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Composite Pavements and Exposed Aggregate Texturing at MnROAD: Cells 70, 71, and 72 Construction Report and Early Performance Evaluation

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MnROAD Office of Materials

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This report summarizes the construction and early performance assessment of three composite (new, multi-layer, construction) test cells at the MnROAD: HMA over a recycled aggregate concrete; diamond grind concrete over recycled aggregate concrete; and exposed aggregate concrete over a low cost concrete. The compilation of this report is strictly a MnDOT activity that documents construction and instrumentation of concrete cells at our MnROAD facility and should not be misconstrued for a SHRP 2 activity. Strength, on board sound intensity, sound absorption, friction, texture and international roughness index were tested to better understand the performance of these, pavement types. Results suggest that the exposed aggregate concrete surface does not provide significant noise reduction. Exposed aggregate surfacing can provide more than adequate friction for skid resistance and safety. Overall, however, these two lift concrete pavements proved to address issues such as high cost of virgin aggregates and high trucking costs for areas that don't have quality aggregates to use. Continued monitoring of these test cells will help develop the extensive understanding of composite pavements needed for effective design and accurate service life models.

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EXECUTIVE SUMMARY

This report summarizes the construction and early performance assessment of three composite (new, multi-layer, construction) test cells at the MnROAD: HMA over a recycled aggregate concrete; diamond grind concrete over recycled aggregate concrete; and exposed aggregate concrete over a low cost concrete. The compilation of this report is strictly a MnDOT activity that documents construction and instrumentation of concrete cells at our MnROAD facility and should not be misconstrued for a SHRP 2 activity. Strength, on board sound intensity, sound absorption, friction, texture and international roughness index were tested to better understand the performance of these, pavement types. Results suggest that the exposed aggregate concrete surface does not provide significant noise reduction. Exposed aggregate surfacing can provide more than adequate friction for skid resistance and safety. Overall, however, these two lift concrete pavements proved to address issues such as high cost of virgin aggregates and high trucking costs for areas that don't have quality aggregates to use. Continued monitoring of these test cells will help develop the extensive understanding of composite pavements needed for effective design and accurate service life models. The report is subdivided in to 3 sections

Section 1 introduces the concept of composite pavements and discusses overview project background and existing cell condition. It highlights cell design instrumentation.
Section 2 discusses the construction sequence. This consists in: mainline pre-construction and demonstration (demo) slab paving, mainline paving and construction time lag between lifts.
Section 3 discusses early performance data: This consists in compressive, flexural strength, bond strength, on board sound intensity sound absorption friction, texture, International roughness index warp and curl.

Lessons Learned

Several important lessons were learned throughout the course of this construction project. These include:

- The material properties of the recycled concrete aggregate were important to consider when introducing into the new concrete mixture, especially the water absorption. The new water added to the concrete mixture needs to take this value into account.

- Concrete mix consistency was an issue with our short test sections. The stiff mixtures on the bottom lift of concrete were especially sensitive to small adjustments at the plant.
- Delivery of the concrete mixtures was a challenge. The Contractor placed a spotter at the end of the project to direct the truck drivers where to go depending on which mix they were hauling. Delivery of the EAC concrete mix was accomplished through a belt placer running alongside the shoulder.
- The exposed aggregate surface of the upper concrete layer was tricky to accomplish correctly. This was the first such surface placed by the Contractor or specified by MnDOT. The application rate of the retarder/curing compound was dialed in by trial and error. The optimal time to brush with a mechanical broom was determined by a University of Minnesota researcher with a hand broom.
- The demonstration slab was informative towards t5he mainline paving Specifically:
  - MnROAD staff perfected their sensor installation techniques, including the way to anchor sensor supports into the aggregate base and a method for installing sensors in the upper concrete layer.
  - The Contractor ironed out his construction techniques, specifically the required consistency and placement of the bottom concrete lift.
  - Inspectors and researchers performed a trial run on material sampling for laboratory testing.
  - Research staff had a dedicated photographer and videographer on hand to capture all aspects of pavement construction.
- Over 500 sensors were installed in the test sections, and these sensors were “live” as the concrete was placed. It took some ingenuity in programming the data collection software to make this happen.
- The innovative diamond grind on Cell 71 was very successful, resulting in an extremely quiet pavement surface.
- Through a hypothetical bid on one of their construction projects on the MnDOT highway and the extrapolation of cost information from the small scale test cell (barring economy of scales), the Contractor demonstrated that composite pavements could be cost-effective, especially in regions where high-quality crushed aggregates were scarce. More information on this experience can be found in Appendix D.

- MnDOT held an open house on August 23, 2010 to showcase the composite pavement project. SHRP II personnel and other experts from around the country attended to hear presentations about the project and tour the MnROAD facility.

INTRODUCTION TO COMPOSITE PAVEMENTS

Recent interest in pavement overlays as a rehabilitation method has led to a relatively high portion of the nation’s interstate system, both urban and rural, to be classified as composite pavement systems. However, other regions, specifically Europe and Canada, have been experimenting with constructing new pavements as composite pavement systems, a technique that can provide several benefits over single layer construction. These new composite pavement systems consist of two distinct layers. New composite pavement systems can be very economically effective, by using low cost materials, such as recycled or moderate quality aggregate, in the lower layer. The surface layer can then provide better performance characteristics, such as low noise characteristics, improved friction and ride characteristics, along with minimal maintenance, by utilizing new innovative pavement techniques. The lower layer of these composite systems is generally much thicker than the upper layer, further reducing costs by requiring less of the more expensive and durable materials. Composite pavements can be done using both asphalt concrete over new concrete, along with construction of two new concrete layers. In summary, composite pavement designs have the ability to provide long lasting, economical and environmentally sustainable transportation.

Many European countries have recognized the benefits of composite pavement and have practiced two-lift construction on a much larger scale than the United States. Belgium, the Netherlands, Switzerland, France and Germany have all been constructing composite pavements on a frequent basis since the 1980s. In Austria, the standard concrete pavement is designed and constructed according to their two-layer Portland Cement Concrete specification [1]. Besides concrete-on-concrete construction, the Netherlands has constructed asphalt over concrete composites on a multitude of new construction projects since 2000. Germany has used stone matrix asphalt over both continuously reinforced concrete pavement and jointed plain concrete pavement.

Although there are many different pavement types which are used on the lower and upper layers of composite pavements, one of the most common techniques is the use of exposed aggregate concrete (EAC) on the surface layer. This type of concrete utilizes very high quality aggregate. The aggregate is exposed to the surface by applying a set retardant to the wet concrete surface and subsequently brushing off the surface mortar. Studies of different EAC in Europe found that aggregate size can vary from less than 1 mm up to 22 mm, but almost always found the best performance in pavements utilizing gap graded aggregate with size less than 8 mm [1]. Construction of two-lift pavements in Europe has varied over time. In the past, the two lifts were constructed using a single paver; however, recent construction is done using multiple pavers simultaneously. The term “wet-on-wet” construction refers to the accelerated construction method in which the second layer is placed immediately after the first to achieve a strong bond between the two layers. Finished exposed aggregate pavements are known for their noise reduction capability and increased durability and friction over conventional pavement surfacing techniques.

Many DOTs have exhibited a growing interest in the use of recycled pavement products. Consequently and additionally, they have initiated programs aimed at reducing pavement costs, achieving better surface characteristics and durability, and consequently, have started experimenting with two lift concrete construction. However, despite this recent effort, the performance of composite pavements is not as clearly understood as it is for rigid and flexible pavements. Design of composite pavements has been hamstrung by the lack of performance models, service life predictions, and life-cycle cost analysis. More performance data is needed for effective design of composite pavements, along with better construction specifications and guidelines.

PROJECT OVERVIEW AND DESIGN

As discussed in the previous section, composite pavements are becoming increasingly popular in Europe. Consequently, many states have been experimenting and evaluating the prospect for utilizing the technique in the United States. In 2005, Congress established the second Strategic Highway Research Program (SHRP 2). This program was created to conduct research focused on four areas of highway transportation: safety, renewal, reliability and capacity. SHRP 2 received four years of funding and is set to be complete by 2013. Part of the SHRP 2 Program is the Composite Pavement Systems R21 project aimed at developing and providing strategies for rapid renewal of the national highway system [2]. Unlike pavement overlays commonly used as a method of rehabilitation, composite pavements are designed and constructed as a new pavement system. Composite pavements consist of two different pavement layers, with a low quality or recycled base layer, and a high quality top layer that provides a better wear surface. This report is however a separate MnDOT activity mutually exclusive to the SHRP 2 Program.

Overview

Cells 70, 71 and 72 at the MnROAD research facility were constructed as part of the SHRP 2-R21 project to evaluate two different types of composite pavements: an asphalt layer over a PCC layer and a high surface quality PCC layer over a lower quality PCC layer. MnROAD consists of two distinct segments of roadway, the Mainline, a segment of Interstate 94, and the Low Volume Road. There are a total of 54 test cells between the Mainline and Low Volume Road, each with a distinct pavement type and design. Maps of the mainline and Low Volume Road that include descriptions of each cell are provided in Appendix A of this report. The three composite pavement test cells discussed in this report are all located on the Mainline.

This project will serve the following three main objectives:

- Establish important material parameters of these particular composite pavements, and identify their behavior and performance characteristics.
- Work to develop mechanistic-empirical performance models for composite pavements that can be used as a design method in the Mechanistic-Empirical Pavement Design Guide (MEPDG).

- Determine recommendations for construction specifications, techniques and other quality management procedures [2].

Project Background

This projected was funded by the second Strategic Highway Research Program (SHRP 2), which was authorized by congress in 2005 and administered by the Transportation Research Board. This project originally developed through a partnership agreement with Applied Research Associates (ARA). ARA had diligently evaluated the tasks associated with managing the construction contract themselves and thus elected that MnDOT administered the contract through a typical low-bid construction letting. MnROAD therefore performed the construction (develop plans, special provisions, bids, construction inspection, and contractor payments) and assist in the research (purchase/install sensors, collect sensor data, and monitor field performance over time).

Some of the interesting challenges for developing the construction bid documents included:

- Use of two concrete pavers used in tandem (wet on wet construction) – something that no local contractor has ever attempted.
- Use of recycled coarse aggregate in the concrete mix that has not been used in Minnesota in the previous 30 years.
- Use of a gradation uncommon to Minnesota but used in Europe for the high quality concrete upper layer. This gradation had very tight specification limits and was difficult for local concrete producers to fit into.
- Use of a new curing compound and retarder that the contractor had no experience with.
- Concrete was finished with a brushed exposed aggregate singular to the European design. The Contractor did not have the same equipment and had to bid the job not knowing exactly how it was going to be done.
- Project originally included a Stone Matrix Asphalt (SMA) into one of the test cells. Minnesota currently does not use SMA pavements very often and contractors don't have much experience with the design and construction of them. The idea was consequently not explored further.

Early in the design process MnDOT held meetings with potential contractors to better understand how to specify and build the test cells needed. These meetings were designed to help exchange information and possibly reduce the risk contractors felt before they committed to a bid. This also helped MnDOT form the plans and special provisions for a letting. MnDOT first held an informational meeting coordinated by our state Concrete Paving Association of Minnesota and our MnDOT Construction office so that MnDOT and ARA could get our three local concrete contractors' feedback on the innovative construction and materials noted above. The Contractor feedback included providing a location at MnROAD so a "practice slab" could be constructed using the two pavers using three different concrete mixes, and help in developing a sense of how to do the exposed aggregate surface before the work was done on the Mainline. A second formal pre-bid meeting was held to again go over the plans and special provisions to help answer any questions before bids were submitted by potential Contractors.

It was hoped we could get the contractors on board with the innovative construction and this would reduce the risks they felt and thus keep the bid price low as possible, to stay within ARA's construction budget. Even with these meetings we had to reject the initial bids because the bids were higher than both the official engineer's estimate and ARA's budget. The project was let during stimulus, which also had an impact on the bid. The meetings did make a difference, but interestingly enough all the bid items were reasonable except for the SMA paving. ARA really wanted to include an SMA surface, but this was simply not feasible in a 500-foot test section (as SMA specifications call for "wasting" 250 tons). The project was re-scoped, removing one composite pavement test section with the SMA, and later re-bid successfully.

Existing Cell Condition

Cells 70-72 were constructed over what was previously Cells 10, 11, 92, and 97. Cells 10 and 11 were some of the original 10-inch concrete cells constructed in 1993. Cell 10 was over 4 inches of permeable asphalt stabilized base over 3 inches of class 3 aggregate base. Cell 11 was over 5 inches of class 5 aggregate base. Cells 92 and 97 were originally constructed in 1997 as 6-inch whitetopping pavements over 7 inches of asphalt. All cells rested over a clay subgrade.

The ride quality in the four cells was beginning to deteriorate, especially in Cell 97 due to joint faulting. However, the main reason for reconstructing was that these cells had served their useful research purposes and new opportunities came along.

Cell Design

The top layer of Cell 70 is high quality hot mix asphalt (HMA). An exposed aggregate concrete (EAC) mix is used as the top layer of Cells 71 and 72. The bottom layer of Cells 70 and 71 is concrete utilizing 50% recycled concrete aggregate (RCA). The bottom layer of Cell 72 consists of an economical "Low Cost" mix (LCC) that utilizes relaxed aggregate specifications. Figure 1 below shows a cross section of the three composite cells along with the aggregate base designations. Although the mix composition changes from cell to cell, the depths of each pavement layer, base, and subgrade remain the same. All cells were constructed with 15 foot long x 12 foot wide panels. Cells 71 and 72 have 1.25-inch epoxy coated dowels at 1-ft spacing throughout both lanes, where Cell 70 has 1.25-inch dowels in the driving lane only. The dowels were placed at mid-depth of the concrete, meaning 6 inches from the asphalt surface on Cell 70 and 4.5 inches from the EAC surface on Cells 71 and 72. The vibrators had to be raised on the paver for the lower lift so as not to catch on the dowel baskets. No. 13 tie bars were placed across the centerline joint at 30 inch spacing in all three cells. More material properties and cost information for the three different mix types are specified in Tables 1 and 2 below.

Cell 70	Cell 71	Cell 72
3" Hot Mix Asphalt	3" Exposed Aggregate Concrete	3" Exposed Aggregate Concrete
6" Recycled Concrete	6" Recycled Concrete	6" Low Cost Concrete
8" Class 7	8" Class 7	8" Class 7
Clay	Clay	Clay

Figure 1: Cell Composition

Table 1: Mix Summary

Mix Designation	Pavement Location	Fly Ash	Aggregate
Exposed Aggregate Concrete	Upper “Wear”	15 %	98% passing 3/8 in.
Low Cost Concrete	Lower	60 %	Relaxed Specifications
Recycled Concrete Aggregate	Lower	40 %	50% Coarse Aggregate from RCA

Table 2: Cost

Mix Designation	Material Qty.	Material Cost	Paving Qty.	Paving Cost
Exposed Aggregate Concrete	255.0 CY	$175/CY	3059 SY	$48/SY
Low Cost Concrete	255.0 CY	$140/CY	4323 SY	$30/SY
Recycled Concrete Aggregate	466.0 CY	$135/CY	4323 SY	$30/SY
	Qty.		**Material and Paving Cost**	
Hot Mix Asphalt	232 tons		$83.50/ton	

Figure 2 illustrates the differences in aggregate gradation for the three mixes, and Tables 3, 4 and 5 provide material information and complete mix designs. The complete mix designs and aggregate gradations are provided in Appendix B of this report.

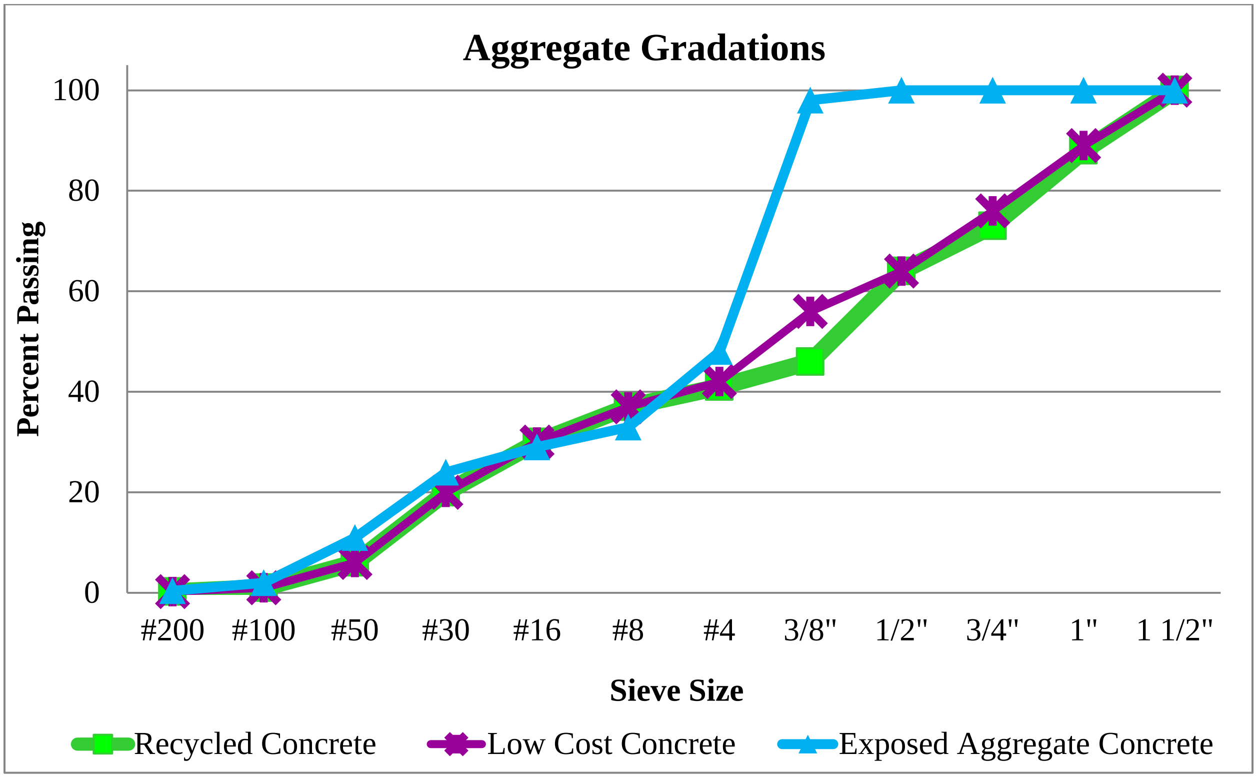


Figure 2: Aggregate Gradations

Figure 2 illustrates the unique gradation of the exposed aggregate mixture, with close to 50% falling between the 3/8 inch and #4 sieve size. This gradation is designed to produce a surface texture with good friction characteristics and reduced noise generation. The gradation of the low cost mix and recycled mix are fairly similar, with the only significant difference being a slightly finer gradation in the low cost mix.

Table 3: Material Information

Recycled Concrete Aggregate						
	Coarse Aggregate 1		**Coarse Aggregate 2**		**Sand**	
Pit Name	Agg. Ind		McCrossan		Agg. Ind	
Town	Elk River		Maple Grove		Elk River	
Size	#4 (1 - 1/2 ")		Recycle		C. Sand	
SG and Abs	2.75	0.90%	2.49	2.93%	2.63	0.90%
Low Cost						
	Coarse Aggregate 1		**Coarse Aggregate 2**		**Sand**	
Pit Name	Agg. Ind.		Agg. Ind.		Agg. Ind	
Town	Elk River		Elk River		Elk River	
Size	#4 (1 - 1/2 ")		#67 (3/4" -)		C. Sand	
SG and Abs	2.75	0.90%	2.69	1.30%	2.63	0.90%
Exposed Aggregate						
	Coarse Aggregate 1		**Coarse Aggregate 2**		**Sand**	
Pit Name	Marietta		Marietta		Agg. Ind	
Town	St. Cloud		St. Cloud		Elk River	
Size	1/2" W. Chips		3/8" W. Chips		C. Sand	
SG and Abs	2.72	0.40%	2.72	0.40%	2.63	0.90%

Table 4: Cement and Fly Ash

All Mixes		
	Cement	**Fly Ash**
Manufacturer	Holcim	Headwaters
Mill/Power Plant	STGBLMO	COCUNND
Type/Class	I/II	C/F
SG	3.15	2.5

Table 5: Mix Designs

Material	Recycled	Low Cost	Exposed Aggregate
Water (lbs/cy)	234	172	283
Cement (lbs/cy)	360	240	616
Fly Ash (lbs/cy)	240	360	109
W/CM	0.39	0.29	0.39
Sand (OD lbs/cy)	1200	1263	843
CA1 (OD lbs/cy)	825	787	1133
CA2 (OD lbs/cy)	920	1102	843
Max Slump (in)	3	3	3
% Air	7	7	7
Multi-Air 25 (oz/cy)	2 - 15	2 - 15	2 - 15
Sike 686 (oz/cwt)	1 - 7	1 - 5	1 - 5
Admixture 3	0-30 oz/cwt Sikaset NC (non-chloride accelerator)	0-30 oz/cwt Sikaset NC (non-chloride accelerator)	0-5 oz/cwt Delvo as needed for slump retentions

The exposed aggregate concrete mix is an extremely rich mixture with more than 600 lbs of cement and 725 lbs of total cementitious material per cubic yard. However, the low cost and recycled aggregate mix only contains a total cementitious content of 600 lbs per cubic yard. This difference between the two mixes is a result of the fly ash content. The low cost mix uses a high class F fly ash content of 360 lbs per cubic yard, where the recycled mix only has 240 lbs per cubic yard. However, the total cementitious content of both the LCC and RCA mixtures was 600lbs per cubic yard. The sources for fine aggregate, cement and fly ash are the same for all three mixes.

