CONSTRUCTION OF SUSTAINABLE PAVEMENTS: TWO-LAYER CONCRETE PAVEMENTS AT THE MNROAD FACILITY (11-0769)

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ABSTRACT

Recent efforts under the Strategic Highways Research Program (SHRP2) project R21, "Composite Pavements," lead to the design and construction of composite portland cement concrete (PCC) pavement sections at the Minnesota Road Research Facility. This construction is part of a larger effort to further understand techniques that lead to an infrastructure that is both rapidly renewed and sustainable. This paper will discuss successes and challenges of composite, or two-layer, PCC pavements, based on first-hand experience at MnROAD and on the SHRP2 R21 scanning tour of European composite pavements. This article represents a follow-up to an earlier article in *Transportation Research Record* No. 2098 on the R21 scanning tour of European composite pavements and observations of European construction practices for composite paving.

INTRODUCTION

The R21 project "Composite Pavements" was developed by the second generation of the Strategic Highway Research Program (SHRP2) to investigate the design and construction of new composite pavement systems. One fork of the R21 research focuses on a composite pavement system featuring a thin portland cement concrete (PCC) layer placed over another PCC layer. The goals of that research were to determine the behavior and identify critical material and performance parameters for PCC/PCC; develop and validate performance models and design procedures consistent with the Mechanistic-Empirical Pavement Design Guide (MEPDG); and recommend specifications, construction techniques and quality management procedures.

This article is a follow-up to an earlier article on the SHRP2 R21 project, "Design and Construction of Sustainable Pavements: Austrian and German Two-Layer Pavements," from *Transportation Research Record* No. 2098 (*1*). That article provided detail on the history of two-layer PCC pavements (PCC/PCC) and the background of PCC/PCC research in the United States. In so doing, it acknowledged the earlier research on PCC/PCC conducted by:

- the 1992 United States Tour of European Concrete Highways (*2*);
- the High Performance Concrete Pavement (HPCP) Test and Evaluation Project 30 (TE-30), also initiated in 1992 (*3*);
- the 2006 International Technology Scanning Program tour of long-life concrete pavements in Europe and Canada (*4*);
- Michigan DOT, in reporting on its PCC/PCC portion of the HPCP project (*5-7*); and
- Kansas DOT, in the future PCC/PCC projects spawned from its HPCP experience (*8*).

In light of existing information on US PCC/PCC construction techniques at the time, the focus of the earlier article was European techniques for PCC/PCC construction. These techniques were observed on the SHRP2 R21 scanning tour of European pavements. The article discussed the possible importation of those techniques for the construction of the SHRP2 R21 full-scale test sections at the Minnesota Road Research facility (MnROAD).

Given that these test sections were completed at MnROAD in April and May 2010, this article describes the overall R21 construction of its PCC/PCC sections for research. The article will detail the concerns of the R21 team heading into construction, the particulars of the SHRP2 R21 construction efforts, and the successes and challenges encountered during those efforts. The construction took place over three days of paving (for a full-scale, 200-foot-long demonstration slab and two full-scale, two-lane 500-foot-long sections along Interstate 94 at MnROAD). Finally, the R21 construction will also be discussed in light of observations from the earlier scanning tour of European PCC/PCC pavements and construction techniques.

PRE-CONSTRUCTION PLANS, CHALLENGES, AND GOALS

PCC/PCC sections to be constructed at MnROAD were designed to feature a 3-inch high-quality exposed aggregate concrete (EAC) PCC lift over a 6-inch "low-cost" or recycled concrete aggregate (RCA) PCC lower lift. The term "low-cost" signifies that the PCC design was such that the lowest possible amount of cement and most inexpensive coarse aggregates were used by the contractor. The designs are described by Table 1.

