FINAL REPORT ~ FHWA-OK-17-01

DEVELOPMENT OF AN ASPHALT PAVEMENT TEST FACILITY AT THE OSU UNMANNED AERIAL VEHICLE FACILITY

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Oklahoma Department of Transportation

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DEVELOPMENT OF AN ASPHALT PAVEMENT TEST FACILITY AT THE OSU UNMANNED AERIAL VEHICLE FACILITY

FINAL REPORT ~ FHWA-OK-17-01
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This report documents the construction and evaluation of the asphalt pavement testing runway at the OSU Unmanned Aerial Vehicle (UAV) facility. Runway surface characterization and performance evaluation results, in terms of pavement roughness, longitudinal profiling, surface texture, and friction, are presented in Part 1 based on the two rounds of data collection performed in 2014 and 2015 using several art-of-the-state instruments. Part 2 presents the results from the construction and evaluation of an experimental shoulder mix placed on the east side of the UAV runway. The dynamic modulus testing and SCB test were performed to evaluate the four mixtures used in the facility.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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CHAPTER 1 INTRODUCTION

1.1 Background

Oklahoma State University (OSU) is developing an airport runway facility near Elgin, Oklahoma to evaluate lightweight Unmanned Aerial Vehicles (UAV), or drones as they are commonly called. The Roadway Design Squad at OSU has been involved with the preliminary design of this project which consisted of construction of an approximately 12 foot wide by 375 foot long taxiway and 60 foot wide by 2,400 foot long runway. There is a planned expansion to the runway in the near future.

UAVs have been widely used for various applications, such as security, search and rescue, monitoring of infrastructure systems, package delivery, disaster management, etc. The construction of this facility and the planned expansion offers an excellent opportunity for ODOT to participate in the construction and have a dedicated test facility for the evaluation of pavement materials including but not limited to plant-mixed warm and hot mix asphalt pavements, high RAP and RAS mixes, asphalt surface treatments, pavement preservation treatments, 100% RAP cold mixes and aggregate bases with surface treatments. It would be difficult to load the proposed roadway to typical highway conditions. Therefore, the test site would be more suitable for measurement and evaluation of surface characteristics and the effects of environmental conditions than structural applications. OSU has stated that the presence of surface treatments and mixes (different surface textures) would not impact their operations and that allowing periodic access to the pavement for surface characteristic evaluations would easily be accommodated as periodic interruptions to runway access would not adversely impact their operations.

ODOT has a long range shoulder replacement/upgrading program. One of the major failure/distress modes of typical HMA shoulders is rapid oxidation and brittleness due to the lack of load applications to keep the material flexible (thixotropic or steric hardening). Once completed, and if funding allows, the UAV runway would provide an excellent opportunity to evaluate various surface treatments and even alternate mixes, for HMA shoulders.

Shoulder mixtures and surface treatments could be evaluated for resistance to thermally induced cracking, moisture intrusion, skid resistance and overall pavement condition. Pavement preservation techniques could easily be accommodated as the majority of these treatments are thin seal coats. Alternative shoulder mixes that could be evaluated might include 100% RAP cold mixes and 50% RAP, 50% crushed stone cold mixes using cement, emulsified asphalt and foamed asphalt as a stabilizing agent, and high RAP RAS mixtures.

The objective of this study is to assist in the construction of the UAV runway to develop a pavement that can be used as a test facility for evaluation of pavement materials including, but not limited to, plant-mixed warm and hot mix asphalt pavements, high RAP and RAS mixes, asphalt surface treatments, pavement preservation treatments, 100% RAP cold mixes and aggregate bases with surface treatments. These mixtures would need to be incorporated into the planned expansion of the facility or placed as an overlay or surface treatment on the planned existing surface. It would be difficult to load the facility to typical highway conditions;

therefore, the facility would be best suited for measurement of environmental effects. At the completion of the construction, ODOT would have a facility available to them through OSU to test and evaluate surface treatments, surface mixes, including high RAP and RAS mixtures, and pavement preservation treatments for a variety of applications.

1.2 Report Outline

This report is presented in two parts. Part 1, containing chapters 2-4, presents the surface characterization and performance evaluation results from the two rounds of data collection performed in 2014 and 2015 on the UAV runway. Part 2, containing chapters 5-7, presents the results from the construction and evaluation of an experimental shoulder mix placed on the east side of the UAV runway.

For Part 1, several state-of-the-art data collection devices were used for both data collection, including the OSU 3D laser imaging technology (named as PaveVision3D Ultra) for 1mm 3D runway surface data, Grip Tester for continuous surface friction, dynamic friction tester (DFT) for dynamic friction coefficients, AMES high speed profiler for pavement roughness and macro-texture, SurPRO 3500 walking profiler for surface longitudinal profiling, and the portable LS-40 3D Surface Analyzer for ultra-high resolution pavement texture. Runway surface characteristics in this report include pavement roughness, longitudinal profiling, surface texture, and friction from Grip Tester and DFT.

Part 2 describes the placement and evaluation of a shoulder mix consisting of a high binder replacement mix using PG58-28 OK binder. The north half of the shoulder was placed using warm mix technology, foamed asphalt. For the south half of the shoulder the same mix was placed without using the warm mix technology. In order to better understand the effects of using a softer grade binder (PG 58-28) on recycled mixtures compared to the typically used PG64-22 binder, two additional mixes were sampled. The third mix sampled was the same mix as the mixtures used for the shoulder but used a PG64-22 binder. The fourth mix used the same aggregates as other three mixes but contained no RAP and used PG64-22 binder. This would allow comparisons of the RAP mixes with different grades of binders to a virgin mix, a comparison of the impact of a softer binder on the recycled mixes and the effect of the warm mix technology.

PART 1

SURFACE CHARACTERIZATION AND PERFORMANCE EVALUATION RESULTS

CHAPTER 2 DATA COLLECTION DEVICES

2.1 PaveVision3D Ultra

The PaveVision3D laser imaging system has evolved into a sophisticated system to conduct full lane data collection on roadways at highway speeds up to 60mph (96.5 km/h) at 1mm resolution (Wang, 2011). Figure 2.1 demonstrates the Digital Highway Data Vehicle (DHDV) equipped with PaveVision3D Ultra, which is able to acquire both 3D laser imaging intensity and range data from pavement surfaces through two separate sets of sensors. Recently, two 3D high resolution digital accelerometers have been installed on the system, capable of reporting compensated pavement surface profiles and generating roughness indices. The collected data are saved by image frames with the dimension of 2,048 mm in length and 4,096 mm in width. In summary, the 1mm 3D pavement surface data can be used for:

- Comprehensive evaluation of surface distresses: automatic and interactive cracking detection and classification based on various cracking protocols;
- Profiling: transverse for rutting and longitudinal for roughness (Boeing Bump Index and International Roughness Index);
- Safety analysis: including macro-texture in term of mean profile depth (MPD) and mean texture depth (MTD), hydroplaning prediction, and grooving identification and evaluation;
- Roadway geometry: including horizontal curve, longitudinal grade and cross slope.

Figure 2.1. PaveVision3D Ultra

2.2 AMES 8300 High Speed Profiler

The AMES Model 8300 High Speed Profiler is designed to collect macro surface texture data along with standard profile data at highway speeds. Texture indices such as MPD can be calculated from the testing data. This High Speed Profiler meets or exceeds the following requirements: ASTM E950 Class 1 profiler specifications, AASHTO PP 51-02 and Texas test method TEX 1001-S. The texture specifications of the Profiler include:

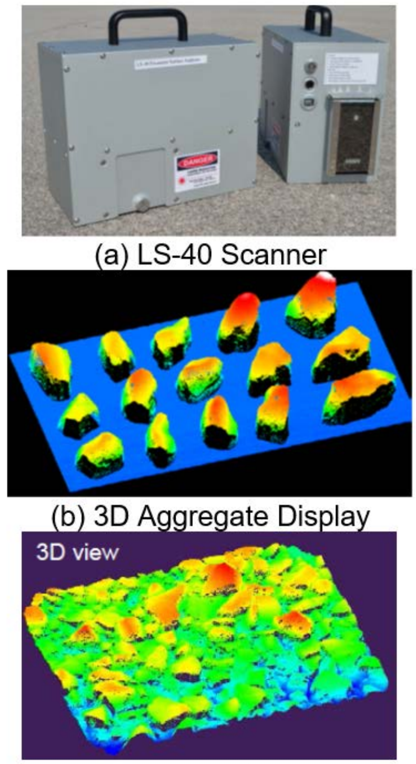
- Capable of collecting measurements at speeds between 25 and 65 mph
- Laser height sensor with a range of 180 mm and a resolution of 0.045 mm
- Horizontal distance measured with an optical encoder that has a resolution of 1.2 mm

- Pavement elevation sampling rate 62,500 samples per second
- Profile wavelength down to 0.5 mm

Figure 2.2 AMES 8300 Survey Pro Profiler

2.3 LS-40 3D Surface Analyzer

The 3D surface measurement and analysis device, named LS-40 Portable 3D Surface Analyzer (Figure 2.3), which scans a 4.25” by 6” or 10” areas and produces a high resolution (0.01mm) digital surface structure with an intensity image and a surface depth related range image. LS-40 provides the data to calculate mean profile depth (MPD) by processing thousands of profiles over the entire scanned surface according to ASTM-1845 specifications, with optional processing modules of measuring other surface features, such as aggregate form factor, angularity calculation based on multiple contour measurements, and micro-texture indicators, such as Slope Variance (SV) and Root Mean Square (RMS). LS-40 can be not only used in the laboratory, but also be placed on a localized pavement surface area in the field to collect 2048 times 5120 cloud points at ultra-high resolution of 0.01mm (0.0004 inches).



