Early Performance of Pervious Concrete Pavement

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ABSTRACT
This paper discusses the construction and early performance of a pervious concrete test cell at the MnROAD facility. The cell is subjected to daily loading of an 80-Kip 5-axle semi-trailer, two times a day, four days a week and 102-Kip 5-axle semi-trailer twice a day, one day a week. Performance was evaluated by comparing Falling Weight Deflectometer (FWD) deflection basins to those of normal concrete pavements of similar thickness design. Stress-strain response of the pavement system was computed from dynamic strain gauge data. Temperatures and freeze-thaw cycles at various pavement depths where monitored. An in-situ method for measuring time rate of flow was developed. Petrographic analysis reveled differences in porosity between the surface and bottom layers as well as drying shrinkage cracking.

Normal sanding and salting operations during the winter do not appear to have impacted the pore structure within the pervious concrete after three years of service. Spalling and raveling were prevalent at the tooled joints and occurred in sections where the surface could have prematurely dried due to overworking. The test cell driveway showed superficial wear near the joints after its first season in service. Large 12x12 ft rectangular block cracking was observed after 2 ½ years as well as reflective cracking propagated from joints of the surrounding curb. Critical parameters including time rate of flow, raveling, and cracking will continue to be monitored.

INTRODUCTION

This paper presents the results of Minnesota Department of Transportation's (Mn/DOT's) study on the effects of traffic and environmental loading on pervious concrete pavement. Although pervious PCC pavements are not new, there is limited data on their performance in hard wet-freeze regions [1]. By adequately evaluating the effects of Minnesota's climate on a pervious concrete driveway, this study will provide a long term performance evaluation as the changes in porosity and infiltration are monitored over time under standard measurable traffic loads, environmental effects, and deicing operations. To facilitate sampling without destroying the test section, replicate test slabs of two different mix designs were constructed on the east side of the test cell. For petrographic and other tests, cores where taken from these pads periodically. This paper details the performance of the pervious concrete after three years of service.

This test cell was constructed in a partnership agreement between Minnesota Department of Transportation (Mn/DOT) and the Aggregate Ready Mix Association of Minnesota (ARM of MN). In this cooperation, Mn/DOT provided the location, equipment, and expertise to instrument and monitor performance of the driveway. ARM of Minnesota provided the materials needed to construct a driveway approximately 16-ft wide by 60-ft long. The section was enclosed by a 6-in. thick by 2-ft wide perimeter curb of normal concrete. The test cell is subjected to daily loading of an 80-Kip 5-axle semi-trailer, two times a day, four days a week and 102-Kip 5-axle semi-trailer twice a day, one day a week, en route the daily loading of the MnROAD low volume loop (LVR).

Paper Objectives

This paper,

- Describes the design, construction, and instrumentation of a pervious concrete pavement test cell in a cold climate.
- Develops a method of measuring changes in hydraulic conductivity of the pavement system in-situ.
- Determines if the mechanical and rheological properties of the pervious pavement are similar to normal PCC pavements and examines pavement response using the Falling Weight Deflectometer.
- Computes the stiffness of the pervious pavement by measured stresses and strains and compares to normal PCC pavements of similar thickness.

1.2 Previous Studies

A study conducted by Schaefer *et al.* [2] on pervious PCC found that it was possible to achieve good freeze-thaw durability and strength while maintaining sufficient permeability. In a study by Kevern [3] it was found that the coarse aggregate durability is more critical in pervious concrete than in normal concrete because concrete paste cover is much thinner and more surface area is exposed to moisture. Aggregates which would be freeze-thaw resistant in normal concrete may not be in pervious concrete.

Performance evaluations on pervious concrete parking lots in freeze-thaw regions showed very little deterioration of permeability with minimal cracking and joint raveling [4]. Clogging was typically caused by debris, wet mixes, and over consolidation while dry mixes led to raveling. Cracking was caused by heavy traffic or insufficient contraction joints. A study conducted by Kwiatkowski *et al.* tested the water that drained through a pervious concrete

infiltration basin. It was found that the ground water did not become contaminated due to infiltration but the chloride concentration of the soil under the pervious concrete did increase and decrease seasonally due to winter deicing chemicals.

Storm water can flush large amounts of toxic pollutants into rivers and watercourses. Pratt [6] discussed the benefits of storm water source control, using a permeable surface and detention subsystem. This method was introduced into the United Kingdom around 1995, and is rapidly becoming the preferred method of handling run-off, especially where there are environmental or capacity limitations. It was found that about 90% of surface pollution was washed of by the initial 20% of heavy rain; if this first 'flush' could be contained at source, flooding and pollution would become much less likely.

Wanielista *et al.* [7] developed a single ring infiltrometer to measure infiltration rates of pervious concrete pavements in the field. Based on pavements where no maintenance had been done and with an average age of 12.8 years, infiltration rates ranging from 1.4 to 627 in/hr were measured. Based on their findings, the authors recommended that stormwater management credit be given for rainwater infiltration through pervious concrete. Chopra *et al.* [8] investigated the effects of pressure washing, vacuum sweeping, and a combination of the two methods on eight pervious concrete pavements in three states ranging from 6 to 20 years of service life. The three maintenance methods typically resulted in a 200% or greater increase in infiltration rates with vacuum sweeping being the recommended method.

Fowler [9] outlined four noteworthy points in relation to the construction process, base, thermal advantages, and need for further research. Pervious concrete utilizes a coarse aggregate base for storing water. Limited research has shown that little clogging occurs over time, but that the initial surface finishing is very important in order to have a permeable surface. Permeable concrete can reduce or eliminate the need for detention ponds, and reduces surface heat. There have been numerous applications, particularly in the southeastern United States.

