MINNESOTA DEPARTMENT OF TRANSPORTATION

RESEARCH

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MnROAD Cell 64 Pervious Concrete First Year Performance Report

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This report evaluates the first year performance of the Pervious Concrete test cell #64 located in the parking lot on the south side of the MnROAD pole barn. Performance measures utilized for this report include examination of stress-strain response through loading from the 80 kip MnROAD truck and Falling Weight Deflectometer (FWD). The FWD deflection basins were compared to those obtained for normal concrete of similar thickness design. The second performance measure was the vibrating wire strain gauge sensor response. Elastic modulus values were computed from the sensor data. In addition, petrographic analyses of cores taken from the test pad and pavements were performed to determine the macroscopic and microscopic characteristics of pervious concrete pavement after the first year. Furthermore, a surface rating of the pavement was performed to corroborate petrographic and freeze-thaw data in order to ascertain the cause of any structural anomalies within the pervious concrete structure.

Overall, the pervious concrete cell #64 is performing well after its first year. Normal sanding and salting operations do not appear to have impacted the pore structure within the pervious concrete to date. However, a more quantitative method of measuring flow through the cell and base materials is needed before a final conclusion can be made about the enduring ability of pervious concrete to pass water. Such a quantitative flow measurement method is currently under development.

The structure of the pervious concrete cell #64 remains strong after a year of FWD/MnROAD truck loading and normal usage by vehicular movement over the driveway. Microcracking observed from petrographics does not appear to be worsening. Spalling and raveling conditions appear to have stabilized and are surficial in nature.

This report concludes that pervious concrete is performing well in cell 64, and with continuous monitoring there will be greater confidence in more low volume applications.

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MnROAD Cell 64 Pervious Concrete
First Year Performance Report

Final Report

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February 2007

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EXECUTIVE SUMMARY

This report evaluates the first year performance of the pervious concrete test cell #64 located in the parking lot/driveway on the south side of MnROAD's pole barn. The performance measures utilized for this report include stress strain response through the use of the Falling Weight Deflectometer (FWD). Deflection basins plots are compared to those obtained for normal concrete of similar thickness and design. The second performance measure is the vibrating wire strain gauge sensor response. Elastic modulus values are computed from the sensor data. In addition, petrographic analysis is performed on cores taken from the test pad to determine the macroscopic and microscopic characteristics of pervious concrete pavement after the first year. Furthermore, a surface rating gives an objective pavement surface evaluation based on methods from the Mn/DOT Pavement Distress Identification Manual.

Stress-strain characteristcs of the pervious driveway 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 6000, 9000 and 15000 lb. loads are 78.8 mils, 118.2 mils, 200 mils, respectively (August 2006). For comparison, the maximum deflection for Cell 53 in the MnROAD Low Volume Road (LVR), similar only in layer thickness but constructed of normal concrete, is 98.9 mils for a 15000 lb. load. The maximum deflection for a 15000 lb. load on TH 100 (Control Section CS2735, 12" pavement) is 39.4 mils. The most important item of note here is that the cell 64 pervious concrete exhibits deflections 2 to 4 times larger than those recorded in non-pervious (normal) concrete pavements.

This report also analyzes the real time impacts of the five-axle MnROAD semi-trailer on the pavement. Loading cell 64 with the MnROAD truck provides data that helps corroborate the deflection and strain response of cell 64 to FWD loads, so that the somewhat arbitrary FWD loading and subsequent deflections can be understood in terms of a real world load perspective.

Elastic moduli (E) computed by extracting and analyzing FWD stress-strain information from the embedded strain gauges (labeled 64-CE-01 and 02) show a consistent increase from the October 2005 to August 2006 tests. E ranges from 1000 to 2250 psi for October 2005, and from 800 to 2900 psi for August 2006, both at a dropstress of 9000 lbs. At a drop stress level of 15000 lbs., the E values generally range from 850 to 3250 psi. The item of greatest note here is that the pervious concrete exhibits E values at the low end of E values for normal PCC, and that the pervious concrete has remained in the elastic domain for all FWD loadings.

Petrographic analyses were performed on cores from the test pads and pervious test cell 64 to examine the structural effects of loading, and the physical and chemical makeup of the cores. Cores were obtained from three different sampling events. Mn/DOT took four cores on February 2, 2006 for petrographic analysis. Cemstone subsequently took four cores for petrographic analysis. The most recent coring event took place on August 14, 2006, where Mn/DOT took two more cores.

Mn/DOT took the first set of cores for petrographic analysis, and performed ASTM C457 Linear Traverse on two separate cores. The petrographic analysis quantified the various constituents of the pervious concrete and show that both mixes contain traces of sand that are not specified in the mix design. Air content of the cement paste matrix consists of $\leq$ 1% entrained air, and the spacing factor is much lower than recommended for freeze-thaw resistance in normal Portland cement concrete (PCC). As examined, air voids in the cores (entrapped air, comprised of the void spaced between the coarse aggregate) varied by as much as 3.5% to 17% between the top and bottom of the core. In all cores examined, the higher air void percentage was observed at the bottom of the core. Furthermore, petrographic examination identified microcracking in the cores, with higher crack density appearing near the tops of the cores. The cracks were observed to run through the paste from void-to-void, air void-to-aggregate, aggregate-to-aggregate, following the aggregate-paste interface, and in some cases, propagating through the coarse aggregate.

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, and 3) exposure of the pervious driveway to heavy loads. Core 6406CC003 exhibits more cracks in the top portion of the sample, has a higher paste-void ratio, and much lower air content. The portion of the mix with higher air content (the bottom of Core 003) shows less distress and cracking while the higher paste content at the top of core 6406CC003 may have lead to higher internal stresses caused by drying and autogenous shrinkage. However, some of the cracks propagated through the aggregate. This characteristic of fatigue-type distresses typically occurs later in the service life of the concrete. Early cracking due to shrinkage generally propagates around, and not through, the aggregate.

Freeze thaw cycles are characterized by analyzing the data from two sensor trees of watermarks and thermocouples within the pavement and subgrade. By superimposing thermocouple and watermark data it is possible to accurately pick freeze-thaw events from the two data traces. Freeze-thaw cycles are important because the durability of pervious concrete may depend on its ability to resist freeze-thaw type weathering. It has been suggested that the observed surface raveling of cell 64 is due to freeze thaw damage, however the phenomenon may also depend on construction discontinuities that are known to affect normal concrete. Mn/DOT personnel dislodged surface aggregate using a prospector's pick in raveled areas to dislodge surficial aggregate that may have been re-tempered and over finished. Through the use of this technique it appears that the scaling/raveling phenomena is topical and is not widespread or in a state of continuing deterioration.

After one year, there is evidence of spalling at tooled joints and ravelling in some areas. The most ravelled areas are those with construction placement discontinuities, possible overfinishing, and/or re-tempering. However, there is no overt evidence of any loss of porosity due to sanding and salting, and the flow at the discharge end of the embedded drainpipe flows uniformly in response to a large volume of water poured on the pavement. Mn/DOT currently conducts qualitative porosity measurements, as it is too early to ascertain or detect minute losses of hydraulic conductivity. A quantitative flow evaluation tool, currently under development, will replace the schematic qualitative hydraulic conductivity measurement.

This report concludes that the cell 64 pervious concrete is performing well with regard to flow capacity, weathering, and load bearing capacity. With further monitoring there will be greater confidence in low volume road applications.

