15	85-89	N	OGFC	2	8/15	2	31
I-15	85-89	N	OGFC	2	8/15	2	32
I-15	85-89	N	OGFC	2	8/15	2	32
I-15	85-89	N	OGFC	2	8/15	2	31
I-15	85-89	N	OGFC	2	8/15	2	33
I-15	85-89	N	OGFC	2	8/15	2	30
I-15	85-89	N	OGFC	2	8/15	2	30
I-15	85-89	N	OGFC	2	8/15	2	31
I-15	85-89	N	OGFC	2	8/15	2	32
I-15	85-89	N	OGFC	2	8/15	2	33
I-15	85-89	N	OGFC	2	8/15	2	32
I-15	85-89	N	OGFC	2	8/15	2	34
I-15	85-89	N	OGFC	2	8/15	2	31
I-15	85-89	N	OGFC	2	8/15	2	28
I-15	85-89	N	OGFC	2	8/15	2	28
I-15	85-89	N	OGFC	2	8/15	2	32
I-15	85-89	N	OGFC	1	1/16	3	34
I-15	85-89	N	OGFC	1	1/16	3	31
I-15	85-89	N	OGFC	1	1/16	3	33
I-15	85-89	N	OGFC	1	1/16	3	33
I-15	85-89	N	OGFC	1	1/16	3	33
I-15	85-89	N	OGFC	1	1/16	3	34
I-15	85-89	N	OGFC	1	1/16	3	33
I-15	85-89	N	OGFC	1	1/16	3	33
I-15	85-89	N	OGFC	1	1/16	3	33
I-15	85-89	N	OGFC	1	1/16	3	35
I-15	85-89	N	OGFC	1	1/16	3	32
I-15	85-89	N	OGFC	1	1/16	3	34
I-15	85-89	N	OGFC	1	1/16	3	31
I-15	85-89	N	OGFC	1	1/16	3	33
I-15	85-89	N	OGFC	1	1/16	3	33
I-15	85-89	N	OGFC	1	1/16	3	33

Las Vegas I-15 Friction Tests *(Continued)*

OGFC							
Route	Milepost	Direction	Mix Type	Lane	Date	Date	SN
I-15	85-89	N	OGFC	2	1/16	3	32
I-15	85-89	N	OGFC	2	1/16	3	33
I-15	85-89	N	OGFC	2	1/16	3	31
I-15	85-89	N	OGFC	2	1/16	3	30
I-15	85-89	N	OGFC	2	1/16	3	31
I-15	85-89	N	OGFC	2	1/16	3	32
I-15	85-89	N	OGFC	2	1/16	3	32
I-15	85-89	N	OGFC	2	1/16	3	29
I-15	85-89	N	OGFC	2	1/16	3	31
I-15	85-89	N	OGFC	2	1/16	3	33
I-15	85-89	N	OGFC	2	1/16	3	34
I-15	85-89	N	OGFC	2	1/16	3	34
I-15	85-89	N	OGFC	2	1/16	3	33
I-15	85-89	N	OGFC	2	1/16	3	32
I-15	85-89	N	OGFC	2	1/16	3	34
I-15	85-89	N	OGFC	2	1/16	3	32
I-15	85-89	N	OGFC	1	6/16	4	39
I-15	85-89	N	OGFC	1	6/16	4	36
I-15	85-89	N	OGFC	1	6/16	4	34
I-15	85-89	N	OGFC	1	6/16	4	34
I-15	85-89	N	OGFC	1	6/16	4	34
I-15	85-89	N	OGFC	1	6/16	4	34
I-15	85-89	N	OGFC	1	6/16	4	34
I-15	85-89	N	OGFC	1	6/16	4	35
I-15	85-89	N	OGFC	1	6/16	4	34
I-15	85-89	N	OGFC	1	6/16	4	34
I-15	85-89	N	OGFC	1	6/16	4	35
I-15	85-89	N	OGFC	1	6/16	4	34
I-15	85-89	N	OGFC	1	6/16	4	35
I-15	85-89	N	OGFC	1	6/16	4	34
I-15	85-89	N	OGFC	1	6/16	4	36
I-15	85-89	N	OGFC	1	6/16	4	35
I-15	85-89	N	OGFC	2	6/16	4	31
I-15	85-89	N	OGFC	2	6/16	4	31
I-15	85-89	N	OGFC	2	6/16	4	30
I-15	85-89	N	OGFC	2	6/16	4	29
I-15	85-89	N	OGFC	2	6/16	4	32
I-15	85-89	N	OGFC	2	6/16	4	33
I-15	85-89	N	OGFC	2	6/16	4	32
I-15	85-89	N	OGFC	2	6/16	4	30