Table 1. SHRP2 R21 PCC/PCC design for MnROAD sections

Section		EAC over RCA PCC (Cell 71)	EAC over Low-cost PCC (Cells 71 and 72)
Upper PCC	Thickness	3 in	3 in
	Mix	High portland cement (~550 lb/yd^3) 15% Fly ash, Class C (FAC)	High portland cement (~550 lb/yd^3) 15% FAC
	Coarse Aggregate	Crushed granite (maximum size 3/8 in)	Crushed granite (maximum size 3/8 in.)
Lower PCC	Thickness	6 in	6 in
	Mix	Low portland cement (~250 lb/yd^3) 60% FAC	Low portland cement (~250 lb/yd^3) 60% FAC
	Coarse Aggregate	50% RCA, 50% Mn/DOT Class A Maximum aggregate size 1.25 in	100% Mn/DOT Class A Maximum aggregate size 1.25 in
Base		8 in, Class 5 unbound	8 in, Class 5 unbound
Subgrade		Clay	Clay
Joint spacing		15 ft	15 ft
Doweling		1.25 in (located 4.5 in from top of base)	1.25 in (located 4.5 in from top of base)
Surface texture		EAC	EAC/Diamond grind

Table 2 presents average strength data from tests conducted on over 80 specimens of each of the three PCC mixes. Specimens were created using field mix at MnROAD during the course of the demonstration slab paving and the paving of the two field test sections.

Table 2. Average strength data for RCA concrete, low-cost concrete, and upper lift (EAC) concrete

PCC mix	Compressive strength (psi)			Modulus of rupture (psi)	
	7 day	14 day	28 day	7 day	28 day
EAC	5044	5315	5601	739	846
RCA	3599	4117	4509	578	658
Low-cost	3773	4364	5003	468	575

Table 2 data includes that of the FHWA Mobile Concrete Lab, which visited the R21 construction site and collected cores and material samples. The RCA PCC/PCC design was used in MnROAD Cell 71 along I-94 (or the "Mainline"), while the low-cost PCC/PCC was used in both MnROAD Cells 71 and 72 on the Mainline. MnROAD's mainline test section experiences approximately 25,000 – 30,000 vehicles per day. Prior to construction of the demonstration slab, the research team met frequently to discuss shared concerns in regard to the following key areas (illustrated in Figure 1).

Figure 1. Project construction concerns at a glance (clockwise from top-left): layer placement, two sensor installations, EAC

Layer placement timing

The upper PCC layer was specified to be placed between 15 and 90 minutes after the placement of the lower PCC layer. This specification was in response to concerns of German and Austrian consultants to the R21 project and observations collected on the R21 scanning tour of European composite pavements. The general consensus among the research team was that the placement the second lift – as soon after the first lift as possible – was important to eliminating problems that might be associated with the heterogeneity of the two concretes in the PCC/PCC pavement. These problems include differential shrinkage, different rates of hydration, and the compound problem of bonding at the interface of the two PCCs. While the use of two pavers was an initial step to meeting this specification, there were other logistics that needed to be fulfilled to ensure the lifts were placed within a maximum of 90 minutes of one another.

Instrumentation

The R21 project included embedding thermocouples, moisture sensors, dynamic strain gauges, and vibrating wire strain gauges in the MnROAD sections. This effort involved considerable efforts in the installation, documentation, and activation of these sensors before, during, and after construction.

Mix design and performance

Many members of the R21 project team had reservations over the use of alternatives to more conventional materials as constituents in the concrete for the lower lift of the PCC/PCC pavement. These alternatives included the replacement of 50% of the coarse aggregate with recycled concrete aggregates (RCA) and the replacement of 60% of portland cement with a supplementary cementitious material (SCM). As both of these materials were not used in these amounts by the contractor in previous work, the project team addressed this challenge through test batches and anticipated that the demonstration slab would provide much information on the final concrete for the lower lift.