Pervious concrete not only reduces the amount of water runoff but also reduces wet weather spray and the noise level from traffic due to reduced noise generation and increased noise absorption [10]. Previous reports and studies have not evaluated the long-term performance of pervious concrete in a wet-hard freeze climate such as Minnesota's. This study develops a model and device to measure changes in permeability in-situ and presents the condition of a pervious PCC test cell after three winters in Minnesota with no maintenance. Izevbekhai and Eller [11] discussed mechanical and microscopic properties of the MnROAD Cell 64 pervious concrete.

TEST CELL DESIGN

Although not part of the MnROAD Mainline or Low Volume Road (LVR), Cell 64, the pervious PCC pavement test cell, is part of the overall MnROAD facility. Cell 64 is located on the south side of the MnROAD pole barn as part of a bituminous parking lot. A 64-ft by 20-ft section of the bituminous driveway was removed in order to place the drainage system, base, pervious concrete, and concrete border surrounding the pervious concrete driveway. The actual size of the pervious concrete portion of the driveway is 60-ft by 16-ft, surrounded by a 2-ft concrete border on all sides as shown in Figure 1. The pavement was designed on the basis of a storage volume requirement in the base and the load levels of a traveling 5-axel semi trailer.

Mix Design

The three mix designs used for the concrete driveway are shown in Table 1, with the coarse

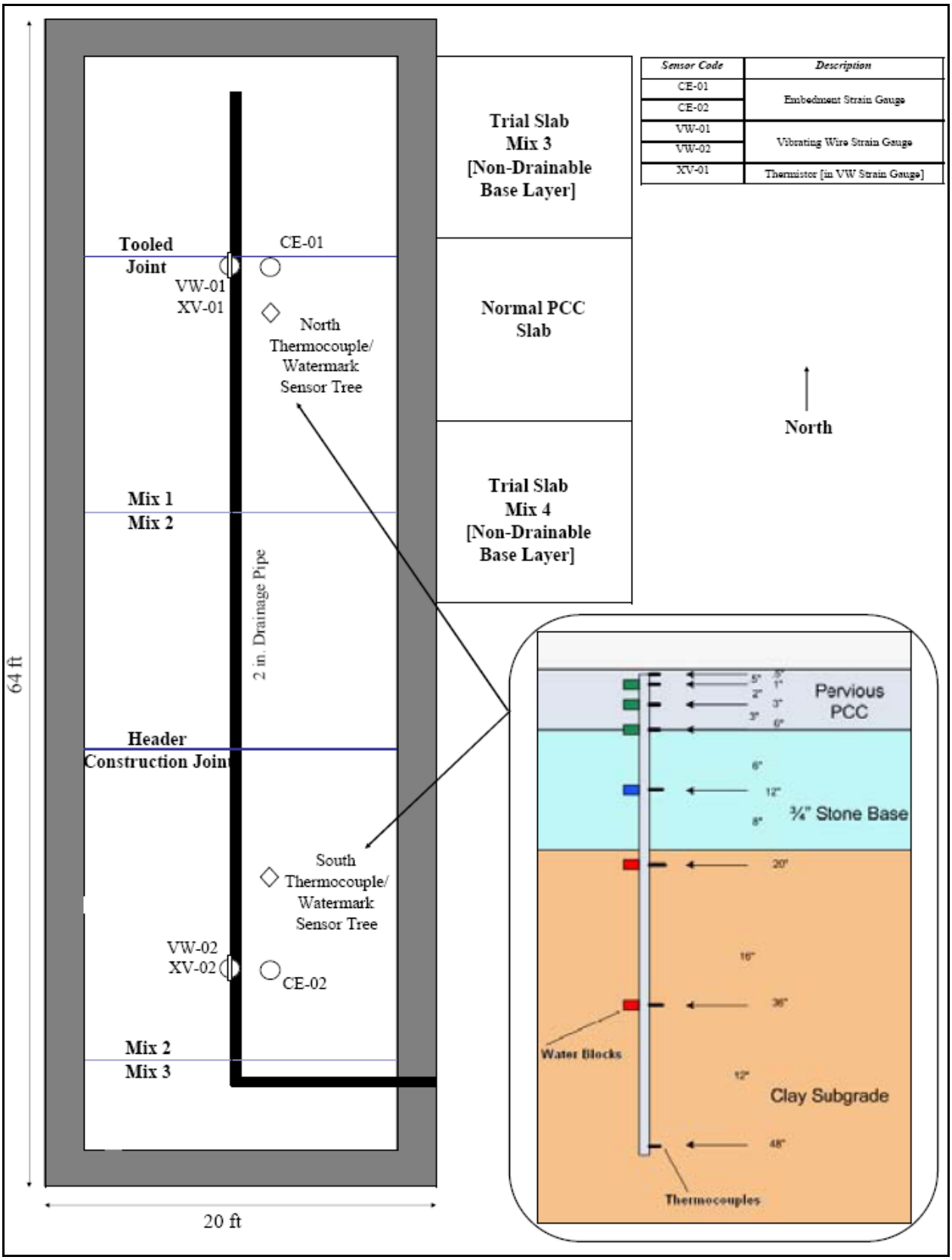

FIGURE 1 Plan and elevation views of test cell and instrumentation.

aggregate being the major component varied between them. Fly ash content, cement content, and water content varied slightly for each mix design, but the water/cementitious ratio and volume of admixtures remained the same between the three mix designs. Mix #1 contained quarried chip limestone aggregates of maximum nominal size ½ in. Mix #2 contained both the ½ in. quarried limestone aggregate in addition to a rounded gravel of maximum nominal size ½ in. Mix #3 contained only a dolomite gravel of maximum nominal size ½ in. Initially, it was intended to use only two different mixes in the test cell but because of yield issues; a third mix was required to finish the placement. The relative placement of the loads and mixes within the pervious concrete driveway are shown in Figure 1.

