FHWA Demonstration Project for

Enhanced Durability of Asphalt Pavements through Increased In-Place Pavement Density

Introduction

The Wisconsin Department of Transportation (WisDOT) was selected to participate in the FHWA Asphalt Mixture Expert Task Group (ETG) study to evaluate increased in-place pavement density. Several means of achieving this increased density were proposed by both industry and the department. The project incorporated eight total test sections, one control and seven experimental to explore various means of altering in-place density. This report details the construction of these eight sections and the respective densities achieved.

Project Location

The eight test sections were constructed as part of Wisconsin State Highway (STH) 21 in Juneau County, between Tomah and Necedah in the central portion of the state (see Figure 1). The total project length was approximately 12 miles (11.876) and was divided into eight nearly equal sections. The pavement design life is 20 years with AADT of 4200 in 2015 growing to an estimated 5000 by 2035, with 25.8% heavy vehicle traffic. Additional traffic details are shown in Table 1.

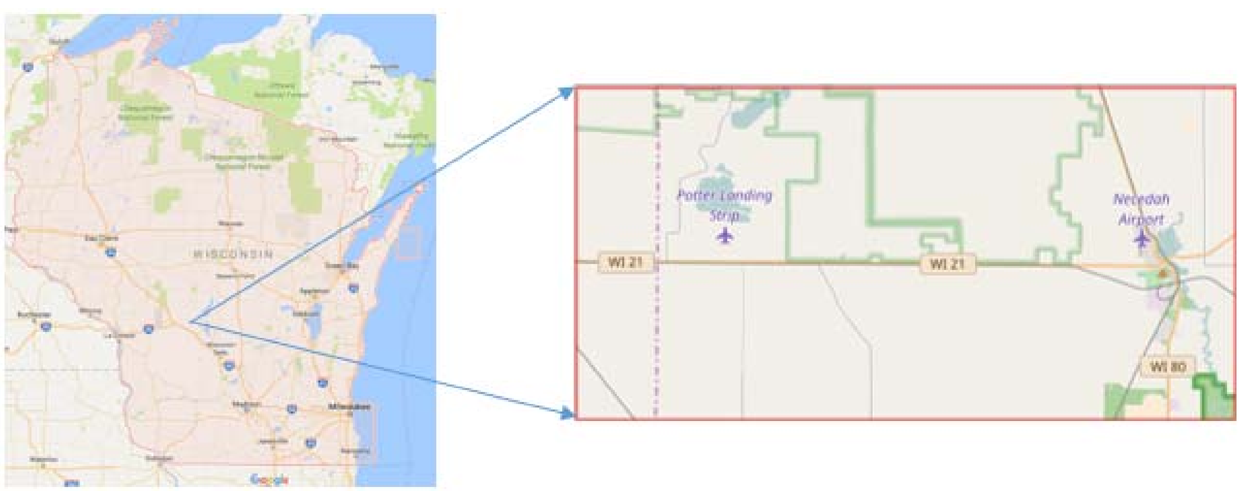

Figure 1: Location of STH 21 project, West County Line to Sheridan St.

Table 1: Design Designation

A.A.D.T.	2015	=	4200
A.A.D.T.	2035	=	5000
D.H.V.		=	869
D.D.		=	62/38
T.		=	25.8
Design Speed		=	60 MPH
ESALS		=	3,500,000

Project Description

The project is a two-lane State Highway, paved as 12 – ft lanes with 5 – ft integral shoulders, between the Monroe/Juneau (West) County Line in the Town of Cutler and Sheridan Street in the Village of Necedah. The existing pavement was eight to nine inches of HMA, some of which was placed over stabilized asphaltic base course. When last rehabilitated in 1994, plans called for an *HV asphalt concrete* pavement overlay of 4 – inch thickness, following a 1 – inch milling of *recycled bituminous* AC overlay from 1983 (placed at 4.5 – inch thickness). The existing pavement showed severe thermal cracking (see Figure 2), calling for a complete reconstruction via full-depth milling/relaying and overlaying with four inches of HMA. The 4 – inch pavement structure was placed in two lifts/layers: a 2.25 – inch 19 mm Lower Layer (Binder Course) and a 1.75 – inch 12.5 mm Upper Layer (Surface Course).

Figure 2: Thermal cracking of existing pavement STH 21 (image courtesy of Google)

The project ran from STA 15+97 to STA 643+00. Between STA 15+97 to STA 492+78, the existing pavement was 9 inches of asphaltic concrete pavement over 5 inches of stabilized asphaltic base course, whereas from STA 492+78 to STA 643+00, the existing pavement was an 8 – inch asphaltic concrete over 7 inches of crushed aggregate base course. Reconstruction produced a 4 – inch HMA over a 6 – inch mill and relay as detailed in Figures 3-5.

The original proposal was to construct test sections approximately 800 feet in length, however, that was revised to divide the nearly 12 mile long project into eight equal test sections approximately 1.5 miles in length. The initial three sections called for constructing the following:

1. *Control Section*: This section will be constructed using standard rolling as done on the majority of the project with a target density minimum of 92.0%.

2. *Additional 1.0-2.0% Density Section*: In this section, an increase in density will be achieved with only additional compactive effort as agreed upon by the advisory team on the project. The advisory team will consist of WisDOT Bureau of Technical Services (BTS) staff along with FHWA representatives. The additional compaction may come from additional roller passes, increasing vibratory efforts, adjusting timing of rolling or other agreed to methods.

3. *Asphalt Binder Regression to 3.0% Voids Section*: This section will be constructed with compaction identical to the Control Section with mix produced with additional Asphalt Binder. Regression interpolates the asphalt content at 3.0% air voids from the mix design. The additional Asphalt Binder will be determined by the engineer.

After additional communication between Industry and Department regarding the demonstration project, the additional initiatives of Warm Mix Asphalt (WMA), compaction aid additive, and varying Nominal Maximum Aggregate Size (NMAS), were added to the scope. With increasing the number of experimental sections, and several requiring adjustments to the mixture at the asphalt plant, 800 feet was no longer deemed appropriate for achieving a representative, consistent production when switching between multiple mixes. The nearly 12 – mile project was divided into eight sections of approximately 1.5 – miles each.