1 THE MNROAD FACILITY AND CELL 64 OVERVIEW

The Minnesota Department of Transportation (Mn/DOT) initially constructed the Minnesota Road Research Project (MnROAD) between 1990 and 1994. MnROAD is located along Interstate 94, approximately forty miles northwest of Minneapolis/St.Paul and is an extensive pavement research facility consisting of two separate roadway segments containing 51 distinct test cells. Each MnROAD test cell is approximately 500 feet long. Subgrade, aggregate base, and surface materials, as well as, roadbed structure and drainage methods vary from cell to cell. All data presented herein, as well as historical sampling, testing, and construction information, can be found in the MnROAD database and in various publications. Layout and designs used for the Mainline and Low Volume Road are shown in Appendix D.

Although not part of the MnROAD mainline or Low Volume Road (LVR), cell 64 is a 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 (See Figure 2). A 64' by 20' 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 slab. The actual size of the pervious concrete portion of the driveway is 60' by 16', surrounded by a 2' concrete border on all sides.

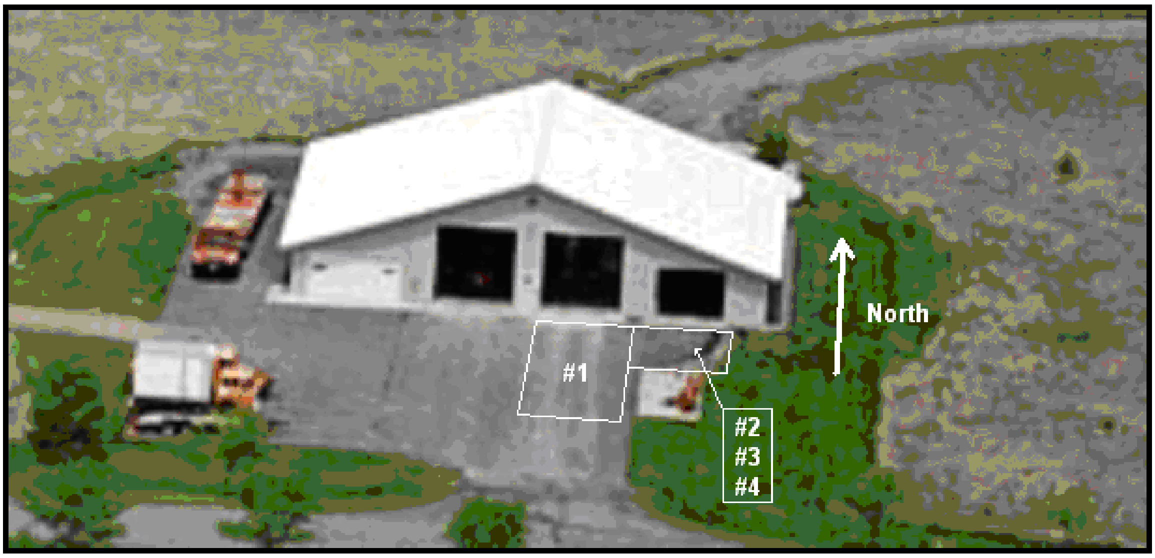
Figure 1. MnROAD Mainline, Low Volume Road, and Cell 64

1.1 MnROAD Mainline and Low Volume Road

The MnROAD mainline consists of a 3.5-mile 2-lane interstate roadway carrying "live" traffic. Mainline cell design/layout can be found in Appendix D-1. The Mainline consists of both 5-year and 10-year pavement designs. Originally, a total of 23 cells were constructed consisting of 14 HMA cells and 9 Portland Cement Concrete (PCC) test cells.

Parallel and adjacent to Interstate 94 and the Mainline is the Low Volume Road (LVR). Cell design/layout can be found in Appendix D-2. The LVR is a 2-lane, 2½-mile closed loop that contains 20 test cells. Traffic on the LVR is restricted to a MnROAD operated vehicle, which is an 18-wheel, 5-axle, tractor/trailer with two different loading configurations. The "heavy" load configuration results in a gross vehicle weight of 102 kips (102K configuration). The "legal" load configuration has a gross vehicle weight of 80 kips (80K configuration). On Wednesdays, the tractor/trailer operates in the 102K configuration and travels in the outside lane of the LVR loop. The tractor/trailer travels on the inside lane of the LVR loop in the 80K configuration on all other weekdays. This results in a similar number of ESALs being delivered to both lanes. ESALs on the LVR are determined by the number of laps (80 per day on average) for each day and are entered into the MnROAD database.

Additional information on MnROAD:
http://mnroad.dot.state.mn.us/research/mnresearch.asp
2004 Pervious construction:



http://www.mrr.dot.state.mn.us/research/construction/2005pervious.asp

Figure 2. The MnROAD pole barn and location of cell 64

- Area #1 – Cell-64 pervious concrete driveway (60' by 16').
- Area #2 – Pervious practice placement (Mix #3).
- Area #3 – Regular concrete placed between Area #2 and Area #4.
- Area #4 – Pervious practice placement (Mix #4).

1.2 Cell 64 Overview

The cell 64 pervious concrete driveway was constructed in late September of 2005 in a partnership agreement with Mn/DOT and the Aggregate Ready Mix Association of Minnesota (ARM of MN) (1). The intent of this partnership agreement was to construct a pervious concrete of similar thickness to typical transportation uses and monitor the response of the concrete to weather and loading. The concrete driveway was poured in one day over the course of approximately 4.5 hours. It took 6 loads of concrete from six different trucks to complete the driveway slab. Placing the pervious concrete is slower than placing normal non-pervious concrete, so small loads were used in each concrete truck so the loads would not get old during placing.

Three mix designs used for the concrete driveway, with the coarse 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/cement ratio and volume of admixtures remained the same between the three mix designs. Mix #1 contained quarried chip limestone aggregate of maximum nominal size ½" for the first 25.5' from the pole barn. Mix #2 contained both the ½" quarried limestone aggregate in addition to a rounded gravel of maximum nominal size ½" for the next 22' from the pole barn. Mix #3, placed in the final 12.5' of the driveway, contained only a dolomite gravel of maximum nominal size ½". See Figure 3 for relative placement of the loads and mixes within the pervious concrete driveway.