TABLE 1 Pervious Concrete Mix Designs

Material	Mix 1	Mix 2	Mix 3	Units
Cement (ASTM C150/ Type I)	495	467	456	lb/yd^3
Fly Ash (ASTM C618/ Class F)	87	83	80	lb/yd^3
3/8 in. Crushed Dolomite	2379	719	0	lb/yd^3
½ in. Gravel Dolomite	0	0	2189	lb/yd^3
3/8 in. Gravel	0	1438	0	lb/yd^3
Water	157	149	145	lb/yd^3
Mid Range Water Reducer (ASTM C494/ Type A) [oz/100 lbm Cementitious Material]	4	4	4	oz
AEA (ASTM C260)	4	4	4	oz/yd^3
Viscosity Modifying Admixture [oz/100 lbm Cementitious Material]	3	3	3	oz
w/cm Ratio	0.27	0.27	0.27	

Mixture proportions were selected to evaluate the stability of both gravel and crushed carbonate aggregates. The mixture proportions were prepared to address the following three items, which are discussed further in Izevbekhai *et al.* [12].

1. Viscosity of the paste fraction to ensure adhesion to the aggregate and stability of the mixture.
2. Freeze-thaw resistance.
3. The provision of voids for drainage in the pervious layer.

Freeze thaw resistance of pervious concrete is imparted by durable aggregates. In conventional PC concrete, freeze-thaw damage presents as surface popouts and D-cracking. Below a depth of about 1-in. the concrete provides enough restraint to prevent popouts from occurring. However due to the porosity of pervious concrete the core does not provide such restraint.

In order to look at this issue two different aggregates were selected. The first is natural gravel conforming to the requirements of Mn/DOT 2137 Class C Aggregate and the second aggregate is crushed low absorption limestone.

Pavement Thickness Design

The pavement was designed to 6-in. nominal thickness underlain by a drainable CA-50 base. The base was slopped from 12-in. at the concrete curb to 18-in. thick at mid-width in order to

accommodate a 2-in. perforated pipe which was aligned in the centerline of the pavement and elbowed at 90 degrees to its outlet located 50-ft away from outer edge of the pavement.
The two trial slabs shown in Figure 1 where used solely to practice placing and finishing the pervious concrete. Mix #3 was used in the north trial slab and Mix #1 was used in the south trial slab. After placing the south slab, it was noticed that the mix was contaminated with sand from a previous load of concrete. This mix was then designated Mix #4. A drainable subgrade was not used in either trial slab. Instead, the pervious concrete was cast directly on top of the clay soil.

CONSTRUCTION

The construction process involved the removal of the existing asphalt and aggregate base to a depth of 22-in. at the center and a minimum of 18-in. at the edge of the pervious concrete. A drainage pipe was placed on the subgrade down the centerline of the driveway and a roof heat tape was installed inside the pipe to ensure a frost-free outlet. The drainage pipe outlet was placed at as low an elevation as possible to ensure natural drainage to the surrounding land.

The pervious concrete was placed using a pneumatic roller screed and a ¼-in. masonite board was used to allow for some compression of the concrete to the height of the perimeter sidewalks. Curing was accomplished by the immediate covering of the pervious concrete after placement with a layer of plastic. This layer remained on the pervious concrete for 14 days. Due to over-excavation and additional compaction, a third mixture was required to complete the placement.

Instrumentation

Six sensors were embedded in the pervious test cell during construction. These sensors included two embedment strain sensors, and two vibrating wire strain gauges with thermistors. In addition to the six sensors within the driveway slab, two sensor trees of thermocouples and water blocks were installed to an approximate depth of four feet below the surface of the driveway to monitor the temperature profile and frost depth within the pervious concrete, base material, and subgrade. Thermocouples and water blocks were placed at discrete locations on the sensor tree as shown in Figure 1. The sensor trees were placed two feet east of the driveway centerline, at 15 ft. north and south of the southernmost and northernmost edges of the pervious concrete driveway, respectively.

Field Sampling

The results for compressive and flexural strength of cylinders and beams cast in the field as well as cores and beams cut from the test cells are shown in Table 2. Cylinders were made on the placement site and tested at 7- and 28-days. Beams were also made and tested for 7- and 28-day flexural strength. The core cylinders and beams were obtained from the test pads and tested at 29-days for compressive strength and modulus of rupture. Although cylinders were made during construction, there was no standard method of rodding and placement to simulate the compactive energy of the mechanical compactor used to place the test cell or to correlate to standard methods of preparing concrete cylinders, ASTM C 31.

PERFORMANCE EVALUATION

Deflection, strain, permeability, temperature, and frost presence were monitored to better understand the performance of the pervious concrete in relation to environmental cycles and loading events. Deflections and strain were measured in conjunction with the FWD apparatus,

and strain data was gathered in conjunction with loading from the MnROAD truck. Vibrating wire strain gauges were used to examine strain cycles imparted by temperature expansion and shrinking of the concrete. In addition to the thermistors, the watermark/thermocouple trees were monitored to identify temperature trends in the soil/concrete profile, and freeze-thaw events.

