



# MnROAD Study of RAP and Fractionated RAP

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# **MnROAD Study of RAP and Fractionated RAP**

## **Final Report**

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## Executive Summary

This report summarizes lessons learned about the field and laboratory performance of the Recycled Asphalt Pavement (RAP) and Fractionated Recycled Asphalt Pavement (FRAP) test cells at the Minnesota Road Research project (MnROAD) between 2008 and 2012. Project scope included: developing specifications, construction, and field and laboratory evaluation of materials.

The laboratory evaluation of materials and mixtures included dynamic modulus testing and fracture testing of the asphalt mixtures as well as complex shear modulus testing of corresponding extracted asphalt binders. The major outcomes were:

- Extracted binder grades met or exceeded design values.
- Fracture energy from semicircular bend (SCB) data was useful in categorizing expected mixture performance in terms of recycle percentage.
- The process of fractionating the RAP into two different sizes resulted in less blending than anticipated as determined from qualitative comparisons of dynamic modulus tests to their counterpart predicted using the Hirsch model.
- Pavement performance evaluations at MnROAD has shown that the RAP, FRAP, and other mixtures performed very well after four years of service. During the fourth year of service, several non-overlay study cells began to exhibit some transverse cracking.
- Additional cracking is anticipated as the pavements are continually exposed to typical low temperature conditions.

# **Chapter 1: Introduction**

Local Road Research Board (LRRB) project number 864, Minnesota State Planning and Research project number MPR 06-(022) study titled, “Recycled Asphalt Pavement: MnROAD Study of Fractionated RAP” was sponsored by the Minnesota Local Road Research Board, the Federal Highway Administration, and the Minnesota Department of Transportation. The 5-year project included: construction, annual monitoring, testing, and reporting for 11 test cells. This report summarizes lessons learned about the performance of the Recycled Asphalt Pavement (RAP) and Fractionated Recycled Asphalt Pavement (FRAP) test cells at the Minnesota Road Research Project (MnROAD) between 2008 and 2012.

## ***Objectives***

In this study, field performance monitoring and a number of laboratory tests were performed for mixtures that contained various percentages of RAP. The objective was to quantify differences between mixtures with future field performance in mind while evaluating individual characteristics.

Observations and conclusions are based on laboratory testing and four years of seasonal field performance monitoring and analysis.



## Chapter 2: Lessons Learned

### *Summary – Testing and Performance*

The laboratory evaluation of materials and mixtures included dynamic modulus testing and fracture testing of the asphalt mixtures as well as complex shear modulus testing of corresponding extracted asphalt binders. Modulus tests were evaluated to determine the amount of blending that occurred between the RAP and virgin binders. The major outcomes from the testing and evaluation were:

- Extracted binder grades met or exceeded design values.
- Fracture energy from semicircular bend (SCB) data was useful in categorizing expected mixture performance in terms of recycle percentage. Mixtures having greater amounts of RAP were shown to be prone to fracture at relatively higher temperatures. This has been partially validated by the field performance of 0, 20, and 30% RAP test cells during their fourth year of service.
- The process of fractionating the RAP into two different sizes actually resulted in less blending than anticipated for a dryer-drum plant process. This was determined from qualitative comparisons of dynamic modulus tests to their counterpart predicted modulus curves calculated from binder test data via the Hirsch model (1). Each of the predicted values was stiffer than those measured in the laboratory. This may be due to use of model parameters better suited to general, rather than project specific, materials.
- The mixtures using PG 58-28 binders exhibited better blending than those with PG 58-34 binders. It is possible that the mixtures using polymer modified (PG 58-34) binders were not sufficiently heated at the plant to activate the binder in the RAP enough to blend with the virgin binder.
- The warm mix asphalt mixture showed the least amount of RAP and virgin binder blending of any of the mixtures at MnROAD. The combination of polymer modified binder and lower production temperatures due to the warm mix technology hindered blending.
- The authors recommend investigating other mixtures from Minnesota in a similar fashion to determine if the lack of blending in the mixtures studied was an isolated incident or if it is typical. If it is found that many other mixtures around the state also suffer from a lack of virgin and RAP binder blending, the question then arises as to the influence on the long term performance of these pavements in the field.

Despite the concerns raised by the laboratory evaluation, pavement performance evaluations at MnROAD has shown that the RAP, FRAP, and other mixtures performed very well after four years of service. If durability of the mixtures is questionable, the pavement failures would be expected within a relatively short time frame. Transverse cracking is one of the primary distress types in Minnesota, and is generally caused by the effects of low temperatures. During the fourth year of service, several non-overlay study cells began to exhibit some transverse cracking even though winter conditions had been unusually mild. Additional cracking is anticipated as the pavements are continually exposed to typical low temperature conditions. Monitoring will

continue and notable results will be reported along on the RAP task report web page that can be accessed at [http://www.dot.state.mn.us/mnroad/lrrb\\_864\\_rap.html](http://www.dot.state.mn.us/mnroad/lrrb_864_rap.html)

The following are observations and comparisons that can be made about pavement performance thus far using the indices available at MnROAD. Details and discussion for each point can be found in Task 1, Task 2, Task 4, and Task 7.