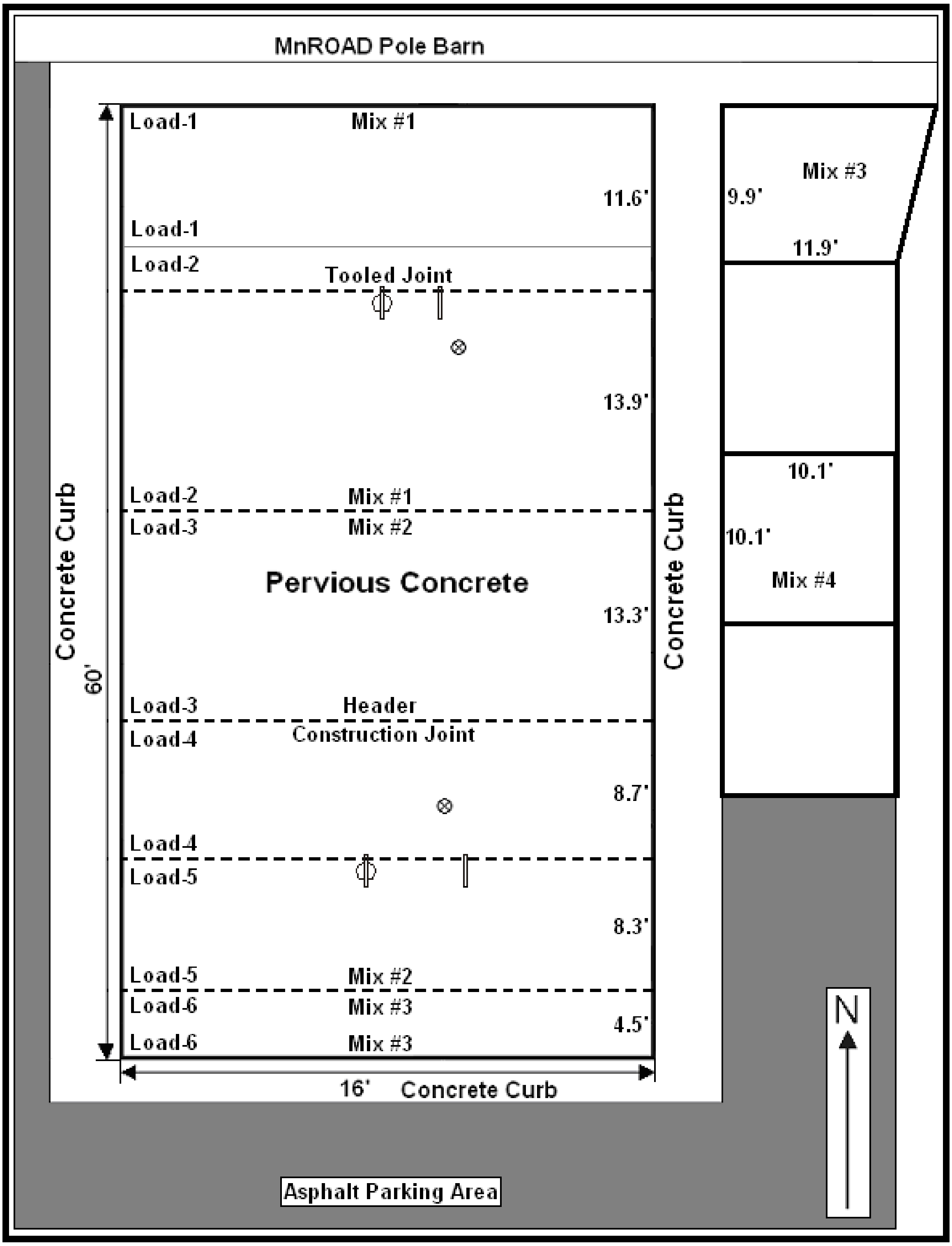


Figure 3. Layout of Mix Designs and Poured Load Placement

2 STRESS/STRAIN RESPONSE AND SENSOR DESCRIPTION

This chapter discusses results of FWD and MnROAD truck testing of pervious and normal PCC pavements for comparison. It also reports and describes the types of sensors and data collected at the MnROAD cell 64 pervious concrete driveway.

2.1 Falling Weight Deflectometer (FWD)

Mn/DOT personnel performed two sets of FWD tests on the Cell 64 pervious concrete driveway since its construction. The tests were performed on November 11, 2005 and August 3, 2006. The purpose of this testing was to gather data before and after the major freeze-thaw events of the winter to see the effects on the pervious concrete.

The FWD tests were performed with MnDOT's Dynatest equipment. In October 2005, nine 9000 lb. drops were performed. This load range was abbreviated to exclude the 6000 lb. and 15000 lb. loads because it was thought that the 6000 lb. load might not impart a detectable response with respect to ambient noise, while it was thought that the 15000 lb load might damage the pervious concrete structure since the driveway had only one month to cure before the first testing event. Since the 9000 lb. 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, 9 drops were performed consisting of 3 drops at a 6000 lb. load rating, 3 drops at a 9000 lb. load rating, and 3 drops at a 15000 lb. load rating. 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 (6000 lbs., 9000 lbs., and 15000 lbs.). In addition each of the three FWD loadings, and their corresponding deflections, were normalized to 6000 lbs., 9000 lbs., and 15000 lbs. in order to compare the FWD strain data with the strain measurements obtained by sensors CE-01 and CE-02. The dual tire load on each side of the rear axles on the 80 kip MnROAD truck is approximately 8500 lbs., derived from the 17000 lb. per axle load rating of the truck (12 kips on the front axle, and 17 kips per each of the four rear axles, for a total of 80 kips). Plots of the FWD deflection basins along with the corresponding strain gauge data from FWD and MnROAD truck loading are shown in Appendices A and B, respectively.

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 (2). 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 because the pervious concrete has not developed macro-cracking due to the daily loading by the 80 kip/102 kip MnROAD truck and quarterly FWD load testing.

2.2 Instrumentation and Sensor Data

Six sensors were embedded in cell 64 during construction. These sensors include two embedment strain sensors, and two vibrating wire strain gauges with thermistors. Table 1 lists the sensor codes, descriptions, and their functions. Figure 4 shows the locations of the sensors within the slab.

Sensor Code	Description	Function
64-CE-01	Embedment Strain Gauge	Measure Dynamic Strain Response
64-CE-02		
64-VW-01	Vibrating Wire Strain Gauge	Measure Environmental Strain Response
64-VW-02		
64-XV-01	Thermistor (in VW Strain Gauge)	Measure Concrete Temperature
64-XV-02		

Table 1. Embedded Sensors

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 according to Figure 5. The sensor trees were placed two feet east of the driveway centerline, at 15' and 45' north of the southernmost edge of the pervious concrete driveway, respectively.

A flow meter (ISCO model 4230) monitors the rate at which water flows from the drainpipe. The base materials beneath cell 64 are not isolated from the base materials of the surrounding parking lot. This means that some water passing through the pervious concrete may migrate horizontally into the adjacent base materials, although the majority of this water will pass through the CA-50 base material and into the drainpipe beneath the base materials.

No sensors were placed within Test Pads 2 or 4 because their main purpose was to place similar mixes and practice placement techniques. Test Pad 3 was placed as a buffer space between Test Pads 2 and 4.