(a) LS-40 Scanner

(b) 3D Aggregate Display

(c) 3D Pavement Surface View

Figure 2.3. LS-40 3D Surface Analyzer

2.4 SurPRO 3500 Walking Profiler

SurPRO comes from words "Surface" & "Profiler", which is a rolling surface profiler used for a large-scale of applications. It is used on pavements, structures, and runway to collect surface roughness data. SurPRO has been used as the reference device due to its high repeatability and accuracy, and its wheel spacing of 250 mm, 12" and 300 mm support several ASTM Standards. Different sample distance intervals could be selected by user from 0.25" to 12" and unfiltered true elevation profiles could be captured by it. SurPRO 3500 was the result of development under FHWA contract "Improving the Quality of Pavement Profile Measurement - Priority Number One: Reference Device" with new features and improvements tested at several pavements at the MnRoad facility in Minnesota and in Wisconsin at the FHWA-sponsored rodeo in September 2010.

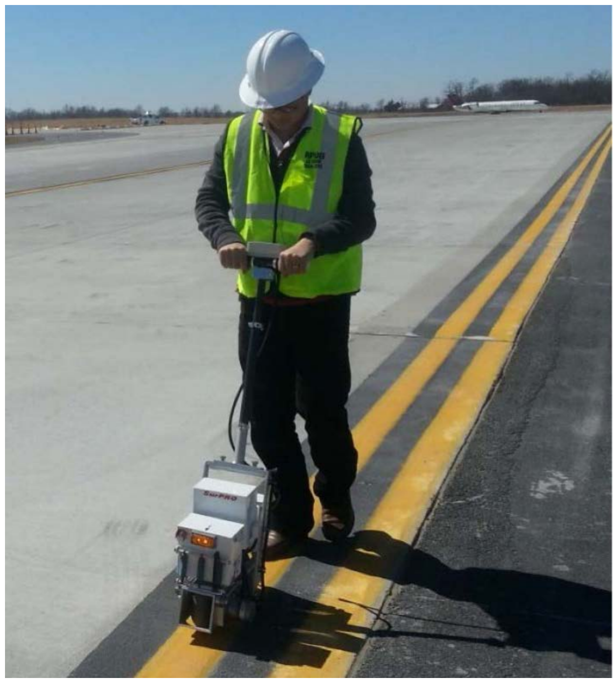


Figure 2.4. SurPRO 3500 Walking Profiler

2.5 Grip Tester (ASTM E274)

Grip tester has been used in recent years by FHWA on many demonstration projects in the United State. It is designed to continuously measure the longitudinal friction along the wheel path operating around the critical slip of an ABS at highway speed across the entire stretch of a road with much lower water consumption, which can provide greater detail about spatial variability and be an ideal option for project and network level friction management. The device has the capability to test at highway speeds (60 mph/100 kph) as well as low speeds (20 mph/32 kph) using a constant water film thickness. The collected data are recorded in 3-ft (0.9 m) intervals by default and can be adjusted by the user. It follows ASTM E274 - 11 "Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire".

Figure 2.5. Grip Tester

2.6 Dynamic Friction Tester (DFT) (ASTM E1911)

This portable instrument is able to measure dynamic coefficient of friction in accordance with the ASTM E1911 specification. DFT has been widely used in friction measurements under various conditions to measure the speed dependency of pavement friction by measuring frictions at various speeds.

Figure 2.6. Dynamic Friction Tester (DFT)

CHAPTER 3 DATA COLLECTION AND ANALYSIS

3.1 Data Collection

The OSU team conducted two rounds of data collection for the UAV runway: the first on September 24^{th}, 2014 and the second on November 23^{th}, 2015 respectively. The location of the UAV airport is shown in Figure 3.1. PaveVision3D Ultra, DFT and LS-40 were utilized for both data collection. SurPRO 3500 was only used in the 2014 data collection for the measurement of pavement roughness and longitudinal profiling immediately after the runway construction. Since the UAV airport is not subject to traffic loading, it is believed that no or minor changes would occur in 2015 in terms of pavement roughness and profiling. The newly acquired Grip Tester was used in the 2015 data collection to measure pavement skid resistance at highway speed.

Figure 3.1. Location of the UAV Runway

Since one pass of PaveVision3D Ultra data collection is only able to cover a full highway lane width (around 13 ft), multiple runs are required to cover the entire extend of the runway (around 60 ft). Therefore, seven longitudinal runs were performed for both data collection in order to survey the entire runway with overlapping between two consecutive runs of data collection. The sequence of the seven longitudinal runs was illustrated in Figure 3.2. The length of the UAV runway is approximately 2400ft, however, only 2100 ft of the runway data were collected considering the acceleration and deceleration distances required for the highway-speed data collection instruments. The multiple runs of data collection can be stitched into a virtual runway with the assistance of computer interface named MHIS3D-Airport developed by the research team. Subsequently, the virtual runway is used to perform preliminary examination of runway surface for distress and defects, conduct PCI analysis, calculate longitudinal profiling indices, measure runway groove dimensions and evaluate groove performance.

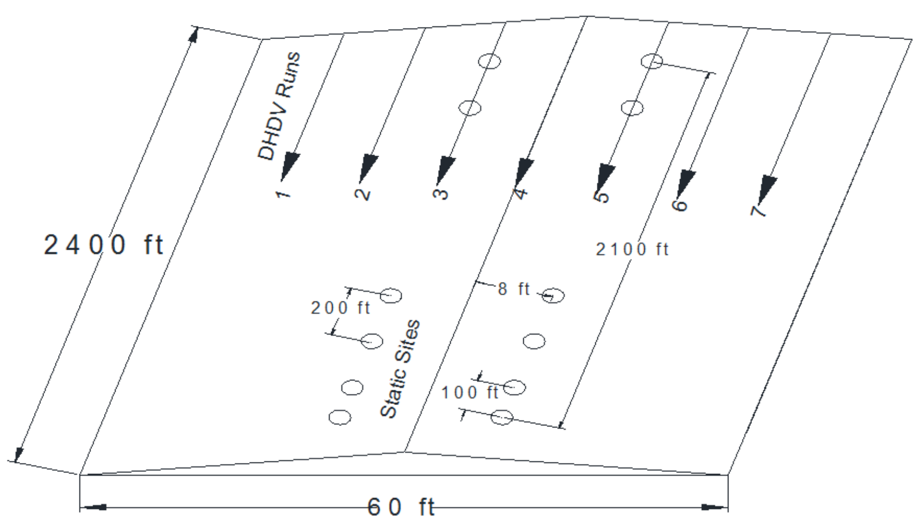


Figure 3.2. Data Collection of UAV Runway

Pavement roughness, texture, and friction data were collected along the two longitudinal paths within the runway keel (Run #3 and Run #5 in Figure 3.2), approximately 8 ft left and right from the centerline of the runway. SurPRO profile data, high-speed AMES texture data, and Grip Tester friction data were collected continuously at highway speed. Two static devices, LS-40 Surface Scanner for texture and DFT for friction, were also used to collect data along these two paths at 200ft interval for the first 10 data points and 100ft interval for the last point with a total of eleven testing points for each path. In addition, eleven transverse profiles were collected using SurPRO 3500 at 200 ft interval for cross slope measurements.

The preliminary analysis results of the two-year data collection are provided below to evaluate the UAV runway surface characteristics:

- Pavement cracking (collected using PaveVision3D Ultra),
- Pavement profile (collected using SurPRO 3500),
- Pavement friction (collected using Grip Tester and DFT),
- Pavement texture (collected using LS-40 and AMES).

3.2 Pavement Cracking

The AASHTO (2013) Designation PP67-10 outlines the procedures for quantifying cracking distresses at the network level and it is incorporated into the PaveVision3D Ultra system. The protocol is designed for fully automated surveys, while minimal human intervention is needed in the data processing. The total cracking length and average cracking width of longitudinal cracking, transverse cracking and pattern cracking are reported for each traffic zone. Figure 3.3 shows an example of automatic cracking detection results in 2D and 3D image for a highway data collection. However, since the UAV runway was newly constructed, no cracking was observed on the pavement surface.