### Visual Distress Survey

Similarities in cracking distress for non-overlay test cells indicate that RAP percentage and fractionation did not greatly influence low temperature performance after four years of service. 46% of the total underlying transverse cracks reflected through the Cell 15 warm mix overlay.

- Cell 16 warm mix developed two transverse cracks, both directly over a lysimeter installed in the base layer.
- Cell 20 and 21 (HMA+30% RAP) developed 2 transverse cracks during service year four.
- Cell 21 (HMA+30% FRAP) and Cell 23 (WMA+20% RAP) developed low severity longitudinal cracks during service year four.
- None of the other cells have shown any visible signs of cracking distress.

### Ride

Mix type and recycle percentage did not influence ride performance more than seasonal variation and base material type.

- Cells 4 and 15 were heavily influenced by seasonal variation (spring-thaw). In both cases the bituminous rests directly on clay subgrade without an aggregate base layer.
- Cells with similar construction histories currently have similar IRI deterioration rates. The ride decay of the cells within the recycled unbound base and FRAP/low temperature cracking groups appears to be very similar. Cell 15 has the highest decay value, followed by Cells 4, 17, and 23. Cells 20 – 22 and 24 exhibited the smallest decline in IRI.

### Rutting

- Rutting was measured, and no significant values, defined as excess of 0.5 in., were measured except for the case of Cell 18. Rutting statistics for Cell 18 show values for the median and maximum were equal to 0.28 and 0.64 in.

### FWD

- The study cells appear to have been constructed with similar structural characteristics, and have maintained their relative deflection relationships through year four.
- During the fourth year of FWD testing, the average deflection basin AREA factor had changed by merely 5%, indicating that overall pavement structural performance had changed very little since construction.

## Noise and Friction

Four years of data show that all test segments currently generate more tire-pavement noise and have somewhat lower friction characteristics than after construction. Seasonal effects are the greatest influence on on-board sound intensity (OBSI) measurements.

- The FRAP Cells (21 and 22) had an initially higher OBSI reading; however Cell 15 has since surpassed the FRAP cells, which are behaving similar to the other study cells.
- All study cells appear to be affected by the seasonal variations in relatively the same way.
- With the exception of Cell 24, the study cells appear to have fairly uniform frictional characteristics with current FN 40 Ribbed near 50 for both driving and passing lanes.
- Portions of Cell 24 received fog seal applications from 2008 through 2012, and FN 40 values were very low. Minimum values occurred in 2010.

### ***Study Cells at MnROAD***

MnROAD is operated by the Minnesota Department of Transportation (MnDOT). MnROAD consists of two unique road segments located parallel to Interstate 94 (2).

During 2008 three FRAP and eight RAP test cells were constructed as part of the MnROAD Phase II Reconstruction (2,3). FRAP was produced by splitting RAP on the 0.25-in. screen. The split materials were added to mixtures according to designs performed by the paving contractor. Ten of the 500-ft test cells were constructed on the mainline (ML), or interstate portion of MnROAD. Test cells and experimental variables are presented in Table 1.

Bituminous designs were based on MnDOT's 2008 Gyrotory Design Specifications. All mixtures had a maximum aggregate size of  $\frac{3}{4}$ -in. (19.0 mm), and a nominal maximum aggregate size of  $\frac{1}{2}$ -in. (12.5 mm). HMA and WMA designations denote Hot Mix Asphalt and Evotherm 3G Warm Mix Asphalt. The mixtures designs were based on 3 to < 10 million ESAL traffic. Wear course mixtures had target air voids of 4.0% and non-wear mixtures had a target air voids content of 3.0%. Test section construction was part of state project 8680-157. The FRAP experiment was carried out in Cells 20 – 22, and the RAP experiment was performed in Cells 4, 15, 16, 17, 18, 19, 23, and 24. The source of all RAP material was the original MnROAD Phase I surface that was constructed in 1993 (1). Additional details can be found in the MnROAD Phase II construction report (4) and other Investigation 864 task reports (1,3,4,5,6, and 7).

Boundaries, descriptions, and layout for the respective test cells are shown in (2). The asphalt, aggregate base, subbase, and granular fill layers were of identical thickness in Cells 19 through 23, but base material types were somewhat variable within this part of MnROAD. See reference (3) for additional construction details.

**Table 1: Bituminous Mixture Designation and Experimental Variables**

<b>Cell</b>	<b>Type</b>	<b>Binder PG</b>	<b>% RAP</b>	<b>Thickness</b>	<b>Notes</b>
4	HMA	64-34	0%	3 in.	
15	WMA	58-34	20%	3 <sup>(a)</sup> in.	Paved in continuous process.
16	WMA	58-34	20%	5 in.	
17	WMA	58-34	20%	5 in.	
18	WMA	58-34	20%	5 in.	
19	WMA	58-34	20%	5 in.	
20	HMA	58-28	30%	5 in.	FRAP experiment
21	HMA + FRAP	58-28	30%	5 in.	
22	HMA + FRAP	58-34	30%	5 in.	
23	WMA	58-34	20%	5 in.	
24	HMA	58-34	20%	3 in.	Same mix as Cell 23
<sup>(a)</sup> 3-in. overlay of badly cracked HMA.					