Although both Cells 71 and 72 were constructed using the high quality exposed aggregate mix in the top layer, three different surface treatments were used to evaluate a broader range of pavement types. Cell 71 was finished with diamond grinding, with an innovative diamond grind in the driving lane and the traditional diamond grind in the passing lane. Cell 72 was treated using common practices for exposed aggregate finishes, by applying a set retarder to the surface.

The set retarder used was MBT Reveal, a water based compound produced by BASF Admixture Systems. This chemical provides etch retention and consistency in temperatures up to 130° F and for up to sixteen hours [3]. MBT Reveal is both odorless and non-flammable. It does not require the use of plastic covers which minimizes the required application labor. This compound allows the unhardened surface mortar to be removed by brushing to reveal the aggregate to the surface.

A practice demo slab was constructed in the stockpile area of the MnROAD test facility. This slab consists of a 100 foot section of recycled concrete mix and a 100 foot section using the low cost concrete. The exposed aggregate mix and surface finish was used as the top layer of the composite throughout both sections. It was placed on the existing class 6 aggregate and has 15 foot panels and 1.25-inch dowels throughout.

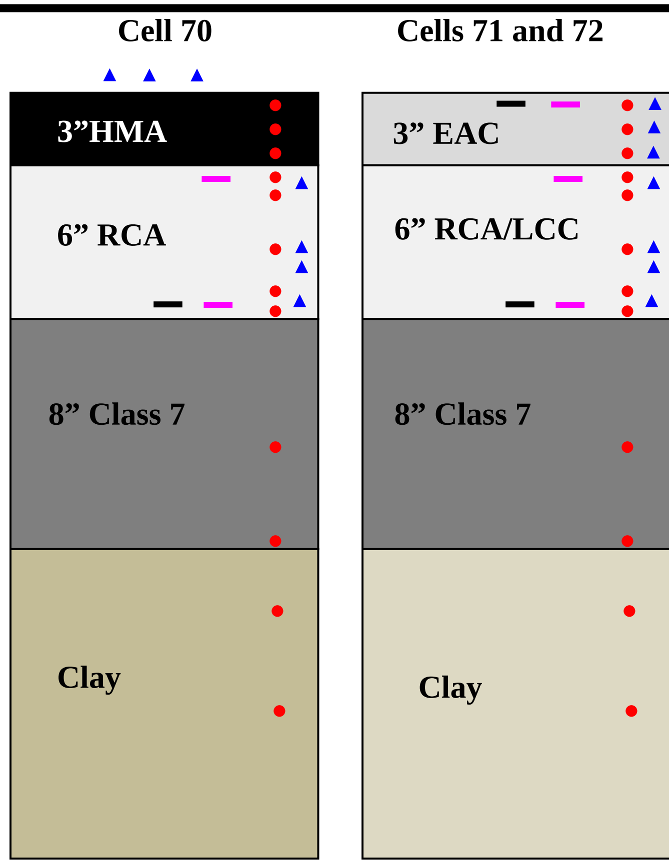
Instrumentation

All three composite cells were equipped with the necessary instrumentation for monitoring humidity, temperature and strain over time. This instrumentation is described in Table 6 below.

Table 6: Instrumentation Description

Sensor	Code	Quantity			Description
		Cell 70	Cell 71	Cell 72	
Concrete Embedment Strain Gauge	CE	26	56	56	Tokyo Sokki, PML-60-20LTSB, with 20 meters of 3-wire lead
Vibrating Wire Strain Gauge	VW	20	30	30	Geokon, 4200A-2, with 02-187V3-E red PVC cable with two twisted pairs
Humidity Sensor	MH	42	42	42	Sensirion, SHT75, Humidity/Temp Sensor PIN +/-1.8% (RoHS compliant)
Thermocouple	TC	72	80	72	Omega, 8TX20PP, Type TX Thermocouple Cable, 20 AWG single strand conductors

The vibrating wire strain gauge measures strain in the pavement due to material shrinkage and environmental factors. The concrete embedment strain gauge measures the pavement response to dynamic loads. The strain gauges were placed at different depths within the concrete pavement layers including in the EAC surface. The humidity and temperature (thermocouple) sensors were placed at different depths throughout the pavement, base, and subgrade using MnROAD designed sensor trees. In addition to the thermocouples shown in the test cells below, 8 thermocouples were placed in the shoulder of Cell 71. The general instrumentation layout is shown in Figures 3 and 4 below.



▬	CE	Concrete Embedment Strain Gauge
▬	VW	Vibrating Wire Strain Gauge
●	TC	Individual Thermocouple
▲	MH	Individual Humidity Sensor

Figure 3: Instrumentation Layout Cross-section

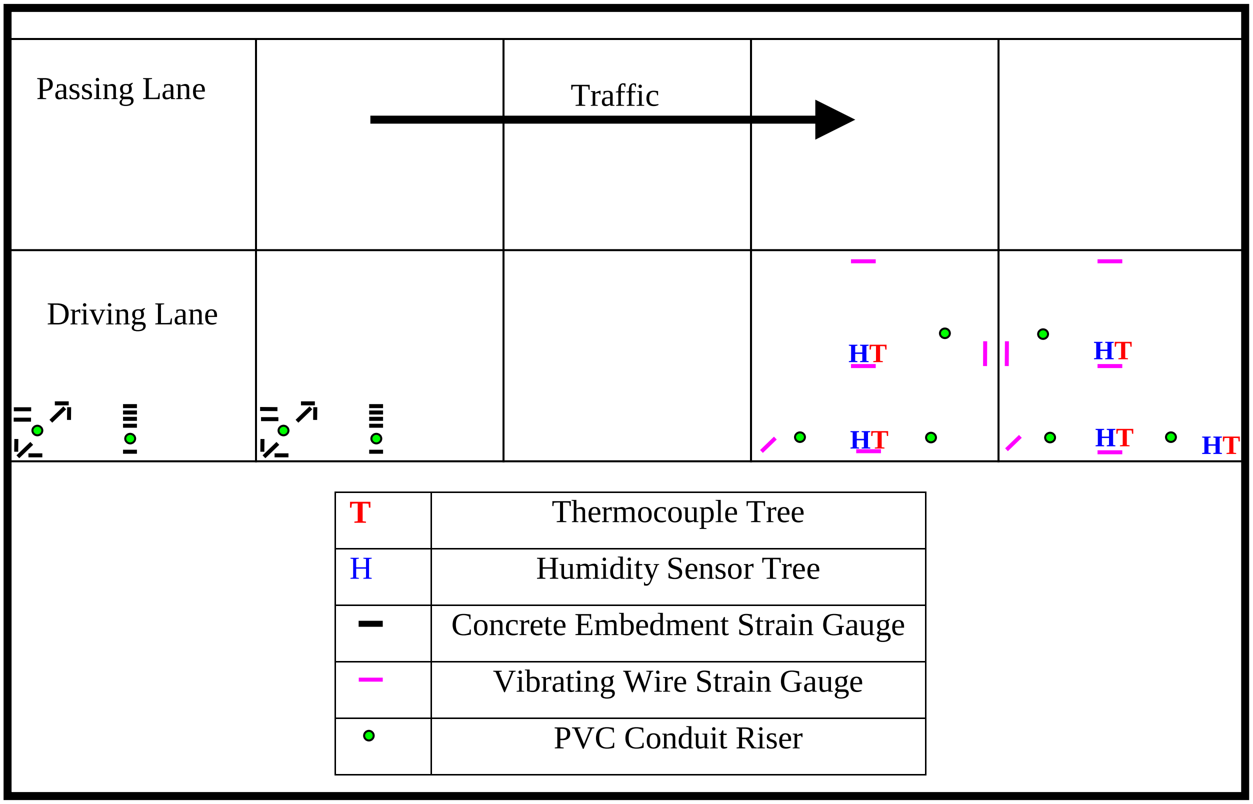


Figure 4: Instrumentation Layout – Cell 70

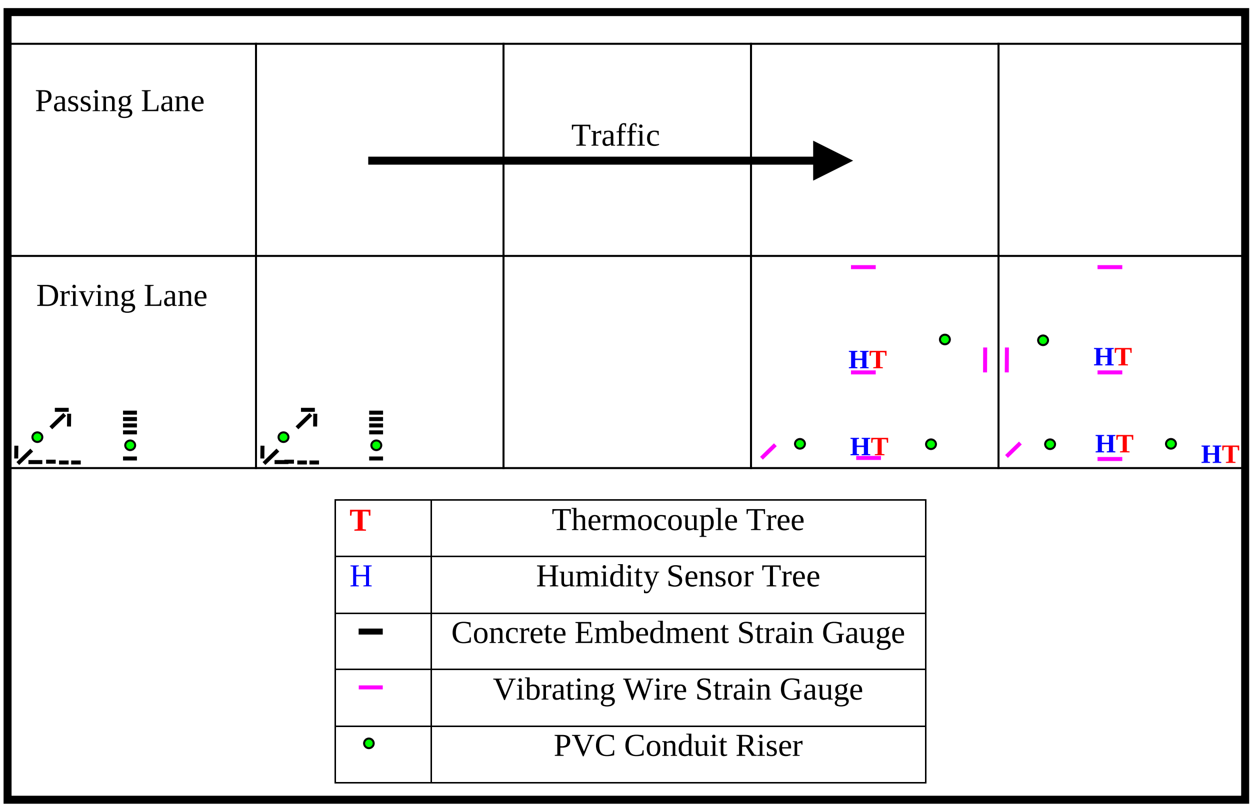


Figure 5: Instrumentation Layout – Cells 71 and 72

SECTION 2

CONSTRUCTION SEQUENCE

The following chapter summarizes the preparation and construction of the three composite cells and demo slab at MnROAD. The construction contract for SP 8680-159 for Cells 70, 71 and 72 was awarded to CS McCrossan, Inc. (CSM) for their low bid of $682,684. Construction was administered and inspected by WSB and Associates.

Mainline Pre-Construction and Demo Slab Paving

Construction of the three composite cells at MnROAD officially began on Monday April 12th, 2010 when the top soil of all three cells was stripped. The top soil berm was to be used for erosion control. The previously in place bituminous shoulders were milled to be used as reclaimed asphalt pavement by CSM. The existing concrete pavement in Cells 10 and 11 was broken, removed and hauled back to CSM to be crushed and used in the new first layer of the composite Cells 70 and 71.

Figure 6: PCC Removal

During the week of April 19th to the 23rd, the subgrade of Cells 70, 71 and 72 was trimmed with a trimming machine and compacted with a steel drum roller. MnDOT researchers collected samples and performed lightweight deflectometer, falling weight deflectometer and dynamic cone penetrometer testing. The class 7 aggregate base was constructed in two four inch lifts. MnDOT researchers placed metallic plates on top of the compacted subgrade and sensor conduits were installed throughout the base layers. Also during this week, the removed PCC was crushed at CSM to be used as recycled aggregate.

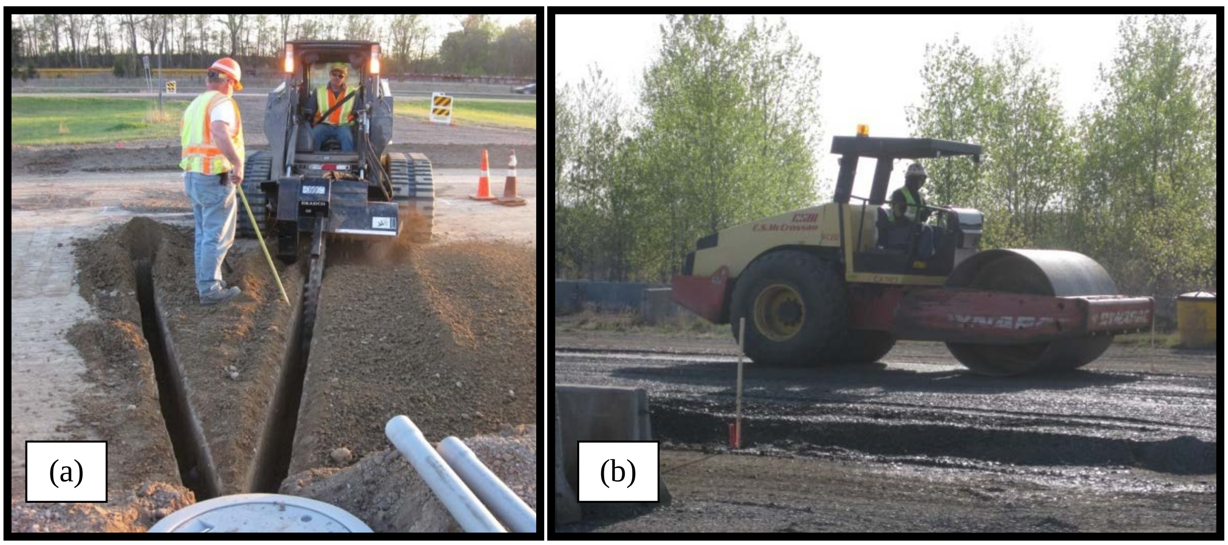


Figure 7: (a) Sensor Conduit Installation and (b) Subgrade Compaction

During the week of April 26th to April 30th before paving the new composite cells, work was done to prepare a demo composite pavement slab. The slab was to be 200 feet in length and was constructed in the stockpile area of the MnROAD research facility. 100 feet of the demo slab was paved using the low cost PCC mix, and the remaining 100 feet was done using the recycled concrete mix. Crews experienced issues with the workability and consistency of the recycled PCC mix. The slowed delivery was expected to influence the degree of bonding between the two layers. However, the issues seemed to be resolved near the end of the slab. The contractor initially experimented with the low cost mix. The first few batches were sent away for being too wet, but adjustments were made in subsequent batches to achieve the desired consistency. The top layer of the entire slab was paved using the exposed aggregate mix. This mix seemed to achieve the necessary properties for placement and finishing.

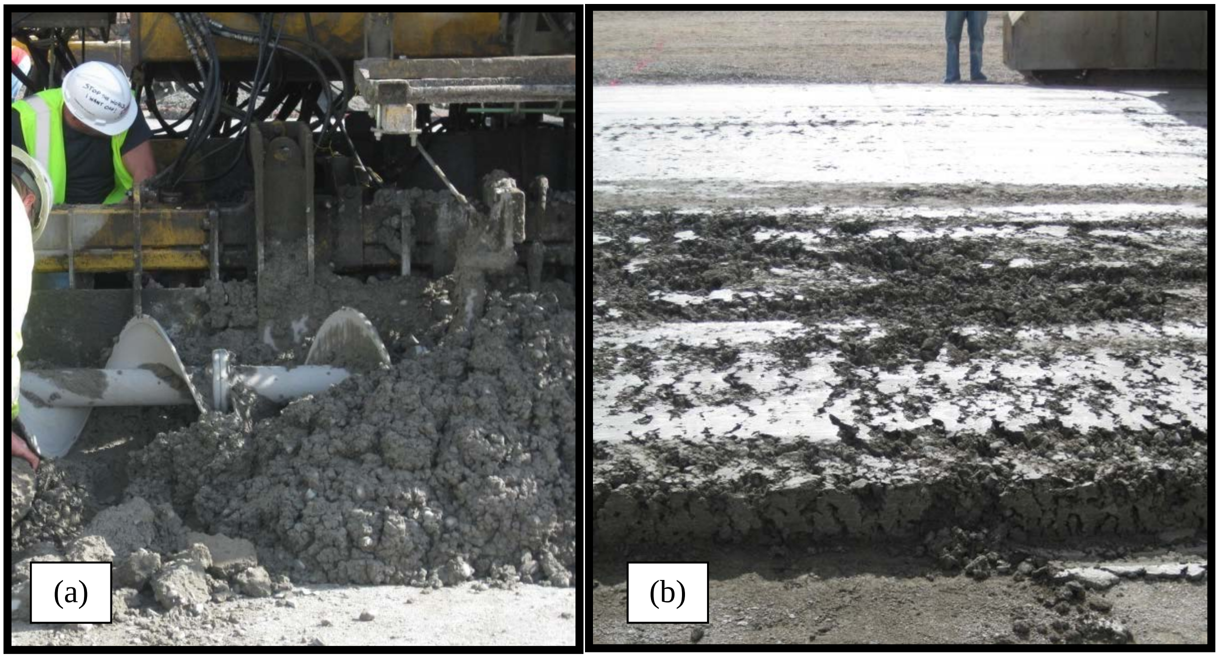


Figure 8: (a) Demo Slab Construction and (b) Demo Slab Bottom Lift

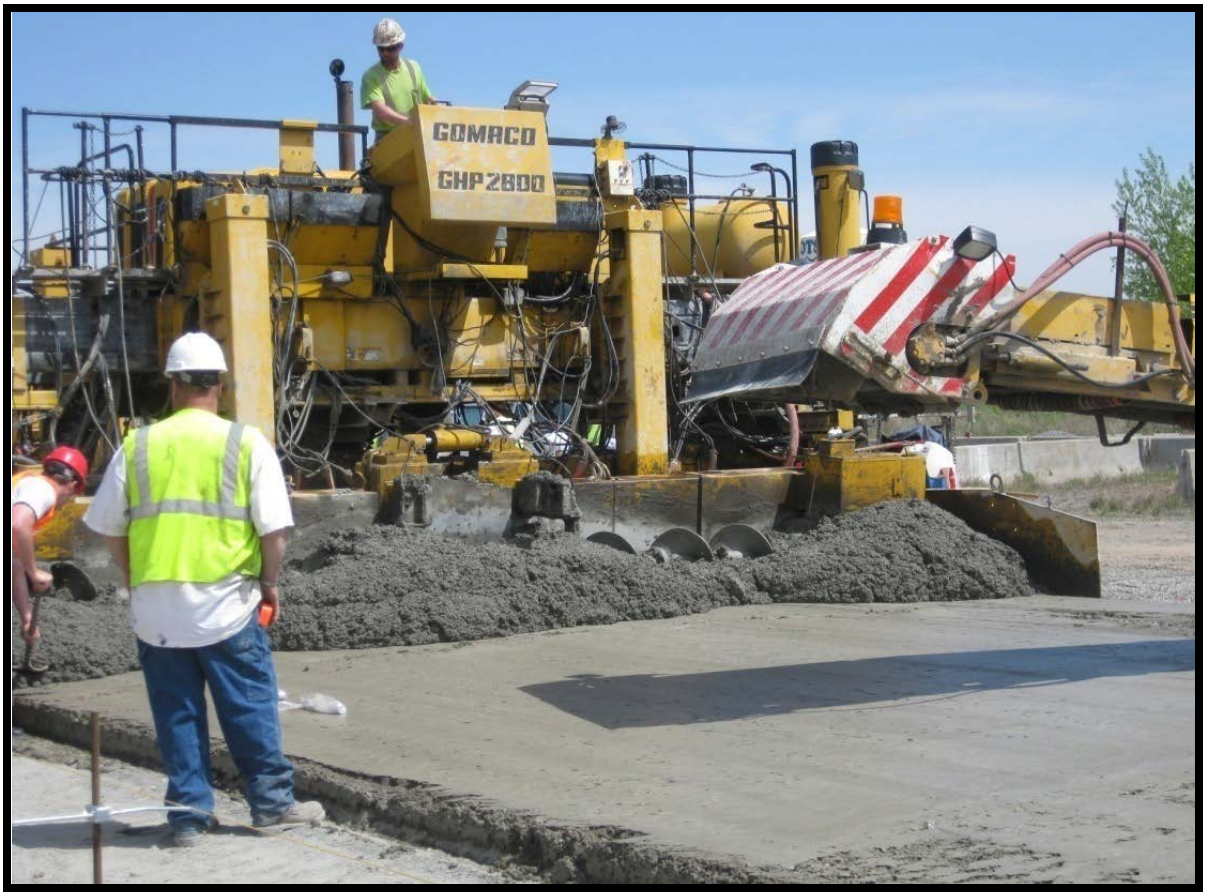


Figure 9: Demo Slab Construction

Figure 10: Demo Slab Finished Surface

Based on their experience with the demonstration slab, the Contractor was able to make adjustments to the concrete mixes and placement techniques for Mainline paving. After paving the demo slab, MnROAD and University of Minnesota personnel continued work on preparation of the aggregate base, sensor layout, and sensor installation for the three test cells.