Mix delivery

While the paving operation was planned to use two pavers in a manner similar to the European methods observed by the R21 on its scanning tour of composite pavements, the MnROAD construction was to use one batching plant and not two (as observed in Europe). The use of one ready-mix plant was immediately recognized as a challenge to the project both in terms of maintaining a consistent mix in alternating between batches and in terms of delivering both the upper and lower concrete mixes in a timely fashion.

Exposed aggregate surface texture

The R21 project elected to use an exposed aggregate concrete (EAC) surfacing for the demonstration slab and mainline sections. While EAC was a successful surface in Europe, the project team was aware of challenges faced by the Kansas and Michigan DOTs in applying these techniques in the United States (*6-8*). One initial problem that the project team resolved was the specified gradation curve for the PCC mix to be used for the upper lift. The challenge was achieving a gradation curve that attempted to meet the EAC standard observed by the R21 team in Europe yet was within the means of the contractor and its ready-mix supplier. Table 3 describes 1) the allowable maximum and minimum passing for each sieve in the specification and 2) the final gradation curve used for the upper lift PCC by the contractor.

Table 3. Gradation curve for EAC mix used in R21 MnROAD construction

Designation	12.7 mm **(1/2 in.)**	9.5 mm **(3/8 in.)**	6.3 mm **(1/4 in.)**	4.75 mm **(# 4)**	2.36 mm **(# 8)**	1.18 mm **(# 16)**	.030 mm **(# 50)**	.015 mm **(# 100)**	.0075 mm **(# 200)**
As-written specifications	--	100-95	75-65	55-45	40-30	35-25	13-7	7-1	5-0
Final EAC blend	100	96	68	51	41	38	15	3	1

In spite of determining an adequate gradation curve for texture and the necessary equipment for the EAC brushing, the timing and extent of brushing were challenges that were still being addressed in the months leading up to construction.

Based on these goals and challenges, the R21 construction is discussed below in three sections:

- <u>General paving operations</u>. A description of these operations includes the timeline of the construction and the use of two pavers and logistics surrounding the use of two pavers, including equipment used to place concretes between pavers. Other concerns that were addressed during paving included accommodating instrumentation and sensors for research.
- <u>Mix design and delivery</u>. This concern is separate from overarching paving operations given the criticality of appropriate mix design and the importance of timing the placement of the layers.

- Surface texturing. This concern is also distinguished to indicate the additional challenge in achieving an adequate surface texture using EAC techniques.

CONSTRUCTION – PAVING OPERATIONS

Paving operations for the R21 test sections at MnROAD began on 28 April 2010 with the construction of a 200-foot demonstration slab and concluded on 10 May 2010 with the completion of 1000 feet total of test sections along the mainline (I-94) test area. The two-lift paving utilized two GOMACO model GHP2800 pavers and a material transfer device spaced between the two pavers to place fresh mix for the upper lift.

Figure 2. Paving train constructing R21 research sections along I-94 at MnROAD (from left to right, the mixer truck, first paver, material transfer device, and second paver)

Many aspects of the paving were similar to those of a normal single-layer PCC pavement. As detailed in Table 1, the pavement design included 1.25 inch dowels, placed at the mid-depth of the full slab using dowel baskets. Furthermore, the design included 0.5 inch tie bars to reinforce longitudinal joints, which the project contractor accommodated through the use of a tie-bar inserter attachment on the first paver. One difference in the use of two pavers in PCC/PCC versus single-layer PCC is that the upper lift paver was adjusted to “crown” the lower lift slab by 0.75 inches on each side – that is, the second paver paved a lift 1.5 inches wider than the first paver in the train.

Unlike the paving trains encountered in Europe, which use low-frequency vibration on the second paver only, the paving train used for the R21 project at MnROAD utilized vibrators in both pavers (the first paver set to 8000 bpm, the second to 4000 bpm). Methods differ on this point due, in part, to the use of automated dowel bar inserters in Europe. Given the dowel baskets, the R21 contractor desired vibration in the first paver to assist in consolidation. The R21 team also felt that the vibration in the second paver was low enough to avoid consolidating the two lifts of PCC at the interface and thus ensure the integrity of the interface of the layers.