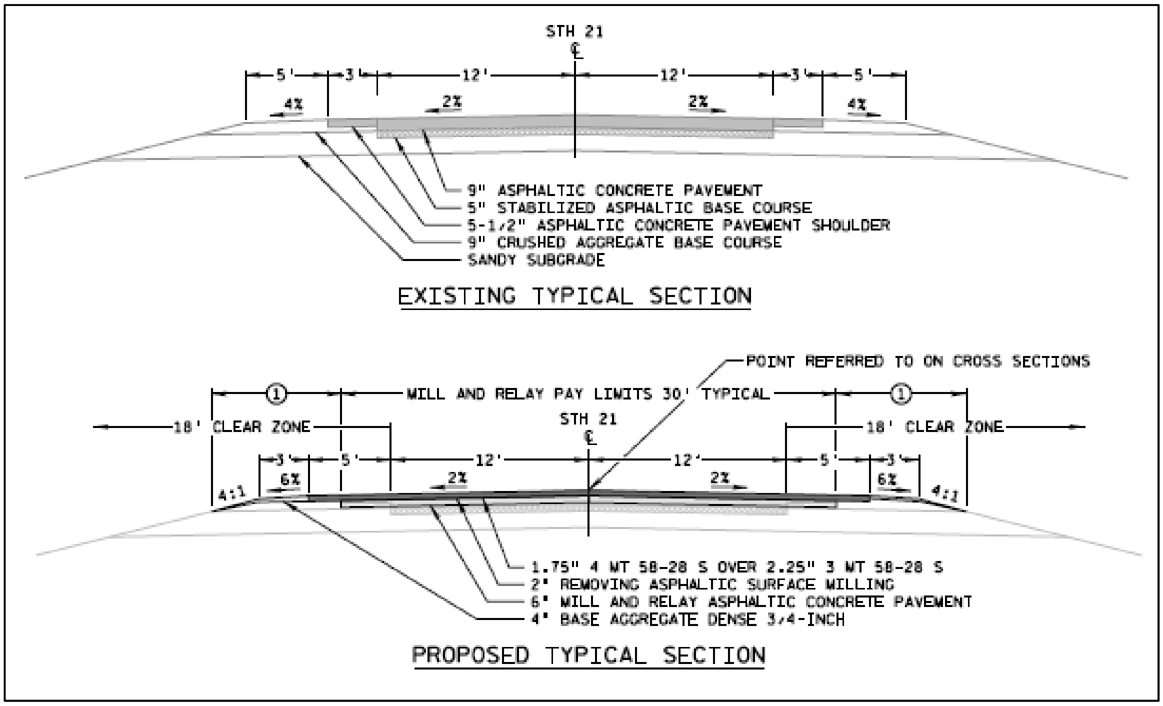

Figure 3: STH 21 reconstruction, Station 15+97 to Station 492+78

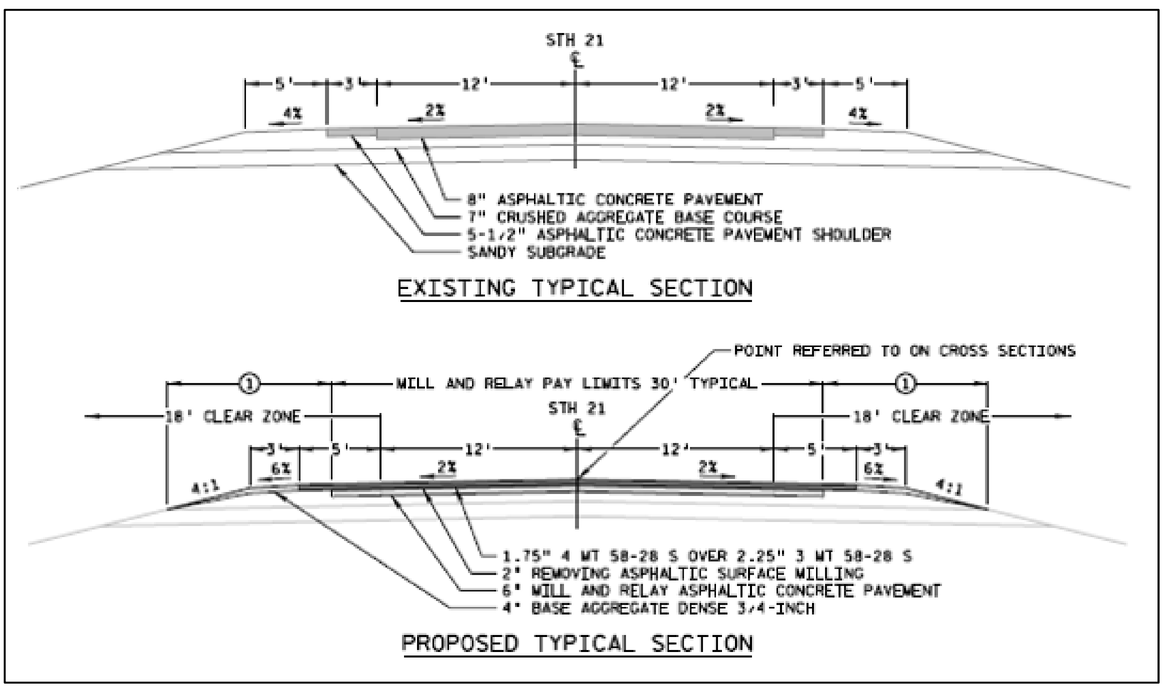

Figure 4: STH 21 reconstruction, Station 492+78 to Station 629+29

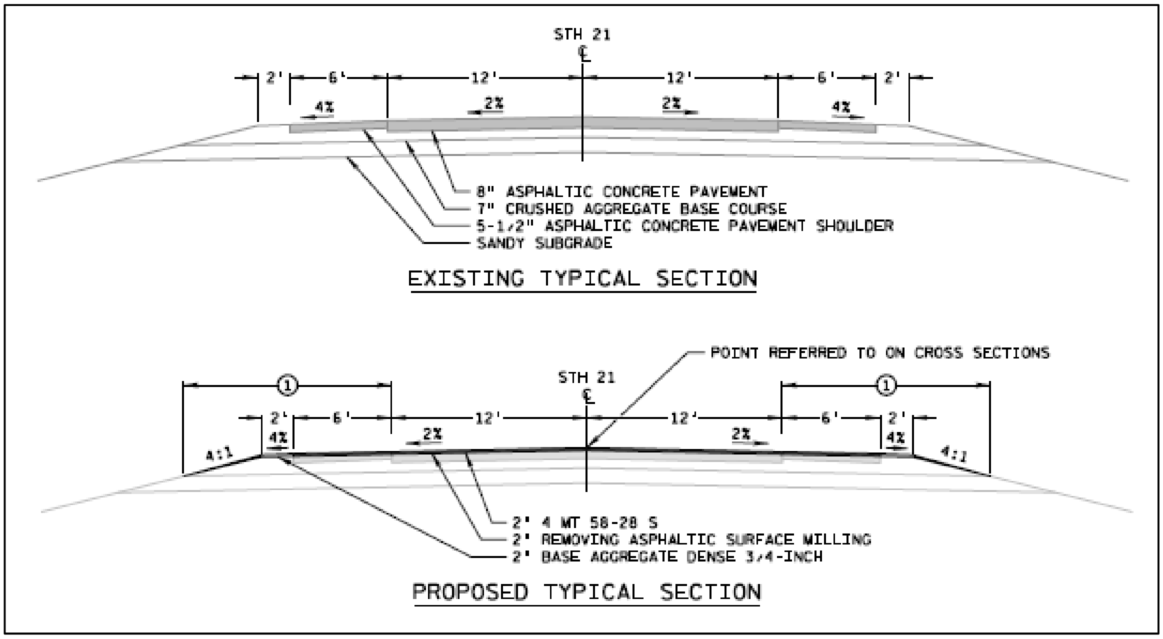

Figure 5: STH 21 reconstruction, Station 629+29 to Station 643+00

The specifics of the eight sections can be seen in Table 2, which includes section descriptions, stationing (and section length), as well as asphalt mix quantities. In addition to the *Control, Additional 1.0-2.0% Density,* and *Asphalt Binder Regression to 3.0% Voids* sections, the expansion now also called for the construction of the following:

4. *3.0% Regressed Voids plus Additional 1.0-2.0% Density section*: In this section, an increased density will be achieved by a combination of additional compactive effort as well as using the mix with an increased asphalt content (corresponding to 3.0% air voids from the mix design). The additional compaction may come from additional roller passes, increasing vibratory efforts, adjusting timing of rolling or other agreed to methods, but is anticipated to be identical to *Section 2* which used increased compactive effort on the control mix.

5. *Warm Mix Asphalt section*: This section is to be constructed with compaction identical to the control section with mix produced as a warm mix asphalt; i.e., the control mix design produced with a warm mix additive and reduced temperatures.

6. *HMA with Compaction Aid Additive section*: This section is to be constructed using the control mix with the addition of the warm mix additive used for the Warm Mix Section and compaction identical to the control; i.e., the warm mix asphalt produced and compacted at temperatures of the *Control* section anticipating that the warm mix additive functions as a compaction aid.

7. *Warm Mix with 3.0% Regressed Air Voids*: In this section, the warm mix asphalt is again used, however, the asphalt content is increased to that corresponding to 3.0% air voids at the design number of gyrations. Once again, identical compaction effort/pattern to the *Control* section is expected.

8. *9.5 mm NMAS max section*: This final section is an alternate mix design utilizing 9.5 mm Nominal Maximum Aggregate Size rather than the 12.5 mm used in aforementioned sections. This also resulted in a slight increase to the asphalt content over the 12.5 mm mix design.