TABLE 2 MnROAD Cell 64 Mechanical and Rheological Concrete Properties

Parameter	***Age***	***Range***
Flexural Strength	7-day	250 psi
	28-day	540 psi
Compressive Strength	7-day	1231-3000 psi
	28-day	3000-4500 psi
Elastic Modulus	28-day	1200 ksi
Porosity	28-day	18-20%
Compression [Core]	28-day	5517-6045 psi
Flexure Beam Cut from Slab	29-day	500-580 psi

The data from the thermocouple and watermark trees is shown in Figure 2. The data has been broken down into graphs that represent the temperature profile and frost events within the pavement, and within the subgrade, respectively. This was done to separate the data curves for the purpose of clarity. The position of each sensor relative to depth is shown in Figure 1. While limited freeze-thaw events are visible in the watermark data due to a mild winter in 2005/2006, during the winter of 2007/2008 many freeze-thaw events occurred. Records from May 5, 2006 to April 25, 2007 where lost.

The top plot of Figure 2 shows only the watermark data in the pavement and subgrade. Since the watermark data indicates a change in phase from liquid to solid, it provides a better way in which to count freeze-thaw cycles than thermocouples which only indicate temperature. Figure 2 accentuates the fact that the subgrade experienced less freeze-thaw cycles than the pavement.

The middle and bottom plots in Figure 2, respectively, show the watermark and thermocouple sensor data for the pavement and subgrade respectively. The resistance read by the watermark sensor for three discrete depth intervals is shown for the pavement and subgrade. The resistance changes markedly when the sensor detects frost, and the graphs show several freeze thaw events that may have even reached to the CA-50 base material. The temperature read by the thermocouples at three discrete depths in the pavement and subgrade is also shown. Overall, the thermocouple temperature data coincide closely with the watermark data for each discrete depth, which helps to properly identify freeze-thaw events. For both the pavement and subgrade, the thermocouple data and watermark data appear similar at each sensor depth.

Petrographic Analysis

The main features highlighted by the petrographic data are the heterogeneity of the air-void structure, micro cracking within the paste-aggregate structure, low water/cement ratio, and surface raveling. The initial set of cores taken were chosen to represent the materials placed, taking into account the presence of three distinct mix designs, and a high potential for variability of the void content and structure. The initial cores taken by Mn/DOT represent mix designs #3 and #4. ASTM C 457 Linear Traverse was performed on both cores to quantify the various elements of the pervious concrete.

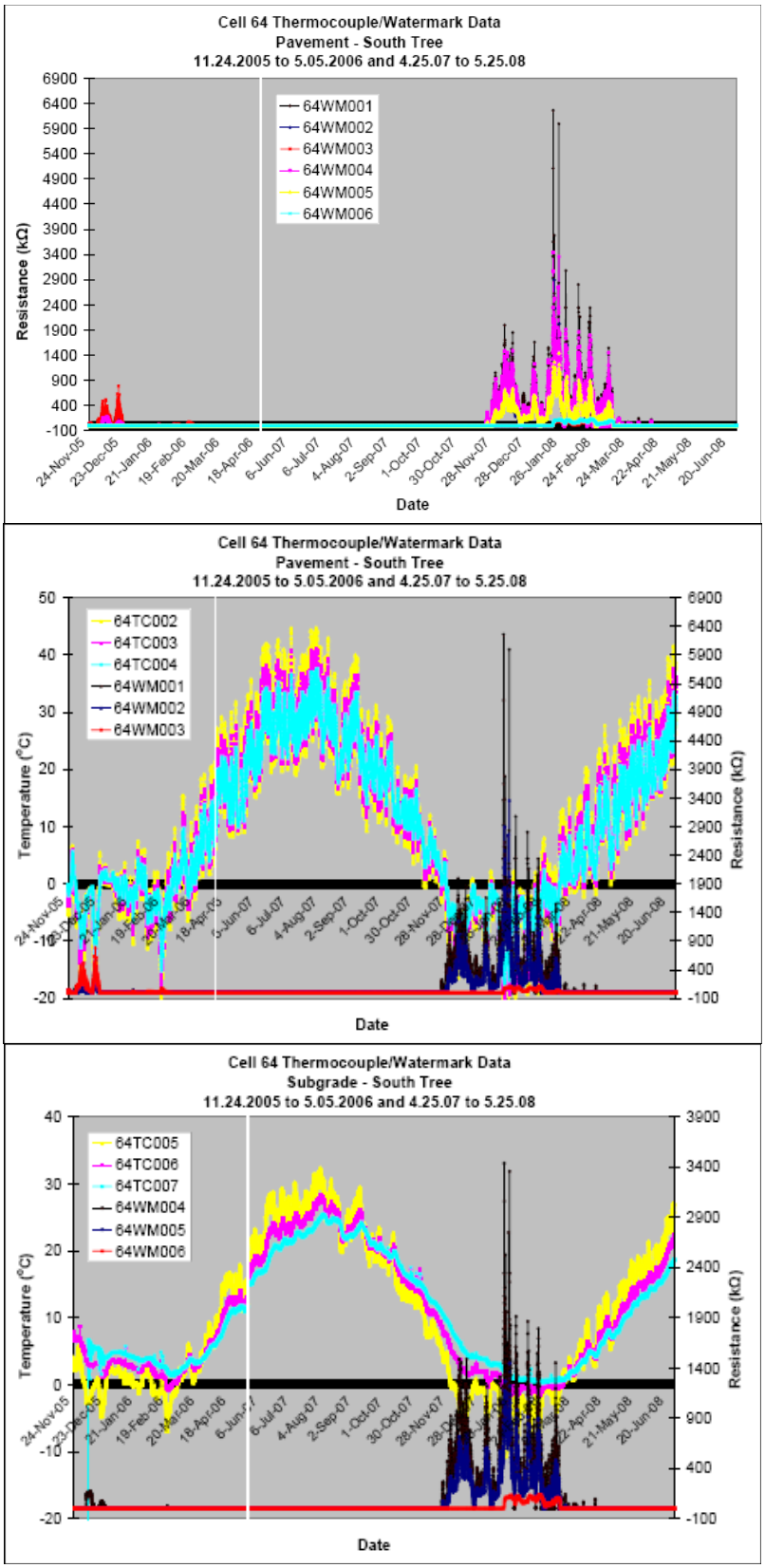

FIGURE 2 Top: water mark, middle: water mark and thermocouple (pavement), bottom: thermocouple and watermark (subgrade).