## Chapter 3: Laboratory Testing Highlights

The laboratory evaluation of MnROAD Phase II mixtures and binders included the tests listed below. Virgin and extracted binder **performance grade testing** results are shown in Table 2 and Table 3. Refer to Marasteanu et al. (8) for additional testing details on direct and double-edge notched tension testing as well as details and comments on relaxation modulus.

- The Dynamic Shear Rheometer (DSR)
- The Bending Beam Rheometer (BBR)
- Direct Tension Test (DT)
- The Double-Edge Notched Tension Test (DENT)
- The Indirect Tension Test (IDT)
- The Semi-Circular Bend Test (SCB)
- Dynamic Modulus ( $|E^*|$ )

**Table 2: Low PG Grades of Asphalt Binders °C**

MnDOT ID	Study Cells	Tested Low Temp Grade	Specified Low Temp Grade
AC 746	20, 21	-31.3	-28
AC 747	22	-37.1	-34
AC 748	15-19, 23	-37.3	-34

**Table 3: High PG Grade from Construction Samples °C**

MnDOT ID	Sample	AC %	Tested DSR Grade	Specified High Temp Grade
BC09-0014	WMA Wear 58-34	5.04	68.1	58
BC09-0015	WMA Non-Wear 58-34	5.60	67.9	58
BC08-0116	30% RAP 58-28 Wear	5.32	64.7	58
BC08-0117	30% RAP 58-28 Non-Wear	5.58	64.2	58
BC08-0118	30% FRAP 58-28 Wear	5.25	64.9	58
BC08-0119	30% FRAP 58-28 Non-Wear	5.51	63.6	58
BC08-0120	30% FRAP 58-34 Wear	5.49	61.5	58
BC08-0121	30% FRAP 58-34 Non-Wear	5.64	62.9	58
BC08-0123	WMA Control 58-34	5.45	60.6	58
BC08-0124	Crushed millings	6.01	69.0	None
BC08-0125	Fine RAP	6.76	71.2	None
BC08-0126	Coarse RAP	4.89	69.9	None

The average **IDT tensile strengths** and range of values produced obtained within the group of Fractionated/RAP/dense-graded mixtures were similar. The creep compliance of each mixture was generated using AASHTO T322. Details were presented in (1).

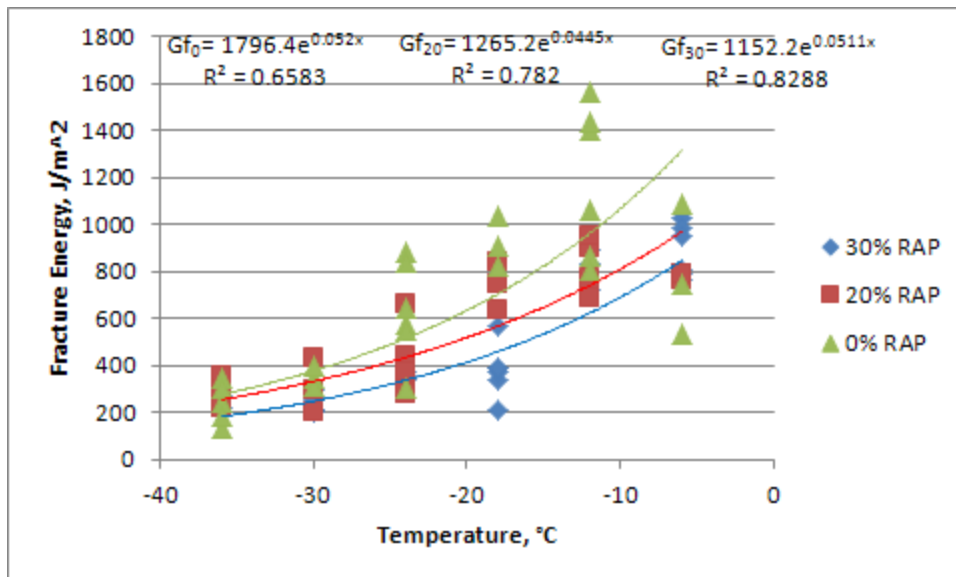
**Semi-Circular Bend** testing was performed on mixture specimens at three temperatures (°C):

- (PG +10) - 12
- (PG +10)
- (PG +10) + 12

Fracture energy (Gf) was calculated according to RILEM TC 50-FMC. Refer to Marasteanu et al. (8) for additional testing details. Fracture toughness ( $K_{IC}$ ) was also calculated from SCB test results.

Materials were grouped by recycle percentage for analysis of fracture energy and toughness. Figure 1 shows best-fit curves developed to differentiate fracture energy performance trends. Several items were apparent in the analyses:

- Three distinct fracture energy trends emerged for mixtures that were grouped by recycle percentage.
- Although the toughness performance trends overlapped for various recycle percentages, the 20% recycle group (composed of PG58-34 WMA and HMA mixtures) maintained relatively lower toughness values throughout the low temperature performance range. This indicates potential for the 20% RAP mixtures to stand out during the field performance phase; however, no remarkable field performance trends were observed.
  - 0% recycled toughness group overlapped with the 20% and 30% groups near the test temperature extremes.
  - 0% and 30% toughness performance equalized at approximately -30 °C. This result was partly verified by the similar cracking performance of the non-overlay cells during the first three years of service.