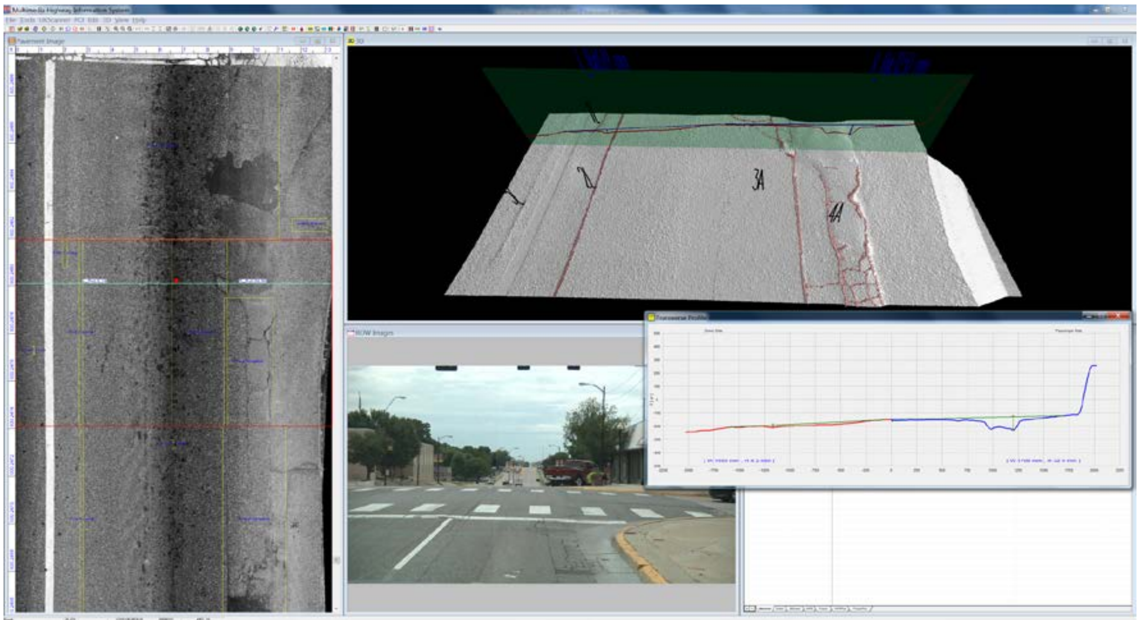


Figure 3.3. Example Highway Cracking Data

3.3 Pavement Roughness (IRI)

Two longitudinal profiles are collected on the airport runway. In total there are 57 in. of height difference along the entire runway with an average longitudinal grade of 0.2%. It should be noted that approximately 300ft of the runway (from 850 ft to 1150 ft) has a close to zero longitudinal slope. International Roughness Index (IRI) is subsequently calculated at 528 ft interval (0.1 miles) from the two longitudinal profile data to evaluate runway roughness condition and the IRI results are plotted in Figure 3.4. The average IRI values are 63.9 in/mi for Run #3, and 63.7 in/mi for Run #5.

In addition, eleven transverse profiles are collected at an interval of 200ft. The centerline of the runway is on average 4.5 in. higher than the two edges with an approximately transverse slop of 1.25%.

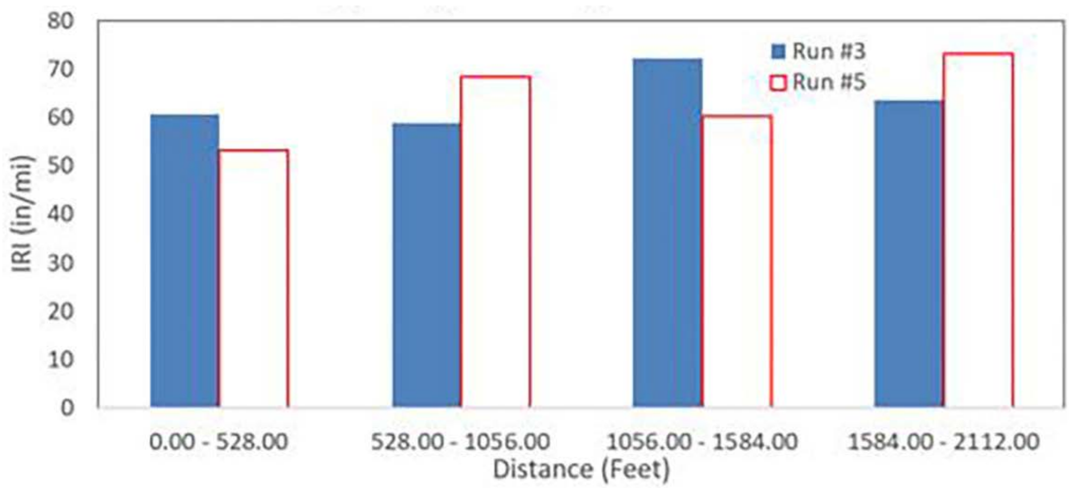


Figure 3.4. Runway Longitudinal Roughness

3.4 Pavement Friction

Skid resistance is the ability of a pavement surface to prevent the loss of tire traction. Pavement friction can be measured statically using DFT or dynamically using Grip Tester or locked-wheel skid testers. In this project, both Grip Tester and DFT were used for the data collection. The Grip Tester friction data were collected continuously along the two paths (Run #3 and Run #5) and reported at 3ft interval, which are shown in Figure 3.5. Results from both testing instruments show that the UAV runway has consistent friction measurements along the entire runway.

The eleven DFT measurements along the two paths are provided in Table 3.1 and plotted in Figure 3.5. It should be noted that the DFT friction numbers measured in 2015 are higher than those in 2014. Paired t-test is performed between the two years of DFT measurements and the results are shown in Table 3.2. The mean DFT friction coefficients are 0.4617 and 0.6171 for 2014 and 2015 respectively. The p-value of the test is 0.00 (less than 0.05), indicating significant difference between these two friction data sets at a 95% confidence interval. A potential reason is that the DFT testing performed in the two years may not be conducted at exactly the same locations since there are no obvious markings (such as centerline) on the runway surface for referencing. In addition, due to the lack of load applications to keep the material flexible (thixotropic or steric hardening), one of the major failure/distress modes of typical HMA mixtures is rapid oxidation and brittleness, which could result in the increase of DFT friction numbers.

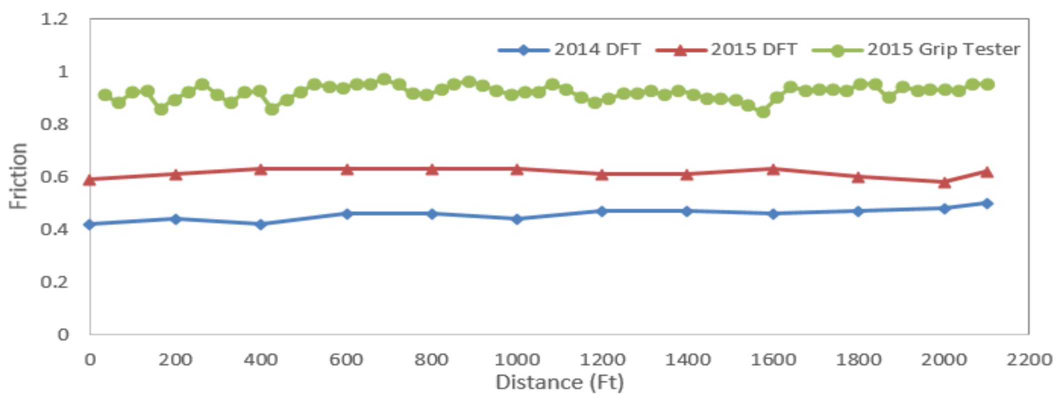
It is also observed that the Grip Tester friction numbers are higher than those collected by DFT. As shown in Figure 3.6, pavement friction coefficient reaches its peak at the critical tire slip. Modern vehicles are engineered to maintain the peak friction using anti-lock braking system (ABS). Grip Tester is designed with 12% tire slip during friction measurements to simulate the ABS technology and acquire friction coefficients close to the peak. On the other hand, DFT measures the friction coefficient between the rubber sliders and pavement surface at target speeds. Therefore, the DFT friction coefficient is measured close to the condition of full sliding (fully-locked). As illustrated in Figure 3.6, friction at full sliding condition is lower than that at critical slip condition. As a result, Grip Tester will generate higher friction coefficients than DFT.

Table 3.1 DFT Friction Results

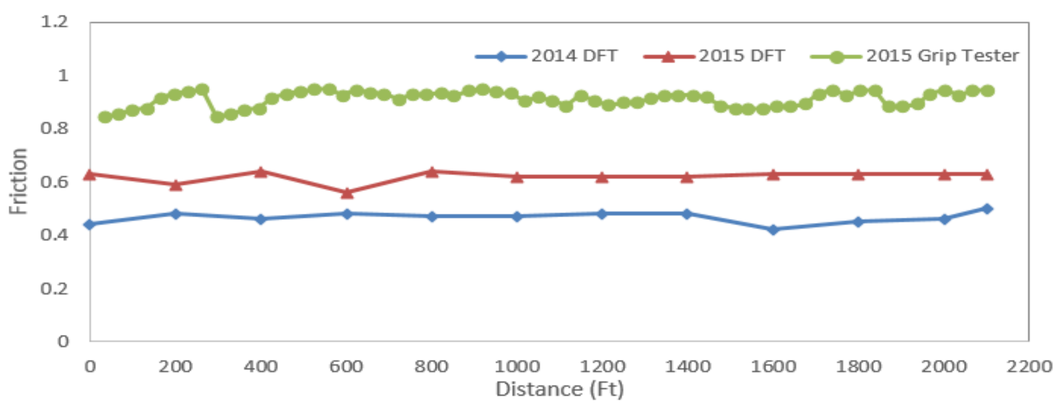
Collection	0 ft	200 ft	400 ft	600 ft	800 ft	1000 ft	1200 ft	1400 ft	1600 ft	1800 ft	2000 ft	2100 ft
2014 Run #3	0.42	0.44	0.42	0.46	0.46	0.44	0.47	0.47	0.46	0.47	0.48	0.5
2014 Run#5	0.44	0.48	0.46	0.48	0.47	0.47	0.48	0.48	0.42	0.45	0.46	0.5
2015 Run #3	0.59	0.61	0.63	0.63	0.63	0.63	0.61	0.61	0.63	0.6	0.58	0.62
2015 Run #5	0.63	0.59	0.64	0.56	0.64	0.62	0.62	0.62	0.63	0.63	0.63	0.63