Table 2: Test Section details

Section No.	Section ID	Date Paved	Direction	Tons	Begin Sta.	End Sta.	Length (mi)
1	Control	7/25/2016	WB	2500.00	629+29	564+50	1.23
			EB		SAME		
2	Add'l Roller	7/26/2016	WB	2500.00	564+50	494+60	1.32
			EB		SAME		
3	3% Regression	8/1/2016	WB	2590.22	494+60	422+50	1.35
			EB		SAME		
4	3% + Add'l Roller	8/2/2016	WB	2733.94	422+50	351+60	1.38
			EB		424+25	351+10	
5	WMA	8/8/2016	WB	2645.00	351+60	278+50	1.38
			EB		351+10	278+50	
6	HMA w/ Compaction Aid	8/10/2016	WB	2667.16	278+50	204+25	1.4
			EB		278+50	206+40	
7	WMA @ 3% Regression	8/12/2016	WB	2487.16	204+25	149+50	1.04 (rain)
			EB		206+40	136+20	1.33
8	5 MT HMA (9.5mm)	8/16/2016	WB	2398.50	149+50	79+30	1.32
			EB		136+20	79+30	1.08

Mix Design Properties

The control mix design was a 12.5 mm NMAS, designed for medium traffic level (2 – 8 million ESALS; i.e., 75 gyrations) using a PG 58-28 unmodified binder, and 19% RAP along with virgin aggregate from Central Wisconsin (Town of Westfield) commonly known for sandstone surrounded by deposits of dolomite, shale, basalt and granite. Conventional Superpave mix design methodology was used (with loosened restrictions on aggregate gradation in terms of control sieves with specific restrictions), however, Wisconsin has recently made the change from AASHTO M 320 to AASHTO M 332 which incorporates Multiple Stress Creep Recovery (MSCR) for binder characterization.

Wisconsin nomenclature defines binder designation level as Standard (S), Heavy (H), Very Heavy (V), or Extremely Heavy (E) along with Performance-Grade. The binder used for the control mix design is an S. Wisconsin does not conduct any performance testing for mixture verification as part of standard specification, however, several performance tests were conducted on loose mix collected during this demonstration project. Performance tests included Hamburg Wheel Tracking and Semi-Circular Bending (with Flexibility Index analysis) on mixtures and will be further discussed later in this report. Tables 3 and 4 show the aggregate gradations and mix properties/volumetrics.

Table3: Mix Properties & Mix Design Volumetrics for Control Mix

Mix Properties

Trial #	1	2	3	4	5	6
AC Content (% by Wt)	4.5	5.0	5.5	6.0		5.5
Compaction Level	**Design**	**Design**	**Design**	**Design**		**Max**
Air Voids V_a (%)	6.9	5.5	4.1	2.8		4.2
$\%G_{mm}$ @ N_i	87.5	88.9	89.9	91.1		89.5
$\%G_{mm}$ @ N_{final}	93.1	94.5	95.9	97.2		**96.7**
VMA (%)	16.2	16.0	15.8	15.8		15.2
VFA (%)	57.3	65.7	74.2	82.3		72.3
Density (kg/m^3)	2365	2382	2399	2413		2419
G_{mb}	2.365	2.382	2.399	2.413		2.419
G_{mm}	2.540	2.521	2.501	2.483		**2.501**

Gyrations	
N_i	7
N_d	75
N_m	115

Antistrip
None

Mix Design

Property	Value	Specification
Design P_b	5.5	
Added P_b	4.5	
V_a	4.0	4.0
VMA	15.8	14.5 Minimum
VFA	74.7	70 - 76
G_{mm}	2.501	
G_{mb}	2.401	
P_{be}	5.1	
P_{ba}	0.5	
Dust/Binder Ratio	0.6	0.6 - 1.2
$\%G_{mm}$ @ N_i	90.1	< 89.0 Rec
$\%G_{mm}$ @ N_d	95.8	~ 96.0
$\%G_{mm}$ @ N_m	96.7	98.0 Max
TSR Ratio	84.4	75 Minimum
Rec. Mix Temp.	275-300	

Table 4: Aggregate Gradations for Control Mix JMF

Sieve		Material							Spec	
		Washed CA 13 Bit Rock	Washed CA 14 Bit Rock	3/8" Washed Gravel Man Sand	5/8" Screened Sand	1/4" Washed Man Sand	RAP (5.2%AC)			
		Ratio								
(Std)	(mm)	9%	12%	29%	14%	17%	19%	JMF	Low	High
2"	50	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
1.5"	37.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
1"	25	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
3/4"	19	100.0	100.0	100.0	100.0	100.0	100.0	100.0	---	100
1/2"	12.5	100.0	88.0	100.0	98.0	100.0	99.0	98.1	90	100.0
3/8"	9.5	78.0	38.0	100.0	94.0	100.0	94.0	88.6	---	90
#4	4.75	22.0	3.5	72.0	84.0	97.0	79.0	66.5		
#8	2.36	4.1	1.5	43.0	76.0	76.0	60.0	48.0	28.0	58.0
#16	1.18	3.2	1.3	26.0	71.0	51.0	46.0	35.3		
#30	0.6	2.9	1.2	17.0	55.0	31.0	36.0	25.1		
#50	0.3	2.7	1.1	9.7	22.0	16.0	23.0	13.4		
#100	0.15	2.4	1.0	3.4	6.0	3.7	14.0	5.5		
#200	0.075	2.3	0.9	1.4	2.5	1.8	9.0	3.1	2.0	10.0
Soundness		225-20	225-20	225-133	225-133	225-127			12 Max	
LAR 100/500 Rev		2014	2014	2016	2016	2015			13 & 45 Max	
Crush 1 Face (%)		100.0	100.0	100.0	34.0	100.0	91.0	94.5	75Min	
Crush 2 Face (%)		100.0	100.0	100.0	31.0	100.0	86.0	93.7	60 Min	
Sand Equiv.								86	40 Min	
Flat & Elong (%)		1.1	0.5	1.4	1.2	3.6	0.7	1.0	5 Max	
Fine Agg Ang								43	43 Min	
Water Abs.		0.4	0.2	1.1	0.6	0.2	1.0	0.7		

(Test Methods: D312, T176/D2419, T11/C117, T27/C136, D4791, D5821, T304/C1252, T96/C131, T209/D2041, T166/D2726)

This Control mix design was used as the basic WisDOT approved mix design (mix design 0-250-0160-2016) for *Sections 1 – 7.* For sections 3 & 4 (with the mixture regressed to 3.0% air voids by adding asphalt binder) the asphalt content of the JMF increased from 5.5% (as seen in Table 4) to 5.9% binder. *Sections 5, 6,* and *7* incorporated 0.4% concentration of a WisDOT approved WMA additive and WisDOT requires an additional mix design submission for approval (and may be subject to further verification) for a warm mix asphalt (mix design 0-250-0161-2016). *Section*

7, along with the warm mix additive, incorporated additional asphalt binder. The increased asphalt binder was determined as that required to result in 3.0% air voids at 75 gyrations for the WMA JMF. *Section 8* was a 9.5 mm mix design incorporating millings from STH 21 as the RAP source at 4.9% asphalt content. Tables 5 & 6 detail the aggregate gradations and mix properties/volumetrics for *Section 8*.

Table 5: Mix Properties & Mix Design Volumetrics for 9.5 mm Mix

Mix Properties

Trial #	1	2	3	4	5	6
AC Content (% by Wt)	5.0	5.5	6.0	6.5		5.7
Compaction Level	**Design**	**Design**	**Design**	**Design**		**Max**
Air Voids V_a (%)	5.8	4.4	3.3	2.3		4.1
$\%G_{mm}$ @ N_i	87.4	88.7	89.4	90.8		88.7
$\%G_{mm}$ @ N_{final}	94.2	95.6	96.7	97.7		**96.6**
VMA (%)	15.8	15.7	15.8	16.0		15.2
VFA (%)	63.4	71.9	79.1	85.5		73.2
Density (kg/m^3)	2370	2386	2396	2402		2405
G_{mb}	2.370	2.386	2.396	2.402		2.405
G_{mm}	2.515	2.496	2.477	2.459		**2.489**

Gyrations	
N_i	7
N_d	75
N_m	115

Antistrip
None

Mix Design

Property	Value	Specification
Design P_b	5.7	
Added P_b	5.3	
V_a	4.0	4.0
VMA	15.7	15.5 Minimum
VFA	74.6	70 - 76
G_{mm}	2.489	
G_{mb}	2.389	
P_{be}	5.0	
P_{ba}	0.7	
Dust/Binder Ratio	0.7	0.6 - 1.2
$\%G_{mm}$ @ N_i	88.9	< 89.0 Rec
$\%G_{mm}$ @ N_d	95.9	~ 96.0
$\%G_{mm}$ @ N_m	96.6	98.0 Max
TSR Ratio	82.8	75 Minimum
Rec. Mix Temp.	275-300	