**Figure 1: Fracture Energy of MnROAD Mixtures at 0, 20, and 30% RAP**

Table 4 presents fracture energy as functions of the best-fit equations from Figure 1. The equations were used to compare the temperatures where groups attained fracture energy

performance levels of 350 to 400 J/m<sup>2</sup>; values where field performance would potentially be affected. It is apparent that for this set of mixtures, higher RAP percentages are prone to fracture at relatively higher temperatures.

**Table 4: Predicted Fracture (Gf) Performance**

Temperature °C	Fracture Energy, J/m <sup>2</sup>		
	0% RAP	20% RAP	30% RAP
<b>-20.70</b>	612	504	<b>400</b>
<b>-23.32</b>	534	448	<b>350</b>
<b>-25.88</b>	468	<b>400</b>	307
<b>-28.88</b>	<b>400</b>	<b>350</b>	263
<b>-31.45</b>	<b>350</b>	312	231
Fit	$1796.4e^{0.052x}$	$1265.2e^{0.0445x}$	$1152.2e^{0.0511x}$
R-squared	0.6583	0.782	0.8288

**Dynamic modulus** testing was performed on specimens that were fabricated from asphalt mixtures sampled from haul trucks at the project site. Testing was done at four temperatures (4.4, 21.1, 37.8, and 54.4 °C) and six frequencies per temperature (25, 10, 5, 1, 0.5, and 0.1 Hz).

A master curve of dynamic modulus vs. frequency was created for each mixture at a reference temperature of 54.4°C with the function shown in the 2004 NCHRP Guide for Mechanistic-Empirical Design (9). Curves were fitted using a simple least squares method. As expected, the mixtures with PG 58-28 binder were stiffer than those with PG 58-34 binder. These stiffer curves show very slight differences, indicating that fractionating the RAP piles can produce slightly softer (and therefore more resistant to cracking) mixtures. The curves also indicated that softer binder produced a softer mixture than those made with PG 58-28 binder. The warm mix was by far the softest material at high temperature (low frequency) conditions. This is likely due to the combination of the PG 58-34 binder, lower RAP content (20%) than the other mixtures (30%), and reduced binder aging due to production temperatures of warm mix technology that were 50 ° lower than corresponding hot mix.

## Chapter 4: Pavement Performance Highlights

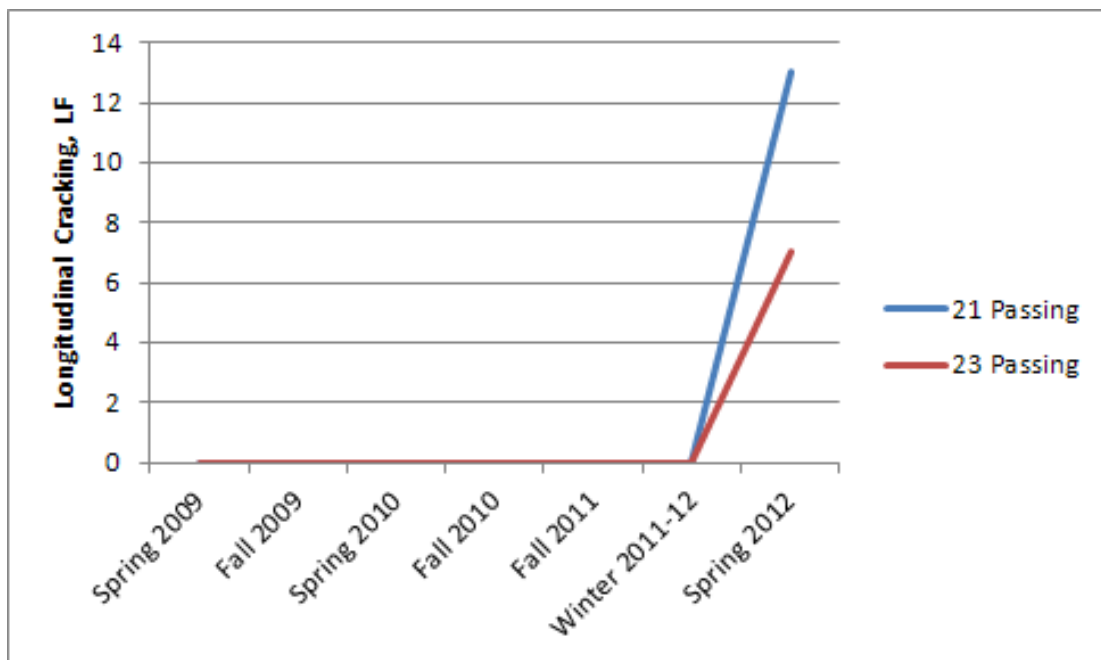
### *Distress*

MnROAD cells were evaluated twice annually following the long term pavement performance (LTPP) evaluation method (10). The location and severity of each distress within the cells was recorded on distress maps. Figure 2 and Figure 3 present the results of the distress surveys through April, 2012. The most common distress type observed thus far was low severity transverse or longitudinal cracking; visible in Cells 15, 16, 20, 21, and 23.