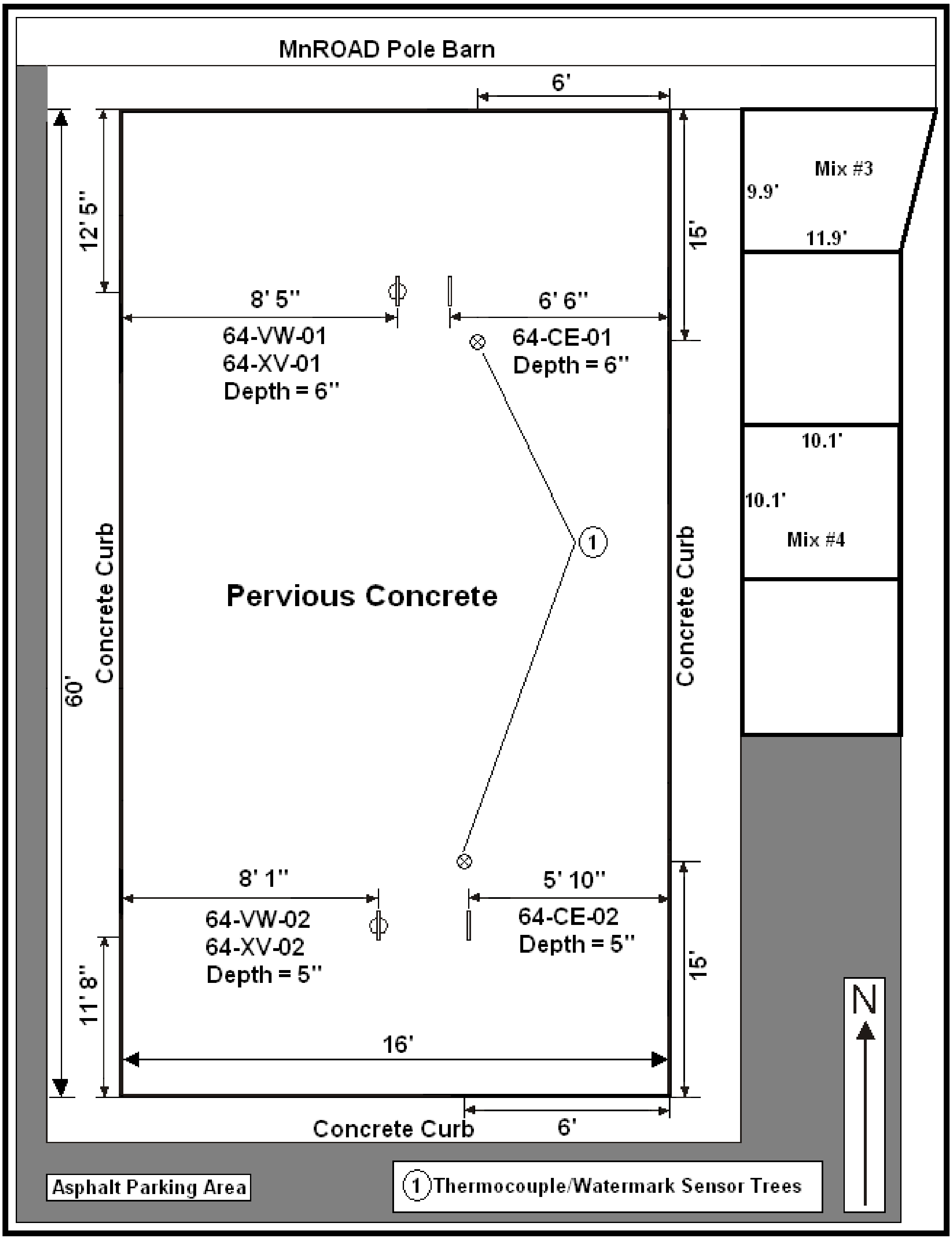


Figure 4. Cell 64 Sensor Locations (Plan View, not to scale)

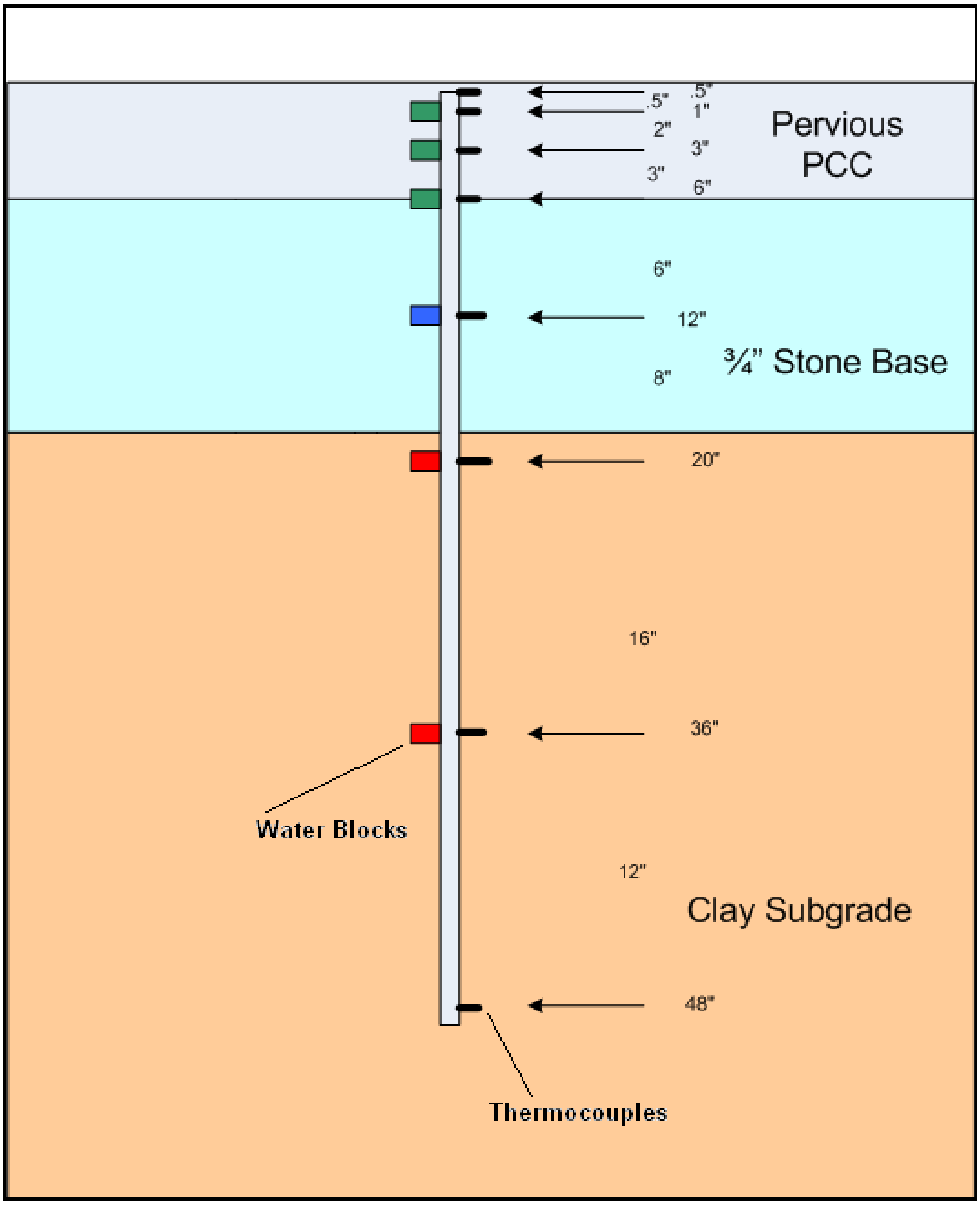


Figure 5. Cell 64 Sensor Tree (Profile View, not to scale)

3 MATERIAL CHARACTERISTICS

In addition to the sensor data collected, cores were taken for petrographic analysis. The petrographic analysis in the current level of detail facilitates a macroscopic and microscopic evaluation of the concrete core. It provides information on the air void system (specific surface and spacing factor), paste content, and historical information such as re-tempering and carbonation or other phenomena associated with cement hydration. It can also detect alkali silica reaction (ASR), or secondary ettringite if present.

Distress mapping was also performed, using the Mn/DOT Pavement Distress Identification Manual as a guide. This will help provide a more comprehensive concept of the overall surface condition of the cell 64 pervious concrete, which may help corroborate future petrographic and stress-strain findings.

3.1 Distress Mapping

Overall, 3 coring events provided samples for petrographic data from the pervious concrete driveway. 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 raveling of the tops of the mentioned cores.

Mn/DOT took four cores on February 2, 2006 for petrographic analysis. Cemstone subsequently took four cores for petrographic analysis. The most recent coring event took place on August 14, 2006, where Mn/DOT took two more cores. See Appendix E for Mn/DOT's petrographic report.