The only complications in the paving itself were those brought about by delays in the delivery of PCC for the two lifts. While the construction specifications indicated that paving of the second lift was to occur no later than 90 minutes after the first lift, on all three occasions of PCC/PCC paving at MnROAD, the paving was frequently stalled for more than 90 minutes while waiting on batched upper lift PCC to arrive. During the construction of the demonstration slab, mix delivery delays led to 90 to 100 foot stretches of the placed lower lift being exposed to the environment for over 120 minutes before the second lift was placed.

These delays resulted in a few problems that could be appreciated immediately on site during paving. The most apparent was the setting up of concrete in the grout box and on the profile pan of the paver. Frequent delays allowed this concrete to hydrate and attach to surfaces, normally assumed to be smooth, that physically form the slab. When paving resumed after long delays, concrete that had clung to these surfaces would "tear" at the freshly paved concrete, resulting in the need for additional finishing. Figure 3 illustrates the tearing discussed above.

Figure 3. At left, "torn" edges and surface due to concrete setting on profile pan; at right, shrinkage crack in the lower lift propagated out and upward

The delays in the delivery of the upper PCC compromised the pavement given that the weather during the demonstration slab paving was unseasonably warm, sunny, and windy. Temperatures were between 60 and 69 °F, the sun was strong with no clouds, and the wind was steady at 5-10 mph with occasional strong gusts. These conditions are especially dangerous when the slab in question is composed of the early batches of PCC that arrived for the demonstration slab, which were considerably dry (with measured slump on site of 0.75 to 1 inch from batch to batch). This early "dry" PCC was used for the 90 to 100 feet of lower lift placed at the beginning of the demonstration slab that waited over 120 minutes for an upper lift. Figure 3 illustrates the most exaggerated of the shrinkage cracking encountered in these early slabs.

Another concern over delays included the integrity of the bond at the interface of the two lifts. Members of the research team were able to assess the sections using an ultrasonic tomography testing device and found that these concerns were well founded. The research team conducted ultrasonic scans at the transverse joints and at midslab of selected slabs. Tomograms from two representative scans are illustrated in Figure 4.

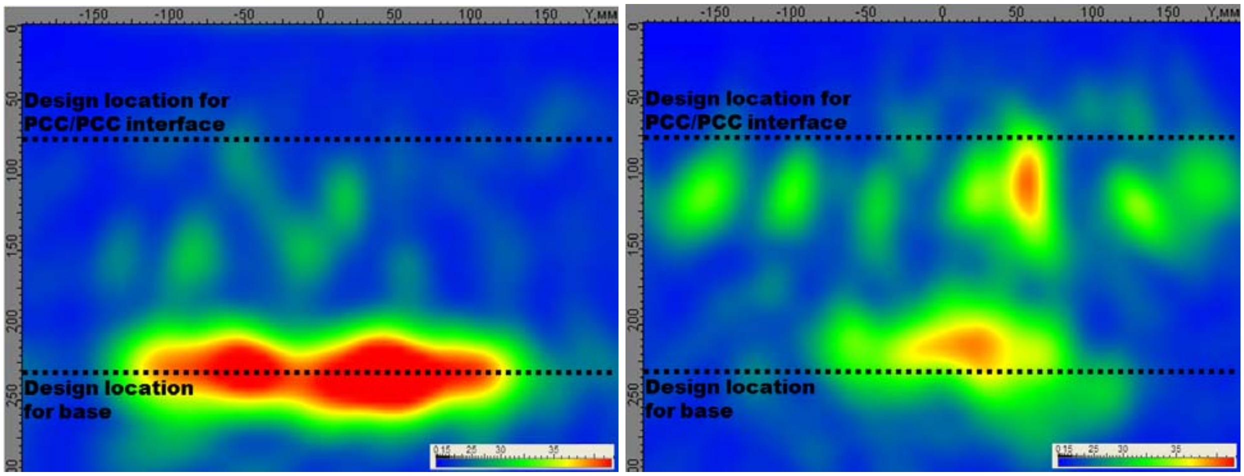

Figure 4. At left, a typical tomogram from the PCC/PCC demonstration slab at MnROAD; at right, tomogram with ultrasonic reflection near the depth of the PCC/PCC interface