Table 6: Aggregate Gradations for 9.5 mm Mix

Sieve		Material							Spec	
		Washed CA 13 Bit Rock	3/8" Washed Gravel Man Sand	1/4" Washed Man Sand	5/8" Screened Sand	3/8" Bit Agg	RAP (4.9%AC)			
		Ratio								
(Std)	(mm)	16%	17%	35%	10%	14%	8%	JMF	Low	High
2"	50	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
1.5"	37.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
1"	25	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
3/4"	19	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
1/2"	12.5	100.0	100.0	100.0	98.0	100.0	97.0	99.6	---	100.0
3/8"	9.5	78.0	100.0	100.0	94.0	100.0	92.0	95.2	90	100
#4	4.75	22.0	72.0	97.0	84.0	76.0	73.0	74.6	---	90
#8	2.36	4.1	43.0	76.0	76.0	52.0	56.0	53.9	20.0	65.0
#16	1.18	3.2	26.0	51.0	71.0	37.0	44.0	38.6		
#30	0.6	2.9	17.0	31.0	55.0	29.0	36.0	26.6		
#50	0.3	2.7	9.7	16.0	22.0	22.0	24.0	14.9		
#100	0.15	2.4	3.4	3.7	6.0	15.0	14.0	6.1		
#200	0.075	2.3	1.4	1.8	2.5	10.4	9.3	3.7	2.0	10.0
Soundness		225-20	225-133	225-127	225-133	225-133			12 Max	
LAR 100/500 Rev		2014	2016	2015	2016	2016			13 & 45 Max	
Crush 1 Face (%)		100.0	100.0	100.0	34.0	100.0	99.0	95.8	75Min	
Crush 2 Face (%)		100.0	100.0	100.0	31.0	100.0	98.0	95.5	60 Min	
Sand Equiv.								83	40 Min	
Flat & Elong (%)		1.1	1.4	3.6	0.2	2.2	0.3	1.3	5 Max	
Fine Agg Ang			46.5	48.5	38.8	47.2	40.7	45	43 Min	
Water Abs.		0.4	1.1	0.2	0.6	1.8	1.0	0.7		

(Test Methods: D312, T176/D2419, T11/C117, T27/C136, D4791, D5821, T304/C1252, T96/C131, T209/D2041, T166/D2726)

Production

The asphalt mixing plant was a mobile with a dryer/mixer capable of utilizing RAP. Producing at a rate of 250 - 300 tons/hour and committing to one test section per day (approximately 2500 tons) required roughly 10 hours of production. The plant was located approximately 33 miles from the East end (Section 1) of the jobsite, requiring minimum haul times of 40+ minutes for the 36-42 trucks used on any given day. See Table 2 for specific tonnages produced and placed per day/test section. Hot mix was produced at approximately 275 - 300^{o}F and placed at roughly 250-260^{o}F, while warm mix was approximately 245^{o}F and 220^{o}F for production and placement, respectively.

Production Mix Properties

WisDOT samples mixtures from a sampling platform directly from the back of the truck following load-out from the silo at the plant. For this particular contractor, a Department-approved mechanical sampling device was used rather than the conventional flat shovel (with modified edges) to sample material from the truck. This plant – sampling adds a level of complexity when attempting to pair mix properties as measured by WisDOT Bureau of Technical Services, as was the case for this research, with precise locations within a given test section (either for pavement core locations or future monitoring/observation) since mixture production was less than consistent within each test section.

It should be noted that at the time of this report, WisDOT does not routinely verify gradation or asphalt content during mixture production, aside from monitoring QC data as provided by the contractor via control chart data. Also note-worthy, the contactor may report asphalt content in accordance with a method of their choosing. Permissible methods include:

- *by calculation* (which is determined using a WisDOT "bucket extraction" method rather than a centrifuge, and assumes the quantity of P200 material to match JMF),
- *by nuclear gauge reading,* or
- *by inventory* (which may include tank stickings, reading of tank meters, or simply plant settings).

WisDOT requires the following testing frequencies for contracts totaling more than 5000 tons of mix:

Table 7: WisDOT Production Testing Frequency for Contracts over 5000 tons

TOTAL DAILY PLANT PRODUCTION FOR DEPARTMENT CONTRACTS in tons	SAMPLES PER DAY[1]
50 to 600	1
601 to 1500	2
1501 to 2700	3
2701 to 4200	4
greater than 4200	see footnote[2]

[1] Frequencies are for planned production. If production is other than planned, conform to CMM 8-36.
[2] Add a random sample for each additional 1500 tons or fraction of 1500 tons.

Based on this requirement, each test sections was sampled three to four times during production. Because only three mix designs were submitted (control, warm mix asphalt, and 9.5 mm mix), process control and quality control data include multiple test sections grouped together as seen in Figures 6 – 8. For this reason, any average values for specific parameters (i.e., Gmb, Gmm, Va, VMA) become less critical than the individual test results also found in the data sheets presented in Figures 6 – 8.

The lack of consistency within a given section that was eluded to earlier can be seen in individual air void (Va %) readings as well as asphalt content (Tot. % AC). For example, the control mix, expected to be at 4.0% air voids began production below 3% (2.7% as measured on 7/25/2016), which leaves little room for comparing a 3.0% air void regressed mixture. The second and third test results for air voids on the control mix were more favorable for comparison purposes (4.4 & 4.7% air voids, respectively) and therefore loose mix used for production of laboratory specimens for performance testing, as well as cores cut from the test section, targeted this latter material. It should be noted that the asphalt content began below the target of 5.5% with the first measurement at 5.4% and dropped further to 5.3% at the time of the more favorable air void material. This drop in asphalt content is also reflected in the increasing Gmm. However, this decreasing asphalt content poses another issue for comparison purposes.

		Date	Test	G_{mb}	Avg G_{mb}	G_{mm}	Avg G_{mm}	V_a (%)	Avg V_a (%)	VMA (%)	Avg VMA (%)	Tot. % AC	Avg % AC	Cum. Tonnage
	Design			**2.401**		**2.501**		**4.0**		**15.8**		**5.5**		(1000
								Low	High	Low		Low		Tons)
	JMF							**2.7**	**5.3**	**14.0**		**5.2**		
	Warning							**3.0**	**5.0**	**14.3**		**5.3**		
		Blend Change					**New Gsb:**	**2.694**						
Sec. 1		7/25/16	1-1	2.421		2.489		2.7		14.9		5.4		
		Blend Change					**New Gsb:**	**2.693**						
		7/25/16	1-2	2.393		2.504		4.4		15.8		5.3		
		7/25/16	1-3	2.387		2.505		4.7		16.0		5.3		2616.00
Sec. 2		***Blend Change***					**New Gsb:**	**2.694**						
		7/26/16	2-1	2.397	2.400	2.511	2.502	4.5	4.1	15.7	15.6	5.3	5.3	
		7/26/16	2-2	2.401	2.395	2.508	2.507	4.3	4.5	15.6	15.8	5.3	5.3	
		7/26/16	2-3	2.396	2.396	2.510	2.509	4.5	4.5	15.8	15.8	5.3	5.3	5130.00
Sec. 3		8/1/16	3-1	2.421	2.404	2.494	2.506	2.9	4.1	15.1	15.5	5.5	5.3	
		8/1/16	3-2	2.419	2.409	2.485	2.499	2.7	3.6	15.1	15.4	5.5	5.4	
		8/1/16	3-3	2.401	2.409	2.501	2.498	4.0	3.5	15.7	15.4	5.4	5.4	
		8/1/16	3-4	2.396	2.409	2.497	2.494	4.0	3.4	15.9	15.5	5.5	5.5	8090.00
Sec. 4		8/2/16	4-1	2.391	2.402	2.500	2.496	4.3	3.8	16.1	15.7	5.5	5.5	
		Blend Change					**New Gsb:**	**2.694**						
		8/2/16	4-2	2.433	2.405	2.498	2.499	2.6	3.8	14.7	15.6	5.6	5.5	
		Blend Change					**New Gsb:**	**2.694**						
		8/2/16	4-3	2.411	2.408	2.488	2.496	3.1	3.5	15.5	15.6	5.6	5.6	
		8/2/16	4-4	2.405	2.410	2.483	2.492	3.1	3.3	15.7	15.5	5.6	5.6	10920.00
Sec. 6		8/10/16	5-1	2.406	2.414	2.500	2.492	3.7	3.1	15.5	15.4	5.4	5.6	
		8/10/16	5-2	2.395	2.405	2.495	2.491	4.0	3.5	15.9	15.7	5.4	5.5	
		8/10/16	5-3	2.403	2.403	2.506	2.496	4.1	3.7	15.6	15.7	5.4	5.5	
		8/10/16	5-4	2.412	2.404	2.500	2.500	3.5	3.8	15.3	15.6	5.4	5.4	13820.00