Both mixes contained traces of sand that were not specified in the mix design. The presence of the sand may have resulted from contamination left in the mixer barrel from previous pours. Air content of the pervious concrete consisted of less than 1% entrained air and the spacing factor was much lower than recommended for freeze-thaw resistance in normal PC concrete. The core from the north trial slab (Mix #3) had a difference in air voids of 3.5% between the top and bottom, while the core from the South trial slab (Mix #4) had an air void difference of 17% between the top and bottom. Both cores had a higher air void percentage near the bottom.

Fine, tight cracks were evident in both cores at all depths. Mix #3 displayed these cracks through the paste running from air-void to air-void, air-void to aggregate, aggregate to aggregate, and occasionally following the aggregate-paste interface. Mix #4 displayed these cracks as well, although they were more apparent near the top of the core than Mix #3. In addition, cracks in Mix #4 ran through the aggregate as well as the paste. It is difficult to determine the cause of these cracks, but some possibilities include: 1) exposure to repeated freeze-thaw cycles, 2) shrinkage from low water/cement ratio, 3) and/or exposure of the pervious driveway to heavy loads. The top portion of Mix #4 exhibited more cracks, had a higher paste-void ratio, and much lower air content. The higher paste-void ratio at the top of the core may have lead to higher internal stresses caused by drying and autogenous shrinkage and hence, more cracking.

Cemstone Ready Mix Concrete Suppliers performed petrographic analysis of four cores taken from the pervious driveway in accordance with ASTM C 856 and ASTM C 457. Of the four cores, three represented the material near the south end of the driveway, Mixes #2 and #3, where raveling of the top layer had occurred and one, Mix #1, represented the northern part of the driveway that exhibited little to no raveling. Cemstone's analysis determined that the water/cement ratio was relatively low (approximately 0.30 to 0.40) based on the optical and physical properties of the cementitious paste. In addition to this, all four core-samples showed paste fraction inhomogeneities of lower water/cement ratio paste within pockets of high water/cement ratio paste, especially within the recesses of the coarse aggregate particles. Moderate microcracking, and subsequent carbonation of those cracks, was common in the top 3-in. of the cores; the top ¼-in. to ½-in. of the cores exhibited extensive microcracking consistent with severe shrinkage. The air void system in these cores consisted mainly of compaction voids that ranged from 21% to 31%.

Hydraulic Conductivity Monitoring

In order to measure the performance of the pervious concrete, a way in which to measure changes in permeability due to winter sanding/salting, plowing, and sweeping is needed to insure that the pervious concrete remains unclogged. Traditional methods for monitoring hydraulic conductivity of pervious concrete involved removing cores and testing them using either continuous or falling head permeability tests [2, 13-14]. In order to measure seasonal variations in permeability and also to prevent destroying the test cell by taking concrete cores, an in-field permeability measurement device was required. Our experiment performed in-situ uses a time function for emptying under a varying head.

The device developed by Mn/DOT was a modified Humboldt H-4245 sand cone as shown in Figure 3. Duct seal compound was used to create a seal between the pervious concrete and the bottom cone flanged opening. The time it took for water to drop between two lines along the straight portion of the 1-gal plastic jar was measured. Measurements were taken at several locations on the pervious test cell. Measurements will periodically be repeated at these same locations in order to determine changes in permeability.

FIGURE 3 In-situ hydraulic conductivity measurement device.

The permeability was determined as follows. From continuity, the flow rate of the water in the plastic jar must equal the flow rate exiting the sand cone, Equation 1.

$$\frac{\pi d^2}{4} dh = v_0 A_0 dt \tag{1}$$

Then Bernoulli gives Equation 2.

$$\frac{P_1}{\rho_1 g} + \frac{v_1^2}{2g} + z_1 + losses = \frac{P_2}{\rho_2 g} + \frac{v_2^2}{2g} + z_2 \tag{2a}$$

$$v_0 = \lambda\sqrt{2gh} \tag{2b}$$

Where λ is a constant that accounts for piezometric head loss due to the sand cone device. Combining equations 1 and 2, reorganizing, and integrating both sides gives:

$$-\frac{\pi d^2 \sqrt{h}}{2\lambda\sqrt{2g}\,A_0} + C = T \tag{3}$$

Then substituting the boundary conditions of h = H when T = 0 gives:

$$-\frac{\pi d^2}{2\lambda\sqrt{2g}A_0}\left(\sqrt{h}-\sqrt{H}\right)=T \quad (4)$$

Equation 4 is different from the equation typically used for falling head permeability because in porous concrete, the term containing the velocity head cannot be neglected; it is typically neglected in soils. To compensate for the losses due to the reduction in cross-sectional area at the valve, the time it takes for the "perveammeter" to empty in air, T_{air} = 10 s, is introduced. When T = 10 s, $\lambda' = 1/\lambda = 1$, and the left side of Equation 4 must equal 10 s which gives:

$$\lambda' 10 = T \quad (5)$$

Equation 5 relates the hydraulic conductivity of the pervious concrete as a multiple of the time it takes for the perveammeter to empty in air. Equation 5 is similar to:

$$Q = KiA \quad (6a)$$

$$V = KiAt \quad (6b)$$

Where Q is discharge, K is hydraulic conductivity, A is area, i is the hydraulic gradient, V is volume, and t is the time of discharge. Assuming a tortuous path around a rounded aggregate, the hydraulic gradient is equal to

$$i = \frac{2r}{r\pi} = 0.64 \quad (6c)$$

The effective porosity of the pavement system for a 7 in. thick pervious concrete with 20% porosity and 12 in. thick drainable base with 40% porosity is 33% therefore the effective volume available to store water is $V_{eff} = 0.33 \cdot 19 \cdot A$. Based on the apparatus used and the minimum time of discharge for good draining pavement, the discharge time for a 6 in. drop in head was 17 s which gives a hydraulic conductivity of K = 0.35 in/s. The effective time (t_{eff}) to fill the storage is given by:

$$t_{eff} = \frac{V_{eff}}{iKA} = \frac{0.33 \cdot 19 \cdot A}{0.64 \cdot 0.35\, in/s \cdot A} = 28s \quad (7)$$