Cell 15 was constructed in 2008 as a 3-in. overlay placed over a deteriorated 11.1-in. full depth asphalt pavement (above clay subgrade). The overlay was the first to develop cracking, and continued to exhibit the most significant cracking during the study period.

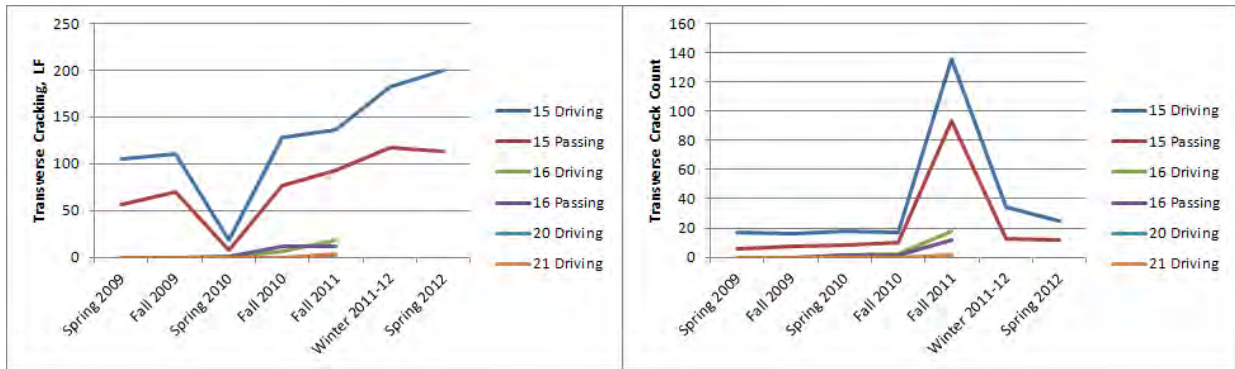
If the transverse cracks present in the new overlay are assumed to be reflective, then (25/44) or 57% of the underlying cracks have reflected through from the driving lane, and (12/37), or 32% of the cracks have reflected through from the passing lane, suggesting that more transverse cracks can be expected to reflect through.

Cell 16 and 23 materials include PG 58-34 asphalt binder and 20% RAP. By 2012 Cell 16 had developed 30 feet of cracking, but this coincided with the location of a lysimeter that was installed in the class 3 base layer. The cell will be closely monitored to see if additional cracks develop. Cell 23 developed 7 feet of cracking. Cells 20 and 21, containing relatively stiffer binder (PG 58-28) and 10% more RAP (30% total), also began to exhibit distress.



**Figure 2: Longitudinal Cracking: Lineal Feet Over Time**





**Figure 3: Transverse Cracking: Lineal Feet and Crack Count Over Time**

### *Ride*

The international roughness index (IRI) simulates a standard vehicle traveling down the roadway and is reported in units of inches/mile (vertical inches of movement per mile traveled). Perfect smoothness equates to an IRI of zero (i.e. no vertical movement of the vehicle). The higher the IRI is, the rougher the roadway (11). Data was collected in both wheel paths of the driving and passing lanes with a certified laser profiler.

Cells 4 and 15 experienced relatively large fluctuations in ride values during spring measurements, with individual collection runs peaking at over 160 in/mile in 2011. The greatest values occurred near the roadway centerline, in the driving lane left wheel path, and right wheel path of the passing lane. Those values subsequently declined below 110 in/mile when the cells recovered in the summer. These large variations were not seen in any of the other cells. These high fluctuations were determined to not be outliers as they had occurred at the same time over a three year period. It is recommended that the trend should be monitored to see if it continues. Cell 4 was a 3-in. HMA pavement constructed over 8-in. of full depth reclamation stabilized with engineered emulsion, above 9 in. of clay stabilized with fly ash. Cell 15 was a HMA overlay over a full depth HMA pavement constructed directly over a clay subgrade.

Every test cell was constructed with an individual initial ride value. Table 5 shows the summary statistics of the change through time of the ride values, averaged across the left and right wheel paths and the driving and passing lanes of all study cells. These statistics excluded the yearly peak ride values measured during the spring-thaw period. The decay column represents the difference between the final and initial IRI values (inches/mile), representing November 2008 through March 2012.