Figure 6: Production QC Test Results for Sections 1 – 4, and 6 (Control, Control plus Add'l Roller, 3% Regressed mix, 3% mix plus Add'l Roller, and HMA w/ compaction aid)

By Section 2 (constructed on 07/26/2016), air voids remained reasonable at 4.5, 4.3, and 4.5, respectively, while asphalt content remained lower than JMF at 5.3% AC. This low asphalt content becomes increasingly problematic when moving to Section 3 where regression was used to determine the asphalt content corresponding to 3.0% air voids from the mix design. Recall, this was determined to be approximately 5.9% according to the control mix design trial volumetrics presented earlier. However, during production for section 3 (and even into Section 4), the asphalt content rose from the low 5.3% in Section 2, to between 5.4 and 5.6%. This is most suitably matching the control JMF rather than the increased asphalt required to achieve 3.0% air voids. This mimicking of the control JMF asphalt content is reflected in the air void readings which returned to 4.0% on 08/01/2016 when the asphalt content reached the control JMF target of 5.5% AC, though this was intended to be the Air Void Regression test section.

	Date	Test	G_{mb}	Avg G_{mb}	G_{mm}	Avg G_{mm}	V_a (%)	Avg V_a (%)	VMA (%)	Avg VMA (%)	Tot. % AC	Avg % AC	Cum. Tonnage
Design			**2.401**		**2.501**		**4.0**		**15.8**		**5.5**		(1000
							Low	High	Low		Low		Tons)
JMF							**2.7**	**5.3**	**14.0**		**5.2**		
Warning							**3.0**	**5.0**	**14.3**		**5.3**		
	Blend Change					**New Gsb:**	**2.694**						
Sec. 5	8/8/16	1-1	2.397		2.494		3.9		15.7		5.3		
Sec. 5	8/8/16	1-2	2.378		2.503		5.0		16.4		5.3		
Sec. 5	**Blend Change**					**New Gsb:**	**2.694**						
Sec. 5	8/8/16	1-3	2.405		2.506		4.0		15.5		5.3		2660.00
Sec. 7	8/12/16	2-1	2.415	2.399	2.493	2.499	3.1	4.0	15.3	15.7	5.5	5.4	
Sec. 7	8/12/16	2-2	2.416	2.404	2.486	2.497	2.8	3.7	15.2	15.6	5.5	5.4	
Sec. 7	8/12/16	2-3	2.404	2.410	2.482	2.492	3.1	3.3	15.7	15.4	5.5	5.5	
Sec. 7	8/12/16	2-4	2.402	2.409	2.495	2.489	3.7	3.2	15.8	15.5	5.5	5.5	2970.00

Figure 7: Production QC Test Results for Sections 5 & 7 (WMA & WMA @ 3% Air Voids)

	Date	Test	G_{mb}	Avg G_{mb}	G_{mm}	Avg G_{mm}	V_a (%)	Avg V_a (%)	VMA (%)	Avg VMA (%)	Tot. % AC	Avg % AC	Cum. Tonnage
Design			**2.389**		**2.489**		**4.0**		**15.7**		**5.7**		(1000
							Low	High	Low		Low		Tons)
JMF							**2.7**	**5.3**	**15.0**		**5.4**		
Warning							**3.0**	**5.0**	**15.3**		**5.5**		
	8/16/16	1-1	2.384		2.465		3.3		15.7		5.5		
	8/16/16	1-2	2.373		2.471		4.0		16.1		5.5		
	8/16/16	1-3	2.375		2.480		4.2		16.1		5.6		2480.00

Figure 8: Production QC Test Results for Section 8 (9.5 mm mix)

Such variability can be seen in additional instances to those mentioned here, and this lack of consistency makes the material throughout the entirety of a single test section less than representative. The WisDOT research team looked closely at this data in an attempt to select the most appropriate material to represent the intent of each section.

This interpretation of the data will be discussed further following presentation of field density results in the *Data Selection* section of this report.

Construction

The project was paved between July 25th and August 16th, 2016. The total quantity of mix produced was just over 20,000 tons, with roughly 2500 tons produced for each of the eight sections. Weather was predominantly sunny and warm with overnight lows in the 50-60's and daytime highs in the 80's. More specific weather conditions are presented in Table 8.

Table 8: Daily Weather Conditions during Construction of STH 21

Section	Mix Description	Date Paved	Condition	Temps High/Low
1	Control	07/25/16	Sunny	83/62
2	Add'l Roller	07/26/16	Sunny	87/58
3	3% Regression	08/01/16	Partly Cloudy	83/58
4	3% + Add'l Roller	08/02/16	Sunny	85/63
5	WMA	08/08/16	Sunny	80/56
6	HMA w/ Compaction Aid	08/10/16	Sunny	89/66
7	WMA @ 3%	08/12/16	Cloudy/Rain	79/69
8	5 MT HMA (9.5mm)	08/16/16	Partly Cloudy	83/60

The existing pavement was milled with portions of it relayed to produce the proposed pavement structures presented in this report. A 19 – mm Lower Layer (Binder Course) containing 23% RAP (at an estimated 5.2% AC) was placed as a 2.25 – inch lift at least a day in advance of each Upper Layer (Surface Course) placement. The test section materials described here within are applicable to the Upper Layer within each test section.

When milling operations were underway, the trucks were used to haul any removed millings from the jobsite back to the plant to increase efficiency with hauling both directions. This operation in addition to the haul time in excess of 40 minutes, required the roughly 40 trucks to run continuous. Further detail on the rollers used are as follows:

Sections 1 & 2

- 1st (Knock-down) Roller: Dynapac CC624HF smooth drum roller
- Add’l (Knock-down) Roller: Volvo DV 140B smooth drum roller
- Intermediate Roller: Hamm GRW280 rubber-tire roller
- Finish (Cold) Roller: Case DV210 smooth drum roller

Section 3

- Finish (Cold) Roller: Case DV210 was swapped out for a Case DV240 (with the DV210 to return by Section 6 to be used primarily to focus on joint density)

Section 4

- Add'l Roller: Volvo model was swapped out for Dynapac CC524HF smooth drum roller
    - (Note: this roller is similar to the primary knock-down roller, with a smaller drum width of 1950 mm compared to 2130 mm)

By *Section 6*, the Case DV210 returned to be used primarily for joint density and by *Section 8*, an Ingersoll Rand 17-291 was used for turn lanes and joint. It should be noted that the last two roller exchanges did not impact the areas represented by collected loose mix nor pavement cores. However, this is an indication of the swapping out of various equipment that took place, including the material transfer device.

The project began using a Terex CR662M Shuttle Buggy and RoadTec RP190 paver with a joint heater. For *Section 2*, the shuttle buggy was swapped out for a Weiler E2850 material transfer device, and *Sections 3 and 4* a Cedar Rapids 18118 transfer buggy before returning to the Weiler E2850 material transfer device for *Section 5* onward.

A summary of the number of passes per roller as well as mix temperature at/behind the paver are presented in Table 9.

Table 9: Roller Pattern & Mix Temperatures per Test Section

Section	Mix Description	Direction	Roller Pattern (passes) Steel Wheel	[Add'l Steel]	Rubber Tire	Finish Roller	**Mix Temp @ Paver**
1	Control	WB	5/7	-/-	11	3/4 vibe 2/5 static	
		EB					
2	Add'l Roller	WB	3 vibe 2 static	3 vibe 2 static	11/13	4 vibe 5 static	245
		EB					255
3	3% Regression	WB	6 vibe 1 static	-/-	11/13	4 vibe 5 static	260
		EB					262
4	3% + Add'l Roller	WB	5	5	13	4 vibe 5 static	262
		EB					263
5	WMA	WB	3/4 vibe 2/3 static	-/-	9/11	9 vibe	217
		EB					219
6	HMA w/ Compaction Aid	WB	7	-/-	11/13	9 vibe	257
		EB					252
7	WMA @ 3%	WB	3 vibe 2 static	-/-	11/13	9 vibe	220
		EB					218
8	5 MT HMA (9.5mm)	WB	7	-/-	11/13	4 vibe 3 static	259
		EB					245

Field Density Results

Quality Control Testing

WisDOT conducts a Quality Management Program (QMP) for HMA Pavement Nuclear Density to determine field density results. The program involves both contractor Quality Control (QC) as well as department Quality Verification (QV) testing. All technicians are required to be WisDOT – certified through the state's Highway Technician Certification Program (HTCP).