Ultrasonic reflection occurs only noticeably at the start of the base layer (measured as approximately 8 in.) in the tomogram at left in Figure 4. In the tomogram at right, however, significant ultrasonic reflections are measured at a depth of approximately 4 in., near the interface of the two PCC layers. This reflection near the interface may be indicative of a poorly developed bond between the two layers of PCC, or it may be indicative of other problems in the pavement. The figure at left is further evidence that the composite layers, from the view of the tomogram, are a unified layer, whereas the reflections in Figure 4 at right suggests the possibility of internal distress (these conclusions were confirmed by cores taken from the demonstration slab). There is great potential for non-destructive testing devices such as ultrasonic tomography in quality assurance for PCC/PCC, especially when debonding at the interface is a concern.

Overall, the project team agreed that the contractor handled paving operations very well given the obstacles faced (e.g. mix delivery and inclement weather for the mainline sections). Paving progressed at anywhere between 1 and 4 linear feet per minute, and the project contractor was confident that this rate would be greatly increased with a larger project and a consistent supply of PCC for paving. While joint cuts, sawed to a depth of 3 inches, did not necessarily propagate well on the demonstration slab due to construction delays and dry mixes (as described above and illustrated in Figure 3), for the mainline sections all saw cuts were found to propagate as anticipated for a single-lift equivalent slab. Finally, the paving operation was deemed a success in terms of the instrumentation of the slabs for research purposes: the paving operation inadvertently destroyed or irreparably harmed only a few sensors, and as of one month after construction, the surviving sensors were functioning and online.

CONSTRUCTION – MIX DESIGN AND DELIVERY

One of the most challenging aspects of the R21 PCC/PCC sections was the concrete itself. This challenge presented itself in: 1) the development of a mix design that uses alternative materials and/or meets “low-cost” specifications and 2) in terms of the logistics behind batching and delivering concrete to meet the demands of the paving operations.

Tables 1 and 2 describe the three PCC mixes used. The most conventional of the three is the EAC mix used for the upper lift, whereas the PCC used for the lower lifts presented challenges to the project in its use of high fractions of fly ash and/or RCA. The specification for up to 60% fly ash in the lower lift PCC was inspired by the high-fraction of SCM replacement in the new St. Anthony Falls (I-35W) bridge in Minneapolis, MN, which used as much as 81% SCM replacement in its mixes (*9*). The research team viewed the lower lift of the PCC/PCC as an opportunity to further investigate high-fraction SCM replacement in pavements.

The existence of a lower lift was also viewed as an opportunity to use a lower-quality aggregate that would normally not be used for PCC paving. To this extent, the SHRP2 R21 research team thoroughly reviewed existing research on the use of RCA in PCC. This review concluded that RCA was a viable coarse aggregate for the lower lift PCC provided the RCA came from a known source, fines were excluded, and the stockpile was properly maintained (i.e. kept saturated to eliminate variable absorption as a concern) (*10*).

Both the use of high-fraction SCM replacement and RCA came with the challenges discussed above, and the contractor met these challenges with a preliminary batch of each design in the laboratory. As a result of these tests, the contractor adjusted the cement content of the EAC mix and adjusted amounts of admixtures for all mix designs. The contractor also had difficulty meeting the specified gradation curve for aggregate in the EAC mix, and as a result the EAC mix design was the last of the mixes to be finalized. Figure 5 illustrates a preliminary batching and brushing of the EAC mix conducted by the research team.