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 (numbered 6406CC-001, 6406CC-002, 6406CC-003, and 6406CC-004) represent mix designs #3 and #4. Cores 6406CC-002 and 6406CC-003 were ultimately chosen to represent mixes #3 and #4, respectively. ASTM C457 Linear Traverse was performed on both cores to quantify the various elements of the pervious concrete. 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 consists of $\leq$ 1% entrained air, and the spacing factor was much lower than recommended for freeze-thaw resistance in normal PC concrete. Core 6406CC-002 had a difference in air voids of 3.5% between the top and bottom, while Core 6406CC-003 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. Core 6406CC-002 displayed these cracks through the paste running from void-to-void, air void-to-aggregate, aggregate-to-aggregate, and occasionally following the aggregate-paste interface. Core 6406CC-003 displayed these cracks as well, although they were more apparent near the top of core 6406CC-003 than core 6406CC-002. In addition, cracks in core 6406CC-003 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) exposure of the pervious driveway to heavy loads. The top portion of core 6406CC-003 exhibits more cracks, has 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 provided petrographic analysis of four cores taken from the pervious driveway in accordance with ASTM C856 and ASTM C457. Of the cores, numbered 6407CC-01 to 6407CC-04, cores 6407CC-01 through 6407CC-03 represent the material near the south end of the driveway where raveling of the top layer has occurred. Core 6407CC-04 represents the northern part of the driveway that exhibits little to no raveling.

Cemstone's analysis determined that the water/cement ratio is relatively low (approximately 0.3 to 0.4) 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" inches of the cores; the top ¼" to ½" 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%. See Appendix F for the complete petrrographic report.

Mn/DOT took the most recent set of cores from the pervious driveway on August 14, 2006. The two cores taken represent mix designs #1 and #2. The cores, numbered m001 and m002, represent parts of the driveway showing low to high severity raveling, respectively. Petrographic analysis of these two cores is pending concurrently.

3.2 Distress Mapping

On 9.21.06, the overall surface condition of Cell 64 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 overall rating of the surface and joints varies highly depending on the location examined on the driveway. Mixes #1 and #3 show less raveling/spall compared to Mix #2 that shows moderate to severe raveling and joint spalling.

Mix #1 shows low spalling at all joints except the tooled joint and the joint where Mix #1 and Mix #2 are co-terminous. These two joints show moderate spalling and raveling, respectively. The surface of Mix #1 shows low raveling of low severity. Mix #2 shows moderate to severe raveling on the surface of the concrete, with moderate to severe raveling and spall at the joints. Mix #3 shows low raveling on the surface with moderate to severe raveling and spall at the joints. See Figure 6 for a complete diagram of the distress map.

In addition to the distress mapping, the chain-drag method of detecting cracks and subsurface defects was used to look for hidden structural problem areas. A Schmidt Hammer was also used to obtain a general sample and variability of the strength of the pervious concrete. The chain drag method was not particularly useful because of the nature of the void structure within the pervious concrete. It is worth noting, however, that the sound emitted by the chain drag procedure did not vary audibly while surveying Cell 64. This suggests that the voids in pervious concrete do not allow for detection of weak spots using this method. The Schmidt hammer results varied widely from 1900 psi up to 3800 psi, which is somewhat comparable to the strength distribution of the curb, 2300 to 4500 psi. Lower derived strength values were obtained in the coring locations that had been filled with normal concrete of non-standard mixes. See Appendix C for photographs of the joints and surfaces of cell 64.

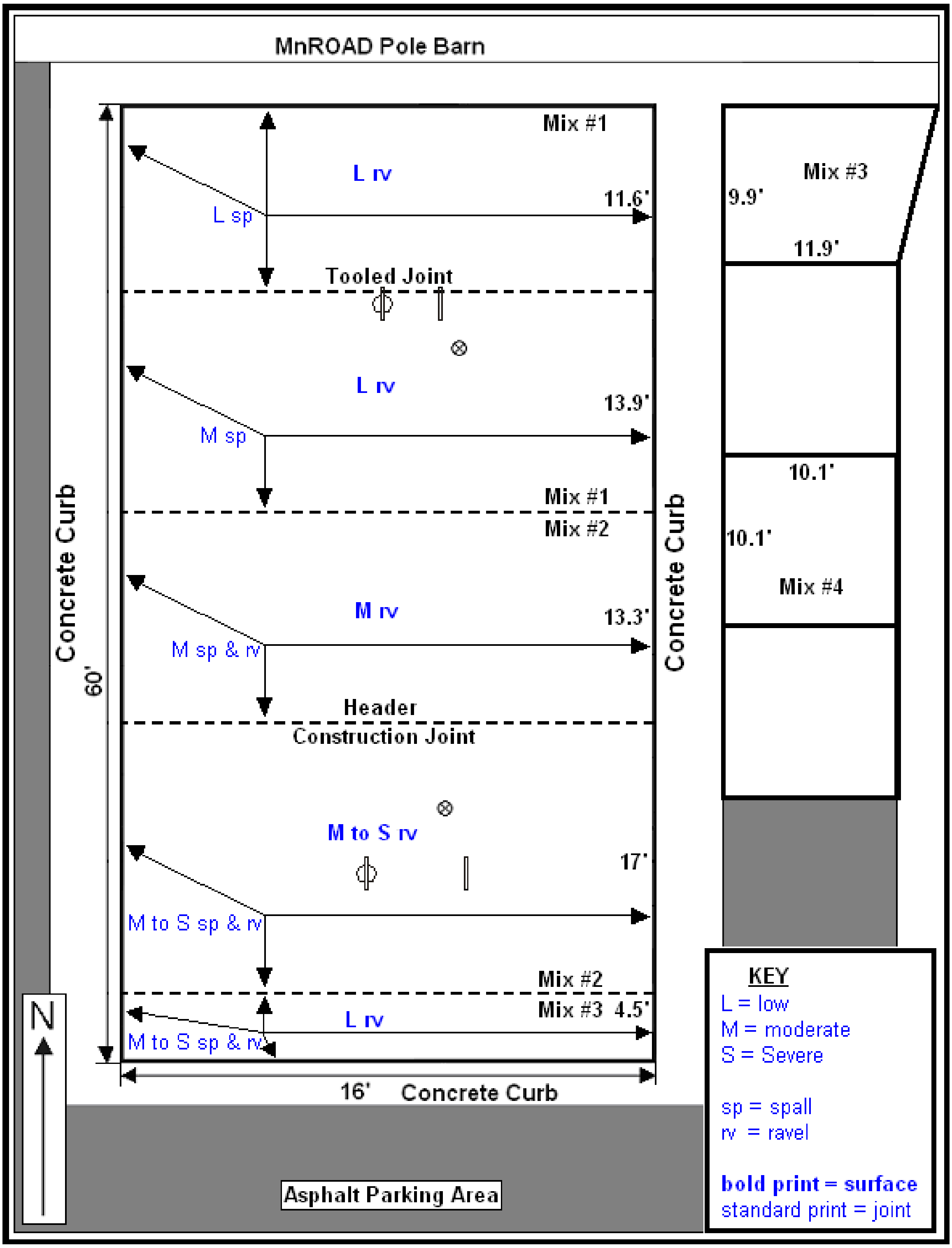


Figure 6. Distress Map of Cell 64, surveyed 9.21.06

4 PERFORMANCE EVALUATION

Deflection, strain, 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.

The FWD was used to monitor deflections due to imparted stresses (see Appendix A for deflection basin graphs). Maximum deflection data was compiled from two different sites to compare with the Cell 64 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. Part of the reason for this may be that the materials and pavement thicknesses differ somewhat between these three pavement sections. The pervious concrete of Cell 64 is 7" thick, while Cell 53 and TH100 pavements are 7.5" and 12" thick, respectively. However, the general pavement and base structure for Cell 64 and Cell 53 are most comparable. Figure 7 shows the maximum deflections of the Cell 64 pervious concrete driveway, the Cell 53 mainline 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 6000, 9000 and 15000 lb. loads are 78.8 mils, 118.2 mils, 200 mils, respectively (August 2006). For comparison, the maximum deflection for Cell 53 in the MnROAD Low Volume Road (LVR), similar only in layer thickness but constructed of normal concrete, is 98.9 mils for a 15000 lb. load. The maximum deflection for a 15000 lb. load on TH 100 (Control Section CS2735, 12" 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 (see Figure 7).