Nuclear gauges must be calibrated by the manufacturer or an approved calibration service within 12 months of the gauge being used on a WisDOT project. Prior to each construction season, and following any calibration of the gauge, the gauge undergoes calibration verification conducted by WisDOT's Bureau of Technical Services.

Once on site, both the QC and QV teams compare gauges to one another to ensure they are reading within 1.0 lbs/ft^3. This is done by selecting 5 locations on the newly placed mat, on the first day of paving. The *average of the difference* in density between the QC and QV gauges is calculated for the five sites. If this average difference exceeds 1.0 lbs/ft^3, an additional 5 locations are selected and all 10 readings are used to determine the average difference. If still exceeding tolerance, a gauge(s) must be replaced and the process repeated.

After this initial comparison is completed, a department – approved project reference site is selected. This site is not to be disturbed for the duration of the project. Ten density tests are conducted on this reference site with each individual gauge. The average of the 10 readings is recorded to establish the gauge's reference value. This reference site is to be measured at least once per day during paving of the project and compared to the gauge's reference value. This daily check must be within 1.5 lb/ft^3 of the reference value, or an additional 5 tests are conducted after identifying a cause for the deviation. If the 5 – test average is not within 1.5 lb/ft^3 of the reference value, the gauge must be removed from the project. (Gauges are not typically correlated to pavement cores.)

During paving, the QC team is to randomly check mainline density once every 1500 lane feet for each layer/course and target density. The number of tests at each random location is determined by the width of the lane being tested. The required number of tests is as follows:

Table 10: Number of Density Tests Required at Each Station/Location

Lane Width	**No. of Tests**	**Transverse Location**
5 ft or less	1	Random
Greater than 5 ft to 9 ft	2	Random within 2 equal widths
Greater than 9 ft	3	Random within 3 equal widths

Shoulders of 5 feet or less in width, as found on this project, require the following as per WisDOT standard specification:

- If all sublot test results are no more than 3.0 percent below the minimum target density, calculate the daily lot density by averaging all individual test results for the day.
- If a sublot test result is more than 3.0 percent below the target density, the engineer may require the unacceptable material to be removed and replaced with acceptable material or allow the nonconforming material to remain in place with a 50 percent pay reduction.

The limits of unacceptable material, for both driving lane as well as shoulder, are determined by measuring the density of the layer at 50 – foot increments both ahead and behind the point of unacceptable density and at the same offset as the original test site. Tests indicating density more than 3.0 percent below the specified minimum, and further tests taken to determine the limits of an unacceptable area, are excluded from the computations of the sublot and lot densities.

Minimum density requirements are shown in Table 11.

Table 11: WisDOT Minimum Required Density[1]

LOCATION	LAYER	PERCENT OF TARGET MAXIMUM DENSITY		
		MIXTURE TYPE		
		LT and MT	HT	SMA[5]
TRAFFIC LANES[2]	LOWER	91.5[3]	92.0[4]	____
	UPPER	91.5	92.0	____
SIDE ROADS, CROSSOVERS, TURN LANES, & RAMPS	LOWER	91.5[3]	92.0[4]	____
	UPPER	91.5	92.0	____
SHOULDERS & APPURTENANCES	LOWER	89.5	89.5	____
	UPPER	90.5	90.5	____

[1] The table values are for average lot density. If any individual density test result falls more than 3.0 percent below the minimum required target maximum density, the engineer may investigate the acceptability of that material.

[2] Includes parking lanes as determined by the engineer.

[3] Minimum reduced by 2.0 percent for a lower layer constructed directly on crushed aggregate or recycled base courses.

[4] Minimum reduced by 1.0 percent for a lower layer constructed directly on crushed aggregate or recycled base courses.

[5] The minimum required densities for SMA mixtures are determined according to WisDOT Construction & Materials Manual (CMM), Section 8-15.

Quality Verification Testing

The department tests randomly at locations independent of the contractor's QC work. The department performs verification testing at a minimum frequency of 10 percent of the sublots and a minimum of one sublot per mix design. Recall that only 3 mix designs were used to construct the eight test sections (i.e., 12.5 mm HMA, WMA, and 9.5 mm HMA mix designs), therefore the typical QV requirements were less than ideal for this project and did not result in the collection of representative data as QV could have as little as a single density reading per section. This limited data is further addressed on the subsequent *Data Selection* section of this report.

Uncorrelated Data

The following table shows the average lot densities as recorded by the QC technician, for the travel lane/direction corresponding to where the loose mix and pavement cores were collected.

Table 11: Average (Uncorrelated) Densities from QC Nuclear Gauge Readings

Section	Mix Description	Direction	Average Density
1	Control	WB	93.8
2	Add'l Roller	WB	95.5
3	3% Regression	EB	94.9
4	3% + Add'l Roller	WB	95.2
5	WMA	WB	94.4
6	HMA w/ Compaction Aid	WB	94.8
7	WMA @ 3% Air Voids	EB	94.7
8	5 MT HMA (9.5 mm)	EB	93.5

It is worth noting that the limited number of mix designs (as submitted and approved by WisDOT for a mix design identification number) determining testing frequencies, becomes increasingly problematic when accounting for WisDOT guidance for selection of theoretical maximum density (G_{mm}) to be entered into the nuclear gauge, which is then used to calculate the percent

G_{mm}, or relative density, as presented in Table 11. WisDOT requirements for G_{mm} selection are as follows:

- On the first day of paving an HMA mixture design, the target maximum density will be the G_{mm} value indicated on the mix design multiplied by 62.24 lb/ft^3.
- The target maximum density for all other days will be the G_{mm} four-test running average from the end of the previous days' production multiplied by 62.24lb/ft^3. If four tests have not been completed by the end of the first day, the average of the completed G_{mm} test values multiplied by 62.24 lb/ft^3 will be used until a four-point running average is established.

The addition of asphalt binder on certain days, which changes the Gmm from the previous day, results in using the wrong (previous day/section) G_{mm} when collecting data for a given test section.

Data Selection

The contractor QC data clearly provides more complete coverage (ten times the coverage) than department QV measurements. For this reason, the research team began taking a closer look at the QC nuclear density results.

Due to the mismatching of G_{mm} entered into the nuclear gauges for each test section, the data presented in Table 11 is incorrect data and must be adjusted based on the true maximum density of the mix used in each test section. The individual test results used to calculate the four-test average values (as found in the data sheets presented in Figures 6 – 8) were used to select a more accurate G_{mm} for each section. The raw numbers from Table 11 were used in conjunction with the erroneous G_{mm} to back calculate a pavement density which was then compared to the appropriate G_{mm} and used to calculate a new average density per test section as shown in Table 12.

Table 12: Average Densities using QC Gauge and Appropriate Gmm

Section	Mix Description	Direction	Average Density (using approp. Gmm)
1	Control	WB	93.7
2	Add'l Roller	WB	95.1
3	3% Regression	EB	95.7
4	3% + Add'l Roller	WB	95.5
5	WMA	WB	94.2
6	HMA w/ Compaction Aid	WB	94.4
7	WMA @ 3% Air Voids	EB	95.5
8	5 MT HMA (9.5 mm)	EB	94.3

Now, because it is widely accepted that nuclear gauges generally result in differing densities than cores cut from the same pavement, a gauge-to-core correlation was performed to determine any offset or difference between gauge readings and cores for each test section material. When cutting cores from each test section, the QV gauge was used to collect readings at core locations prior to extracting the cores. The QV gauge was selected based on availability/convenience as the QC gauge was occupied monitoring paving operations elsewhere on the project at the time cores were being taken. All footprint testing conducted throughout the project indicated that the QC and QV gauges produced similar results for each test section, therefore the team did not find it unreasonable to use the QV gauge for correlating to cores. The offset between cores and gauge readings was determined per section and used to correct the average densities presented in Table 12. This was done because the QC gauge again provided the most complete coverage and therefore is more representative of the test section as a whole than a single coring location. The offset and corrected density readings for each section are presented in Table 13 and Figure 9.