Las Vegas I-15 Friction Tests *(Continued)*

OGFC							
Route	Milepost	Direction	Mix Type	Lane	Date	Date	SN
I-15	85-89	N	OGFC	2	6/16	4	31
I-15	85-89	N	OGFC	2	6/16	4	30
I-15	85-89	N	OGFC	2	6/16	4	32
I-15	85-89	N	OGFC	2	6/16	4	34
I-15	85-89	N	OGFC	2	6/16	4	31
I-15	85-89	N	OGFC	2	6/16	4	32
I-15	85-89	N	OGFC	2	6/16	4	31
I-15	85-89	N	OGFC	2	6/16	4	31
I-15	85-89	N	OGFC	1	11/17	5	42
I-15	85-89	N	OGFC	1	11/17	5	42
I-15	85-89	N	OGFC	1	11/17	5	41
I-15	85-89	N	OGFC	1	11/17	5	42
I-15	85-89	N	OGFC	1	11/17	5	41
I-15	85-89	N	OGFC	1	11/17	5	43
I-15	85-89	N	OGFC	1	11/17	5	43
I-15	85-89	N	OGFC	1	11/17	5	42
I-15	85-89	N	OGFC	1	11/17	5	43
I-15	85-89	N	OGFC	1	11/17	5	41
I-15	85-89	N	OGFC	1	11/17	5	44
I-15	85-89	N	OGFC	1	11/17	5	43
I-15	85-89	N	OGFC	1	11/17	5	43
I-15	85-89	N	OGFC	1	11/17	5	43
I-15	85-89	N	OGFC	1	11/17	5	44
I-15	85-89	N	OGFC	1	11/17	5	
I-15	85-89	N	OGFC	2	11/17	5	37
I-15	85-89	N	OGFC	2	11/17	5	37
I-15	85-89	N	OGFC	2	11/17	5	36
I-15	85-89	N	OGFC	2	11/17	5	37
I-15	85-89	N	OGFC	2	11/17	5	38
I-15	85-89	N	OGFC	2	11/17	5	37
I-15	85-89	N	OGFC	2	11/17	5	37
I-15	85-89	N	OGFC	2	11/17	5	39
I-15	85-89	N	OGFC	2	11/17	5	39
I-15	85-89	N	OGFC	2	11/17	5	39
I-15	85-89	N	OGFC	2	11/17	5	39
I-15	85-89	N	OGFC	2	11/17	5	40
I-15	85-89	N	OGFC	2	11/17	5	38
I-15	85-89	N	OGFC	2	11/17	5	39
I-15	85-89	N	OGFC	2	11/17	5	38
I-15	85-89	N	OGFC	2	11/17	5	39

Elko SR 535 Friction Tests

Route	Milepost	Direction	Mix Type	Lane	Date	SN	Milepost	Direction	Mix Type	Date	SN
SR-535	1-2	E	OGFC	1	11/14	50	0-1	E	Dense	11/14	64
SR-535	1-2	E	OGFC	1	11/14	50	0-1	E	Dense	11/14	60
SR-535	1-2	E	OGFC	1	11/14	52	0-1	E	Dense	11/14	61
SR-535	1-2	E	OGFC	1	11/14	51	0-1	E	Dense	11/14	61
SR-535	1-2	E	OGFC	1	8/15	40	0-1	E	Dense	8/15	40
SR-535	1-2	E	OGFC	1	8/15	40	0-1	E	Dense	8/15	43
SR-535	1-2	E	OGFC	1	8/15	42	0-1	E	Dense	8/15	41
SR-535	1-2	E	OGFC	1	8/15	41	0-1	E	Dense	8/15	40
SR-535	1-2	E	OGFC	1	1/16	53	0-1	E	Dense	1/16	53
SR-535	1-2	E	OGFC	1	1/16	56	0-1	E	Dense	1/16	53
SR-535	1-2	E	OGFC	1	1/16	55	0-1	E	Dense	1/16	50
SR-535	1-2	E	OGFC	1	1/16	55	0-1	E	Dense	1/16	53
SR-535	1-2	E	OGFC	1	6/16	49	0-1	E	Dense	6/16	48
SR-535	1-2	E	OGFC	1	6/16	48	0-1	E	Dense	6/16	49
SR-535	1-2	E	OGFC	1	6/16	48	0-1	E	Dense	6/16	45
SR-535	1-2	E	OGFC	1	6/16	50	0-1	E	Dense	6/16	46
SR-535	1-2	W	OGFC	1	11/14	52	0-1	W	Dense	11/14	64
SR-535	1-2	W	OGFC	1	11/14	53	0-1	W	Dense	11/14	64
SR-535	1-2	W	OGFC	1	11/14	53	0-1	W	Dense	11/14	61
SR-535	1-2	W	OGFC	1	11/14	54	0-1	W	Dense	11/14	58
SR-535	1-2	W	OGFC	1	11/14	53	0-1	W	Dense	11/14	53
SR-535	1-2	W	OGFC	1	8/15	45	0-1	W	Dense	8/15	46
SR-535	1-2	W	OGFC	1	8/15	45	0-1	W	Dense	8/15	47
SR-535	1-2	W	OGFC	1	8/15	46	0-1	W	Dense	8/15	39
SR-535	1-2	W	OGFC	1	8/15	46	0-1	W	Dense	8/15	39
SR-535	1-2	W	OGFC	1	8/15	47	0-1	W	Dense	8/15	36
SR-535	1-2	W	OGFC	1	1/16	57	0-1	W	Dense	1/16	54
SR-535	1-2	W	OGFC	1	1/16	57	0-1	W	Dense	1/16	58
SR-535	1-2	W	OGFC	1	1/16	57	0-1	W	Dense	1/16	54
SR-535	1-2	W	OGFC	1	1/16	55	0-1	W	Dense	1/16	53
SR-535	1-2	W	OGFC	1	1/16	45	0-1	W	Dense	1/16	56
SR-535	1-2	W	OGFC	1	6/16	28	0-1	W	Dense	6/16	45
SR-535	1-2	W	OGFC	1	6/16	29	0-1	W	Dense	6/16	48
SR-535	1-2	W	OGFC	1	6/16	54	0-1	W	Dense	6/16	45
SR-535	1-2	W	OGFC	1	6/16	51	0-1	W	Dense	6/16	45
SR-535	1-2	W	OGFC	1	6/16	46	0-1	W	Dense	6/16	45

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