Table 3.2 T-Test Results for DFT Friction Data

Data Collection	Mean	Variance	df	t-value	p-value	Sign Diff?
2014	0.4617	0.0005				
2015	0.6171	0.0004	23	-22.9132	0	Yes



(a) Run #3



(b) Run #5

Figure 3.5. Runway Friction Results

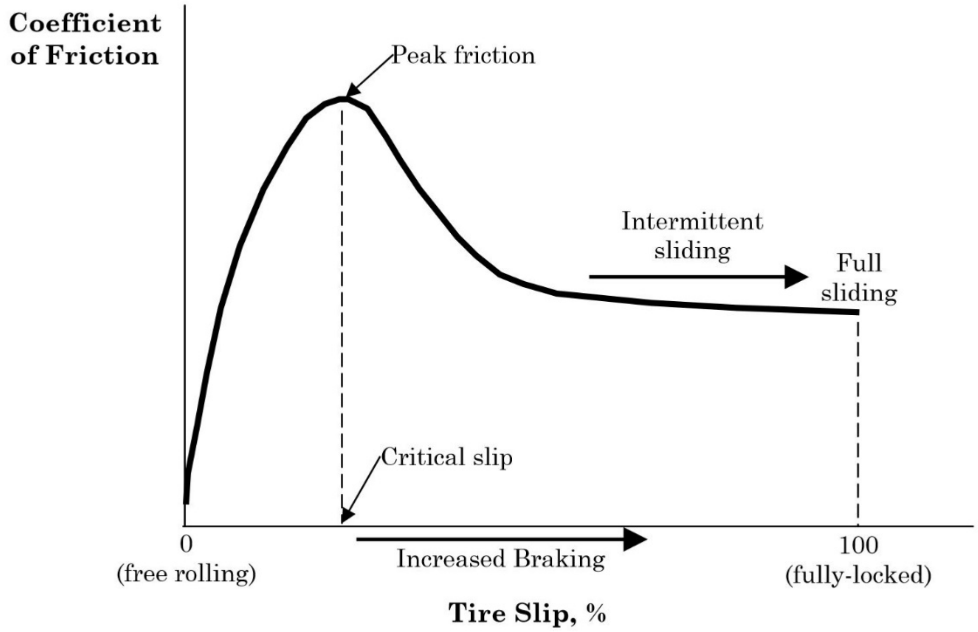


Figure 3.6. Pavement Friction VS Tire Slip (Hall et al., 2009)

3.5 Pavement Macrotexture

The methodologies for texture measurement can be grouped into two categories: static and high-speed methods. The measurement of pavement macrotexture at high-speed was conducted only in 2015 using the AMES high-speed profiler at the two longitudinal paths: Run #3 and Run #5. The texture index in terms of mean profile depth (MPD) is reported at 1 ft interval and the results are shown in Figure 3.7. The average MPD values are 0.175 in. for Runs #3 and 0.156 in. for Run #5.

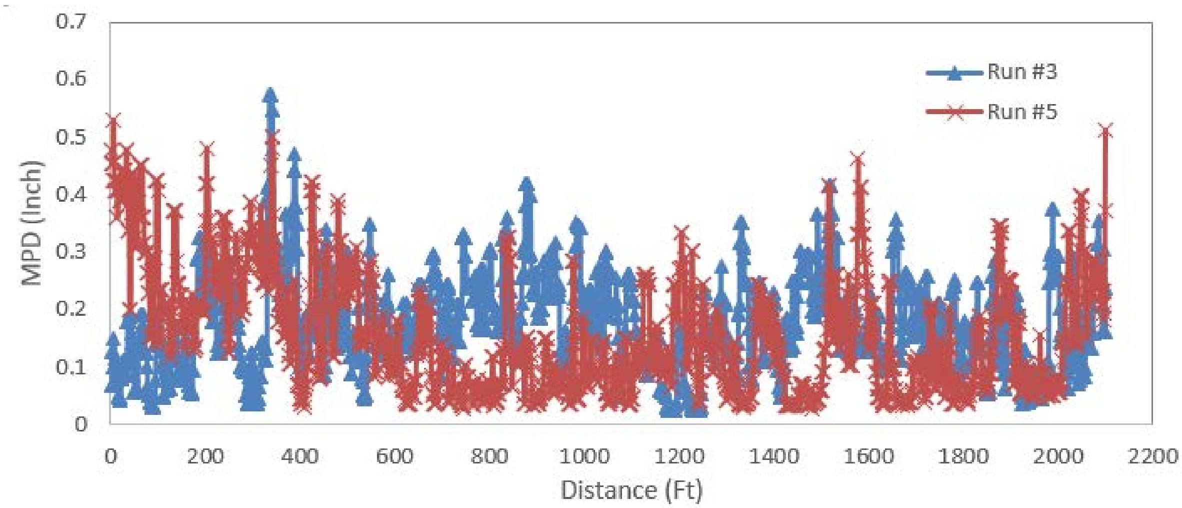


Figure 3.7. AMES MPD Results (2015)

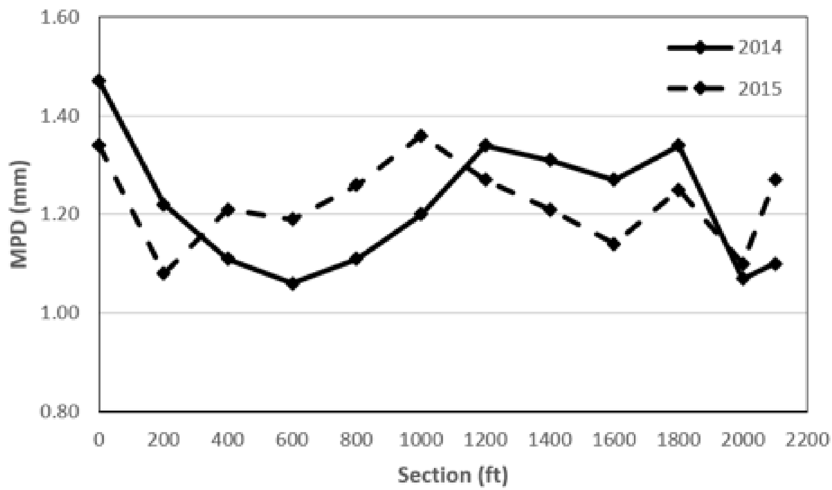
The LS-40 Surface Analyzer was also used for static measurements of MPD at the eleven locations discussed previously, and the LS-40 MPD results are summarized in Table 3.3. The comparison of the two LS-40 MPD data sets from 2014 and 2015 data collection is plotted in Figure 3.8. Similarly, statistical t-test is performed and the results are provided in Table 3.4. The mean LS-40 MPD values are 1.2363 mm and 1.2113 mm in 2014 and 2015 respectively. The p-value is 0.34 indicating that no significant difference between these two MPD data sets at 95% confidence interval.

Table 3.3 T-Test for LS-40 MPD Data

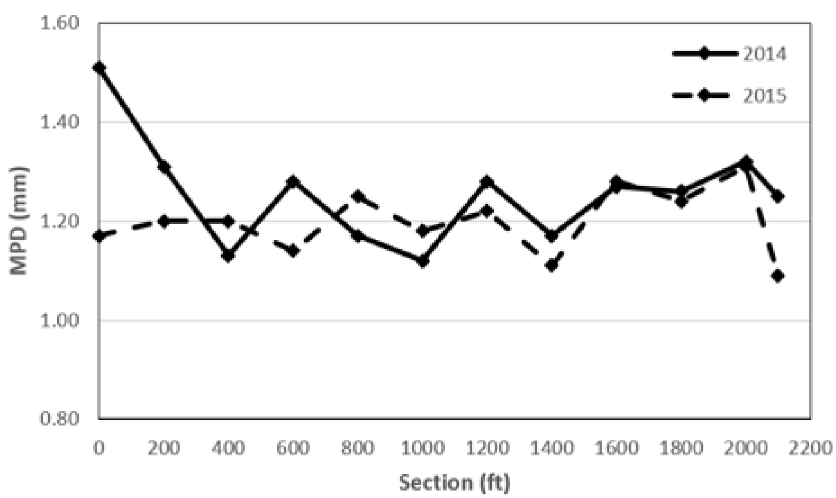
Data Collection	Mean	Variance	df	t-value	p-value	Sign Diff?
2014	1.2363	0.0139				
2015	1.2113	0.0058	23	0.9765	0.34	No

Table 3.4 LS-40 MPD Results

Collection	0 ft	200 ft	400 ft	600 ft	800 ft	1000 ft	1200 ft	1400 ft	1600 ft	1800 ft	2000 ft	2100 ft
2014 Run #3	1.47	1.22	1.11	1.06	1.11	1.2	1.34	1.31	1.27	1.34	1.07	1.1
2014 Run#5	1.51	1.31	1.13	1.28	1.17	1.12	1.28	1.17	1.27	1.26	1.32	1.25
2015 Run #3	1.34	1.08	1.21	1.19	1.26	1.36	1.27	1.21	1.14	1.25	1.1	1.27
2015 Run #5	1.17	1.2	1.2	1.14	1.25	1.18	1.22	1.11	1.28	1.24	1.31	1.09



(a) Run #3



(b) Run #5

Figure 3.8. LS-40 MPD Results

CHAPTER 4 CONCLUSIONS: PART 1

Part 1 of this report documents the two data collection efforts in 2014 and 2015 and subsequently surface characterization for the OSU UAV airport runway. PaveVision3D Ultra, Grip Tester, DFT, AMES high speed profiler, SurPRO 3500 walking profiler, and portable LS-40 3D Surface Analyzer were used for the data collection. Runway roughness, profiling, surface texture, and friction data are analyzed in the report.