Mainline Paving Construction

Paving of the composite cells on the Mainline of MnROAD began on May 5th 2010 with Cell 70. This cell was 474 feet in length, with the first composite layer consisting of 6 inches of recycled concrete aggregate concrete (RCA) and a 3 inch top composite layer of hot mix asphalt (HMA). The RCA was placed on May 5th. The HMA was to be placed over the hardened concrete on a subsequent date. The first few batches of RCA experienced some problems with consistency and air content compared the RCA used in the demo slab, with more desirable workability and a slump near 1.5 to 1.75 inches, allowing foot traffic after only 45 minutes. The table below shows the slump and air content of the RCA over the duration of paving.

Table 7: Cell 70 Fresh Concrete Testing

Mix	Time	Slump (in)	Air Content (%)
RCA	7:30 am	0.75	7.0
RCA	7:50 am	1.5	10.8
RCA	8:15 am	-	10.6
RCA	9:07 am	3.25	8.5
RCA	9:43 am	1.5	6.8
RCA	10:55 am	1.75	6.8

It began raining during the afternoon of paving Cell 70. However, paving finished fifteen minutes after the rain began, and the entire cell was covered with poly another thirty minutes later.

Figure 11: MnROAD Mainline Cell 70 – Lower Lift Construction

Paving of Cell 71 began on Thursday May 6th. The concrete supplier had a shortage of recycled aggregate concrete due to a 40% loss of the old PCC during washing and two loads of RCA being rejected for high slump. Consequently, Cell 71 only reached 266 feet in length. The paving, however, did not encounter any other issues in either the RCA or 3 inch layer of exposed aggregate concrete (EAC). The first load of RCA was poured by 7:56 am, and the last load was poured by 10:24 am. The first load of EAC was poured by 8:23 am and the last load by 11:22 am. The time between the two lifts varied between approximately 30 minutes to an hour while paving. The RCA achieved better slump and consistency than the demo slab. Table 2 shows the air content and slump of both the RCA and EAC in Cell 71.

Table 8: Cell 71 Fresh Concrete Testing

Mix	Time	Slump (in)	Air Content (%)
RCA	8:10 am	1.25	6.6
EAC	9:10 am	2.25	5
EAC	9:20 am	2.25	6.2

Figure 12: MnROAD Mainline Cell 71 Construction

The paving of Cell 72 was scheduled for Friday, May 7th; however rain forced a rescheduled date of Monday, May 10th. Cell 72 was constructed to be 681 feet long, accounting for the 208 feet which were not paved in Cell 71. Once again, this cell consists of a 6 inch layer of low cost concrete mix (LCC) and a wet-on-wet 3 inch overlay of exposed aggregate concrete (EAC). Paving encountered multiple obstacles throughout the day. Three loads of concrete were rejected, two by the contractor and one by MnDOT. The first load of low cost concrete was poured by 8:13 am, and the last load at 3:18 pm. The first load of top lift EAC was poured by 9:15 am, and the last load around 3:55 pm. Similar to Cell 71, the time between paving the top and bottom lifts varied between thirty minutes to over one hour as paving progressed. It began raining 15 minutes after the last load had arrived. The surface was treated with a MBT Reveal, a water-based top surface retarder intended for exposed aggregate concrete. After brushing of the cell to expose the aggregate surface, the slab was covered with plastic sheeting. Because of the complications from rain and low temperature, there were some difficulties in brushing of the surface. Table 3 below shows the slump and air content of the low cost concrete and the exposed aggregate concrete mixes.

Table 9: Cell 72 Fresh Concrete Testing

Mix	Time	Slump (in)	Air Content (%)
LCC	8:23 am	2.75	7.2
LCC	9:33 am	2.5	6.4
EAC	10:14 am	3.25	5.7
EAC	10:55 am	2.0	9.0
EAC	11:12 am	2.5	7.5

Figure 13: (a) Fresh Concrete Testing and (b) MnROAD Mainline Cell 72 Construction

Figure 14: MnROAD Mainline Cell 72 Construction

The morning of the day after paving of Cell 72, the surface of the remaining sections were brushed. This effort was much more successful at achieving the desired texture than the previous day. The plastic sheeting was removed from the cell. It rained on site after paving had been completed.

Figure 15: MnROAD Mainline Cell 72 Brushing (1)

Figure 16: MnROAD Cell 72 Brushing (2)

On Wednesday, May 12, MnDOT mix and repair procedures were used to repair the spalled concrete and a corner break on Cell 70 and a curing compound was applied to the slab. On Thursday, May 20th, the shoulders were prepared for a class 2 aggregate, the bituminous tack coat was placed on the concrete surface, and the paving of the HMA layer of Cell 70 was completed. This bituminous paving was done in two lifts. Over the next week, she second lift of shoulders was placed, joints were sawed and sealed in the HMA in Cell 70, and the aggregate shoulders were placed and sealed with asphalt emulsion.

Figure 17: (a) through (d) MnROAD Mainline Cell 70 - Top Lift Construction

On Tuesday, May 25th, the passing lane in Cell 71 was ground using the conventional diamond grind. The innovative diamond grind of the driving lane in Cell 72 was completed on the 27th. The final sweeping of the project was done on Friday, May 28th.

The week after paving had been completed was used for initial testing and evaluation. Cells 70, 71 and 72 on the Mainline were officially opened to traffic on Monday June 7th. Periodic lane closures were used to monitor the performance of the composite cells. Results from this evaluation will be discussed in the next chapter.

Time Lag between Lifts

The time between paving the first lift and second lift of "wet-on-wet" composite pavements is an important factor influencing the bond between the two layers. Although data is not available for the actual time lag between the two pavers during construction of Cells 71 and 72, the truck arrival time taken from the contractor's batch tickets can be used as a reasonable estimate for the time paving began. Each truck of bottom lift and top lift concrete delivered approximately 8 cubic yards of material. Because each cell is 24 feet wide (12 ft. driving and passing lanes), each load can pave approximately 18 longitudinal feet of bottom lift concrete and 36 longitudinal feet of top lift concrete. Using this information, the time lags between lifts have been estimated in the tables below and plotted in Figure 18. The rejected truck loads were not included in the calculations for the amount of material delivered.

Table 10: Time Lag Between Lifts – Cell 71

Longitudinal Feet Delivered	Time of Arrival		Paving Lag
	RCA	EAC	
16	7:56		
32	8:05	8:23	0:18
48	8:10		
64	8:12	9:10	0:58
80	8:15		
96	8:26	9:32	1:06
112	8:36		
128	9:17	9:42	0:25
144	9:24		
160	9:38	9:52	0:14
176	9:47		
192	9:59	10:22	0:23
208	9:58		
224	10:03	10:38	0:35
240	10:09		
256	10:16	11:00	0:44
272	10:24		
288		11:15	
304			
320		11:22	
Total	**RCA**	**EAC**	**Combined**
Number of Trucks	17	10	27
Longitudinal Feet Paved	266	266	

Table 11: Time Lag Between Lifts – Cell 72

Longitudinal Feet Delivered	Time of Arrival		Paving Lag
	LCC	EAC	
16	8:13		
32	8:23	9:15	0:52
48	8:30		
64	8:45	9:57	1:12
80	8:55		
96	9:20	10:14	0:54
112	9:28		
128	9:33	10:36	1:03
144	9:45		
160	9:48	10:55	1:07
176	9:54		
192	9:58	11:12	1:14
208	10:03		
224	10:18	11:41	1:23
240	10:25		
256	10:39	11:49	1:10
272	10:45		
288	11:00	12:05	1:05
304	11:05		
320	11:20	12:16	0:56
336	11:29		
352	11:41	12:38	0:57

Longitudinal Feet Delivered	Time of Arrival		Paving Lag
	LCC	EAC	
368	11:56		
384	12:04	12:58	0:54
400	12:18		
416	12:37	13:34	0:57
432	12:48		
448	12:53	13:26	0:33
464	13:04		
480	13:09	13:38	0:29
496	13:17		
512	13:20	14:27	1:07
528	13:31		
544	13:35	14:51	1:16
560	13:41		
576	13:42	14:51	1:09
592	14:04		
608	14:13	15:03	0:50
624	14:32		
640	14:37	15:14	0:37
656	14:45		
672	14:56	15:25	0:29
688	15:18		
		15:55	

Total	LCC	RCA	Combined
Number of Trucks	22	11	33
Longitudinal Feet Paved	688	688	

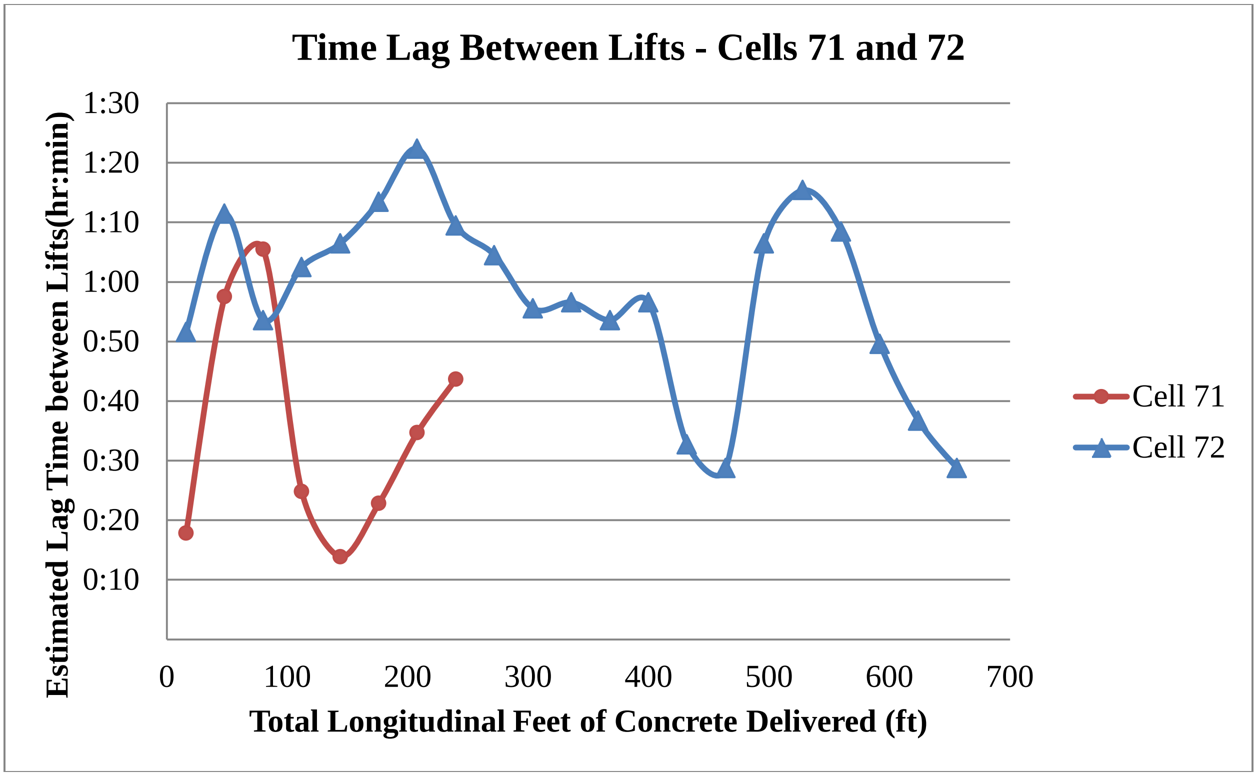


Figure 18: Time Lag Between Lifts – Cells 71 and 72

This plot clearly illustrates the differences in lag time between the two cells and within the cells themselves. Cell 72; however, does seem to generally have a much longer delay in paving between the two lifts than Cell 71. This may be because construction of the top lift of Cell 71 began much sooner after the bottom lift than in 72. However, paving of the top lift in Cell 71 seemed to slow down as time went on, with the major drop in lag time due to two loads of lower lift concrete being rejected. The lag between lifts in 72 seems to be more erratic, with more frequent jumps and dips. The two plots below show progression of each lift separately to illustrate which layer was experiencing delays. A larger gap between the two lines corresponds to a longer lag between pavings of the two lifts.

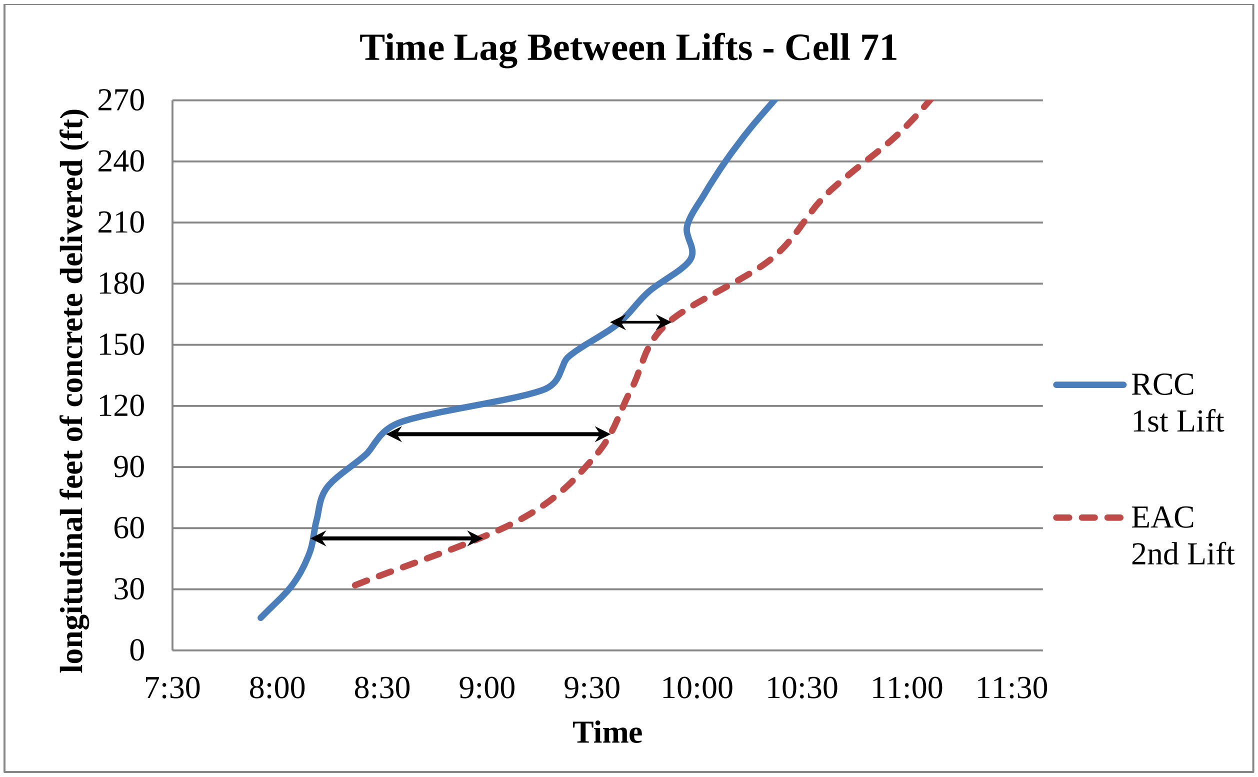


Figure 19: Time Lag Between Lifts – Cell 71

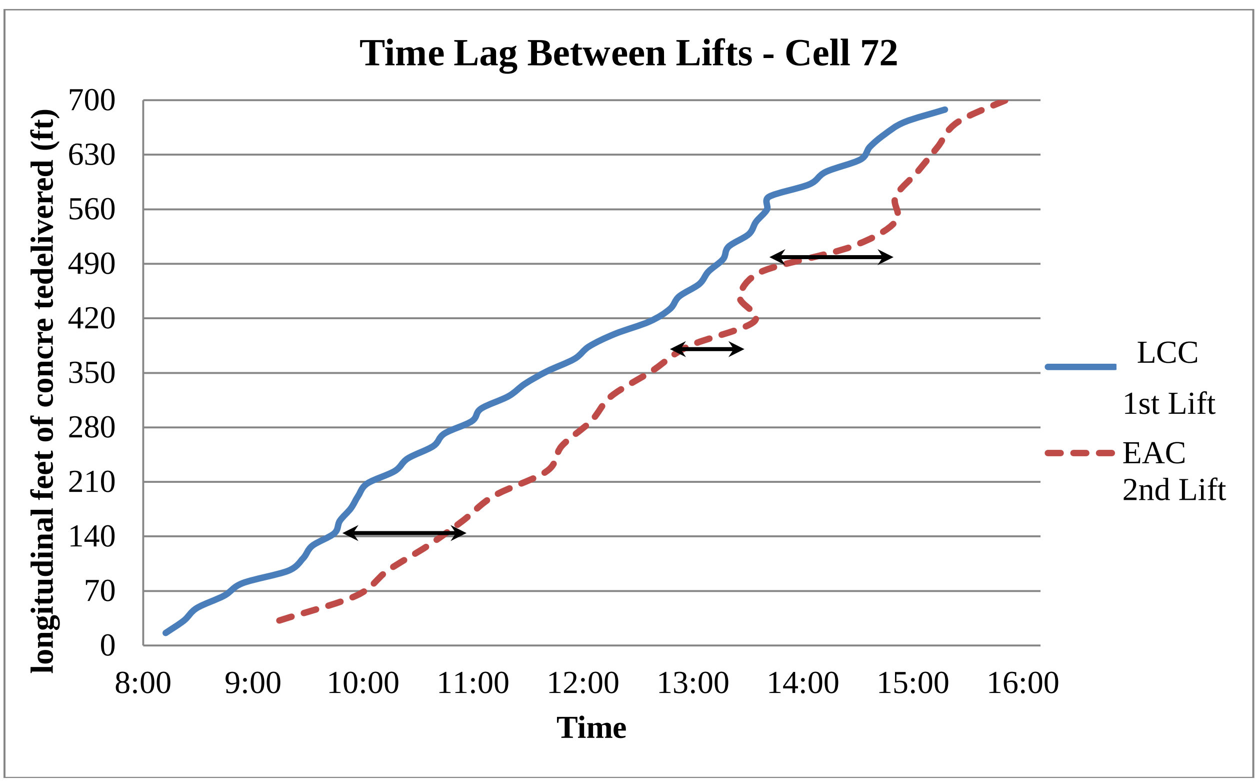


Figure 20: Time Lag Between Lifts – Cell 72

SECTION 3

EARLY PERFORMANCE EVALUATION

The last chapter described the construction method of the three composite test cells at the MnROAD facility. This chapter will provide the test methods and results from the early performance assessment of the Cell 70 (hot mix asphalt over recycled aggregate concrete), Cell 71 (diamond ground concrete over recycled aggregate concrete) and Cell 72 (exposed aggregate concrete over low cost concrete). Flexural, compressive and bond strength, along with noise and surface characteristics of the three cells will be discussed in this chapter. This includes on board sound intensity, sound absorption, friction, and surface texture and the international roughness index. Coefficient of thermal expansion results from testing conducted by the FHWA's Mobile Concrete Laboratory will also be discussed in Appendix C of this report.