Figure 5. At left, EAC specimens cast by the research team in preparation for the paving and brushing of the PCC/PCC demonstration slab; at right, EAC mix being placed in front of the second paver on site at MnROAD

Prior to the construction of the demonstration slab, the contractor also developed a 3 yd^3 batch of the RCA mix to check both slump and air entrainment after batching and after delivery. These preliminary tests were declared satisfactory by the contractor prior to paving at MnROAD.

While this preliminary work addressed some challenges, the MnROAD R21 paving revealed a larger problem for the concrete in terms of consistency from batch to batch. The challenge of providing a consistent batch from truck to truck was thought to be overcome after the demonstration slab. However, paving on the mainline again suffered from the consistency problem, particularly in the case of the lower mixes, whose as-delivered slump oscillated between 0.25 and 2.75 inches (the target slump was 1 inch). While the causes of this inconsistency are still uncertain, there are a number of possible causes. First, the ready-mix supplier used by the contractor did not frequently design concretes using a large fraction of fly ash. As a result, it is very possible that the ready-mix supplier's inexperience in fly ash led to the mix designs being inadequately composed to handle such large amounts of this SCM (in terms of water demands, admixtures, so on).

Furthermore, as noted in reporting prior to the construction, the use of RCA required close attention. The contractor had secured RCA of a known source and had washed the RCA of fines, however the preparation of the RCA for batching – most notably, its degree of saturation – was not consistent. One explanation of the inconsistency from batch to batch, as evident in the variable slump, is the inadequate maintenance of the RCA stockpile (Figure 6). It is possible that the stockpile had been allowed to dry.

Figure 6. RCA stockpile being processed and saturated at a concrete recycling facility

Another concern to emerge from the use of RCA was the underestimate of unprocessed recycled concrete required to achieve a coarse aggregate of a desired size. Early estimates missed the amount of recycled concrete required by nearly 50%, which led to only 266 feet of PCC/PCC using the RCA mix being paved instead of the originally planned 500 feet.

A final challenge in meeting the mix design for the PCC/PCC pavements was the use of a local ready-mix supplier for the PCC/PCC concrete. This decision lead to the use of a local ready-mix plant – instead of the contractor's mobile batching plant – and the use of one plant instead of two (as observed in Europe). Furthermore, mix delivery was accomplished through mixer trucks instead of dump trucks (again, as in Europe). Both the batching plant and mixer trucks are demonstrated in Figure 7. The contractor's decision was based solely on cost: given the limited size of the project, using one or more mobile batching plants was not feasible.

Figure 7. At left, a ready-mix batching plant similar to the plant used for the R21 PCC/PCC construction; at right, mixer truck used for delivery

The observed delays in mix deliveries, then, may have been due to the use of a ready-mix supplier that was inexperienced in certain mix designs and in delivering those designs in sufficiently large volumes. While the contractor maintained that one plant was enough to accommodate the three mixes, the contractor stated that a ready-mix plant was not sufficient to provide consistency in mix design and delivery. Rather, the contractor was confident that in using their own mobile batching plant with their own staff, rather than subcontracting this work to a local ready-mix supplier, mix consistency/delivery would not complicate PCC/PCC paving.

Though the problems with the mixes and the mix delivery created problems for construction, it also supplied the project with perspective in the internal discussion among the R21 project team. On the one hand, it was a lesson in what techniques are economically viable. On the other hand, it had far reaching effects on the mixes themselves and the overall PCC/PCC paving operations. A lesson from the R21 construction experience is that, until two-lift paving is an established practice, the contractor should specify the development of viable mix design from a given supplier to ensure adequate mix design and delivery.