Since it is a newly constructed runway surface, no cracking nor noticeable rutting is observed based on the collected 1mm 3D runway surface data. The runway also demonstrates a low surface roughness in terms of IRI values. The mean LS-40 MPD values are 1.2363 mm and 1.2113 mm in 2014 and 2015, and no significant difference of MPD is found based on statistical pared t-test. Since Grip Tester simulates the principle of ABS technology and maintains peak friction during data collection, the measured Grip fiction coefficients are higher than the DFT friction numbers. The average Grip Tester friction coefficient is 0.917 in 2015, which indicates that the runway has a superior skid resistance performance. The DFT friction coefficients in 2014 and 2015 are 0.4617 and 0.6171 respectively.

PART 2

CONSTRUCTION AND EVALUATION OF AN EXPERIMENTAL SHOULDER MIX PLACED

CHAPTER 5 DESCRIPTION OF PROJECT

5.1 Background

The initial plan was to use these project funds to help with the construction of a runway at OSU's Unmanned Aerial Facility (UAV) in Comanche County, Oklahoma. There were numerous issues initially encountered with the beginning of this project and due to work schedules, the runway was completed prior to execution of the contract. However, all constructions funds in this project were withheld for an expansion of the runway. A meeting was held with ODOT and the PI to clear up confusion about the project. It was determined that money was available for placement of an ODOT approved mixture as shoulders for the existing runway.

Construction plans to add shoulders to the existing runway were completed by OSU's consultant. The revised project called for placing an 8 foot wide shoulder on each side of the existing runway for 1,700 to 2,200 linear feet, depending on available funds. The planned shoulder mix consisted of 4 inches of a PG58-28 S4 mix, placed in two lifts, on 6 inches of a Type A aggregate base on a prepared subgrade. A separator fabric was specified between the subgrade and aggregate base. One side of the runway was to receive conventional hot mix asphalt (HMA) with the other side receiving warm mix asphalt (WMA). No bids were received on the original letting. The project went out for rebid in July 2015. Only two bids were received. They were within 7% of each other but exceeded the available project funds by over 250%.

A meeting was held with one of the bidders and suggestions were made to get the project scaled back to fit the project budget. The plans were scaled back to placing an 8-foot wide shoulder on the east side of the existing runway for 2,200 linear feet. The shoulder mix was specified as four inches of a PG58-28 S4 mix with recycled asphalt pavement (RAP), placed in two lifts, meeting the requirements of SP 708-21. Half of the shoulder was specified as HMA, the other half WMA. The aggregate base was deleted and the asphalt mix placed on a prepared subgrade. The plans and bid documents were prepared and sent out to bid in December 2015 and the low bid was by Markwell Paving Company, Inc. The bid was within the funds available for the project.

5.2 Project Description

According to the original construction plans, the existing runway is approximately 2,200 feet long and runs north to south. The pavement section consists of four inches of a Type B mix placed on six inches of aggregate base. It is believed a separator fabric was placed on top of the prepared subgrade prior to placing the aggregate base. The paved section of the runway is 60 feet wide with a 1.5% crown. The runway has a 1.5% cross-slope extending from the centerline of the runway in both directions to the edge of the paved runway and then extends another 30 feet, at the same slope, to drainage ditches that extend the full length of the runway on both sides. This 30 foot wide section is covered in grass. The aggregate base extends approximately 12 to 18 inches beyond the edge of the paved runway but does not extend to the surface. Soil was placed over the extended aggregate base. In other words, the paved runway is built in a “bath-tub” section with any water that enters the aggregate base having no quick way to exit the pavement section as the drainage ditch is 30 feet away. Figure 5.1 shows the existing runway. The drainage ditches along the sides of the runway are not visible in the photo.

Figure 5.1. Existing Runway at OSU's UAV Facility

5.3 Project Mixtures

The new shoulder consisted of two, 2-inch lifts of two different ODOT S-4 mixes. The mixes were the same except one mix was produced using a warm mix technology, foamed asphalt. Both mixes were made using PG58-28 OK asphalt cement and contained just over 25 percent RAP. From the mix design, the binder replacement from the RAP was 26 percent.

In order to better understand the effects of using a softer grade binder (PG 58-28) on recycled mixtures compared to the typically used PG64-22 binder, two additional mixes were sampled from Markwell Paving. The third mix sampled was the same mix as the mixtures used for the shoulder, with the exception that it possibly had slightly less RAP and used a PG64-22 binder. To complete the comparison a fourth mix was sampled from Markwell Paving that used the same aggregates as used in the other three mixes, but contained no RAP and used PG64-22 binder. This would allow comparisons of the RAP mixes with different grades of binders to a virgin mix, a comparison of the impact of a softer binder on the recycled mixes and the effect of the warm mix technology. Table 5.1 shows the mix designations with the ID used in this report to identify the four mixtures.

Table 5.1 Mixtures Evaluated and Mix ID

Mix	Mix ID	Binder	Where Placed	% RAP	Warm Mix Technology
S4	W S-4 R PG58	PG58-28	North half of runway	26	Foam
S4	S-4 R PG58	PG58-28	South half of runway	26	None
S4	S-4 R PG64	PG64-22	Not placed on project	25	None
S4	S-4 PG64	PG64-22	Not placed on project	0	None

CHAPTER 6 CONSTRUCTION

6.1 Subgrade Preparation

The proposed addition of a shoulder to the existing runway consisted of placing two, two-inch lifts of asphalt mix on a compacted subgrade. Subgrade compaction consisted of ODOT type B compaction, a minimum of 95% of the maximum dry density determined in accordance with AASHTO T 99.

As previously described, the existing runway consisted of four inches of a Type B mix placed on six inches of compacted aggregate base. The aggregate base extended approximately 12 to 18 inches beyond the edge of the paved runway. A clay soil with grass vegetation growing on top extended over the aggregate base to the edge of the paved runway. The contractor chose to use a cold planer (milling machine) to excavate the shoulder area to the required four-inch depth and 1.5% cross-slope. Even though construction occurred on August 23, 2016, the material excavated was moist and occasionally came up in chunks. Figure 6.1 shows the cold planer excavating the material to the required depth and cross-slope.

After excavation, the exposed subgrade was compacted with a pneumatic roller. No pumping of the subgrade or soft, wet areas were noted. CEC Materials Testing obtained a sample of the subgrade material on August 23, 2016 to determine the maximum dry density and optimum moisture content in accordance with AASHTO T 99 and to classify the soil in accordance with ASTM D2487, the unified soil classification system. The subgrade soil was classified as brown, lean clay (CL). The soil has a liquid limit (LL) of 32, plastic limit (PL) of 16 and a plasticity index (PI) of 16.

Figure 6.1. Cold Planer Excavating Material for Shoulder Placement

Density tests were performed by CEC on the compacted subgrade on August 25, 2016. Subgrade testing was performed in accordance with AASHTO T 310. All density measurements were performed in direct transmission mode with a probe depth of six inches. The results of the density testing are shown in Table 6.1. All density tests exceeded the required minimum percent compaction of 95%. The maximum dry density and optimum moisture content are 111.8 pcf and 12.4% per AASHTO T 99All in-place moisture content readings were over the AASHTO T 99 optimum moisture content, ranging from 0.3 to 1.6% wet of optimum.

Table 6.1 Results of Testing on Compacted Subgrade

Test	Location	Wet Density (pcf)	Moisture (%)	Dry Density (pcf)	% Compaction
1	350’ from North end, 3’ right	122.7	14	107.6	96.2
2	800’ from North end, 2’ right	123.2	12.7	109.3	97.8
3	1,300’ from North end, 4’ right	121.6	13.6	107	95.7
4	1,850’ from North end, 5’ right	122.2	13.8	107.4	96.1

6.2 Paving Operations

Placement of the asphalt shoulder mixes occurred on August 26, 2016. Rain fell on the site late on the 25th. Prior to beginning paving operations the subgrade was proof rolled with a pneumatic roller. No areas of pumping subgrade were noted but there were several areas of standing water in the excavation. The contractor chose to over excavate these areas and fill the excavation in with 3/4 inch crusher run material as shown in figure 6.2. The crusher run material was compacted with a steel-wheel roller.

Figure 6.2. Over Excavation Area Filled With Crusher Run Material

The new shoulder consisted of two, 2-inch lifts of two different ODOT S-4 mixes. The mixes were the same except one mix was produced using a warm mix technology, foamed asphalt. Both mixes were made using PG58-28 OK asphalt cement and contained just over 25 percent RAP. For this study, the two mixes are identified as W S-4 R PG58 for the warm mix and S-4 R PG58 for the other mix. The mixes were stacked for placement, meaning that both lifts of the conventional S-4 R PG58 mix were placed on the south end on the runway followed by both lifts of the W S-4 R PG58 mix on the north end. Stationing was started at the south end of the runway, sta. 0+00, and proceeded north to the end of the runway at sta. 22+00 for a total length of 2,200 feet.

Construction began on the south end with the S-4 R PG58 mix. Prior to placement of the first lift the edge of the existing runway was tacked as shown in figure 6.3. The first lift of the S-4 R PG58 mix was placed from sta. 0+00 to sta. 11+00. Next, the second lift of the S-4 R PG58 mix was placed from sta. 0+00 to sta. 10+33. A tack coat was placed between the lifts. The first lift of the W S-4 R PG58 mix was then placed from sta. 11+00 to sta. 22+00. The second lift was placed from sta. 10+33 to sta. 22+00. Again, a tack coat was placed between the lifts.