Compressive, Flexural and Bond Strength

Compressive and flexural strength specimens were made at the construction site at the time of paving using the three different concrete mixes used in Cells 70, 71 and 72. Composite beams with 2 different mix layers were made using different combinations of the three mixes. The specimens were transported back to the MnDOT Office of Materials and Road Research after initial curing. They were tested by the concrete laboratory staff using ASTM C39, standard test method for compressive strength of cylindrical concrete specimens, and ASTM 257, standard test method for flexural strength of concrete using a simple beam with third-point loading. The results are shown in the plots below.

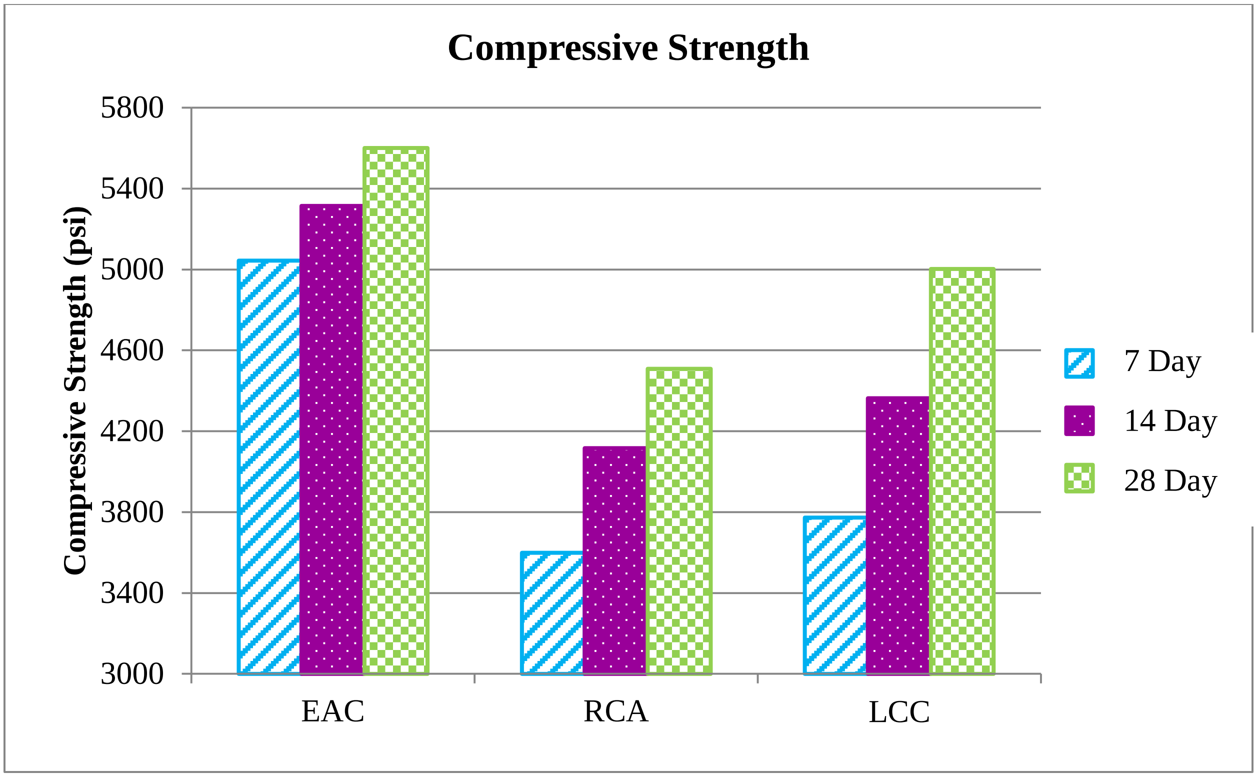


Figure 21: Compressive Strength

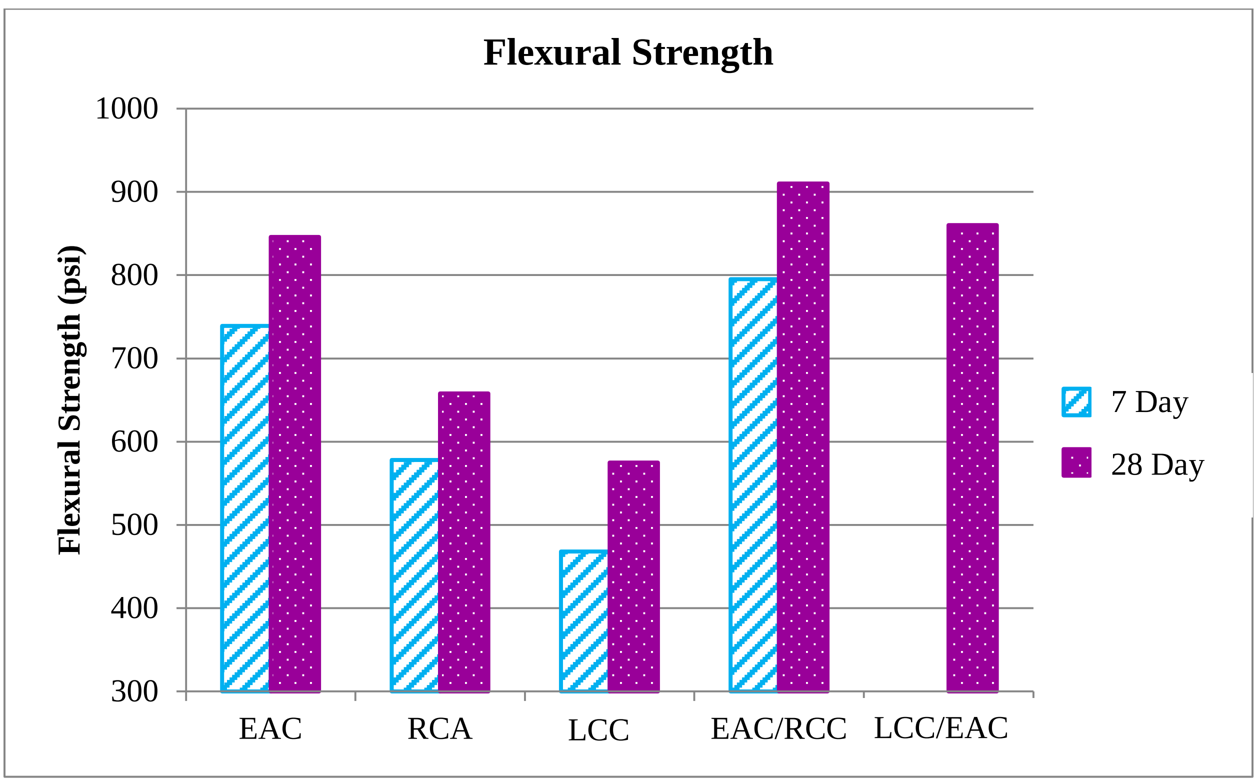


Figure 22: Flexural Strength

As expected, the exposed aggregate concrete achieved higher flexural and compressive strength than the low cost mix and the recycled mix. This difference in strength illustrates the change in quality between the two layers of the composites. Interestingly, however, the two composites (exposed aggregate concrete with both the low cost mix and the recycled mix) achieved slightly higher strength than the fully exposed aggregate concrete beams. When the composites were tested, they were placed in the third point bending machine such that the exposed aggregate concrete layer was in tension, and the lower quality (RCA or LCC) mix was in compression. Because of this load orientation, the measured flexural strength was essentially the strength of the exposed aggregate concrete. This explains why exposed aggregate beam and the composite beams achieved comparable flexural strengths. In the future, composite beams should be tested in a multitude of different orientations, with the bond plane both vertically and horizontally, to avoid this phenomenon.

The bond strength between the two layers of the composite pavements is another very important property that may influence long term performance. Due to the brittle nature of concrete, it is difficult to test bond strength by applying tension. Instead, slant-shear cylindrical specimens were made to test bond strength in accordance with ASTM C882, standard test method for bond strength of epoxy-resin systems used with concrete by slant shear. The specimens were made at the paving site by bonding two layers of concrete, EAC over LCC or EAC over RCA, at an angled plane in a cylinder. An example of a slant shear specimen is shown in Figure 23. The two layered specimen is then tested in compression. Due to the specific angle of the bonded plane and the resulting stresses at the interface layer, the measured maximum applied compressive load is the bond strength between the two layers. The following plot shows the measured bond strengths of EAC over RCA from Cell 71 and EAC over LCC from Cell 72. Specimens were also made and tested using the concrete from the demo slab.

Figure 23: Slant Shear Specimen

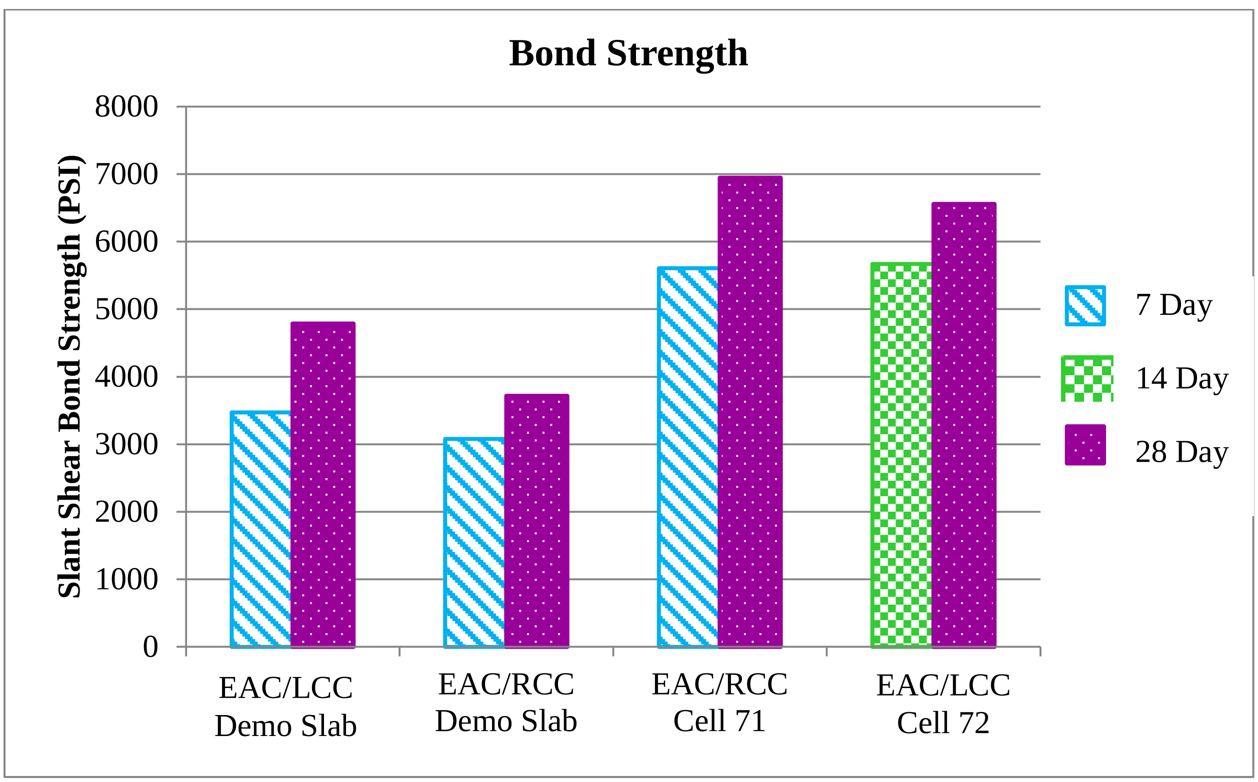


Figure 24: Bond Strength

All of the specimens tested achieved a bond strength above 1000 psi, the minimum to be considered adequate a bond between concrete in pavement applications. It is interesting to note the reduced bond strength in the specimens made from the demo slab concrete. Also, the bond between EAC and LCC seems to be stronger than the EAC and RCA in the demo slab concrete, however the opposite trend was observed in the specimens made from Cells 71 and 72.

On Board Sound Intensity

The On Board Sound Intensity (OBSI) test measures the noise generated from the tire – pavement interaction. MnDOT became one of only five states to utilize OBSI when it began testing in 2007. One advantage of using the OBSI method to measure sound generation making it favored to the traditional Statistical Pass By Method is that it allows the noise generated from the pavement-tire interaction to be isolated from other sources, such as engine noise and the surrounding landscape noise. OBSI testing is done according to the AASHTO TP 79-08 procedure. The process analyzes data recorded with microphones located close to the tire-pavement contact. The dominant noise generation source becomes the tire-pavement interaction when cars travel at freeway speeds. Therefore, the test is performed at 60 mph over a 440 foot stretch of pavement to adequately capture the desired noise source.

The OBSI test set-up consists of a sedan outfitted with four Gras sound intensity meters, a Bruel and Kjaer front-end four-channel frequency analyzer and a standard reference test tire (SRTT). The microphones are suspended from the vehicle frame and positioned at 3 inches vertical displacement and 2 inches lateral displacement from the leading and trailing end of the standard reference tire and pavement contact. The microphones are anchored to a free rotating ring mounted on the right wheel that allows the microphone assembly to be fixed in position and direction without inhibiting the rotation of the tire.

Figure 25: OBSI Device

PULSE noise-and-vibration software is installed in a connected computer. The computer receives and analyzes the data categorizing the response into component third octave frequency output. Pavement noise response from the microphones is condensed into a third octave frequency sound intensity plot averaged for the leading edge and trailing edge. The OBSI parameter is the average of the logarithmic sum of the sound intensity at 12 frequencies **(**400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, and 5000 Hz). OBSI analysis is based off the AASHTO TP76-08 protocol. It is computed for the two microphones using the following equation, where SI_i (i= 1, 2, 3…12) are sound intensities in dBA at each of the 12 third octave frequencies.

$$OBSI = 10 * \log(10^{SI_1/10} + 10^{SI_2/10} + \ldots + 10^{SI_{12}/10})$$

The implication of an OBSI difference in terms of actual percentage reduction in sound level deserves explanation. A 3-dBA reduction is tantamount to approximately 50 percent loss of sound intensity from a uniform source. If $OBSI_1 - OBSI_2 = n$, and the respective sound intensities are I_1 and I_2 in Watts /m^2 respectively, then 10 log $\left(\frac{I_2}{I_0}\right) - 10 \log \left(\frac{I_2}{I_0}\right)$ equals n, where I_0 is the sound intensity at the threshold of human hearing. Therefore, $\left(\frac{I_2}{I_1}\right) = 10^{\frac{n}{10}}$. For instance, when the difference in OBSI is equal to 3 dBA, the ratio of actual sound intensity is 2.

When the difference in OBSI is equal to 6 dBA, the ratio of sound intensity is 4. The results from OBSI testing done in 2010 are shown in the plots below.

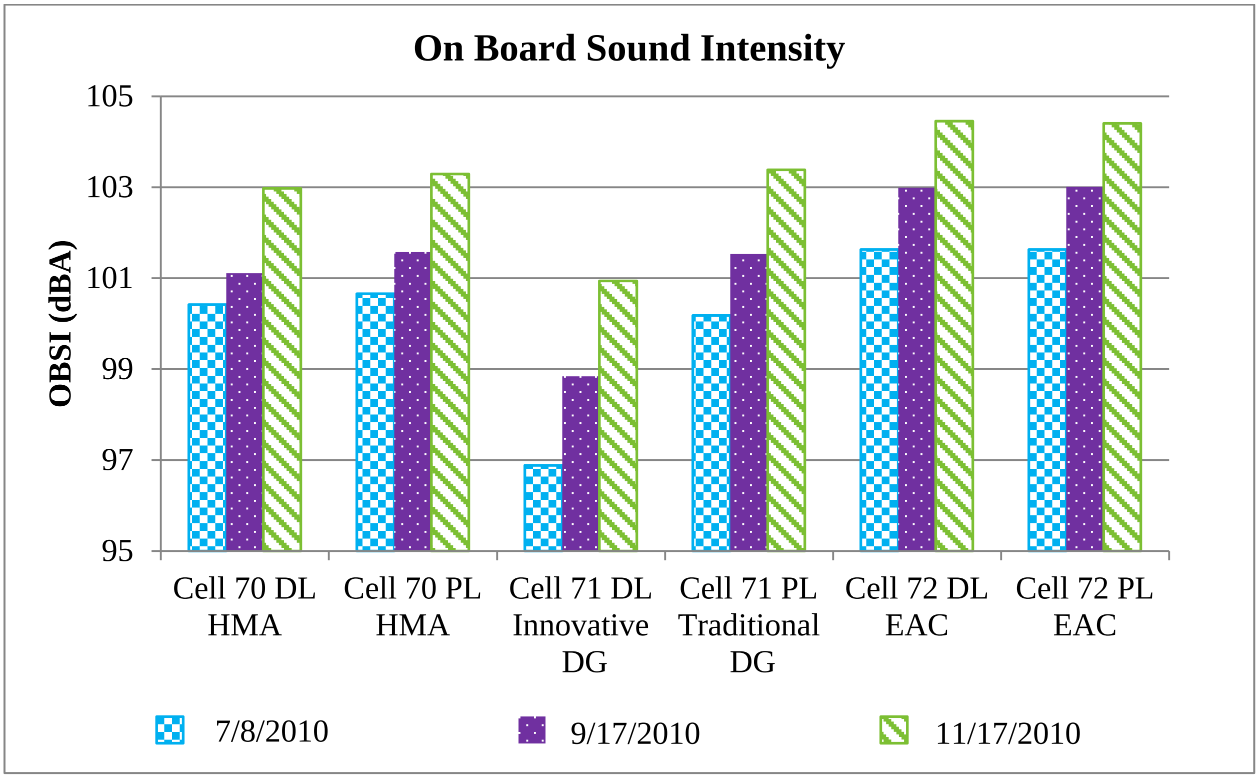


Figure 26: OBSI – All lanes

This chart shows that the innovative diamond ground exposed aggregate concrete in Cell 71 has the lowest OBSI throughout the three months tested. The traditional diamond grind has similar OBSI to the hot mix asphalt. More significantly, the exposed aggregate finish consistently has the highest OBSI. There is not a considerable difference between the OBSI in the passing lane versus the inside lane in either Cells 70 or 72. Pavements are usually considered quiet when they achieve an OBSI less than 100 dBA, in which case the data suggests that the diamond grind in Cell 71 is the only composite pavement to be considered quiet. In a survey of exposed aggregate concrete pavements in Europe conducted by the National Concrete Pavement Technology Center, OBSI values were found to range from 101 to 106 dBA, which is similar to the results obtained for Cell 72 [4]. The 1/3 octave sound intensity spectrums used to calculate the OBSI values above are show in the following three figures. All cells show similar shape in their sound intensity spectra.