CONSTRUCTION – SURFACE TEXTURING

The most uncertain aspect of the MnROAD construction was the surface texturing. Initially, the project had planned on the import of European experts to guide the project contractor in the EAC brushing efforts on site at MnROAD. However, these experts were unable to guide the project personally, and instead their advice was used by the project team to develop its own expertise. Furthermore, the gradation for the EAC mix was not final until later in the pre-construction phase, and one result of this was that the maximum aggregate size for the EAC was increased from 8 mm to 12.7 mm (0.3 to 0.5 inches) (please note that the convention for the R21 project was metric units in specifying the EAC texturing, hence they are presented first). The project team was uncertain what consequences this small fraction of larger aggregate would have on the performance of the EAC texture. These unforeseen circumstances made the texturing the greatest challenge of the R21 team's early concerns.

The finishing platform used for the construction was a GOMACO model TC600 with Power Pavers Inc TC 2700T spray attachment. After paving, a compound was applied to the surface that both acted as a moisture barrier (curing agent) and as a retarder of hydration in the concrete at the surface. This curing/retarder compound was MBT Reveal from BASF Building Systems. Early applications of the surface treatment were delayed due to mechanical problems on the finishing platform, which provided insufficient pressure to the spray nozzles. The treatment (Figure 8) was intended to be applied almost immediately after finishing of the placed second lift, however due to frequent delays, the treatment was applied anywhere between 60 and 90 minutes after the completion of paving a given segment.

For the demonstration slab and the first day of mainline paving, brushing was initiated anywhere between 5 and 8 hours after paving of a given section had completed. The team's first-hand experience in judging the brush timing was based on limited laboratory tests, which did not mimic field conditions closely. Hence, to compensate for the lack of experience, the team frequently tested the surface at regular intervals, judging the brush readiness of the surface by the amount of cement and aggregate dislodged using a metal rod and/or handheld brush.

Figure 8. Treated surface and finishing platform (at left); equipment for EAC brushing (at right)

The brushing itself was accomplished using a small front-end loader with rotating wire brush attachment (Figure 8). The brushing was complicated by the inability for the operator to know the depth of texturing with any kind of precision. Hence, the brushing was done in multiple passes to gauge the level of cement removal between the aggregates, thus slowly revealing the EAC texture in pass after pass (Figure 9).

Figure 9. At left, surface after first pass with brush; at right, finished EAC surface

The extent of brushing was determined using a combination of a sand patch test and an aggregate peak counting test (Figure 10). More detail on these techniques can be found in Tompkins et al, Weinfurter et al, and Fick (*1,6,8*). Though not specified, the aggregate peak counting test was an informal quality control for the brushing adapted from Austrian methods. It aimed for a count of anywhere between 40 and 50 aggregate points per 25 cm^2 (3.88 in^2), according to Haider et al (*11*). The sand patch test was conducted according to ASTM E965 at intervals as a quality control measure during brushing to ensure that the depth of brushing was between 0.8 and 1.2 mm (0.03 to 0.05 inches).

Figure 10. Quality control tests for brushing: at left, 25 cm^2 test to count aggregate peaks, and at right, sand patch test to determine texture depth

This range for texture depth originated in the specifications for the EAC texturing, which required a uniform texture depth of 1.0 mm with an allowable range of 0.2 mm either shallower or deeper. This target was based in part on German and Austrian specifications for texture depth (0.6-0.8 mm and 0.8-1.0 mm respectively) (*1*). The completed mean texture depth for the EAC surfacing on the R21 sections at MnROAD was reported by Mn/DOT to be 0.76 mm (0.030 inches).

The above brief discussion of the EAC texturing has neglected any mention of the second day of paving on the mainline. This is due to the sudden onset of rain in the late afternoon. A majority of the finished, treated PCC/PCC paved that second day was subjected to the rain for as many as 3 hours before being covered with polyurethane sheeting. The delay in sheeting was due to delays in paving and then in the application of the surface treatment. For these reasons, the brush timing was uncertain, and brushing was not initiated until the morning of the next day, twenty hours after the second lift had been placed. The situation was a stern reminder of the need to remain aware of the weather and sheet the slab as soon after placement as possible should rain occur.