CEC developed a rolling pattern during the first 500 feet of paving the first lift to meet the minimum specified 94 percent compaction, based on the mix design maximum theoretical density. The mix readily compacted, requiring only two vibratory passes and one static pass before the density peaked and/or began to drop. As paving proceeded northward, it was difficult to tell if the subgrade was beginning to pump and/or was the mix began to act as a tender mix. As paving continued to the north several areas were encountered where it appeared the subgrade was pumping. The rolling pattern was checked and was changed to one vibratory and one static pass of the double drum steel wheel roller as two vibratory passes was causing the density of the mix to go down. However, density measurements with the new rolling pattern indicated approximately 94% compaction, based on the mix design maximum theoretical density, was still being achieved. Reducing the vibratory passes seemed to help with pumping of the subgrade. The reduced rolling pattern was followed on the second lift of the S-4 R PG58 mix; however, the same subgrade areas that pumped on the first lift continued to pump on the second lift, increasing in severity.

The W S-4 R PG58 sections were placed using the same rolling patterns as previously described. The initial rolling pattern of two vibratory passes and one static pass was originally used. Pumping of the subgrade was again noticed during placement of the first lift, though not as often nor as severe as on the south end. The second vibratory pass was deleted to help with subgrade pumping. The reduced rolling pattern was followed on the second lift of the warm mix; however, the same subgrade areas that pumped on the first lift continued to pump on the second lift, increasing in severity.

All nuclear density testing used to establish the rolling patterns indicated adequate compaction was being achieved. Results were not reported by CEC as it was intended to come back and cut cores on the completed pavement. Due to the pumping of the subgrade it was later decided by the PI and ODOT to forgo coring of the mixes. A shuttle buggy was used to transfer the mix from the haul trucks to the paver hopper, keeping all unnecessary construction traffic off the subgrade. It should be noted that all haul trucks drove over unpaved ground for a considerable distance to reach the north end of the runway. No pumping or distortion of the ground north of the runway was noted during or after completion of the paving operations. Figure 6.3 shows the paving train used to construct the paved shoulder.

Figure 6.3. Paving Train Placing Shoulder Mix

Warm mix technologies can be used to reduce production temperatures, increase haul distances and improve compaction. Placement temperatures of the mixtures were monitored using a hand help infra-red probe. Measurements were made approximately two feet behind the screed to give an indication of the mix temperature at placement. Measurements were made approximately every 250 feet starting at sta. 1+35. The average results for each lift of each mix are shown in Table 6.2. The mix delivery temperature for each lift of each mix was very consistent, from 270 to 272 °F for the S-4 R PG58 mix and from 244 to 245 °F for the W S-4 R PG58 mix. The warm mix was delivered approximately 25 °F below the conventional mix.

Table 6.2 Mixture Placement Temperatures

Mix	Lift	Station	Average Mix Temperature Behind Screed
S-4 R PG58	First	0+00 to 11+00	272 °F
	Second	0+00 to 10+33	270 °F
W S-4 R PG58	First	11+00 to 22+00	245 °F
	Second	10+33 to 22+00	244 °F

CHAPTER 7 EVALUATION OF PLANT PRODUCED MIXTURES

7.1 Mixtures Evaluated

In order to better understand the effects of using a softer grade binder (PG 58-28) on recycled mixtures compared to the typically used PG64-22 binder, two additional mixes were sampled from Markwell Paving. The two mixtures placed as shoulder mixes at the runway were the same mix, the only difference being the use of a warm mix technology (foam) with one of them. A third mix was sampled from Markwell Paving that was the same as the mixtures used for the shoulder with the exception that it possibly had slightly less RAP and used a PG64-22 binder, designated as an S-4 R PG64 mix. To complete the comparison a fourth mix was sampled from Markwell Paving that used the same aggregates as used in the other three mixes, but contained no RAP and used PG64-22 binder, designated as S-4 PG64. This would allow comparisons of the RAP mixes with different grades of binders to a virgin mix, a comparison of the impact of a softer binder on the recycled mixes and the effect of the warm mix technology. All four mixes were sampled at the plant by Markwell Paving.

Testing of the plant produced mixes included the following:

- Theoretical Maximum Specific Gravity, AASHTO T 209
- Binder content, AASHTO T 308
- Recovered gradations, AASHTO T 30
- Lab molded mix properties (AASHTO R 35) of

- Air Voids (Pa)
- Voids in Mineral Aggregate (VMA)
- Voids Filled with Asphalt (VFA)

- Dynamic modulus, AASHTO TP 79
- Semicircular bend (SCB) test, AASHTO TP 124

Dynamic modulus and SCB testing were performed at the National Center for Asphalt Technology (NCAT) at Auburn University. All other testing was performed at Oklahoma State University.

Table 7.1 shows the results of the asphalt content testing and gradation analysis of the recovered aggregate. The mix design information for the three recycled mixes and the virgin mix are included as well.

Table 7.1 Results of Asphalt Content and Recovered Gradation Analysis

Mix	W S-4 R	S-4 R	S-4 R	S-4 R	S-4	S-4
Binder	PG58-28	PG58-28	PG64-22	Mix design	PG64-22	Mix design
3/4 inch	100	100	100	100	100	100
1/2 inch	94	97	96	93	90	93
3/8 inch	86	90	89	86	83	84
No. 4	70	73	67	70	67	58
No. 8	53	55	48	52	50	43
No. 16	39	40	36	39	37	32
No. 30	32	32	30	29	30	25
No. 50	24	25	24	20	23	16
No. 100	12	13	12	10	11	8
No. 200	6.1	6.9	6.8	5.6	5.8	5.2
Pb (%)	5.6	5.6	5.8	5.1	5.2	5.2

The recovered gradations were within the ODOT tolerances on all sieves for each mix evaluated. The gradations were fairly consistent for mixtures containing RAP. The binder content of the recycled mixtures were all well above the mix design value for the three recycled mixtures. The S-4 R PG64 mixture had 0.2% more binder that the two PG58-28 recycled mixtures.

7.2 Lab Molded Properties

Samples of the plant produced mixes were reduced to testing size in accordance with AASHTO R 47 for determination of maximum specific gravity and lab molded void properties of air voids, VMA and VFA. Maximum specific gravity was determined in accordance with AASHTO T 209. Lab molded samples were heated to 300 °F and compacted in accordance with AASHTO T 312. Lab molded void properties were determined in accordance with AASHTO R 35. The bulk specific gravity of the aggregate, required for VMA calculations, was determined using the ODOT procedure described in Table 708.11 of ODOT’s Standard Specifications. The results are shown in Table 7.2.

The ODOT specification requires that lab molded samples be compacted to 94.5 to 97.4 percent of Gmm at Ndes and 85.5 to 91.5 percent of Gmm at Nini. The S-4 R PG64 mix is the only mix that falls outside this range at Ndes. All mixtures meet the ODOT requirement at Nini, indicating that the mixtures should not be tender. All mixtures exceed the minimum VMA requirement of 14.0%. ODOT does not have a current requirement for VFA but old SHRP mix design requirements were 70-80% for very low traffic and 65-78% for low traffic. The three recycled mixtures have high VFA, caused by the binder contents being 0.4 to 0.6% higher than the mix design value. The binder contents of the three recycled mixes are all above the 0.0 to 0.40 tolerance for full pay and within the 0.41 to 0.80 range for reduced pay. The added binder content could improve durability of the mixtures but harm the stability.

Table 7.2 Lab Molded Properties And ODOT Specification Requirements

Mix	W S-4 R	S-4 R	S-4 R	S-4	ODOT Table 708.11 Requirements
Binder	PG58-28	PG58-28	PG64-22	PG64-22	N/A
Gmm	2.510	2.497	2.507	2.501	N/A
Mix Bulk Specific Gravity, Gmb	2.420	2.423	2.447	2.412	N/A
%Gmm@Ndes	96.4	97.0	97.6	96.4	94.5 - 97.4
%Gmm@Nini	90.3	90.8	91.5	90.5	85.5 - 91.5
Voids in Mineral Aggregate, VMA (%)	15.5	14.9	14.8	14.0	≥ 14.0
Voids Filled Asphalt, VFA (%)	76.8	79.9	83.8	74.3	N/A
Binder Content, Pb (%)	5.6	5.6	5.8	5.2	N/A

N/A: Not Applicable.

7.3 Dynamic Modulus

Dynamic modulus testing was performed by NCAT. Samples were prepared for testing in accordance with AASHTO PP 60-14 (AASHTO, 2014). Three replicates were prepared for each mixture at 7.0 ±0.5 % air voids, after cutting and coring. Dynamic modulus testing was performed in accordance with AASHTO TP 79-15 (AASHTO, 2015a) using a high test temperature of 40 °C for all mixtures. Results are shown in Table 7.3 and presented graphically in figures 7.1, 7.2 and 7.3 for samples tested at 4 °C, 20 °C and 40 °C, respectively.