Since the water in our test is not restricted to vertical flow and can flow horizontally as well, an equipment multiplier must be used to convert the effective hydraulic conductivity to one-dimensional flow. This conversion factor is obtained by diving the effective time to fill the storage (t_{eff}) by the minimum time measured in clean pervious concrete.

$$EM = \frac{t_{eff}}{t} = \frac{28s}{17s} = 1.65 \quad (8)$$

The effective time (t_{eff}) of discharge when the hydraulic conductivity is reduced to 10% of its initial clean value is 280 seconds. Then using the equipment multiplier (EM), the actual measured time using the developed perveammeter is:

$$t_d = \frac{t_{eff}}{EM} = \frac{280s}{1.65} = 170s(2.8\,\text{min}) \quad (9)$$

This procedure suggests ≈3 min. as the threshold for clogging when clogging is defined as a reduction of 90% in hydraulic conductivity.

Distress Mapping

The overall surface condition of the pervious test cell was surveyed using Mn/DOT's Pavement Distress Identification Manual as a guide. The methods described in the manual are typically utilized for much larger stretches of roadway. However, the manual provides a standardized method as well as a terminology familiar to most transportation and pavement engineers. The top ¼-in. of the central to southern part of the pervious driveway had raveled somewhat due to freeze thaw action, frequent use by MnROAD equipment, and/or possible overworking of the concrete during placing. Further degradation of the driveway beyond this top quarter inch does not appear to be present, and the cores taken by Mn/DOT in August, 2006 exhibit no macro cracking. The northern portion of the driveway exhibits no superficial macro cracking, very little raveling, joint spall, or other abnormal condition, and appears to be in very good condition overall. Furthermore, the pervious driveway and trial slab Mix #4 have not experienced frost heave. Trial slab Mix #3 experienced approximately 1-in. of frost heave after the first winter, most likely due to the lack of stable base material, and freeze-thaw action.

The overall rating of the surface and joints varied greatly depending on the location examined on the driveway. Mixes #1 and #3 showed less raveling/spalling compared to Mix #2 which showed moderate to severe raveling and joint spalling. Mix #1 showed low spalling at all joints except the tooled joint and the joint between Mix #1 and Mix #2. These two joints show moderate spalling and raveling, respectively. The surface of Mix #1 showed raveling of low severity. Mix #2 showed moderate to severe raveling on the surface of the concrete, with moderate to severe raveling and spalling at the joints. Mix #3 showed low raveling on the surface with moderate to severe raveling and spalling at the joints.

Falling Weight Deflectometer (FWD)

Mn/DOT personnel have performed two sets of FWD tests on the pervious concrete driveway since its construction. The tests were performed in October, 2005 and August, 2006. The purpose of this testing was to gather data before and after the major freeze-thaw events of the winter to determine the effects on the pervious concrete.

The FWD tests were performed with Mn/DOT's Dynatest equipment. In October 2005, nine 9-kip drops were performed. This load range was abbreviated to exclude the 6-kip and 15-kip loads because it was thought that the 6-kip load might not impart a detectable response with respect to ambient noise, while it was thought that the 15-kip load might damage the pervious concrete structure since the driveway had only one month to cure before the first testing event. Since the 9-kip load did not appear to affect the macrostructure of the concrete, Mn/DOT had more confidence in performing the full spectrum of loads. Subsequently, in August 2006, nine drops were performed consisting of three drops each at the 6, 9, and 15-kip load ratings. The data

was then plotted to reveal deflection basins and stress distribution curves. The load-bearing pad on the FWD apparatus was placed directly above the strain gauge sensors CE-01 and CE-02 for each test, as marked on the pervious driveway surface. This was done to provide consistency between data sets and to impart the maximum strain on the gauges within the pavement. Strain response data was collected from gauges CE-01 and CE-02 in conjunction with the FWD load deflections.

Deflection basins and stress distribution curves were plotted for each load setting (6, 9, and 15-kips). In addition each of the three FWD loadings, and their corresponding deflections, were normalized in order to compare the FWD strain data with the strain measurements obtained by sensors CE-01 and CE-02 [11]. Although an adequate comparison, the FWD deflection/strain data differs somewhat from the Mn/ROAD truck strain data due to the proximity of the truck tires to the CE-01 and CE-02 sensors. Furthermore, the load application for the two loading types is different (falling impact versus slow rolling weight). The FWD and truck pass strain data show that the pervious concrete can withstand the stresses typically placed on standard pavements. The pervious concrete has not developed macro-cracking due to the daily loading by the 80 kip MnROAD truck and quarterly FWD load testing.