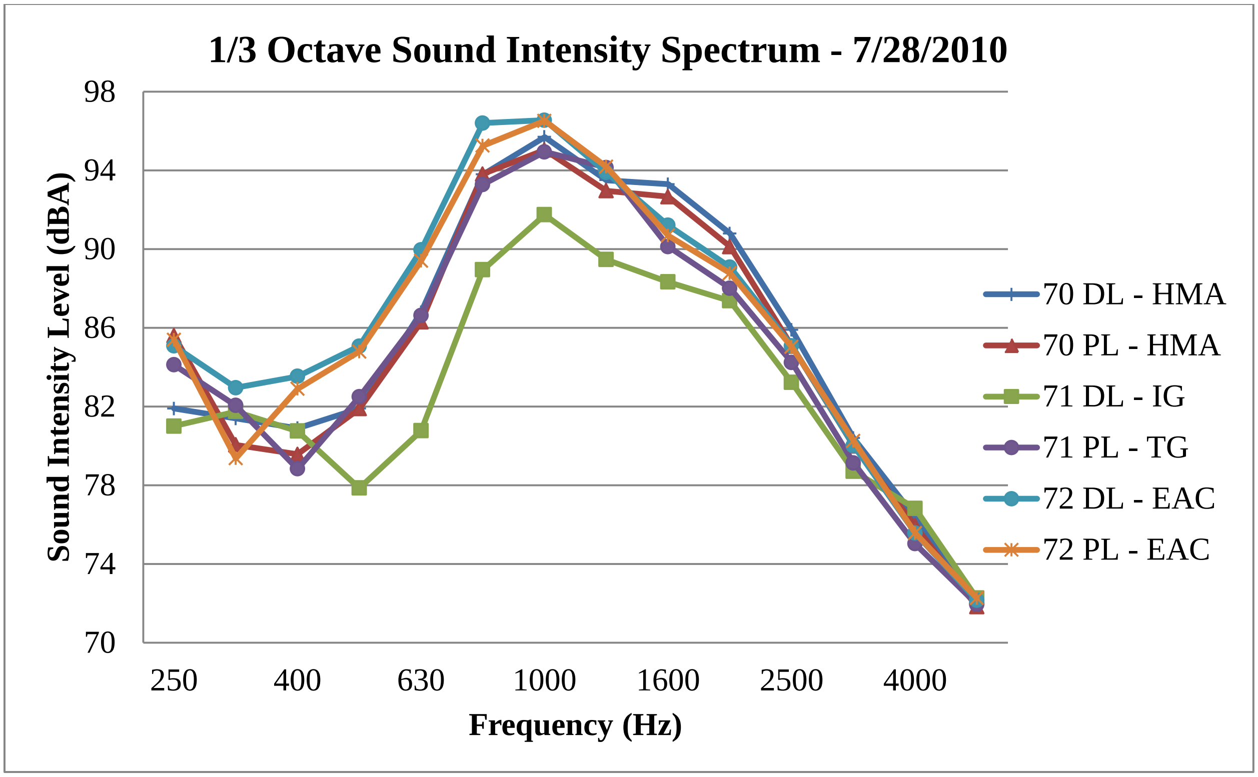


Figure 27: Sound Intensity Spectrum – 7/28/2010

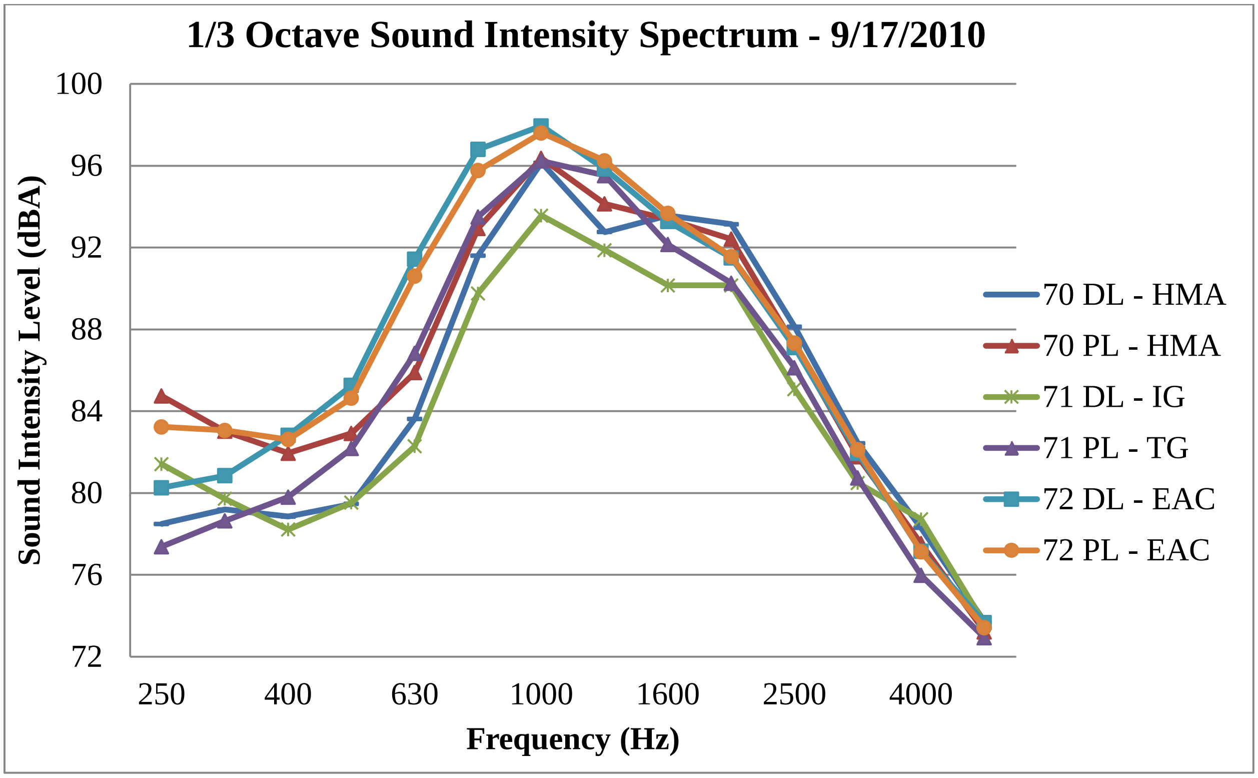


Figure 28: Sound Intensity Spectrum – 9/17/2010

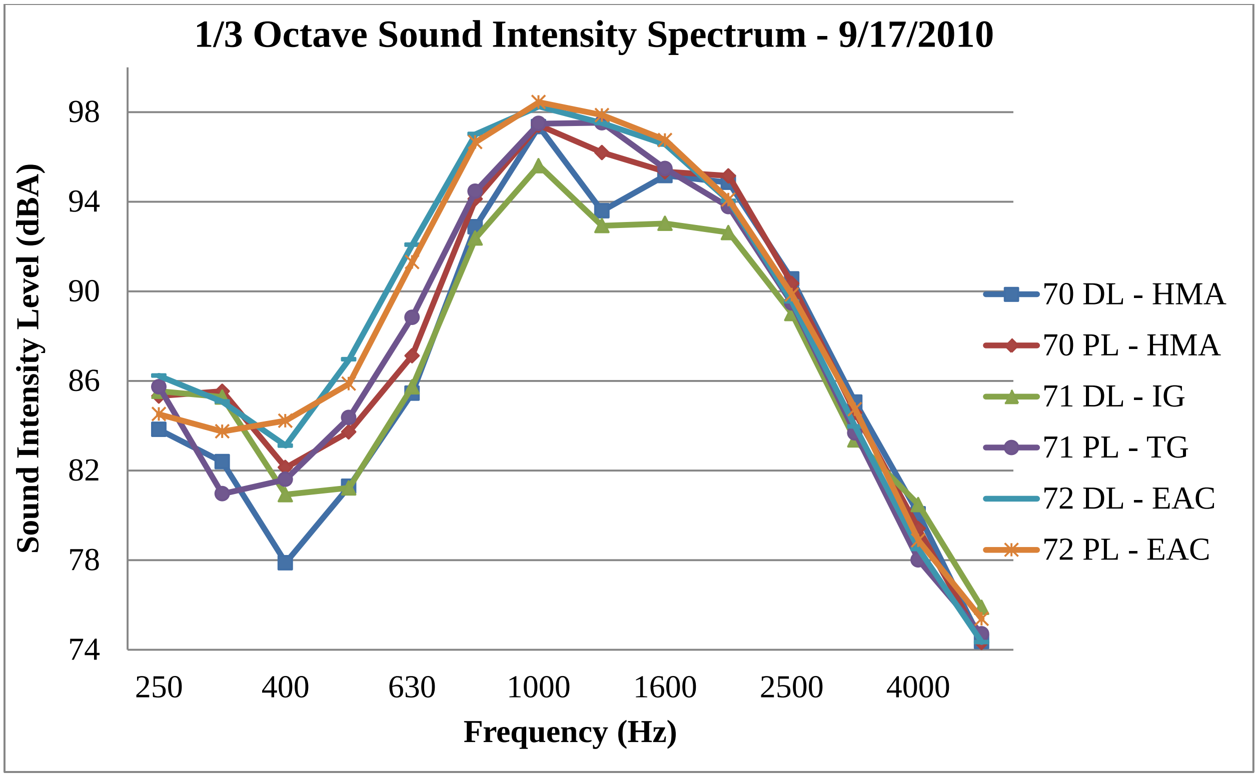


Figure 29: Sound Intensity Spectrum – 9/17/2010

Sound Absorption

The Sound Absorption Coefficient is the ratio of the absorbed sound energy to the transmitted sound energy of the pavement surface. The ratio is measured when a white noise of frequency ranging from 315 to 1800 Hz is projected into the pavement within an impedance tube placed normal to the pavement surface. The setup for measuring Sound Absorption using a BSWA 425 device is shown in Figure 30.

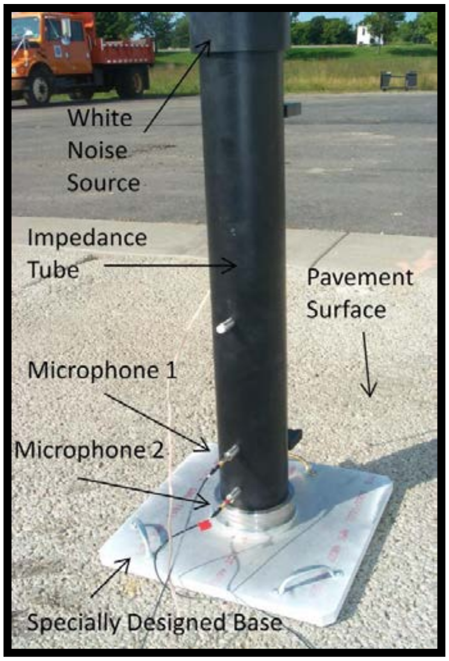


Figure 30: Sound Absorption Impedance Tube

During the sound absorption test, the sound analyzed is generated by a white noise source above the impedance tube. White noise is a random audio signal with a flat power spectral density that contains noise at the same power at all frequencies. During the test, the impedance tube is placed on the pavement surface and a set of sensitive microphones are attached to the pre-installed housing at the lower end of the tube. These microphones are also connected to an analyzer. The noise source sends the incident sound energy (white noise) to the surface and the incident and reflected waves are captured by the two microphones. Software then windows the reflected waves and converts the data to the 3rd octave sound absorption coefficient at 315, 400, 500, 750, 1000, 1250 and 1650 Hertz. A range of frequencies of the n-th octave are determined by the following equation.

$$For\ the\ n^{th}\ octave: \quad \frac{F_{n+1}}{F_n} = 2^{\left(\frac{1}{n}\right)}$$

$$Such\ that\ if\ \ n = 3\ \ and\ F_1 = 400\ Hz$$

$$F_2 = 400 * \ 2^{\left(\frac{1}{3}\right)} = 500\ Hz$$

$$F_3 = 500 * \ 2^{\left(\frac{1}{3}\right)} = 630\ Hz \ldots$$

Sound absorption coefficients range between one and zero, where a value of one would mean that all of the sound is being absorbed.

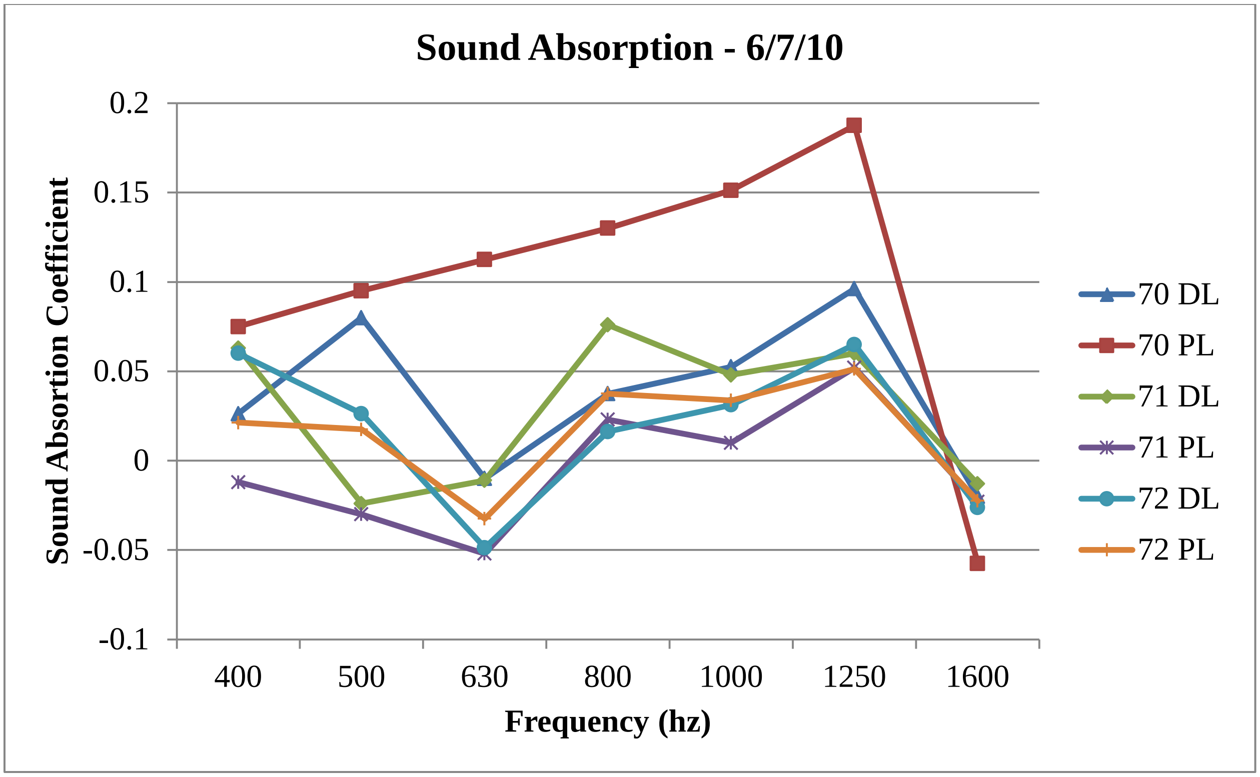


Figure 31: SA Coefficient Spectrum – 6/7/10

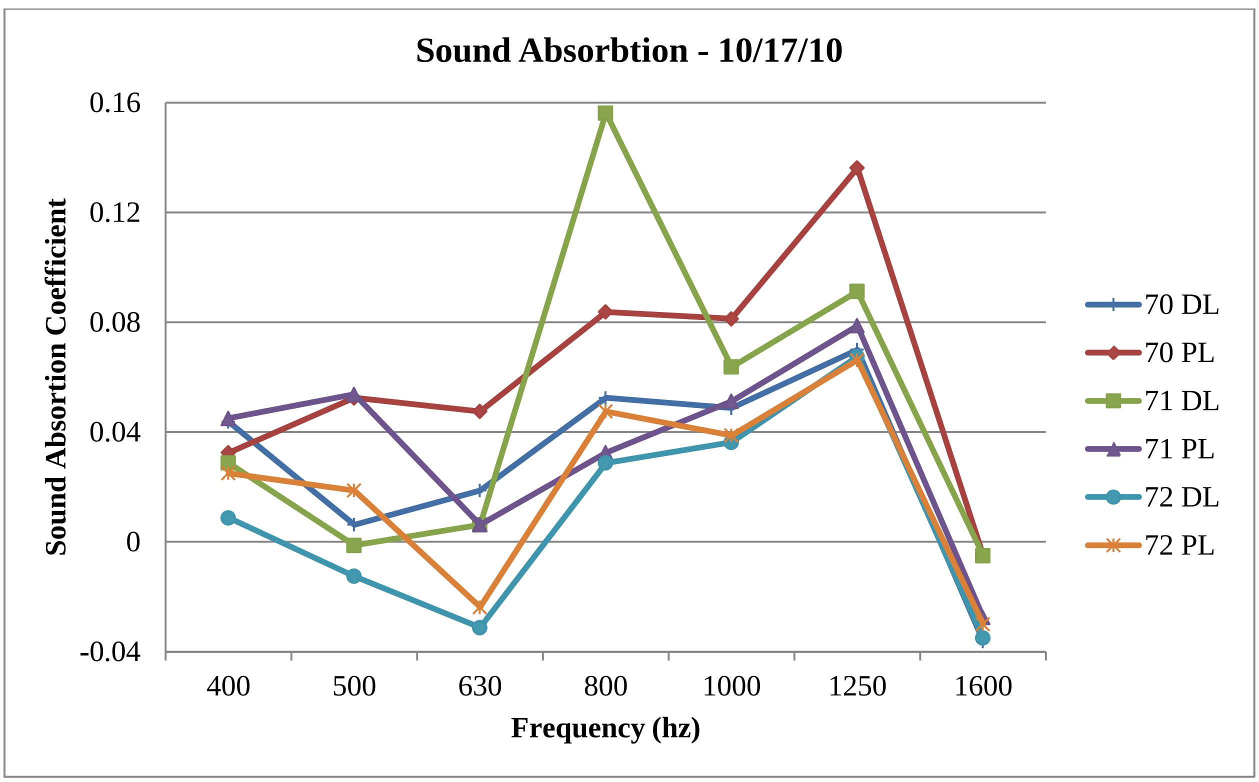


Figure 32: SA Coefficient Spectrum – 10/17/10

The negative sound absorption coefficients in the plots above imply that more sound is being measured by the microphones than is being emitted from the noise source. This suggests that there was “contamination” during testing and the tube-base combination did not adequately block sound from outside noise sources. For a more useful comparison between the sound absorption in different cells, the absorption coefficients at 1,000 Hz are given in the chart below. The 1,000 Hz frequency is chosen because it is commonly considered the frequency at which the tire-pavement interaction noise is the highest [5].

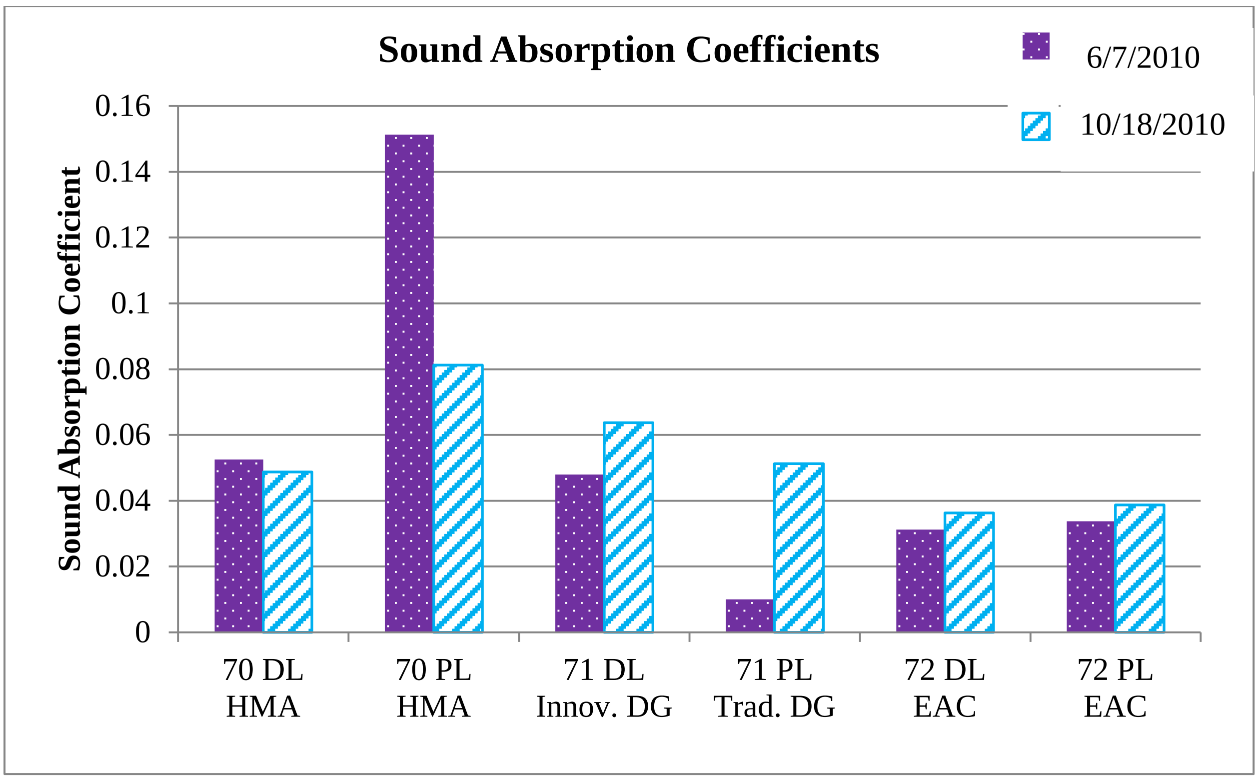


Figure 33: Average SA at 1000 Hz – All Cells

The hot mix asphalt shows the highest sound absorption of all the composite cells. The diamond grind in Cell 71 generally has higher absorption than the exposed aggregate in Cell 72. As expected, the innovative diamond grind has higher sound absorption than the traditional diamond grind.

Friction

The standard method for testing friction at MnROAD utilizes the KJ Law Friction Trailer to perform skid testing of the pavement surface. Friction testing is done in accordance with the following three ASTM standards: ASTM E274 standard test method for skid resistance of paved surfaces, ASTM E501 skid testing using a standard ribbed tire, and ASTM E524 skid testing using a smooth tire. Both ribbed and smooth tires are used because they each measure adhesion and hysteresis differently. Since the ribbed tire removes the water from the surface more efficiently than the smooth tire, it generally examines the pavement friction on the micro-texture portion. The smooth tire, however, is more affected by the macro-texture. If the macro-texture doesn't adequately drain water on the pavement surface, the smooth tire will hydroplane and result in lower friction values. The locked-wheel skid trailer and truck setup is shown in the figure below.