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 8 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 8. 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 as mentioned in the Cell 64 Pervious Concrete Driveway Construction Report (1). 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, we assumed that the deformation of the pervious concrete remains in the elastic regime.

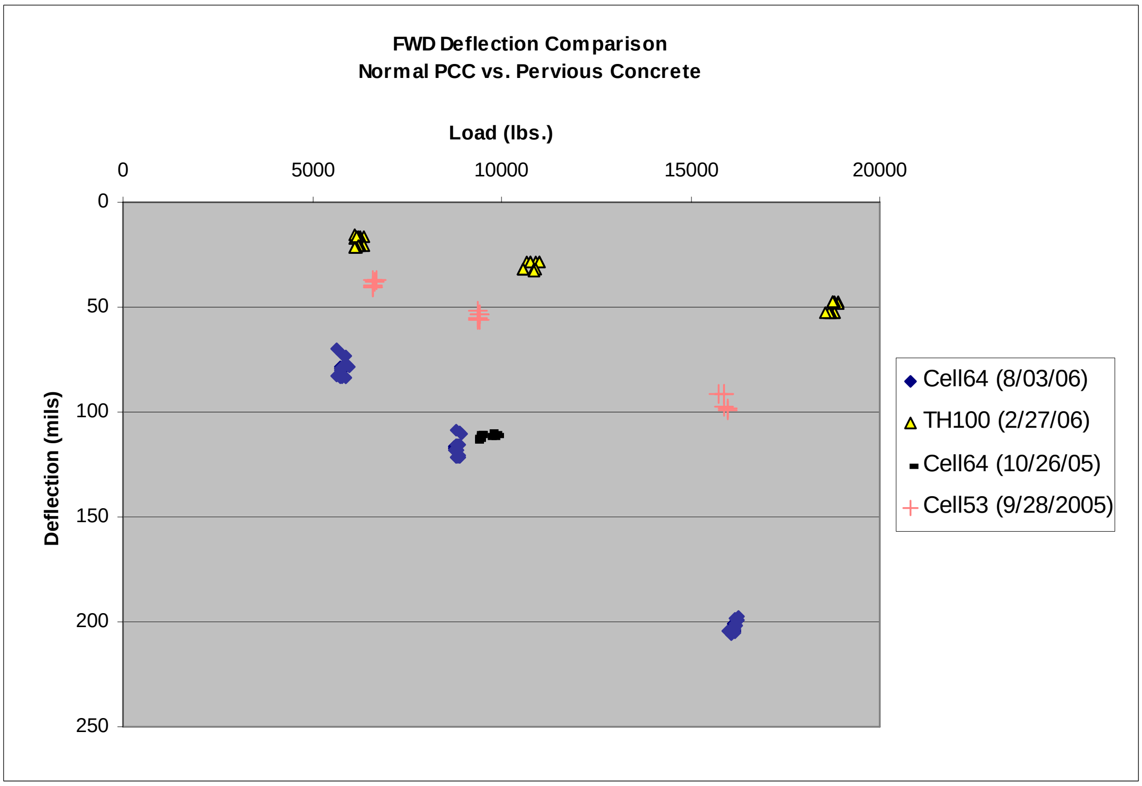


Figure 7. Comparison of Maximum FWD Deflections in Normal PCC versus Pervious PCC

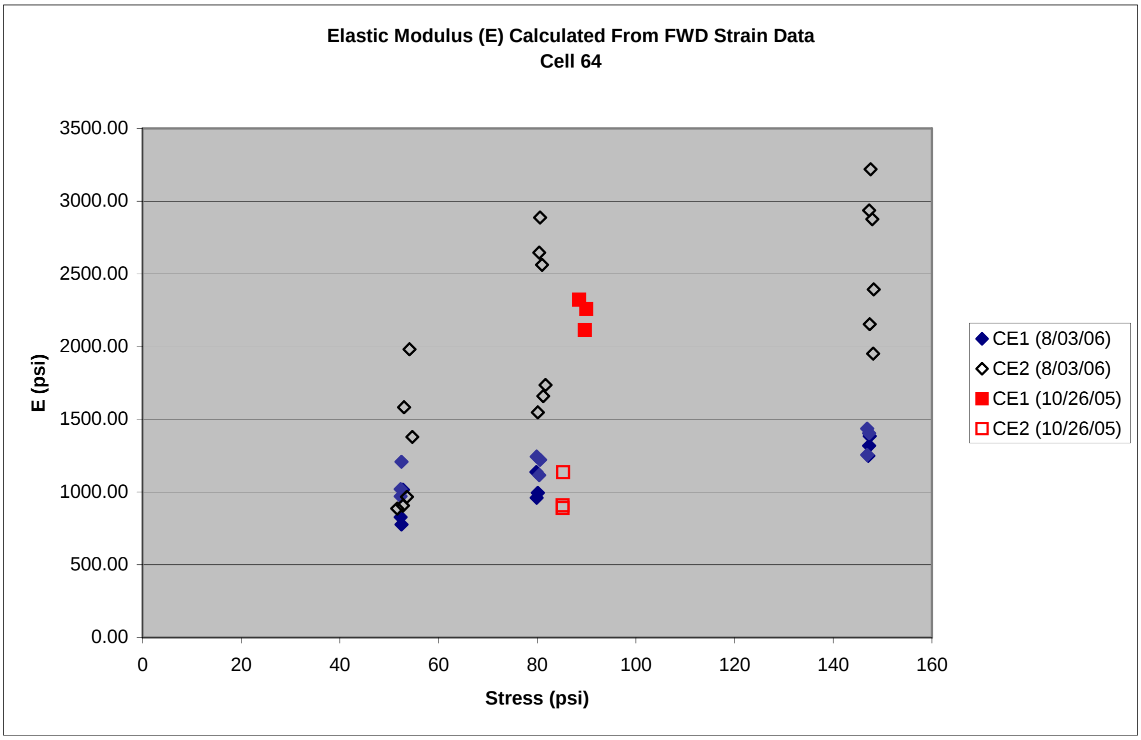


Figure 8. Elastic Moduli Calculated from Cell 64 FWD Strain Data

Strain data recorded for the 80 kip Mn/ROAD truck passes on gauges CE-01 and CE-02. These strain values have been extrapolated to the surface of the concrete using plane strain theory, as with the FWD strain measurements. The depth of each sensor dictates the multiplier that the data is paired with. For this data CE-01 is multiplied by 1.4, and CE-02 is multiplied by 1.5. This correction factor is based on the thickness of the concrete and the relative depth of the strain gauge in the pavement, which will be confirmed once the gauges are cored out at some time in the future.

Figure 9 shows the corrected strain data for each axle set of the Mn/ROAD truck as it passed over the strain sensor. It is difficult to determine any trends at this point, though the average strains from CE-01 are less than the average strains measured by CE-02 (See the Table B1 in Appendix B). Additionally the measured peak strain is less accurate, relative to the FWD measured peak strains, due to difficulties with aligning the truck tires to the sensor locations.