Table 13: Gauge-to-Core Correlation Offsets & Corrected QC Nuclear Densities

Section	Mix Description	Offset @ cores (%)	Corrected Nuclear Density (% Gmm)
1	Control	-0.2	93.5
2	Add'l Roller	-0.1	95.0
3	3% Regression	-1.1	94.6
4	3% + Add'l Roller	-0.1	95.4
5	WMA	-1.7	92.5
6	HMA w/ Compaction Aid	-1.0	93.4
7	WMA @ 3% Air Voids	-1.5	94.0
8	5 MT HMA (9.5 mm)	0.9	95.2

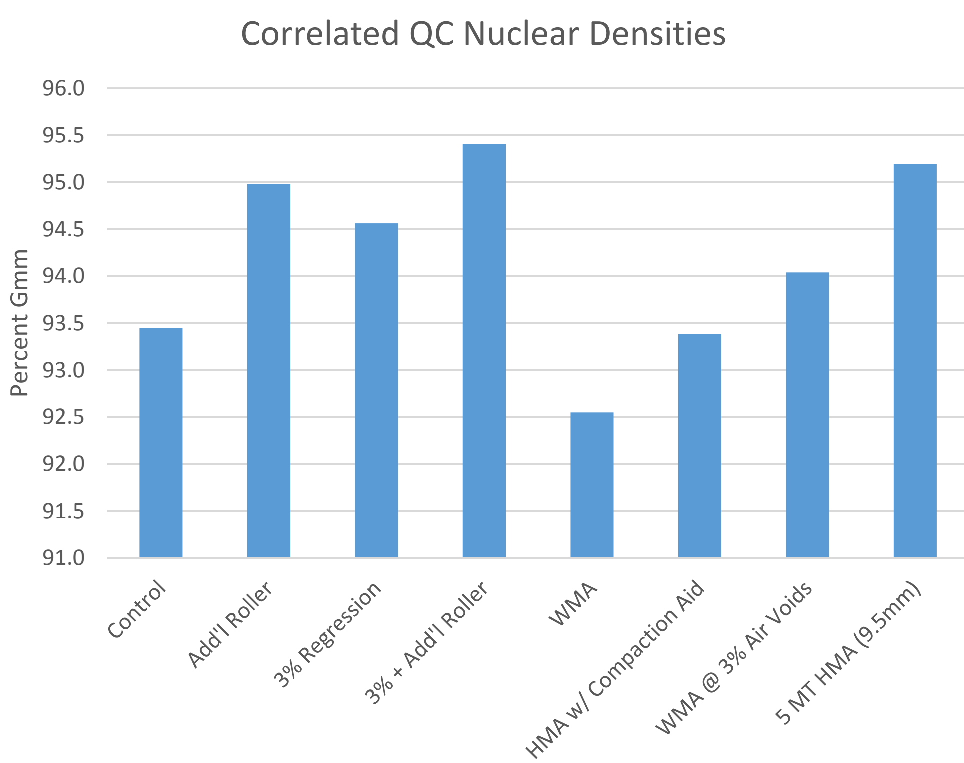

Figure 9: QC Nuclear Density Measurements Correlated using Core Offsets

In summary, an increase in field density was observed when using an additional roller, increasing asphalt content, or a combination of the two. This can be summarized as follows:

Table 14: Change in Field Density by Process

PROCESS	Δ DENSITY %
Additional Roller (*Section 2*)	1.5
3% AV Regression (*Sections 3 & 7*)	1.3
Composite: 3% + Add'l Roller (*Section 4*)	1.9
WMA (*Section 5*)	-1.0
Increased Temp (WMA @ HMA temp, *Section 6*)	0.9
HMA 9.5mm (*Section 8*)	1.7

Figure 10 presents similar information to that tabulated above, but in a graphical format. *Sections 1 – 4* total densities are presented as the density achieved in *Section 1: Control* section, plus any additional density achieved contributed to the altered process for that section, i.e., additional roller for increased compactive effort, increased asphalt content corresponding to the *air void regression* approach of selecting the asphalt content which corresponds to 3.0% air voids at the design number of gyrations, or a combination of additional compactive effort and increased asphalt content.

Sections 5 – 7 all incorporate the WMA mix design and Figure 10 presents the decrease in average section density from the control to *Section 5: WMA* and even the slight decrease from the *Control* section to the *HMA with a compaction aid additive* as found in *Section 6*. *Section 6* mix is really no more than the WMA mix design produced and compacted at the conventional HMA temperatures rather than the WMA temperatures, therefore the increased density achieved in *Section 6* over *Section 5* is displayed as contributed to that increased temperature used on the same mix. The increase in density achieved when adding a roller to *Section 7* is also reflected in Figure 10 information.

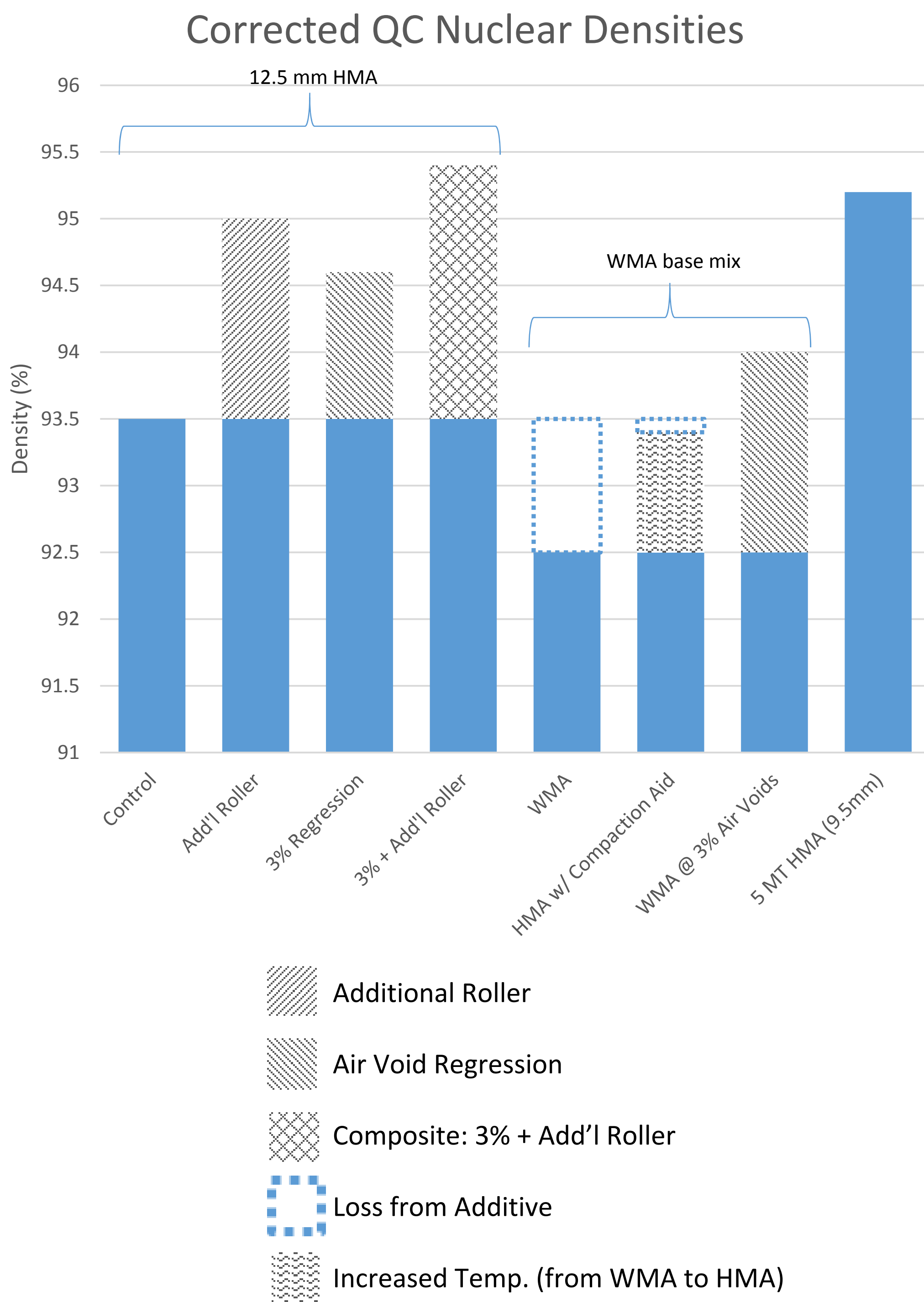

Figure 10: Field Density Results according to Alternate Process

Performance Test Results

Loose mix was collected at the plant (as is typical Wisconsin practice) during the production of the material for each test section. Time of sampling was selected as *representative* for the section based on process control data.