Figure 34: KJ Law Friction Trailer and Truck

The vehicle carries a supply of water that is sprayed directly in front of the test tire to test the pavement when it is wet. The trailer is towed behind a vehicle at a speed of 40 miles per hour to measure the coefficient of friction. When the skid trailer reaches the testing area, a measured amount of water is applied to the pavement in front of the test tire. Then the tire, ribbed or smooth, locks in place and the wheel is pulled along for a specified length. This setup applies both vertical load forces and horizontal drag forces to the pavement. The device measures the amount of tractive force required to pull the trailer. The measured force is then sent to a laptop, which is stored inside the tow vehicle. Finally, the friction number is calculated by the ratio of tractive force to the known wheel load multiplied by 100.

The test is performed on both wheel paths: left wheel path for the ribbed tire and right wheel path for the smooth tire. The test generates friction numbers ranging from 0 to 100, with higher numbers indicating higher friction. A pavement with a friction number of 25 from a smooth tire is considered a safe pavement with adequate skid resistance, while a pavement with a friction number less than 15 would require rehabilitation to achieve sufficient skid resistance [6]. The measured friction numbers from Cells 70, 71 and 72 using both a ribbed and smooth tire are shown below.

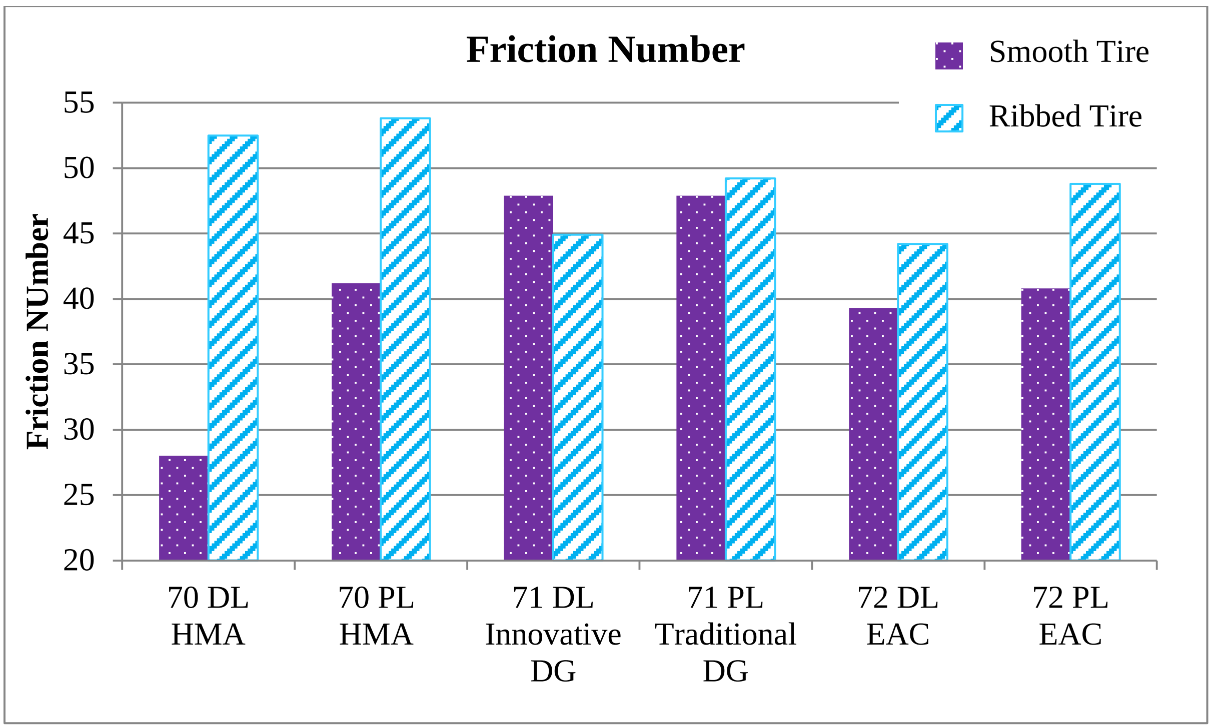


Figure 35: Friction Number

This plot shows that all three test cells achieved adequate skid resistance for driver safety. The hot mix asphalt in Cell 70 achieved the highest friction number when testing with the ribbed tire, but achieved the lowest friction number with testing with the smooth tire. The diamond grind in Cell 71 consistently achieved better friction that the exposed aggregate in Cell 72. However, this difference is only significant in tests done with the smooth tire. When testing with the ribbed tire, the diamond grind and exposed aggregate achieved comparable results.

Texture

The circular track meter (CTM) shown in Figure 36 below is a laser-equipped device that scans the surface of a pavement in accordance with ASTM E2157. The CTM is equipped with a charged coupled device (CCD) laser displacement sensor that sweeps the pavement surface in a circle 11.2 inches in diameter and 35 inches in circumference. The displacement sensor for this instrument is mounted on an arm that rotates at 3 inches (80-mm) above the surface. The arm moves at a tangential velocity of 6 m/min. Using this mounting, the CCD displacement is sampled 1,024 times per revolution, providing a sample spacing of 0.87 mm. The data is segmented into eight 111.5 mm arcs of 128 samples each. From each segment, the computer software computes the mean profile depth (MPD), the root-mean-square texture depth (RMS) of each segment, and the average of all eight-segments. A plot of the 8 segments of MPD is also produced. This plot is difficult to decipher unless the sweeping action of the laser in each sector is visualized. Effectively, only 2 of the 8 segments mimic the texture. The mean profile depth generated from the CTM on two different occasions is shown in the plot below.

Figure 36: Circular Track Meter

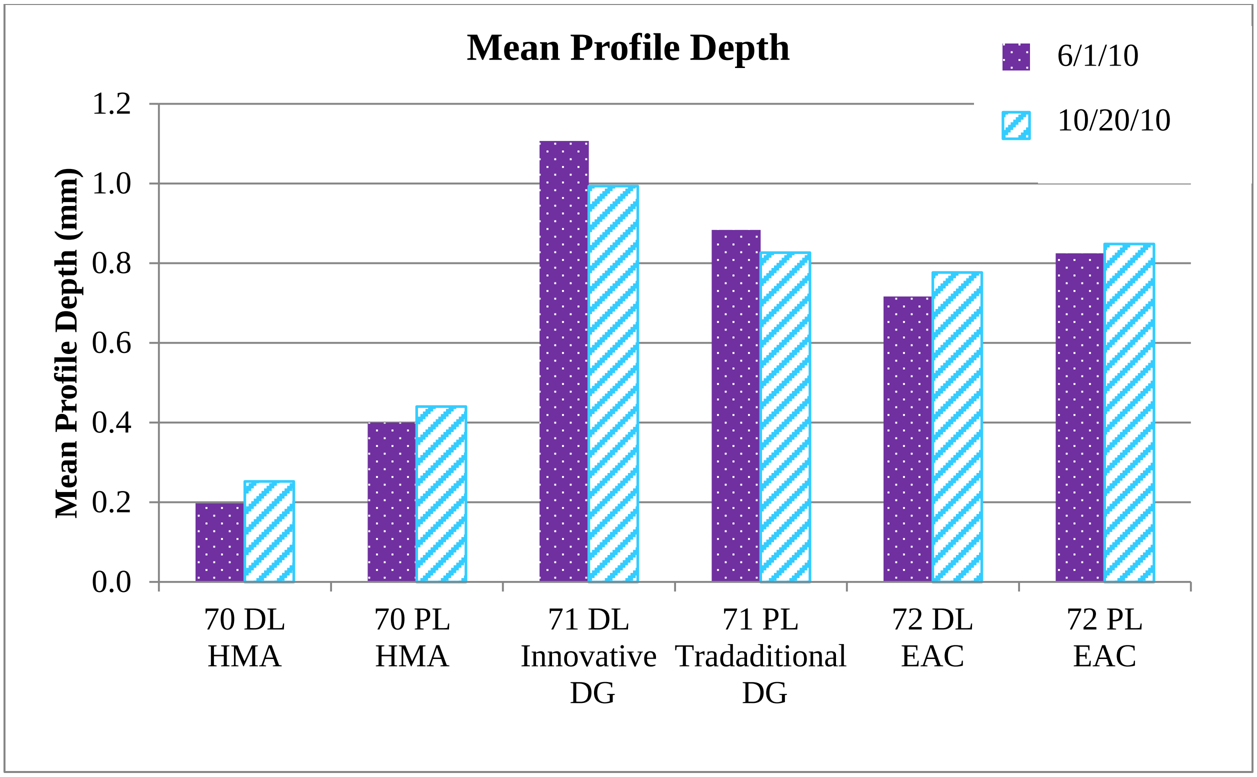


Figure 37: Mean Profile Depth

The diamond grind in Cell 71 and the exposed aggregate in Cell 72 have significantly higher mean profile depth (MPD) than the HMA in Cell 70. There is a consistent increase in MPD from the driving lane to the passing lane for Cells 70 and 72, which suggests traffic loading can influence pavement texture. The innovative diamond grind in Cell 71 was consistently higher than both the traditional grind and the exposed aggregate concrete. There was no trend in the change in MPD from summer to winter months.

International Roughness Index

The international roughness index (IRI) is the universally accepted standard measure of ride quality and pavement smoothness. IRI is a mathematical property of a two-dimensional road profile, or a slice of the road showing elevation as it varies with longitudinal distance along a travelled track. The international roughness index is based on the vertical acceleration of a quarter car's suspension in response to a pavement surface while riding at speed of 50 miles per hour. More specifically, IRI is the sum of the quarter car's vertical displacement from an assumed neutral plane surface per unit horizontal distance traveled. This measurement is only as good as the degree to which the applied ride algorithm responds to the preponderant frequencies in the pavement surface. Because the rider tends to be more sensitive to certain frequencies than others, the response multiplier algorithm shown in Figure 38 is applied when calculating IRI to more accurately mimic the human response. The IRI multiplier algorithm is not uniform in all wavelengths. The gain algorithm peaks at the quarter car resonant frequencies as well as what are assumed to be the body excitation frequencies. Wavelengths that are considered to significantly reduce rider comfort receive higher gain in the IRI algorithm.

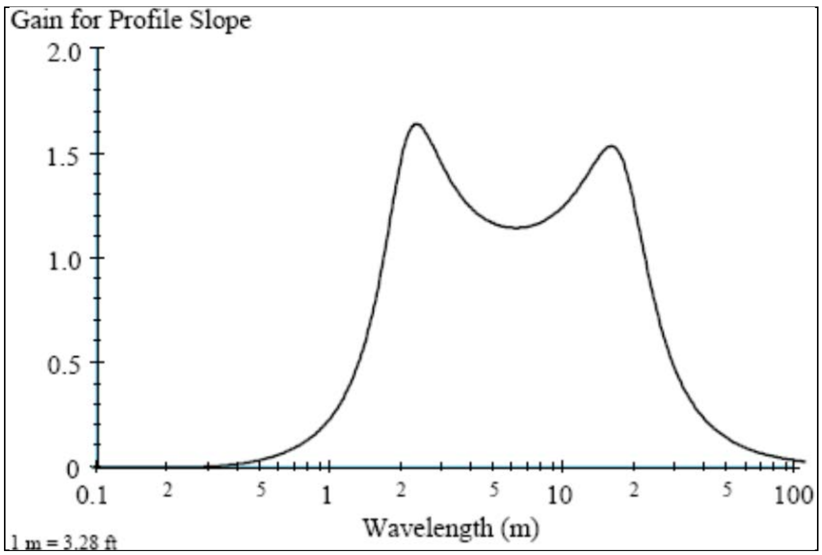


Figure 38: IRI Multiplier Algorithm

IRI can be calculated from profiles obtained with any valid measurement method, ranging from static rod and level surveying equipment to high-speed inertial profiling systems. MnDOT measures IRI with a Lightweight Inertial Surface Analyzer (LISA) shown in Figure 39. The LISA is a profile device that measures the amount of vertical rise over a horizontal distance. This is done with two separate laser sources on the side of the vehicle. One laser takes continuous profile measurements over a four inch path while the other measures three discrete profiles across the four inch path. The raw data from these lasers is then used to calculate the IRI, with higher IRI corresponding to rougher pavement. IRI measurements of the composite cells made using the LISA device are shown in Figure 40 below.

Figure 39: Lightweight Inertial Surface Analyzer

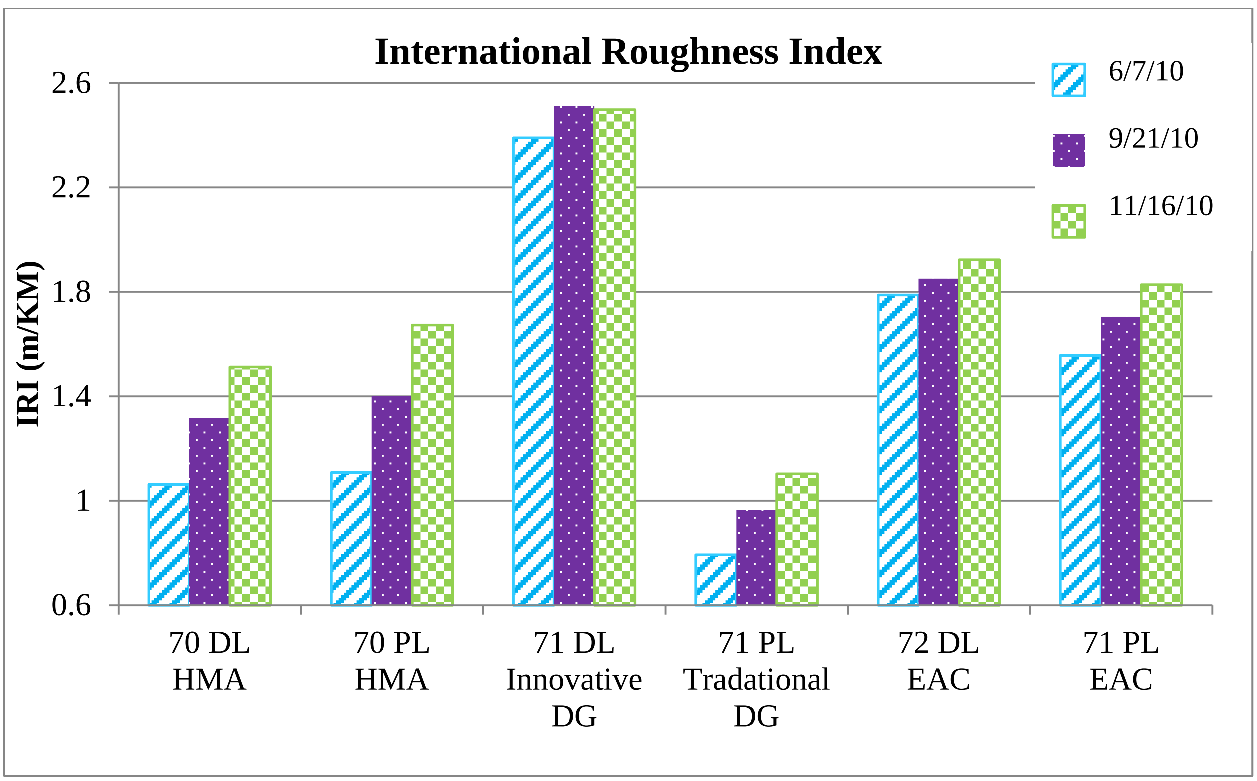


Figure 40: International Roughness Index

The FHWA roughness categories place pavements with IRI values less than 1.5 as in "good" condition, while pavements with an IRI more than 2.6 are considered "unacceptable". By this standard, all test cells achieved acceptable IRI, but only the hot mix asphalt and traditional grind concrete were categorized as “good” pavement. More significantly, the exposed aggregate has higher IRI values than all surfaces except for the innovative diamond grind.

Warp and Curl

MnDOT recently developed the second Automated Laser Profile System (ALPS 2) to analyze ‘warp and curl’ that pavements experience. Pavement warping and curling refers to the bending stresses caused by temperature and moisture differentials throughout the pavement depth. For example, during evening hours when the ambient temperature drops, the top portion of the pavement cools quickly while the bottom remains heated. This causes the pavement to curl upwards while the weight of the slab acts as the restraint producing bending stresses. A similar effect can occur in the afternoon, when high ambient temperatures heat the pavement surface while the lower pavement stays cool. Some believe that composite pavements may have the ability to mitigate warping and curling. However, relatively little work has been completed to fully understand composite pavements’ reaction to the driving environmental forces and the impact on long term performance. Monitoring the composite cells using the ALPS 2 equipment was done to better understand this behavior. Testing began immediately after construction, with test runs completed twice a day. To obtain profile measurements when the most extreme warp and curl is expected, test runs were conducted at 3 am and 3 pm, during the average daily minimum and maximum temperatures respectively.

The MnROAD developed ALPS 2 device shown in Figure 41 collects automated measurements of the pavement profile. The device consists of a 15 foot laser mounted to a vehicle that travels down the roadway. The profile measurements are taken at one inch intervals in both the longitudinal and transverse directions. All of the data collected from the profiler for a particular test is then saved in an EXCEL comma-delimited file which contains thousands of lines of data from various runs, tests cells, and panels. The file is run through a macro which sorts the data based on the run number, panel, and test cell. The data is then graphed to allow the user to easily understand the measurements. An example of the resulting profile graph from a typical pavement is given in Figure 42 below. This three dimensional figure demonstrates how clearly the physical warp and curl of the pavement surface can be detected.

Figure 41: (a) and (b) ALPS 2 Equipment

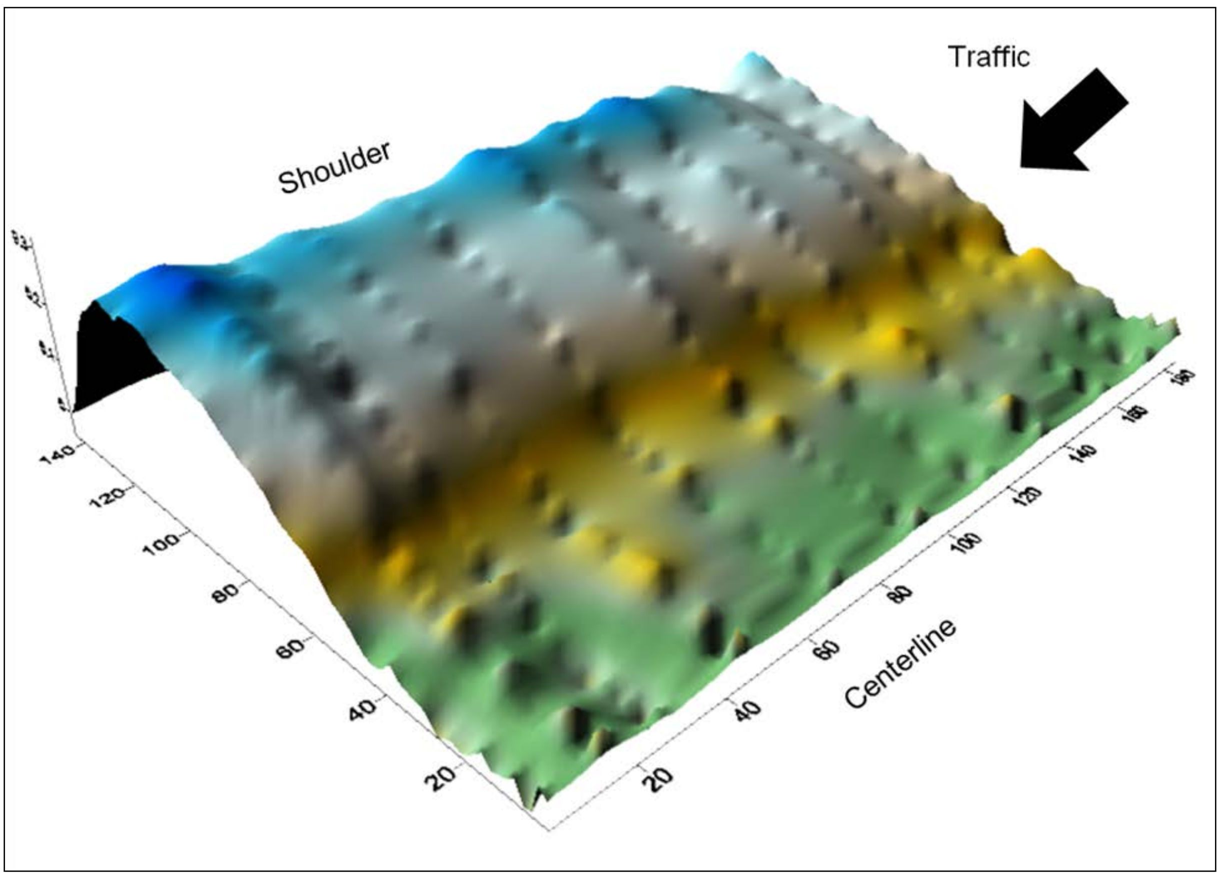


Figure 42: ALPS 2 Profile Example

The profile measurements collected from ‘warp and curl’ monitoring of Cells 70, 71 and 72 using the ALPS 2 device will be very useful in understanding composite pavement behavior to environmental factors. This data, along with recent measurements of OBSI, sound absorption, friction, texture and IRI from further monitoring will be included in future performance reports.