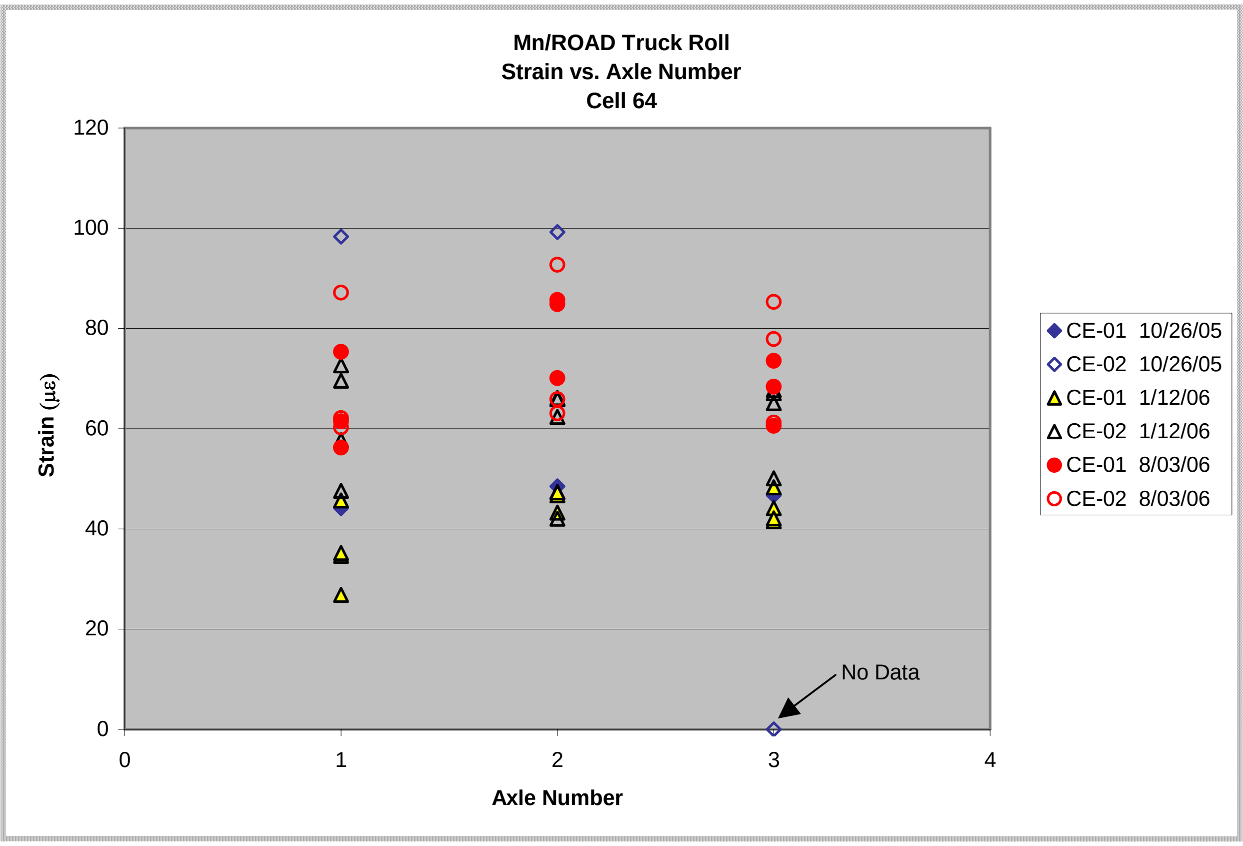


Figure 9. 80 kip MnROAD Truck Passes on Strain Gauges CE-01 and CE-02

Over the winter of 2005, the top ¼" of the central to southern part of the pervious driveway has 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 on August 14, 2006 exhibit no macro cracking. The northern portion of the driveway exhibits no surficial macro cracking, very little raveling, joint spall, or other abnormal condition, and appears to be in very good condition overall. Furthermore, the Cell64 driveway and Test Pad 4 have not experienced frost heave. Test Pad 3 experienced approximately 1" of frost heave most likely due to the lack of stable base material, and freeze-thaw action.

Figures 8 through 11 show the data from the thermocouple and watermark trees. 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. Each individual watermark and thermocouple is numbered sequentially increasing downward. See Figure 5 for an illustration of the position of each sensor relative to depth. Limited freeze-thaw events are visible in the watermark data due to a mild winter, however, the temperature and watermark data correlate very well with the few freeze-thaw events that occurred. Mn/DOT will maintain continuous collection of the watermark/thermocouple data for months that have the potential for freezing conditions.

The black, dark-blue, and red lines show the resistance read by the watermark sensor for three discrete depth intervals. 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 yellow, pink, and light-blue lines show the temperature at the corresponding thermocouple depth. Overall, the thermocouple temperature data coincide closely with the watermark data for each discrete depth, which helps to properly identify freeze-thaw events. For each graph, the yellow TC line matches the relative sensor depth of the black WM line, the pink TC line matches the relative sensor depth of the dark-blue WM line, and the light-blue TC line matches the relative sensor depth of the red WM line.