Maximum FWD deflection data was compiled from two different normal PCC pavement sites to compare with the pervious test cell deflection data. The FWD loads imparted greater deflections on the pervious concrete than either the control section of TH100 or the concrete paving of Cell 53, a typical concrete pavement on the MnROAD Low Volume Road (LVR). Part of the reason for this may be that the materials and pavement thicknesses differ somewhat between these three pavement sections. The pervious concrete is 7-in. thick, while Cell 53 and TH100 pavements are 7.5-in. and 12-in. thick, respectively. However, the general pavement and base structure for the pervious test cell and Cell 53 are most comparable. Figure 4 shows the maximum deflections of the Cell 64 pervious concrete driveway, the Cell 53 LVR concrete paving, and the TH100 control section.

Stress-strain characteristics of the pavement structure show FWD deflection basins that are larger than those of normal concrete, but within the same order of magnitude. The maximum deflections at drop stresses of 6, 9, and 15-kips are 78.8, 118.2, and 200-mils, respectively (August 2006). For comparison, the maximum deflection for Cell 53 in the MnROAD LVR, similar only in layer thickness but constructed of normal concrete, is 98.9-mils for a 15-kip load. The maximum deflection for a 15-kip load on TH 100 (12-in. pavement) is 39.4-mils. The most important item of note here is that the Cell 64 pervious concrete exhibits deflections 2 to 5 times larger than those recorded in non-pervious (normal) concrete pavements (Figure 4).

In addition to the monitored deflections from FWD testing, dynamic strain gauges CE-01 and CE-02 monitored the response to applied loads from the 80 kip Mn/ROAD truck, as well as loads from the FWD. The strain data was extrapolated to the surface of the driveway using plane strain theory, from which a modulus of elasticity (E) could be calculated knowing the stress imparted by the FWD. Figure 5 shows a comparison of the elastic moduli calculated from the Cell 64 FWD stress/strain data.

The strains measured by the concrete embedment sensors CE-01 and CE-02 exhibit time/temperature variability, which may explain a portion of the differences in the calculated moduli shown in Figure 5. The modulus values calculated for CE-02 may be higher, relative to CE-01, because the pervious concrete may have a lower porosity due to reduced air voids from overworking of the concrete during placement [10]. The moduli were calculated using a simple $\sigma = E^*\varepsilon$ strain equation where σ, E & ε are stress, elastic modulus (E), and strain, respectively.

The strain is the value read from the CE strain gauges extrapolated to the surface of the pervious concrete, and the stress is the value calculated from the applied load over the footing area of the load actuator. To use this equation, it was assumed that the deformation of the pervious concrete remained in the elastic regime.

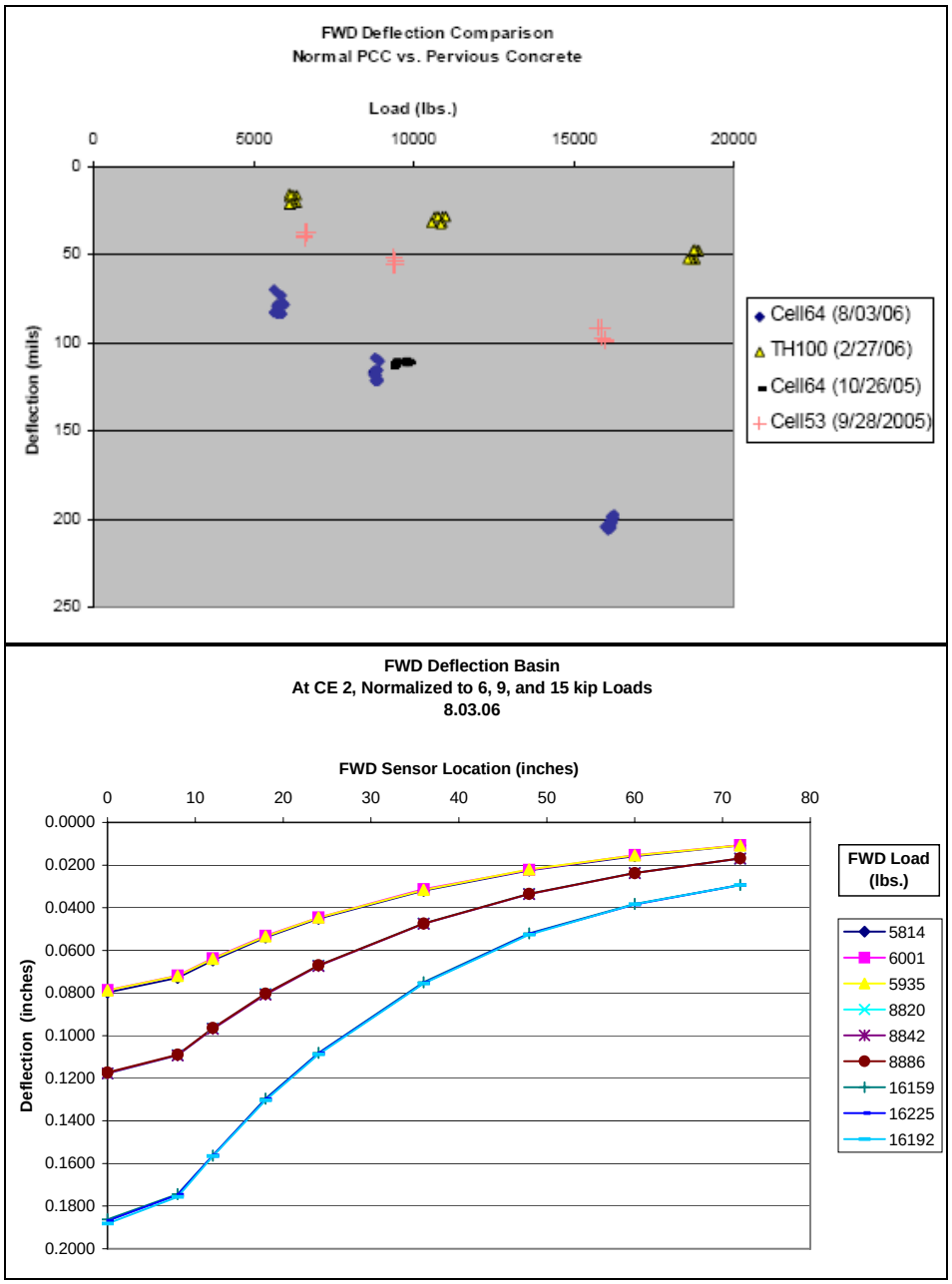

FIGURE 4 Comparison of maximum FWD in normal PCC and pervious PCC and pervious PCC normalized FWD deflection basin.