CONCLUSIONS

This paper summarizes the construction and early performance assessment of three composite test cells at the MnROAD: Cell 70, HMA over a recycled aggregate concrete; Cell 71, diamond grind concrete over recycled aggregate concrete; and Cell 72, exposed aggregate concrete over a low cost concrete. The construction of Cells 70, 71 and 72 was part of R21 Composite Pavement project of second Strategic Highway Research Program. The following conclusions were made on the different composites and surfaces tested:

- Construction of 2 lift concrete and traditional asphalt-over-concrete composite pavements was demonstrated successfully.
- The collaborative nature of this project, including partnerships between MnDOT and various research entities and pre-bid meetings with potential construction Contractors, contributed to the success of this project.
- Early performance assessment of the three test cells suggest that the exposed aggregate concrete surface does not provide significant noise reduction, as it had higher OBSI than both the HMA and traditional diamond grind surfaces tested.
- Innovative diamond grinding of composite pavements may be beneficial for noise reduction, as it showed lower OBSI than the HMA, EAC, traditional grind surfaces, and also had greater sound absorption than EAC.
- Exposed aggregate surfacing can provide more than adequate friction for driver safety, but does not show any improvement from typical HMA or diamond ground surfaces.
- Exposed aggregate surfaces have a similar texture (or mean profile depth) to traditional diamond ground surfaces. However, EAC may have reduced ride quality as IRI values were higher than both HMA and traditional diamond grind surfaces.
- It is important to note the large improvement in the exposed aggregate surfacing between that which was done on the demo slab to that which was done on the on the Mainline test cells. This supports the concept that achieving a proper exposed aggregate texture is a process, as preliminary adjustments and calibration is necessary.
- The successful project execution and performance results of these test cells proved that two lift concrete pavements can be a solution to issues such as scarce availability of

quality virgin aggregates and high costs for transporting this material to where it is needed.

Although composite pavement systems have become extremely popular in Europe, they are still a relatively new concept to the United States, creating a demand for more research and performance data. Continued monitoring of these test cells will help develop the wide understanding of composite pavement performance needed for more effective design and accurate service life models.

REFERENCES

[1] Derek Tompkins, Lev Khazanovich and Michael I. Darter. *2008 Survey of European Composite Pavements*. Transportation Research Board. Washington DC, 2010.

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[3] Products and Innovations. "MBT Reveal." BASF Construction Chemicals. Cleveland, OH. March 29, 2011. http://www.basf-admixtures.com/en/products/retarders_release/mbt_reveal/Pages/default.aspx

[4] Rob Rasmussen. "Hearing is Believing." General Blog, Concrete Pavement Surface Characteristics Program. March 24, 2011. http://www.surfacecharacteristics.com/index.php?q=blog

[5] Aybike Ongel, John T. Harvey, Erwin Kohler Qing Lu, and Bruce D. Steven. *Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types: First- and Second-Year Results.* University of California Pavement Research Center. Berkley CA. February 2008.

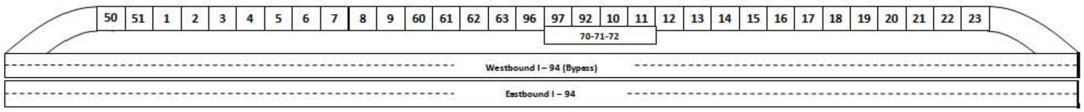
[6] Izevbekhai, B.I. and Akkari, A. (2011) "Pervious Concrete Test Cells on MnROAD Low-Volume Road" MnDOT, St Paul, MN 55155.

[7] *Composite Pavements Project*. FWHA MCL Project # MN 1001. United States Department of Transportation Federal Highway Administration . Washington, DC. April 2010.

APPENDIX A

MnROAD Mainline and Low Volume Road
Layout and Descriptions

MnROAD Mainline



1	6" 58-28 75 blow; 33" Class 4 (Driving Lane 1.5" 52-34 HMA inlay 2006); Clay	Sep 92	Current
2	1" TBWC; 2" 64-34; 6" FDR + EE; 6" FDR; 26" Class 4; Clay	Oct 08	Current
3	1" TBWC; 2" 64-34; 6" FDR + EE; 2" FDR; 3" Cl 5; 33" Class 3; Clay	Oct 08	Current
4	1" 64-34; 2" 64-34; 8" FDR + EE; 9" FDR + Fly Ash; Clay	Oct 08	Current
105	4"; 1" PSAB; 7.5" cracked '93 PCC; 3" Cl 4; 27" Class 3 (15x14 15x13 no dowels; Trad Grind); Clay	Oct 08	Current
205	4"; 1" PSAB; 7.5" '93 PCC; 3" Cl 4; 27" Class 3 (15x14 15x13 no dowels; Trad Grind); Clay	Oct 08	Current
305	5"; 1" PSAB; 7.5" '93 PCC; 3" Cl 4; 27" Class 3 (15x14 15x13 no dowels; Trad Grind); Clay	Oct 08	Current
405	5"; 1" PSAB; 7.5" cracked '93 PCC; 3" Cl 4; 27" Class 3 (15x14 15x13 no dowels; Trad Grind); Clay	Oct 08	Current
106	2" 64-34; 5"; 6" Cl 1 Stab Agg; 6" Class 5; Clay (Mesabi 4.75 SuperP; 15'x12' 1" dowel)	Oct 08	Current
206	2" 64-34; 5"; 6" Cl 1 Stab Agg; 6" Class 5; Clay (Mesabi 4.75 SuperP; 15'x12' no dowels)	Oct 08	Current
7	7.5" Trans Tined; 4" PSAB; 3" Cl 4; Clay (20x14 20x13 1" dowel; 2007 Innov Grind)	Sep 92	Current
8	7.5" Trans Tined; 4" PSAB; 3" Cl 4; Clay (15x14 15x13 13' PCC Should 1" dowel; 2007 Trad Grind)	Sep 92	Current
9	7.5" Trans Tined; 4" PSAB; 3" Cl 4; Clay (15x14 15x13 13' PCC Should 1" dowel; 2008 Improved Innov Grind)	Sep 92	Current
60	5" sealed; 7" 58-28 93HMA; Clay (Astro Turf 6x5)	Oct 04	Current
61	5" noseal; 7" 58-28 93HMA; Clay (Astro Turf 6x5)	Oct 04	Current
62	4" sealed; 8" 58-28 93HMA; Clay (Astro Turf 6x5)	Oct 04	Current
63	4" noseal; 8" 58-28 93HMA; Clay (Astro Turf 6x5)	Oct 04	Current
96	5.9"; 7" 58-28 93HMA; Clay (Trans Tined 6x5 Polypro)	Oct 97	Current

2009 SHRP-II Composite Pavements

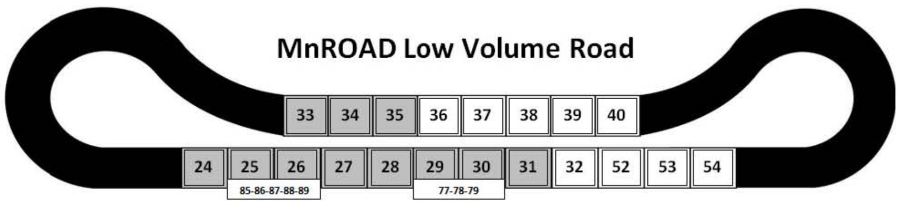
Thin Concrete

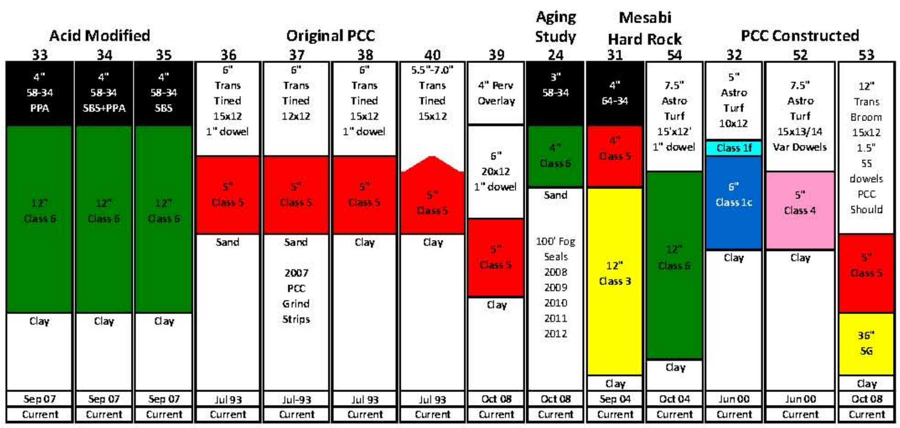
2008 Whitetopping

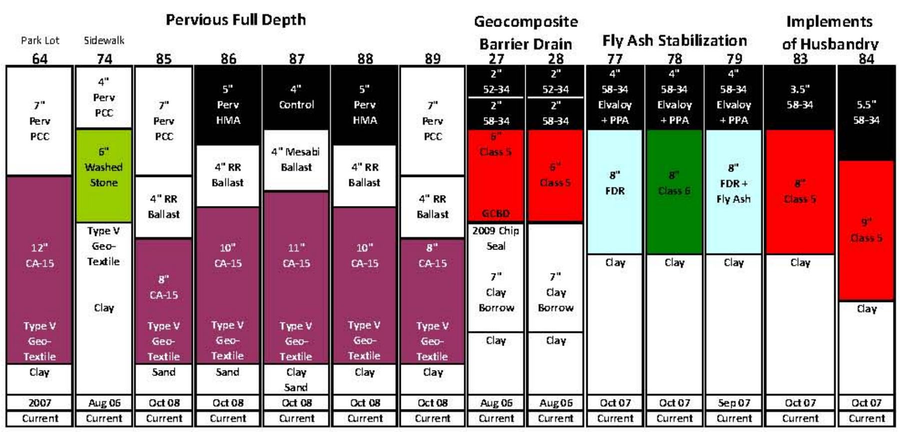
70	3" 64-34 Saw/Seal; 6" PCC Recycle; 8" Class 7; Clay (15'x12' 1.25" dowels driving none passing)	May 10	Current
71	3" PCC EAC; 6" PCC Recycle; 8" Class 7; Clay (Innovative DG (driving) Convent. DG (passing) 15'x12' 1.25" dowels)	May 10	Current
72	3" PCC; 6" PCC Low Cost; 8" Class 7; Clay (EAC Surface 15'x12' 1.25" dowels)	May 10	Current
12	9.5" Trans Tined; 5" Class 5; Clay (15x12 15x12 1.25" dowel)	Sep 92	Current
113	5"; 5" Cl 1 Stab Agg; 5" Class 5; Clay (heavy turf; 15'x12')	Oct 08	Current
213	5.5"; 5" Cl 1 Stab Agg; 4.5" Class 5; Clay (heavy turf; 15'x12')	Oct 08	Current
313	6"; 5" Cl 1 Stab Agg; 4" Class 5; Clay (heavy turf; 15'x12')	Oct 08	Current
413	6.5"; 5" Cl 1 Stab Agg; 3.5" Class 5; Clay (heavy turf; 15'x12')	Oct 08	Current
114	6" long broom; 5" 58-28 93 HMA; Clay (6'x6' 1" dowels driving; no dowels passing)	Oct 08	Current
214	6" long broom; 5" 58-28 93 HMA; Clay (6'x6' No dowels)	Oct 08	Current
314	6" long broom; 6" 58-28 93HMA; Clay (6'x6' 1" dowels driving; no dowels passing)	Oct 08	Current
414	6" long broom; 6" 58-28 93HMA; Clay (6'x6' no dowels)	Oct 08	Current
514	6" long broom; 7" 58-28 93HMA; Clay (6'x6' 1" dowels driving; no dowels passing)	Oct 08	Current
614	6" long broom; 7" 58-28 93HMA; Clay (6'x12' Flat dowels driving; no dowels passing)	Oct 08	Current
714	6" long broom; 7.5" 58-28 93HMA; Clay (6'x6' 1" dowels driving; no dowels passing)	Oct 08	Current
814	6" long broom; 8" 58-28 93HMA; Clay (6'x6' no dowels)	Oct 08	Current
914	6" long broom; 8" 58-28 93HMA; Clay (6'x6' 1" dowels driving; no dowels passing)	Oct 08	Current

15	3" WM58-34; 11" 64-22 1993 HMA; Clay	Sept 08	Current
16	5" WM 58-34; 12" 100% recycle PCC; 12" Class 3; 7" Select Gran; Clay	Sept 08	Current
17	5" WM 58-34; 12" 50% RePCC 50% Class 5; 12" Class 3; 7" Select Gran; Clay	Sept 08	Current
18	5" WM 58-34; 12" 100% RAP; 12" Class 3; 7" Select Gran; Clay	Sept 08	Current
19	5" WM 58-34; 12" Class 5; 12" Class 3; 7" Select Gran; Clay	Sept 08	Current
20	5" 58-28; 12" Class 5; 12" Class 3; 7" Select Gran; Clay (30% Non Fract RAP)	Sept 08	Current
21	5" 58-28; 12" Class 5; 12" Class 3; 7" Select Gran; Clay (30% Fract RAP)	Sept 08	Current
22	5" 58-34; 12" Class 5; 12" Class 3; 7" Select Gran; Clay (30% Fract RAP)	Sept 08	Current
23	5" WM 58-34; 12" Mesabi Ballast; 12" Class 3; 7" Select Gran; Clay	Sept 08	Current

* All thicknesses shown as design thickness







* All thicknesses shown as design thickness

APPENDIX B

Mix Approval Requests and

Job Mix Formulas

REQUEST FOR CONCRETE MIX APPROVAL

Requested by: Tom Schmit — Phone: 651-319-2369
Firm Name: Aggregate Industries
Agency Enginner/Inspector: ______ — S.P.: 8680-159

Proposed Aggregate Sources

	CA #1		CA #2		CA #3	Sand	
Pit Number	71041		71041			71041	
Pit Name	Agg. Ind.		Agg. Ind.			Agg. Ind.	
Nearest Town	Elk River		Elk River			Elk River	
Size	#4 (1-1/2")		#67 (3/4"-)			C. Sand	
Sp. G. & Abs. (Provided by MN/DOT)	2.75	0.90%	2.69	1.30%		2.63	0.90%

Proposed Cementitious Sources

	Cement	Fly Ash	Other
Manufacturer/Distributor	Holcim	Headwaters	
Mill/Power Plant	STGBLMO	COCUNND	
Type/Class	I/II	C/F	
Specific Gravity	3.15	2.5	

Proposed Mix Designs

MN/DOT Mix Number	CHPMR60		
Water (lbs/C.Y.)	173		
Cement (lbs/C.Y.)	240		
Flyash (lbs/C.Y.)	360		
Other Cementitious (lbs/C.Y.)			
W/CM Ratio	0.29		
Sand (Oven Dry, lbs/C.Y.)	1263		
CA #1 (Oven Dry, lbs/C.Y.)	787		
CA #2 (Oven Dry, lbs/C.Y.)	1102		
CA #3 (Oven Dry, lbs/C.Y.)	0		
Maximum Slump	3" Max		
% Air Content	7.00%		
Admix. # 1 (oz/100 # CM)	2.0 - 15.0 oz/cuyd Multi-Air 25		
Admix. # 2 (oz/100 # CM)	1.0 - 5.0 oz/cwt Sika 686		
Admix. # 3 (oz/100 # CM)	0.0 to 30 oz/cwt Sikaset NC (non-chloride accelerator)		

The above mixes are approved for use, contingent upon satisfactoiry site perfromance and continuous acceptability of all materials sources, by:

Maria Masten — 4/1/2010
Concrete Engineering ~~Specialist~~ — Date

Comments: attached composite gradation JMF 10-001 shall comply with the gradation requirements in the supplemental agreement No.1 Table 3137-4(a) + 3137-4(b).

REQUEST FOR CONCRETE MIX APPROVAL

Requested by: Tom Schmit Phone: 651-319-2369

Firm Name: Aggregate Industries

Agency Enginner/Inspector: ____________ S.P. 8680-159

Proposed Aggregate Sources

	CA #1		CA #2		CA #3	Sand	
Pit Number	71041		27005			71041	
Pit Name	Agg. Ind.		McCrossan			Agg. Ind.	
Nearest Town	Elk River		Maple Grove			Elk River	
Size	#4 (1-1/2")		Recycle			C. Sand	
Sp. G. & Abs. (Provided by MN/DOT)	2.75	0.90%	2.49	2.93%		2.63	0.90%

Proposed Cementitious Sources

	Cement	Fly Ash	Other
Manufacturer/Distributor	Holcim	Headwaters	
Mill/Power Plant	STGBLMO	COCUNND	
Type/Class	I/II	C/F	
Specific Gravity	3.15	2.5	

Proposed Mix Designs

MN/DOT Mix Number	RCCMR		
Water (lbs/C.Y.)	234		
Cement (lbs/C.Y.)	360		
Flyash (lbs/C.Y.)	240		
Other Cementitious (lbs/C.Y.)			
W/CM Ratio	0.39		
Sand (Oven Dry, lbs/C.Y.)	1200		
CA #1 (Oven Dry, lbs/C.Y.)	825		
CA #2 (Oven Dry, lbs/C.Y.)	920		
CA #3 (Oven Dry, lbs/C.Y.)	0		
Maximum Slump	3" Max		
% Air Content	7.00%		
Admix. # 1 (oz/100 # CM)	2.0 - 15.0 oz/cuyd Multi-Air 25		
Admix. # 2 (oz/100 # CM)	1.0 - 7.0 oz/cwt Sika 686		
Admix. # 3 (oz/100 # CM)	0.0 to 30 oz/cwt Sikaset NC (non-chloride accelerator)		

The above mixes are approved for use, contingent upon satisfactoiry site perfromance and continuous acceptability of all materials sources, by:

[signature] 5/4/10

ASST Concrete Engineering ~~Specialist~~ Date

Comments: Attached gradation must be met

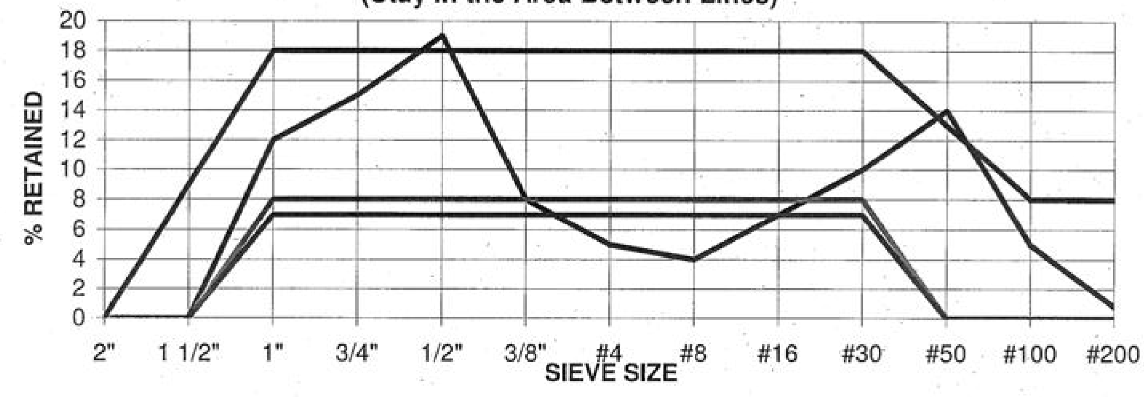
RCCMR JMF (8680-159)
Job Mix Formula

AGGREGATE SIZE	CA #1	CA #2	CA #3	CA #4	FA #1	FA #2	TOTAL % PASSING	WORKING RANGE LIMITS	JMF WORKING RANGE		TOTAL % RETAINED
	C. Sand	RC	1-1/2"								
PROPORTION, %	41.00%	31.00%	28.00%				100.00%				
2"	100.0	100.0	100.0				100	± 5	95	100	0
1 1/2"	100.0	100.0	100.0				100	± 5	95	100	0
1"	100.0	100.0	55.5				88	± 5	83	93	12
3/4"	100.0	99.0	5.8				73	± 5	68	78	15
1/2"	100.0	43.0	0.5				54	± 5	49	59	19
3/8"	100.0	15.0	0.3				46	± 5	41	51	8
#4	100.0	0.2	0.0				41	± 5	36	46	5
#8	90.6	0.0	0.0				37	± 4	33	41	4
#16	74.2	0.0	0.0				30	± 4	26	34	7
#30	49.9	0.0	0.0				20	± 4	16	24	10
#50	15.5	0.0	0.0				6	± 3	3	9	14
#100	1.9	0.0	0.0				1	± 2	0	3	5
#200	0.4	0.0	0.0				0.2	1.6% max	0.0	1.6	1