**Table 5: Summary Statistics and 3.5-Year Decay of Average Ride Values (Non-Spring-Thaw)**

Study Group	Cell (study variable)	Initial	2012 Final	Decay	Yearly Rate
HMA	4 (Clay & cement)	81.6	96.6	14.9	4.3
WMA	15 (Overlaid full-depth)	58.2	78.9	20.7	5.9
WMA & Recycled Unbound Base	16 (PCC base)	59.5	68.9	9.4	2.7
	17 (50/50 base)	67.0	81.1	14.1	4.0
	18 (RAP base)	52.0	64.0	12.0	3.4
WMA	19 (PG-34)	58.2	67.3	9.1	2.6
HMA-FRAP	20 (PG-28)	50.5	53.0	2.5	0.7
	21 (PG-28)	40.6	44.1	3.5	1.0
	22 (PG-34)	53.4	59.2	5.8	1.7
WMA	23 (Taconite base)	84.8	97.9	13.1	3.7
HMA	24 (Aging)	68.8	69.3	0.5	0.2

Cells having similar construction and base characteristics, described earlier, were categorized into study groups. The ride decay for cells within the recycled unbound base group appears to be very similar. The decay values of the cells within the FRAP/low temperature cracking group also appear to be relatively low and very similar. Cell 15 (mill and overlay of full-depth asphalt) has the highest decay value, and experienced the greatest decline in IRI, followed by Cells 4, 17, and 23. Cells 20 – 22 and 24 appear to have experienced the smallest decline in IRI. It appears to be too early to draw strong conclusions on the ride performance related to: fractionation of RAP, the proportion of RAP, and virgin binder PG grade as well as the use of WMA technology.

### ***Rutting***

The Automated Laser Profile System (ALPS) was used to characterize the rutting of all study cells. The ALPS collected rutting measurements in both wheel paths of both lanes at 50-ft intervals, with measurements stored every 0.25 in. along the transverse profile.

The distribution of this data was examined and outliers (~4% of data set) were removed from the data set using the interquartile range (IQR) rule; based on the range between the 25<sup>th</sup> and 75<sup>th</sup> percentile. According to MnDOT’s pavement management practice, the pavement distress rating is impacted only when rutting values are greater than 0.5 in. During 2012, with the exception of Cell 18, all of the cells had rutting values below the 0.5-in. threshold value, and 75% of all the conditioned data were below 0.2577 in.

### ***Pavement Deflection***

Falling weight deflectometer (FWD) data was collected on all of the bituminous cells in the months following construction. The normalized Area Factor was calculated from the deflection basin, and used to draw conclusions about performance similarities of the bituminous cells. It is well documented that FWD results for bituminous pavements are influenced by base condition (saturated, frozen, unfrozen) and temperature. Because of this, comparisons focused primarily

on data collected in the late summer and fall months, when base materials were likely to be stable and surface temperatures relatively moderate.

$$AreaFactor = 6 \left( 1 + 2 \left( \frac{D_{12}}{D_0} + \frac{D_{24}}{D_0} \right) + \frac{D_{36}}{D_0} \right) \quad \text{Equation 1}$$

Where:

- $D_0$  = Deflection measured at the center of FWD load plate
- $D_{12}$  = Deflection measured 12 in. (305 mm) from the center of FWD load plate
- $D_{24}$  = Deflection measured 24 in. (610 mm) from the center of FWD load plate
- $D_{36}$  = Deflection measured 36 in. (914 mm) from the center of FWD load plate

The average Area Factor for the study cells fluctuated very little during the course of the study; 19.0 for the fall of 2009 compared to 19.6 for the spring of 2012. All but three cells produced Area Factors within 10 percent of the average throughout the study and the relative relationships among the cells were the same during all years. The deflection basins of the FRAP, HMA and WMA cells exhibited similar Area Factor values. This is an indication that structural performance remained fairly constant during the course of the study.

**Table 6: Comparison of FWD Area Factors MnROAD**

Cell	Fall 2009				Fall 2010				Fall 2011				Spring 2012			
	Avg Area Factor	Stdev	Count	% Above Average	Avg Area Factor	Stdev	Count	% Above Average	Avg Area Factor	Stdev	Count	% Above Average	Avg Area Factor	Stdev	Count	% Above Average
4	20.3	2.235	60	6.6%	17.6	0.7898	15	2.3%	19.0	2.194	60	6.6%	18.5	1.686	90.0	-7.1%
15	25.6	2.175	30	34.4%	23.5	1.9775	30	36.6%	24.9	1.384	30	39.2%	26.3	2.048	30.0	32.1%
16	18.4	1.413	30	-3.4%	16.7	1.2976	30	-2.9%	15.5	1.420	60	-13.1%	18.4	0.704	30.0	-7.5%
17	18.3	1.464	30	-4.0%	17.8	0.5703	15	3.5%	16.2	2.206	60	-9.5%	18.7	0.819	30.0	-6.4%
18	17.4	2.2	30	-8.5%	15.9	0.6154	15	-7.6%	17.2	0.479	15	-3.5%	18.1	0.565	30.0	-9.0%
19	17.5	1.807	30	-8.1%	14.7	0.6929	15	-14.5%	16.0	1.088	45	-10.2%	18.4	0.502	30.0	-7.5%
20	17.3	2.469	45	-9.1%	16.8	0.649	15	-2.3%	16.9	2.417	45	-5.6%	21.5	0.321	30.0	7.8%
21	18.6	2.6	60	-2.1%	16.3	0.6552	15	-5.2%	16.5	2.567	45	-7.8%	20.9	0.345	15.0	5.0%
22	18.5	1.489	30	-2.8%	17.2	0.5665	15	0.0%	15.9	2.442	45	-10.8%	18.1	1.880	75.0	-9.3%
23	20.4	1.996	30	7.3%	17.2	1.113	15	0.0%	19.3	2.378	57	8.1%	22.5	0.693	30.0	12.9%
24	17	2.934	30	-10.4%	15.8	0.8723	15	-8.1%	19.0	1.780	27	6.6%	17.7	1.259	30.0	-11.1%
Total	19				17.2				17.9				19.9			