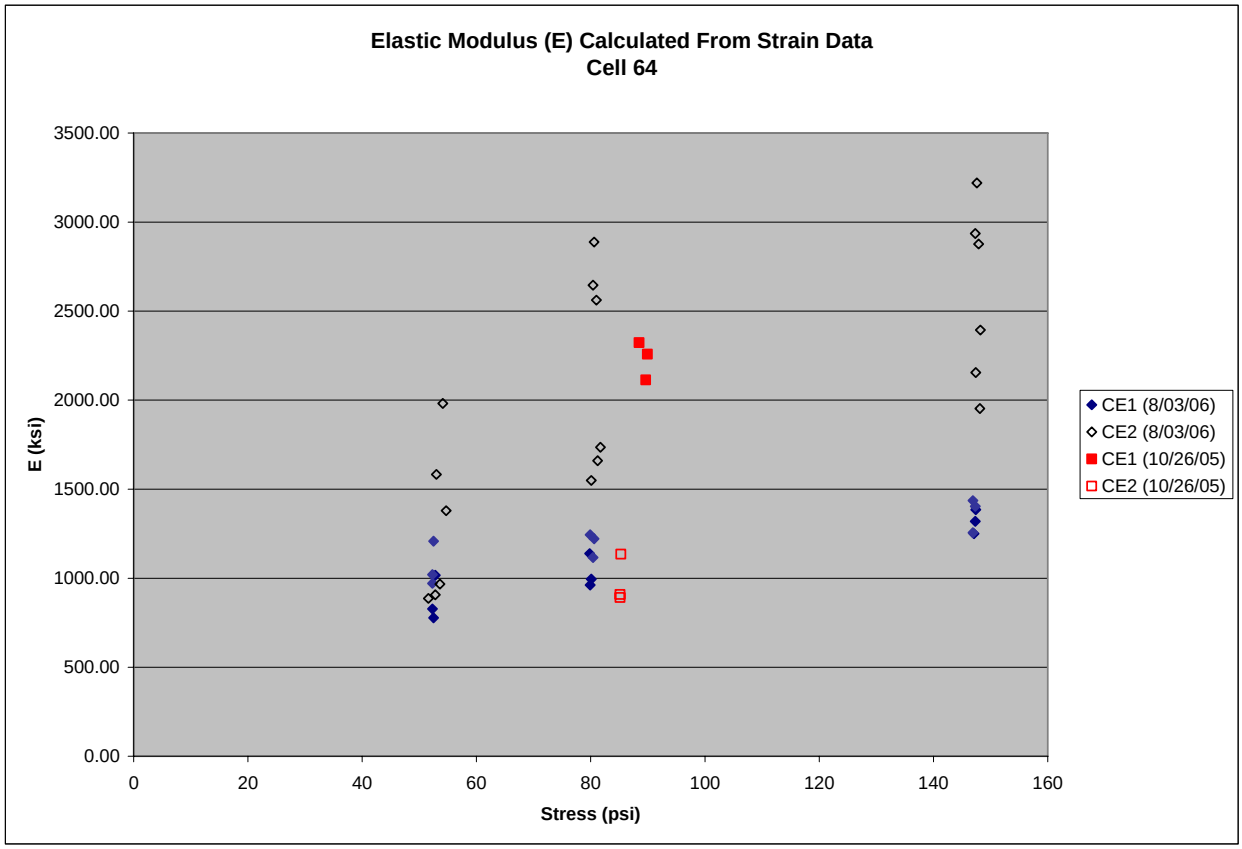

FIGURE 5 Elastic Modulus Calculated From FWD Strain Data.

CONCLUSION

The Cell 64 pervious concrete driveway shows apparent wear for its first three seasons in service including structural macro cracking, and raveling at the joints. Modulus of rupture obtained from prisms indicated that the Cell 64 pervious concrete would have tolerated similar opening time criteria as normal concrete if based on flexural strength. However, FWD results showed larger deflection basins by a factor of 2 to 5 depending on the magnitude of the load. That observation was corroborated by the elastic modulus values that ranged from 725 to 2900 ksi (5.00 to 19.99 N/mm^2). The upper limit of this range is comparable to typical elastic moduli of normal concrete (2000 to 6000 ksi) [15].

Distress observations indicate that poor finishing techniques resulted in raveling and spalling of the pervious driveway surface. The most severe observations of spall/ravel were located in areas that may have been affected by over finishing during placement, the majority of which have occurred in the months after placing the pervious concrete. After further examination, the distress was found to be topical and has not visibly worsened after three years. In general, the mixture consisting of crushed aggregate performed better than the mix of crushed and rounded aggregates. This corroborates the findings of the Iowa mix design report for Pervious Concrete by Schaefer *et al.* [2].

Protocol for monitoring hydraulic conductivity was developed and seasonal changes will be monitored. FWD deflection and strain data will continue on a quarterly basis, as will monitor of the vibrating wire strain gauges and thermistors. Thermocouple and watermark data are continually logged by the MnROAD automated system.

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