The loose mix was returned to WisDOT's Bureau of Technical Services laboratory for specimen preparation for mixture performance testing. Testing conducted as of the time of this report included Hamburg Wheel Tracking Test data (conducted at 46^{o}C) as well as Semi-Circular Bend (SCB) testing following Illinois Test Procedure 405. Past research has shown that performance test results are sensitive to air voids, i.e., density of the mix. For this reason, all performance test specimens were prepared from loose mix at similar air voids of 7.0 $\pm$ 1.0 percent for HWTT and 7.0 $\pm$ 0.5 percent for SCB, with more specific measured air voids presented in Table 15. (Note, air voids were measured on the fabricated/prepared geometry for each test specimen.) For FI, eight replicates were tested and the high and low discarded before averaging the remaining six replicates. HWTT was conducted using two wheel paths, with maximum rut depth averaged between said wheel paths (AASHTO T 324).

A summary of the results for rut depth and Flexibility Index (FI) as determined from the SCB data are presented in the following table:

Table 15: Test Results for HWTT and FI

Mixture ID	Rut Depth (mm) @ 5000 passes	Ave. Va of HWTT (%)	Flexibility Index	Ave. Va of FI (%)
Control HMA	5.54	7.3	5.9	6.8
3% Va HMA	7.34	7.4	11.4	7.1
WMA	6.44	7.7	6.7	6.6
HMA w/ additive	5.92	6.8	9.9	7.2
3% WMA	8.8	7.0	12.4	7.0
9.5 mm HMA	8	7.5	9.8	6.9

When this data is plotted on the same set of axes, as seen in Figure 11, the criticality of a balanced mix design becomes increasingly apparent as the rut depth and the flexibility index trend together. So, for the test sections/mixes investigated in this study, an increase in asphalt content from the control mix provided greater flexibility, i.e., resistance to cracking as indicated by the Flexibility Index, but this increased asphalt content may also be responsible for the increased rut depth at 5000 passes using the Hamburg Wheel Track Test (HWTT).

Wisconsin has not yet enforced any specific criteria/thresholds for mixture performance, therefore it is difficult to discuss in further detail whether each mix is appropriate for use or not. The data is presented to provide a relative performance of each material for those individuals more familiar with typical results or performance-based specification requirements in their region or state.

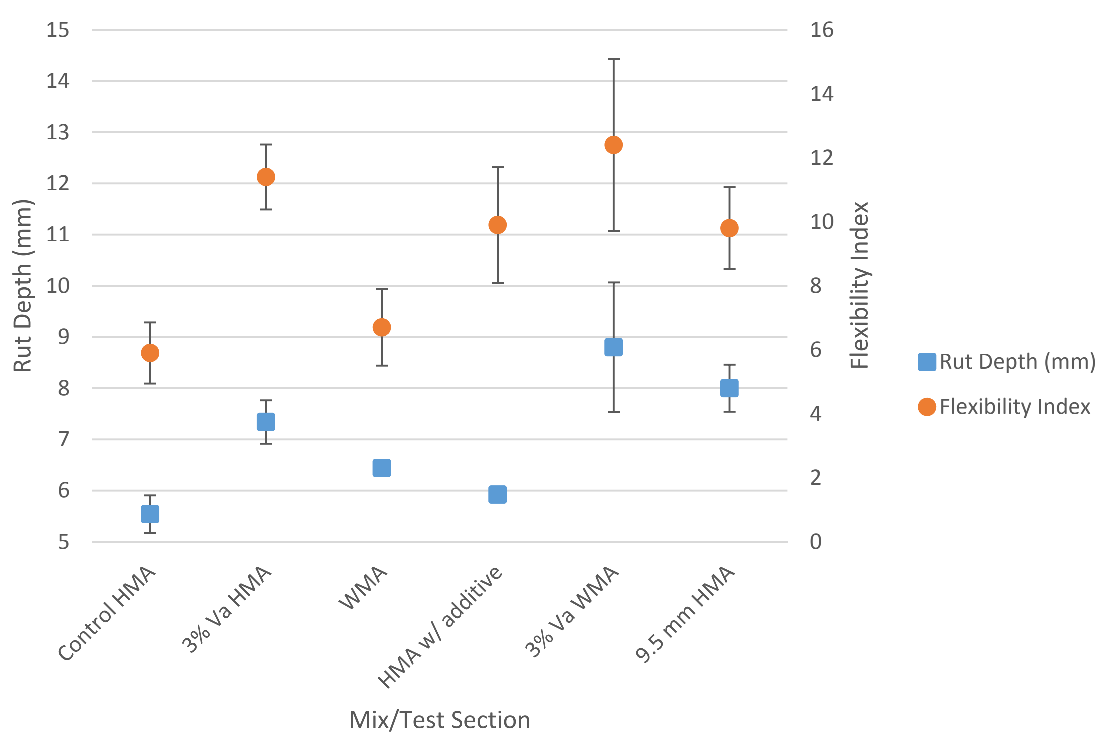

Figure 11: Test Results for HWTT and FI (error bars represent ± one standard deviation)

Summary

From this data, the following preliminary findings can be stated:

- The contractor's typical rolling pattern and compaction effort is capable of exceeding the minimum density requirements of WisDOT (see Table 11 for minimum density requirements)
- An additional roller provides increased densities (approximately 1.5% increase) beyond the contractor's typical compaction used for the control section
- Regressing the control mix to 3% air voids with additional asphalt binder resulted in over 1% increase in density under similar (control) compactive effort
- An additional roller on a 3% air void mix results in further increased densities, showing a cumulative gain from each the additional roller as well as the increased asphalt content
- The WMA resulted in lower densities (1% lower on average) than the control HMA under similar compactive effort, though the WMA still met current WisDOT minimum requirements
- A warm mix additive used in the control HMA as a compaction aid (at contractor's typical dosage rate) resulted in a negligible change in density under similar compaction.
- WMA regressed to 3% air voids resulted in roughly 0.5% increase in density over the control, but as much as 1.5% increase over the standard WMA section.
- Though a different mix design, the smaller NMAS of 9.5 mm not only required an increased optimum asphalt content, but also resulted in more than 1.5% increase in density over the control; nearly matching the increase seen when using both an increased asphalt content and an additional roller on the 12.5 mm control mix, all without using the additional roller on the 9.5 mm section. This resulted in an improved Flexibility Index for the 9.5 mm mix when compared to the control mix, however, the 9.5 mm mix also exhibited a 67% increase in rut depth at 5000 passes.
- An increase in asphalt content, while providing increased flexibility, also correlates with an increased rut depth at a given number of cycles.

Concluding Remarks/Notes:

As the adage states, hindsight is 20/20. If conducting a similar demonstration project again, the research team would make the following suggestions:

- WisDOT BTS staff have increased authority in dictating construction operations in order to maintain a more consistent operation, i.e., compaction pattern, production, equipment, etc
- Break away from monitoring construction using current WisDOT requirements, which would include cutting cores at a frequency determined to be appropriate for this particular project objective

From the data, the following recommendations can be stated as opportunities to address several observations/findings:

- WisDOT should verify asphalt content to not only encourage consistency of said parameter, but asphalt content also influences additional parameters used to monitor consistency and ultimately material acceptability (e.g., Gmm)
- WisDOT should not hesitate to increase asphalt content via *Air Void Regression* for HMA and WMA or call for smaller NMAS mixtures
- The Department should strongly consider moving toward individual density locations to eliminate overlooking problematic areas of lower density caused by averaging
- Strong consideration should be given to increasing testing frequencies, particularly that of QV
- WisDOT minimum density requirements should be increased, especially when averaging for sublots and lots
- A warm mix additive used in a HMA as a compaction aid does not appear to be economically beneficial and should not be encouraged or paid for (based on the limited dataset of this study)