### Surface Characteristics

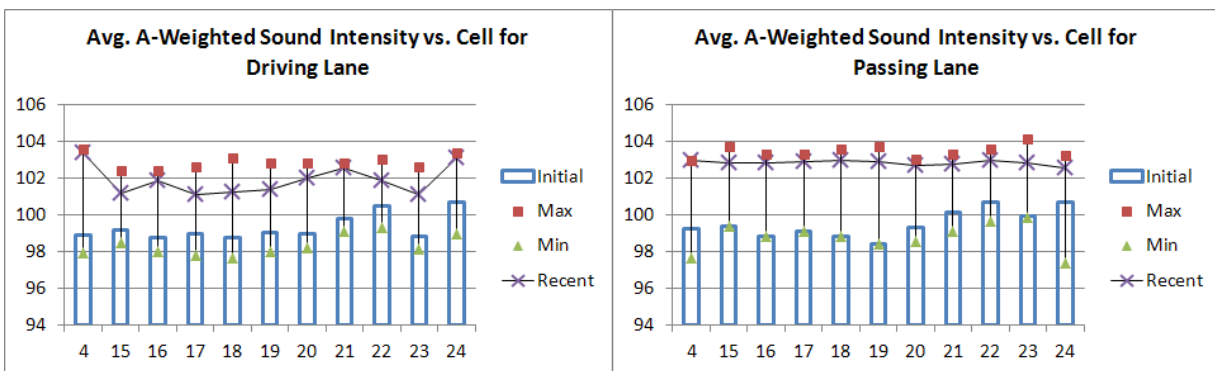
#### Noise

Sound intensity was measured using an on board sound intensity (OBSI) apparatus, which is a close proximity method. The intensity meters are attached to a standard reference test tire installed at the rear passenger side of a Chevrolet sedan. The unit measures tire pavement interaction noise of the tire pavement contact patch at a speed of 60 miles an hour for a period of five seconds. Performance is reported using a logarithmic scale used to mimic human hearing. If there are 2 sources with the same sound intensity, the cumulative intensity is 3 dBA higher than the individual intensity, implying that a reduction of the sound intensity by 3 dBA is

equivalent in effect to a traffic reduction to 50 % of original ADT (12). OBSI was collected from October 2008 through 2012.

Figure 4 compares the change in sound intensity of each study cell of the driving and passing lanes. Observation of the data showed the initial seasonal effects seemed to influence intensity measurement results more than construction type. In addition, the seasonal effects on the intensity measurements appeared to have an influence over all of the study cells; contrast this result to the ride values (Table 5), where few cells experienced dramatic seasonal variations. The data collected since November 2010 showed all cells holding the OBSI levels through several seasonal changes. Recent OBSI measurements showed most cells in the passing lane were performing at uniform levels just below their four-year maximum OBSI levels. Driving lane cells showed more variability in intensity data, but were all below the four-year maximums.

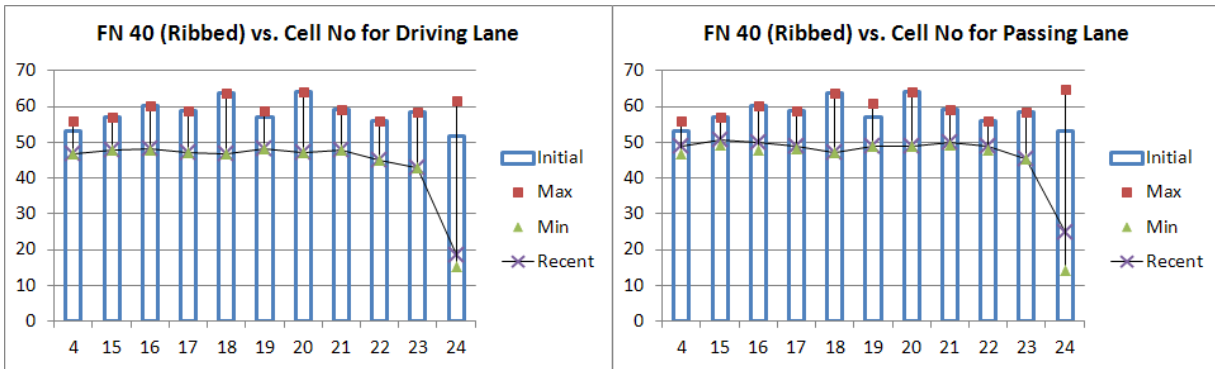
Even though the FRAP cells had an initially higher OBSI reading, this was later surpassed by Cell 15 and others. This suggests that the presence of FRAP in the HMA mixture has less of an influence on the measured sound than other factors, such as pavement distress, ride and others. It must be stressed that the initial relative noisiness of the FRAP cells appears to have dissipated. Note that although MnDOT is currently investigating the use of quiet pavements at MnROAD, there currently is no noise standard for the construction of HMA pavements and MnDOT does not currently consider quiet pavements as an alternative to noise walls.