Table 7.3 Results of Dynamic Modulus Testing (ksi)

Frequency	Temperature	W S-4 R	S-4 R	S-4 R	S-4
Binder		PG58-28	PG58-28	PG64-22	PG64-22
0.1 Hz	4 °C	1,176	1,107	1,346	930
0.1 Hz	20 °C	349	302	400	234
0.1 Hz	40 °C	65	61	73	43
1 Hz	4 °C	1,562	1,468	1,716	1,286
1 Hz	20 °C	580	509	656	409
1 Hz	40 °C	123	114	141	80
10 Hz	4 °C	2,001	1,877	2,199	1,698
10 Hz	20 °C	924	822	1011	689
10 Hz	40 °C	246	228	280	172

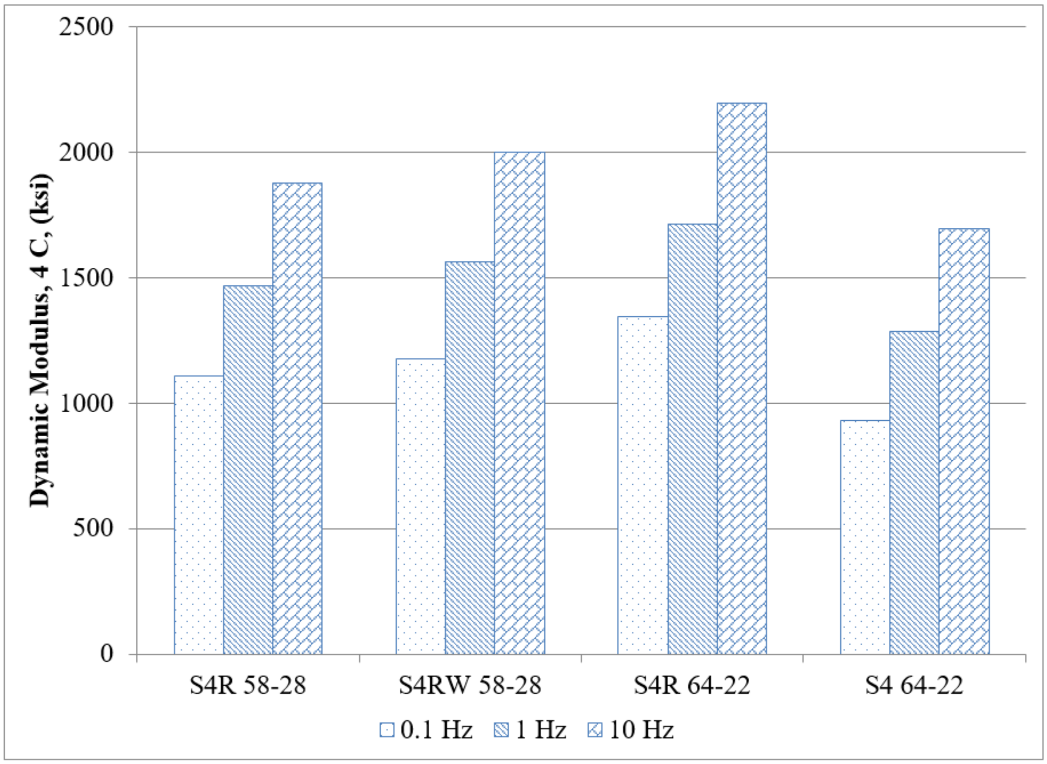


Figure 7.1. Dynamic Modulus Results At 4 °C

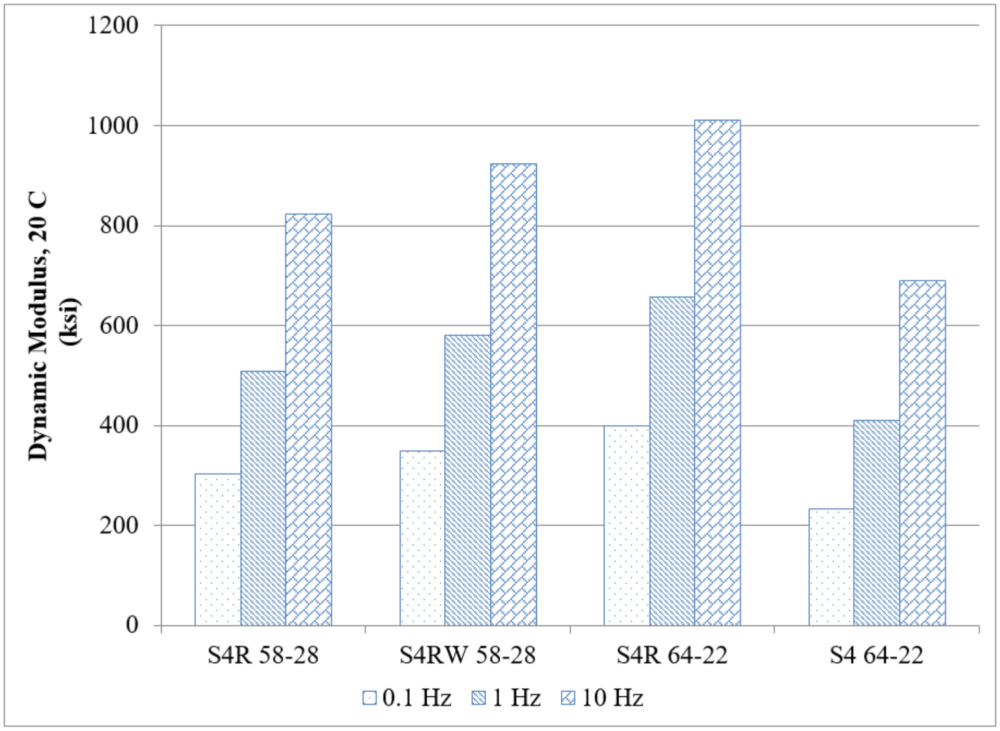


Figure 7.2. Dynamic Modulus at 20 °C

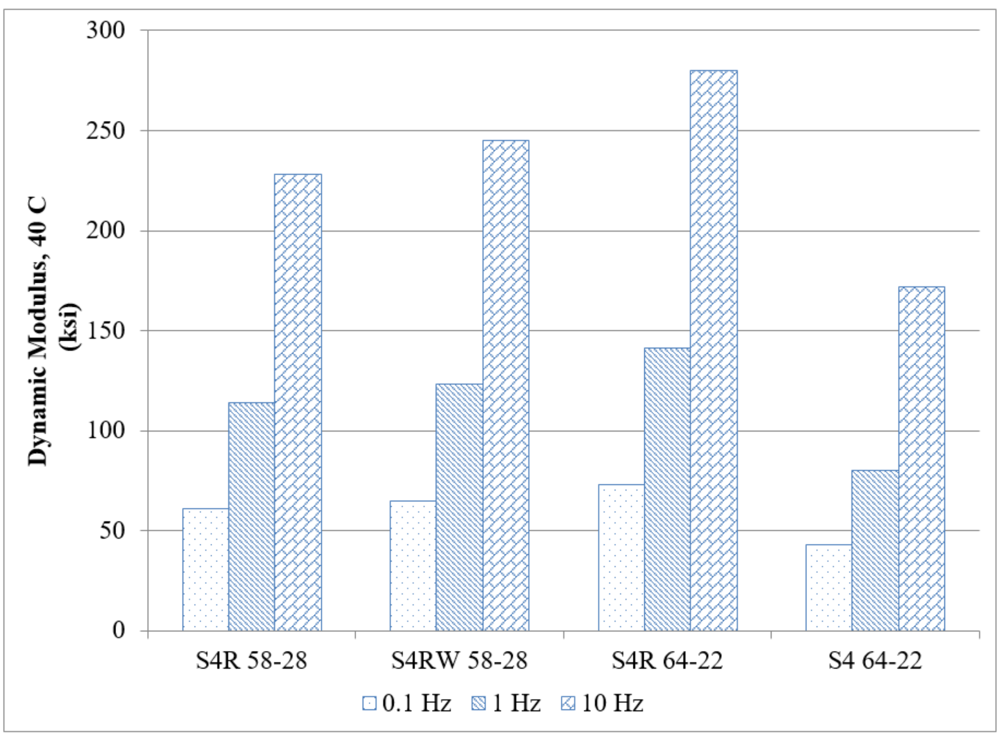


Figure 7.3. Dynamic Modulus, 40 °C

There was a consistent trend in dynamic modulus at all test temperatures and loading frequencies. The presence of RAP should stiffen the mix at all temperatures and frequencies. The S-4 PG64 mix had the lowest modulus of all mixes tested regardless of temperature and frequency. The S-4R PG64 used the same binder as the virgin mix (PG64-22), one grade stiffer than the other two recycled mixes (PG58-28), resulting in the stiffest mix at all test temperatures and frequencies. The two PG58-28 mixes were not able to blend with the existing binder in the RAP to soften the mixes to near the S-4 PG64 mix at the any of the test temperatures evaluated. The use of the PG58-28 binder did result in a less stiff mix than the S-4 R PG64-22 mix at all test temperatures and test frequencies. The use of the warm mix technology did not result in a less stiff mix than the recycled mix made with the same binder. This is not what was expected and not what previous research has shown. The extremely small sample size could be having an adverse effect on the results.

7.4 Semi-Circular Bend Testing

Semicircular bend testing (SCB) was performed by NCAT in accordance with AASHTO TP 124-16 (AASHTO, 2015b). Samples were prepared for testing by reheating the mix to 300 °F and compacting into 160 mm tall gyratory samples. Four SCB samples were obtained from each of the larger 160 mm gyratory samples. Six SCB specimens with an air void content of 7.0 ±0.5 % air voids were tested. Reported test results include fracture energy and an empirical flexibility index (FI). According to AASHTO TP 124 (AASHTO, 2015b), fracture energy is the energy required to create a unit surface area of crack. It is calculated by dividing the work of fracture by the ligament area. The work of fracture is the area under the load versus the load line displacement, or displacement measured in the direction of the applied load. The ligament area is the radius of the sample minus the length of the saw cut multiplied by the thickness of the sample. Flexibility Index is the fracture energy divided by the slope of the post peak load displacement curve measured at the inflection point. The results of the SCB testing are shown in Table 7.4.