Workability Factor 37
(% passing #8)

Coarseness Factor 86
(% retained above 3/8" / % retained above #8)

Optional Or Required Gradation Incentive Specification
(Stay in the Area Between Lines)



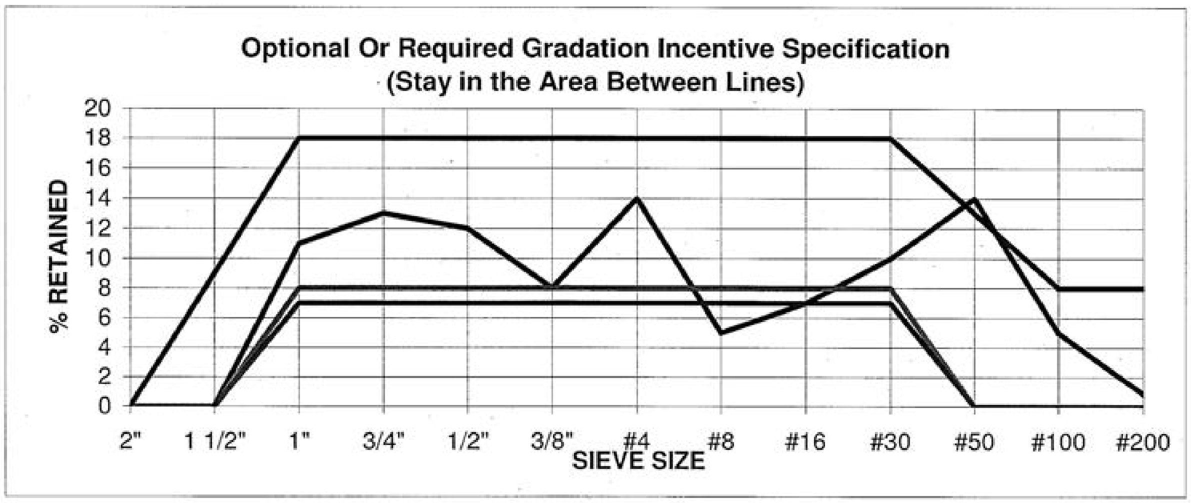
JMF10-001

CHPMR60 JMF (8680-159)
Job Mix Formula

AGGREGATE SIZE	CA #1	CA #2	CA #3	CA #4	FA #1	FA #2	TOTAL % PASSING	WORKING RANGE LIMITS	JMF WORKING RANGE		TOTAL % RETAINED
	C. Sand	3/4"-	1-1/2"								
PROPORTION, %	40.00%	35.00%	25.00%				100.00%				
2"	100.0	100.0	100.0				100	± 5	95	100	0
1 1/2"	100.0	100.0	100.0				100	± 5	95	100	0
1"	100.0	100.0	55.5				89	± 5	84	94	11
3/4"	100.0	99.2	5.8				76	± 5	71	81	13
1/2"	100.0	68.3	0.5				64	± 5	59	69	12
3/8"	100.0	45.4	0.3				56	± 5	51	61	8
#4	100.0	5.3	0.0				42	± 5	37	47	14
#8	90.6	2.5	0.0				37	± 4	33	41	5
#16	74.2	0.0	0.0				30	± 4	26	34	7
#30	49.9	0.0	0.0				20	± 4	16	24	10
#50	15.5	0.0	0.0				6	± 3	3	9	14
#100	1.9	0.0	0.0				1	± 2	0	3	5
#200	0.4	0.0	0.0				0.2	1.6% max	0.0	1.6	1

Workability Factor 37
(% passing #8)

Coarseness Factor 70
(% retained above 3/8" / % retained above #8)



REQUEST FOR CONCRETE MIX APPROVAL

Requested by Tom Schmit | Phone 651-319-2369
Firm Name Aggregate Industries
Agency Enginner/Inspector | S.P. 8680-159

Proposed Aggregate Sources

	CA #1	CA #2	CA #3	Sand
Pit Number	73006	73006		71041
Pit Name	Marietta	Marietta		Agg. Ind.
Nearest Town	St. Cloud	St. Cloud		Elk River
Size	1/2" W. Chips	3/8" W. Chips		M. Sand
Sp. G. & Abs. (Provided by MN/DOT)	2.72 0.40%	2.72 0.40%		2.63 0.90%

Proposed Cementitious Sources

	Cement	Fly Ash	Other
Manufacturer/Distributor	Holcim	Headwaters	
Mill/Power Plant	STGBLMO	COCUNND	
Type/Class	I/II	C/F	
Specific Gravity	3.15	2.5	

Proposed Mix Designs

MN/DOT Mix Number	EACMR		
Water (lbs/C.Y.)	283		
Cement (lbs/C.Y.)	616		
Flyash (lbs/C.Y.)	109		
Other Cementitious (lbs/C.Y.)			
W/CM Ratio	0.39		
Sand (Oven Dry, lbs/C.Y.)	843		
CA #1 (Oven Dry, lbs/C.Y.)	1133		
CA #2 (Oven Dry, lbs/C.Y.)	843		
CA #3 (Oven Dry, lbs/C.Y.)	0		
Maximum Slump	3" Max		
% Air Content	7.00%		
Admix. # 1 (oz/100 # CM)	2.0 - 15.0 oz/cuyd Multi-Air 25		
Admix. # 2 (oz/100 # CM)	1.0 - 5.0 oz/cwt Sika 686		
Admix. # 3 (oz/100 # CM)	0 - 5.0 oz/cwt Delvo as needed for slump retention		

The above mixes are approved for use, contingent upon satisfactoiry site perfromance and continuous acceptability of all materials sources, by:

Maria Masten | 4/1/2010
Concrete Engineering ~~Specialist~~ | Date

Comments: attached composite gradation JMF 10-002 shall comply with the gradation requirements in supplemental agreement No. 1 Table 3137-3.

JMF10-002

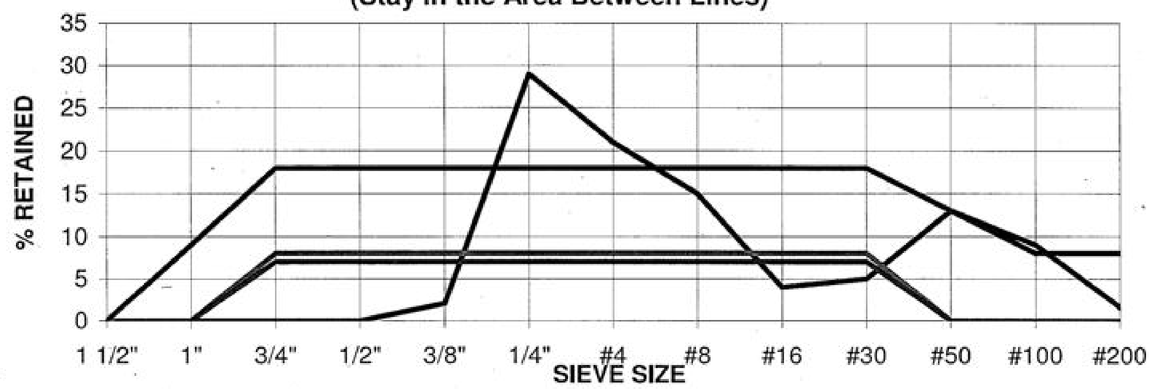
EAC JMF (8680-159) (unprotected)
Job Mix Formula

AGGREGATE SIZE	CA #1	CA #2	CA #3	CA #4	FA #1	FA #2	TOTAL % PASSING	WORKING RANGE LIMITS	JMF WORKING RANGE		TOTAL % RETAINED
	M. Sand	3/8" Chip	1/2" Chip								
PROPORTION, %	30.00%	30.00%	40.00%				100.00%				
1 1/2"	100.0	100.0	100.0				100	± 5	95	100	0
1"	100.0	100.0	100.0				100	± 5	95	100	0
3/4"	100.0	100.0	100.0				100	± 5	95	100	0
1/2"	100.0	100.0	100.0				100	± 5	95	100	0
3/8"	100.0	100.0	94.0				98	± 5	93	100	2
1/4"	100.0	69.0	46.0				69	± 5	64	74	29
#4	100.0	35.0	19.0				48	± 5	43	53	21
#8	98.6	6.0	3.0				33	± 4	29	37	15
#16	93.5	2.0	1.0				29	± 4	25	33	4
#30	79.9	0.0	0.0				24	± 4	20	28	5
#50	37.9	0.0	0.0				11	± 3	8	14	13
#100	7.8	0.0	0.0				2	± 2	0	4	9
#200	1.4	0.0	0.0				0.4	1.6% max	0.0	1.6	2

Workability Factor 33
(% passing #8)

Coarseness Factor 46
(% retained above 3/8" / % retained above #8)

Optional Or Required Gradation Incentive Specification
(Stay in the Area Between Lines)



APPENDIX C

FHWA Mobile Concrete Laboratory
Coefficient of Thermal Expansion Results

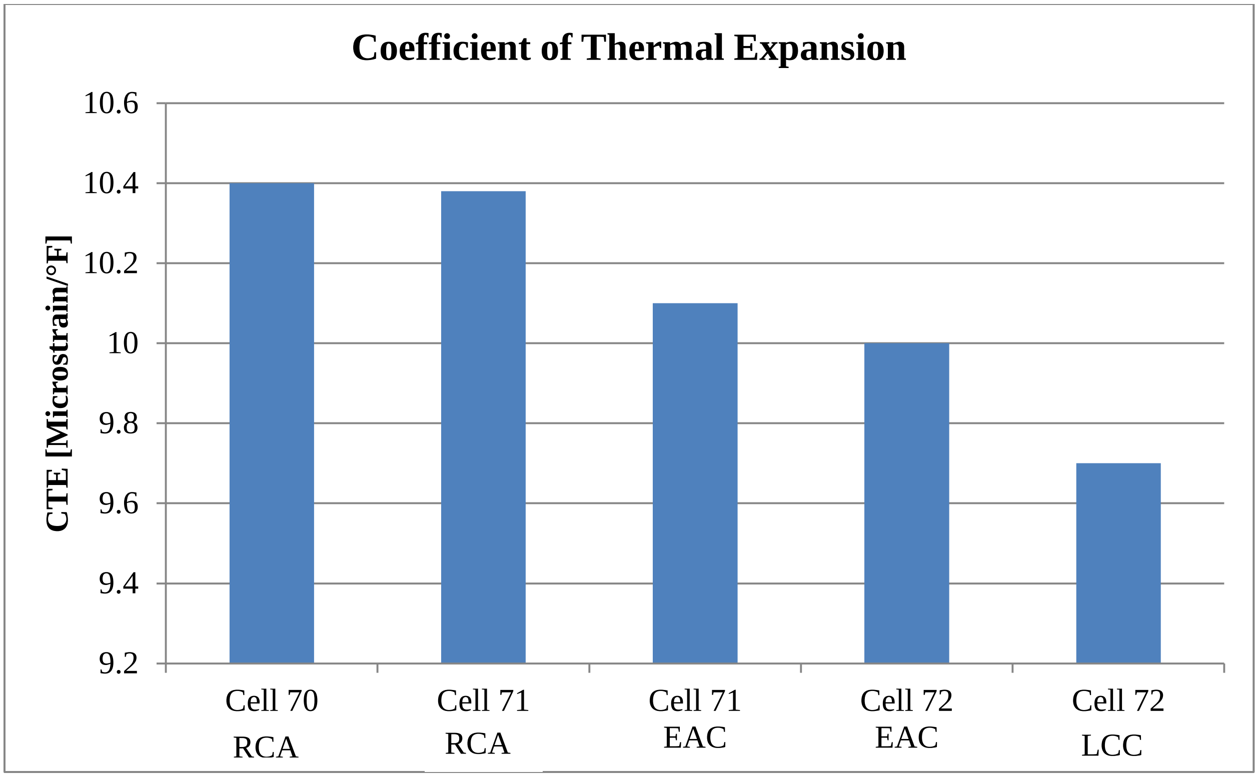
The coefficient of thermal expansion of the three different concrete mixes was measured by the FHWA's Mobile Concrete Laboratory (MCL) during its visit to MnROAD at the time of construction of the composite pavement test cells. The objective of the MCL's visit was to conduct the necessary tests to produce Level 1 material inputs for the three concrete pavement types which are needed for the Mechanistic Empirical Pavement Design Guide (MEPDG). [7]

The coefficient of thermal expansion (CTE) is a property of concrete that measures the amount of length change caused by a change in temperature. The coefficient of thermal expansion is an important property as it can influence the temperature gradient throughout a slab. Temperature gradients and expansion effect joint opening, along with warping and curling of pavement slabs. The unit for CTE is strain per unit temperature, or in other words, length change per unit length per unit temperature. By knowing the CTE for a pavement material, better predictions can be made for stress and movement in a slab as a result of a temperature change.

CTE tests conducted by the MCL were done in accordance with AASHTO TP 60 on five different samples taken during construction. The results are shown in the table below.

Coefficient of Thermal Expansion Results [7]

Mix	Cell	Cast Date	Test Date	Length	TP 60 - CTE Microstrain/°C	TP 60 - CTE Microstrain/°F
RCA	70	5/5/2010	5/20/2010	178.39	10.5	5.8
			5/28/2010		10.3	5.7
			Average		**10.4**	**5.8**
RCA	71	5/6/2010	5/21/2010	178.36	10.4	5.8
			6/1/2010		10.4	5.8
			Average		**10.4**	**5.8**
EAC	71	5/6/2010	5/24/2010	178.46	10.1	5.6
			6/2/2010		10.0	5.6
			Average		**10.1**	**5.6**
LCC	72	5/10/2010	5/26/2010	178.36	9.5	5.3
			6/3/2010		9.8	5.4
			Average		**9.7**	**5.4**
EAC	72	5/10/2010	5/27/2010	178.18	10.1	5.6
			6/7/2010		10.0	5.6
			Average		**10.0**	**5.6**



Coefficient of Thermal Expansion Summary [7]

Results show there was very little difference in coefficient of thermal expansion between the two RCA mixtures in Cells 70 and 71, and also between the two EAC mixtures in Cells 71 and 72. This indicates good mix and aggregate consistency over the different paving days. There was a notable difference in CTE between the three mixes. However, the measured CTE values for all the mixes fell within the range of what is considered normal for concrete.

APPENDIX D

“Conventional vs. Composite Paving”

By C.S. McCrosson Paving Division

Conventional vs. Composite Paving

CASE STUDY

By C.S. McCrossan Paving Division

OVERVIEW: To compare the costs of Conventional Concrete Paving with the costs of Composite Paving. Composite Paving or Wet on Wet paving is a process that involves paving the roadway in two lifts. The first lift being one thick, low quality layer of concrete utilizing recycled concrete as the main aggregate with lower percentages of quality aggregates in the mix design. The second lift is a fairly thin high quality layer (2-3 inches) that has high quality aggregates, with none of the recycled material present.

The benefit of Composite Paving is said to be in areas where high quality aggregates are of a high cost or a low supply, and low quality materials throughout one layer is not an option. Composite paving allows the lower layer to be produced using cheaper recycled material, allowing the higher priced or more scarce high quality aggregates to be used in the upper layer. The recycled material in the base layer is not expected to affect the structural quality of the slab as a whole. This makes Composite Paving an attractive option when paving in areas where high quality aggregates are difficult or expensive to find.

OBJECTIVE: Find a project in Minnesota that is located in an area not readily accessible to high quality aggregates. Take the original conventional pavement bid, and compare it to the expected costs of paving had it been bid using Composite Paving techniques. The extra cost of operating two paving operations as well as two batch plants will be compared to the expected costs for the aggregates using recycled material instead of Class A material for the base layer. The objective being to find what the saving on the recycled material would have to be to break even in comparison to the Conventional Method.

PROJECT: U.S. Highway 14 Concrete Paving

LOCATION: Near Waseca, MN

GENERAL STATS:

- 90,000 Cubic Yards of Concrete
  - 80,000 CY Mainline Paving. 310,000 Sq. Yards
  - 10,000 CY Crossroads and Ramps
- 19.5 Miles of paving
- 22 total days mainline paving scheduled
- Mainline Paving 27' width at 9" thickness
- Closest Class A aggregate source was New Ulm Quartzite (2 hour round haul)

COMPARISON: On the following page is a comparison of the crew and equipment used in a Conventional Paving operation, compared to crew and equipment that would be necessary for Composite Paving. Following that is a breakdown of the expected differences in the extra cost to place the pavement compared to the savings in producing the structural concrete.

Conventional vs. Composite Paving

Conventional

- 1 Boom Truck
- 1 Paver
- 1 Belt Placer
- 1 Cure/Texture
- 1 Skidsteer
- 1 Pickup
- 1 Service Truck
- 1 Flatbed Truck
- 1 Water Truck
- 13 Crew Members
- Assumed Mainline paving production of .90 miles per day
- Unit cost to pave/tie/green saw of $2.98 per Square Yard. $923,800 Total
- Mobilize and Operate 1 Plant
- Conventional Plant operations cost of $1.60 per Cubic Yard to batch mix.
  - Cost includes plant operator, loader, and operator

Composite

- 1 Boom Truck
- 2 Pavers
- 2 Belt Placers
- 2 Cure/Texture
- 1 Skidsteer
- 1 Pickup Truck
- 1 Service Truck
- 1 Flatbed Truck
- 1 Water Truck
- 1 Steel Bristle Broom
- 18 Crew Size
- Assumed identical production of .90 miles per day with two paver train.
- Unit cost to pave/tie/green saw of $3.70 per Square Yard. $1,147,000 Total
- Mobilize and Operate 2 Plants
  - Marginal cost to mobilize second plant $50,000 or a $.55 per cubic yard premium.
- Composite Plant operations cost of $3.82 per Cubic Yard to batch mix.
  - 2 plant operators, loader, and operator

-The Big Question is how much would the price for aggregates have to change to match the added cost of operating two paving crews and an extra batch plant?

Conventional vs. Composite Paving

Conventional Paving	
Pave, Tie, Green Saw	
Sq. Yds.	310,000
Per Sq. Yd.	$ 2.98
Total Cost	$ 923,800.00

Conventional Paving	
Structural Concrete	
Cubic Yards	80,000
Per CY	$ 71.54
Total Cost	$ 5,723,200.00

Conventional Paving	
TOTAL COST	$ 6,647,000.00

Composite Paving	
Pave, Tie, Green Saw	
Sq. Yds.	310,000
Per Sq. Yd.	$ 3.70
Total Cost	$ 1,147,000.00

Composite Paving	
Structural Concrete	
Cubic Yards	80,000
Per CY	$ 69.31
Total Cost	$ 5,544,800.00

Composite Paving	
TOTAL COST	$ 6,691,800.00

Total difference for the two is $44,800. The price differential is mainly due to the increased costs of placing the concrete. Laydown costs for the Composite Paving increased $.72 compared to Conventional as a result of the increased costs to run an extra paver and larger crew size. However the savings from the concrete aggregates was equal to $2.23 per cubic yard. This savings was due entirely to using recycled aggregate. These savings are achieved by crushing concrete on or near the site and using the recycled material as the main aggregate source in the thick base layer. By using substituting Recycle instead of Class A as the course aggregate material, you reduce the amount of high quality Class A aggregates needed for the job. The cost savings per ton of the recycle is between $5 and $6. Additionally, the haul time for high quality aggregates was a 2 hour round trip, but by crushing on site the haul time could be reduced to a 20 minute round. This results in just over $6 per tons savings in trucking costs. The tables below detail the difference in the amount of aggregates used as well as the cost differential between Class A and Recycled aggregates.

Conventional Aggregates	
Type	Tons
¾" Class A	34,270
1 ½" Class A	37,213
Total Tons	71,483

Composite Aggregates	
Type	Tons
¾" Class A	11,310
1 ½" Class A	12,280
Recycled Agg.	47,893
Total Tons	71,483

Class A	
Material $/Ton	$ 12.78
Trucking (2 hour)	$ 7.46
Total $ Per Ton	$ 20.24

Recycled	
Material $/Ton	$ 7.00
Trucking (20 min)	$ 1.45
Total $ Per Ton	$ 8.45

CONCLUSION: These examples were prepared using a real life project and the numbers it took to be a low bidder on the project. Our examples have shown that in the areas of the state in which Class A aggregates are not readily available or are very expensive, Composite Paving is a viable alternative to Conventional Paving. Although this example was an extreme case of having no readily available Class A aggregates, it has shown that it is possible for an alternative technique such as Composite Paving to compete to within 1% of the capabilities of a Conventional Paving process on this particular job.