**Figure 4: Average A-Weighted Sound Intensity (dBA) versus Cell: Nov. 2008 – Apr. 2012**

### Friction

Tire-pavement friction was evaluated using a Dynatest Locked-Wheel Skid Trailer in accordance with ASTM E 247 (13). Friction numbers were measured when locking a ribbed test tire at a speed of 40 miles per hour (100% slip condition). The measured values are denoted as FN40 (Ribbed). Values obtained from the friction tests are intended for comparison with other pavements over time, not to determine vehicle stopping distances (13). Figure 5 shows the initial reading taken on October 2008, the most recent measurement, and corresponding maximum and minimum measurement values that occurred during the analysis period for the driving and passing lanes.



**Figure 5: Average Friction (FN40Ribbed) versus Cell (Lane): Oct. 2008 – Apr. 2012**

In June 2009 the average MnROAD bituminous friction number was found to be 47.3. All study cells produced initial friction number readings at or above 40. The current and minimum measured values are all still well above 40, and closer to the 50's. Driving and passing lanes show similar performance at this time. For this group of cells, the overall mean FN40 values have declined by 20.3% between October 2008 and September 2011 (18.1% median decline). The friction performance of the study cells is relatively uniform, and the experimental variables of: FRAP, varying proportions of RAP, and grades of virgin asphalt binder, as well as the use of warm mix asphalt technology do not appear to influence the results significantly.

The only cell significant degree of friction loss occurred on Cell 24 due to application of a series of heavy fog seal treatments beginning in 2008 as part of a national pooled fund study.

### ***Pavement Performance Summary***

The study cells have been evaluated using common performance indicators to assess whether or not the experimental variables of: FRAP, varying proportions of RAP, and grades of virgin asphalt binder, as well as the use of warm mix asphalt technology had a measureable influence on pavement performance. The indicators included: pavement surface distresses, ride, and rutting measurements. Overall, the study cells have exhibited few distresses during four years of service life; limiting the conclusions that can be drawn about their performance with respect to the experimental variables. The visual distresses, ride and rutting were not observed to be influenced by the experimental variables.

The pavement distress survey revealed that only one cell (Cell 15) has experienced substantial distresses, and this is related to the underlying pavement that it was constructed on and not the experimental variables. Two cracks were observed in Cell 16, but underlying instrumentation was assumed to be an influence in crack development. At the time of this report, only limited amounts of distress were observed in cells 16, 20, 21, and 23. With regard to experimental variables, Cell 21 (PG58-28 FRAP) developed 13feet of longitudinal cracking.

An analysis of ride measurements revealed that the test cells had different initial ride values, and over the measurement history, two (cells 4 and 15) were prone to exhibit substantial variations coinciding with spring-thaw. It was thought that this behavior was related to factors underlying the pavement and not to the pavement surface itself. The decay of the ride (IRI) over the performance history of the cells was examined. This revealed that performance was similar

within study groups: i.e., WMA, FRAP, and Recycled Base. Rutting results revealed that rutting was not an issue for any of the study cells as measured by the ALPS laser. Only in one case (Cell 18) did rutting measurements exceed 0.5 in. (the value at which rutting impacts a pavements distress rating). Rutting statistics for Cell 18 show the respective median and maximum values were equal to 0.28 and 0.64 in. Future work should include rutting performance checks for study groups related to Cell 18. A cursory comparison of the 2012 FWD data found that the maximum deflections for Cell 18 were within the range measured for the other 10 cells.

The study cells have been tested for structural and surface characteristics to assess whether or not the experimental variables of: FRAP, varying proportions of RAP, and grades of virgin asphalt binder, as well as the use of warm mix asphalt technology have a measureable influence on pavement performance. The performance indicators included: structural characterization using Falling Weight Deflectometer testing and the AREA Factor, as well as noise and friction measurements. FWD testing revealed that the initial structural response was similar among the cells, and the relative relationships were maintained in the years following construction.

OBSI sound measurements indicated that FRAP cells had an initially higher (noisier) value, but the difference quickly dissipated and they are now behaving in a similar manner to other study cells. Seasonal climate swings seemed to influence OBSI measurements more than did any particular construction type. Recent OBSI measurements showed most cells in the passing lane were performing at uniform levels just below the four-year maximum OBSI levels. Driving lane cells showed more variability in OBSI data, but were all below the four-year maximums.

Currently one of the noisiest study cells is Cell 15, which is also in the worst condition in terms of IRI and surface distress. Friction testing revealed that the experimental variables are not having a noticeable influence on the frictional characteristics of the pavements as the study cells are behaving relatively uniformly.

At the time of this report, the pavements were four years old, and only one study cell was constructed as an overlay. The influence of the experimental variables could become more apparent as the study progresses and the pavements experience more traffic and environmental loadings. The experimental variables did not appear to have an observable effect on the structural, noise or frictional characteristics of the pavement. The current performance of the study cells cannot be explained by the experimental variables, however, this could change with time as cells receive more environmental and traffic loadings.

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