Table 7.4 SCB Results

Mix	W S-4 R	S-4 R	S-4 R	S-4
Binder	PG58-28	PG58-28	PG64-22	PG64-22
Fracture Energy (J/m^2)	1,076	1,072	1,117	1,130
Flexibility Index	3.14	2.83	2.41	5.96

According to AASHTO TP 124 (AASHTO, 2015b), a mixture's calculated fracture energy indicates its overall capacity to resist cracking related damage. A mixture with higher fracture energy should be able to better resist stresses and have higher damage resistance. A study by Illinois (Al-Qadi, 2015) was not able to satisfactorily correlate fracture energy with observed performance. However, the general trend of higher fracture being associated with less pavement cracking was observed. The results of the SCB fracture energy tests are shown in figure 7.4.

As shown in figure 7.4, the evaluated mixtures were ranked from highest to lowest fracture energy as the S-4 PG64 mix, the S-4 R PG64 mix, the W S-4 R PG58 mix and the S-4 R PG58 mix. It was expected that the S-4 PG64 mix would have the highest fracture energy, due to the lack of RAP in the mix. However, it was expected that the PG58 mixes would have more fracture energy and better cracking resistance than the S-4 R PG64 mix. It should be noted that the Illinois study (Al-

Qadi, 2015) reported than fracture energy did not correlate to field performance as well as Flexibility Index.

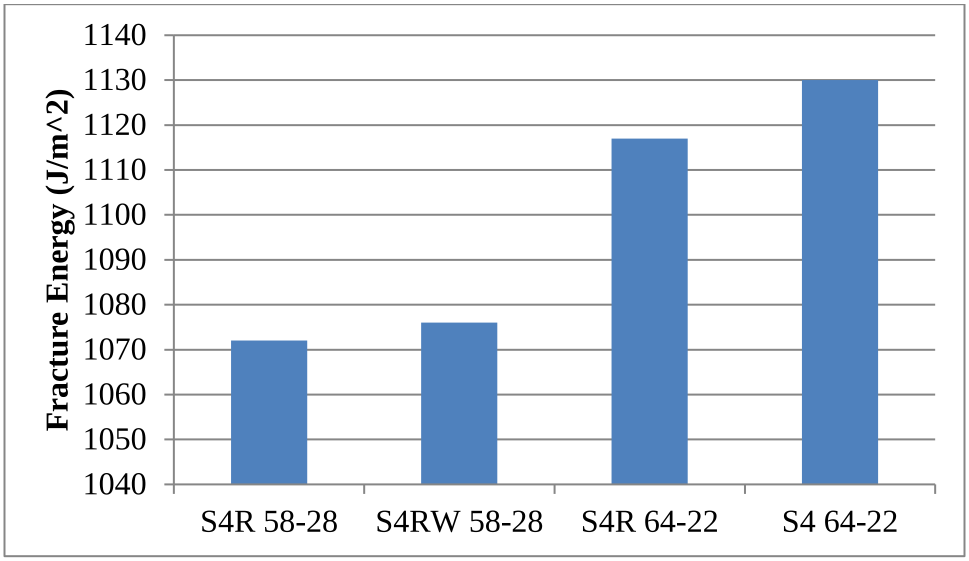


Figure 7.4. SCB Fracture Energy

Two Illinois studies (Al-Qadi, 2015 & Ozer, 2016) recommended using the Flexibility Index from the SCB test to rank the cracking resistance of asphalt mixtures. The study suggested that mixtures with an FI ≤ 2 would be prone to cracking and that mixtures with a FI > 6 would show good cracking resistance. The results of the SCB flexibility index are shown in figure 7.5.

As shown in figure 7.5, the ranking of the mixtures followed the expected trend with the three recycled mixtures having a lower FI than the S-4 PG64 mix. It was expected that the S-4 PG64 mix would have the highest flexibility index, due to the lack of RAP in the mix and that the PG58-28 mixes would have better cracking resistance than the S-4 R PG64 mix. The reduced production temperature of the recycled warm mix (W S-4 R PG58) even had a slightly higher FI than the S-4 R PG58 mix. It should be noted that all of the mixes fell in an intermediate range between 2 and 6. The S-4 PG64 mix had the highest FI, followed by the W S-4 R PG58 mix, the S-4 R PG58 mix, and the S-4 R PG64 mix. It appears the FI test did a better job of ranking the fracture resistance than the fracture energy.

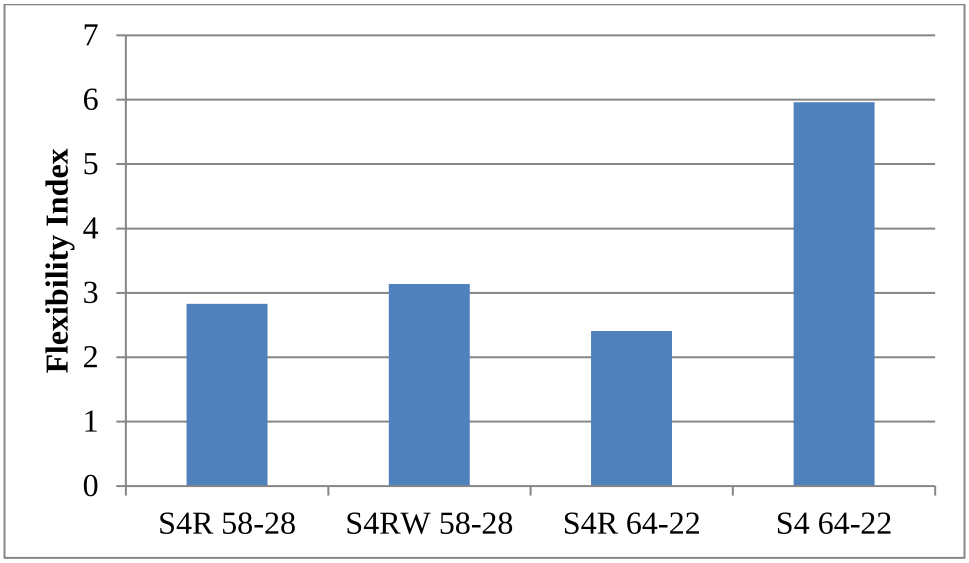


Figure 7.5. SCB Flexibility Index (FI)

CHAPTER 8 CONCLUSIONS: PART 2

8.1 Placement Operations

There were numerous issues associated with placement of the shoulder mix at the UAV facility. These issues included possible tenderness of the mix and pumping of the subgrade. Tenderness of the mix will be addressed in the next section.

It was beyond the scope of this project to determine the exact cause of the pumping of the subgrade. It did rain on the site the night before paving and several wet spots were noted at the edge of the runway. These areas were over excavated by the contractor and replaced with crusher run material at his own expense. It should be noted that pumping did not occur during proof rolling of the subgrade or during compaction of the crusher run material in the over excavated areas. No pumping or distortion of the ground was noted between the road and the north end of the runway where all the haul trucks entered the site.

We were informed that the entire southern portion of the runway had previously been under water back in the spring but that the drainage ditches diverted the water efficiently. However, any rain water that would fall on the runway would sheet flow to the side of the pavement and then be expected to flow through vegetation, that was taller than the edge of the runway, at a 1.5% slope to a drainage ditch approximately 30 feet away. It appears the majority of the water would flow to the edge of the runway, go down into the aggregate base, which extended 12 to 18 inches past the pavement, and sit there as there is no path for the water to drain to the ditches. The runway was basically constructed in a “bathtub” section with little chance for water that got into the aggregate base to drain. We were informed by OSU that the 30 foot length to the drainage ditches and 1.5% slope were required for safety reasons. This would not be the case for a highway pavement.

As paving proceeded north, pumping of the subgrade subsided some but the mix was still very soft. The north half of the runway was constructed using warm mix technology (foam). The mix was still soft and easy to compact, requiring the same roller pattern, but not as soft as the south section. It was impossible to determine if this was due to the mix itself or a drier subgrade to work on.

If these “bath-tub” situations exist on any ODOT roads that are planned for shoulder additions, extra testing to assess the condition of the subgrade should be made or contingencies planned for possible extensive over excavation of soft areas.

8.2 Mixture Evaluation

Although the Nini testing did not indicate the two shoulder mixes were tender, they were right up to the upper specification limit. It could not be determined if the softer binder or the fact that the mixes were produced over the optimum asphalt content caused the possible tender behavior.

The dynamic modulus testing did not completely show the trends that were expected. The results showed that the two recycled mixes with PG58-28 binder, W S-4 R PG58 and S-4 R PG58 would be softer than a recycled mix with PG64-22 binder, S-4 R PG64, but not as soft as a virgin mix with PG64-22 binder, S-4 PG64.

The dynamic modulus testing did not indicate a softer mix for the WMA mix, W S-4 R PG58, compared to the HMA mix, S-4 R PG58.

The flexibility index ranked the cracking resistance of the four mixtures as expected, with the virgin mix, S-4 PG64 having the best cracking resistance followed by the WMA W S-4 R PG58 mix, the HMA S-4 R PG58 mix and then the S-4 R PG64 mix. In order to prevent the use of brittle high binder replacement mixtures, ODOT should consider adoption of a SCB test.

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