However, given fair weather, the project team felt capable of a quality EAC surface based on its preparations. While some of the successes in EAC at MnROAD could be traced to preliminary tests in the lab, a large share of credit is due to the project's consultants in Europe, Drs. Walter Fleischer of Heilit+Woerner in Munich, Germany, and Dr. Hermann Sommer of the Austrian Concrete Institute, who shared their expertise in the R21 scanning tour and through correspondence during the construction planning and pre-construction stages.

CONCLUSIONS

The overall impression from the PCC/PCC paving operations at MnROAD was that PCC/PCC paving can be conducted in the United States using the existing infrastructure for conventional single-lift paving. Furthermore, many of the complications in the construction were foreseen in the preliminary work leading up to construction: for instance, the challenge of the mix designs, the use of a single ready-mix batching plant, or the need to understand EAC brushing. The construction itself allowed these complications to be further understood. First, the use of a single batching plant for the production of two distinct mixes was not viewed as a major obstacle if conducted differently. The mix designs, and difficulties with the subcontractor for the concrete, could be traced directly to logistics and planning more than the fundamental need for two distinct batching plants. However, more than any other challenge, the EAC brushing was the aspect of the project that was left unresolved at the conclusion of construction. Future noise and friction data on the EAC texturing that survived will further resolve this issue. In the meantime, the R21 project will document what was done in hopes that it will lead to a PCC/PCC alternative for paving in the United States that is economical, sustainable, and quickly renewable.

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REFERENCES

1. Tompkins, D., L. Khazanovich, M. Darter, and W. Fleischer. Design and Construction of Sustainable Pavements: Austrian and German Two-Layer Pavements. *Transportation Research Record: Journal of the Transportation Research Board, No. 2098,* Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 75–85.

2. Darter, M.I. *Report on the 1992 U.S. Tour of European Concrete Highways*. Publication No. FHWA-SA-93-012. Federal Highway Administration, Washington, D.C., 1993.

3. Federal Highway Administration. *High Performance Concrete Pavements, Project Summary*. Publication No. FHWA-IF-06-031. Federal Highway Administration, Washington D.C., 2006.

4. Hall, K.. *Long-life Concrete Pavements in Europe and Canada*. Publication No. FHWA-PL-07-027. Federal Highway Administration, Washington D.C., 2007.

5. Wojakowski, J.B. *High Performance Concrete Pavement*. Report No. FHWA–KS–98/2. Kansas Department of Transportation. Topeka, Kansas, 1998.

6. Weinfurter, J. A., D. L. Smiley, and R. D. Till. *Construction of European Concrete Pavement on Northbound I-75—Detroit, Michigan*. Research Report R-1333. Michigan Department of Transportation. Lansing, Michigan, 1994.

7. Buch, N., Lyles, R., and Becker, L. *Cost Effectiveness of European Demonstration Project: I-75 Detroit. Report No. RC-1381*. Michigan Department of Transportation. Lansing, Michigan, 2000.

8. Fick, G. Final Two-Lift Paving Report. *2008 National Two-Lift Paving Open House, October 15-16, 2008, Salina and Abilene, Kansas*. http://www.cptechcenter.org/projects/two-lift-paving/documents/Finalopenhousereport-FICK.pdf

9. "Concrete Is Remixed With Environment in Mind," *New York Times*, 30 Mar 2009

10. Vancura, M., Tompkins, D., and L. Khazanovich. Reappraisal of Recycled Concrete Aggregate as a coarse aggregate in concretes for rigid pavements. *Transportation Research Record: Journal of the Transportation Research Board, No. 2113,* Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 149–155.

11. Haider, M., Steigenberger, J., and Piber, H. "Long-term Performance of Low-noise Concrete Pavements." *Proceedings of the 10th International Symposium on Concrete Roads*. Brussels, Belgium. 18-22 September 2006.