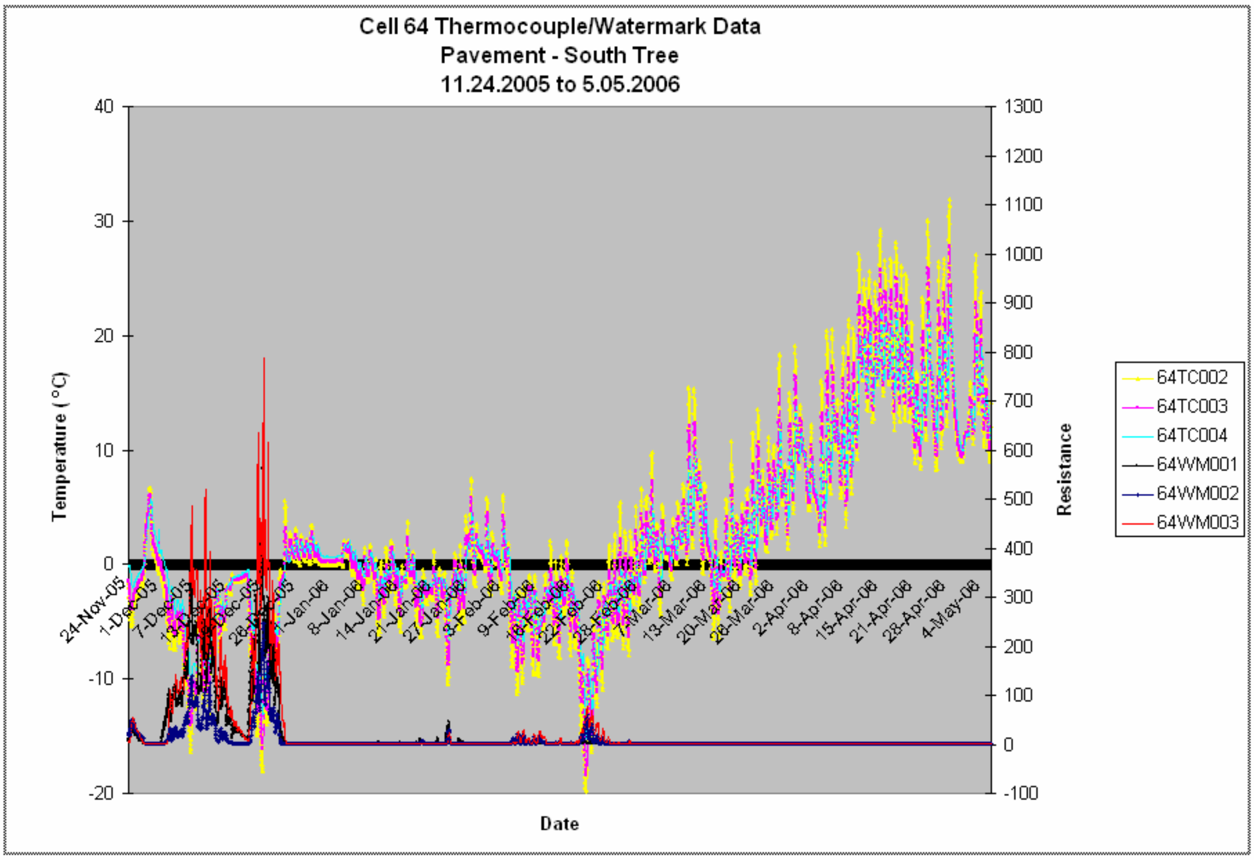


Figure 10. South Tree Thermocouple/Watermark Data, Pavement

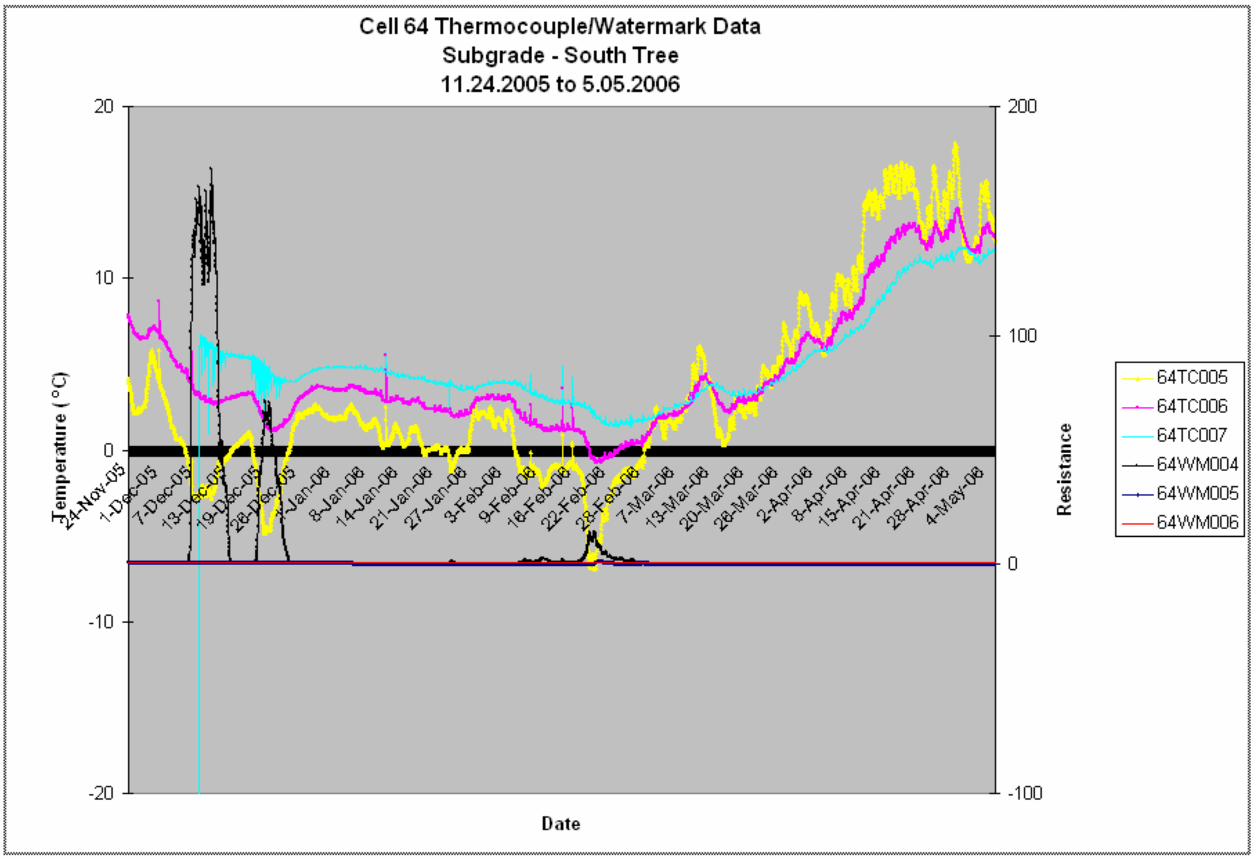


Figure 11. South Tree Thermocouple/Watermark Data, Subgrade

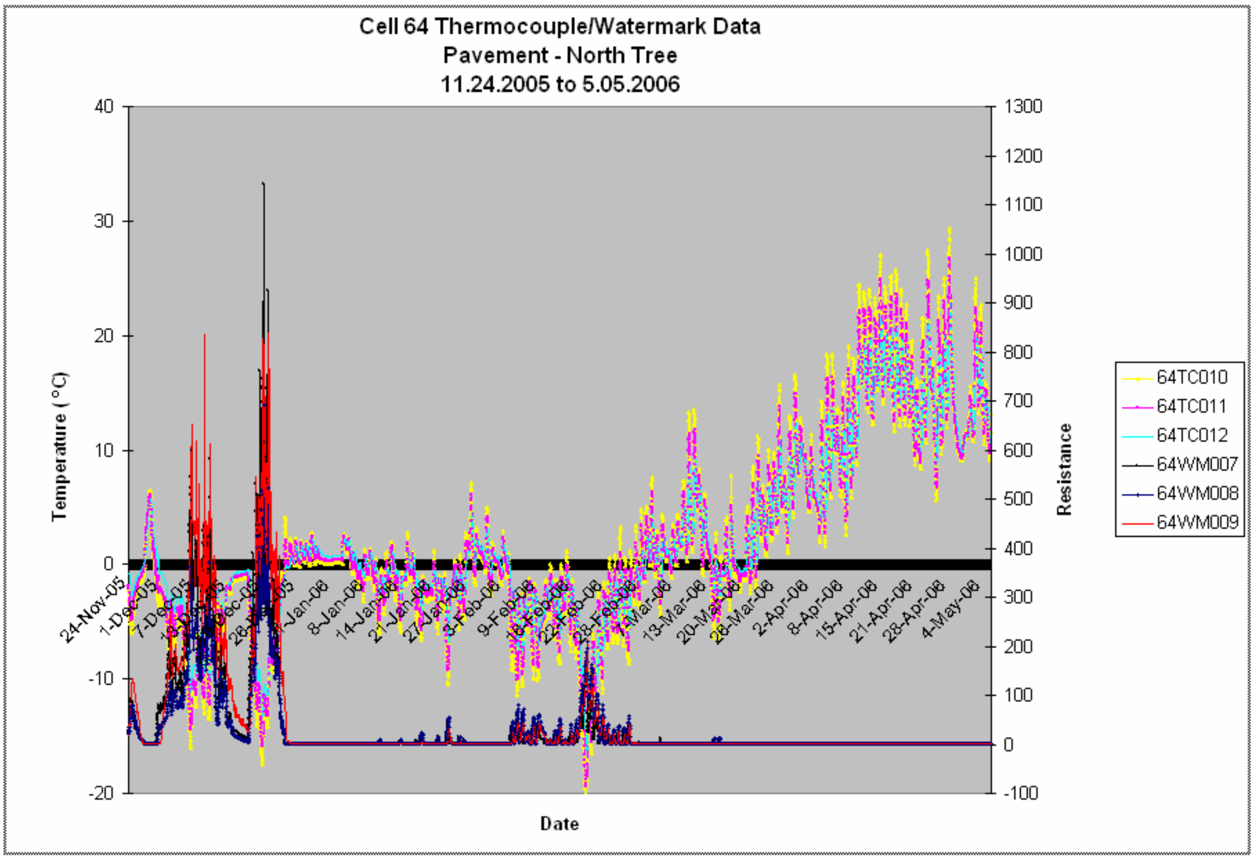


Figure 12. North Tree Thermocouple/Watermark Data, Pavement

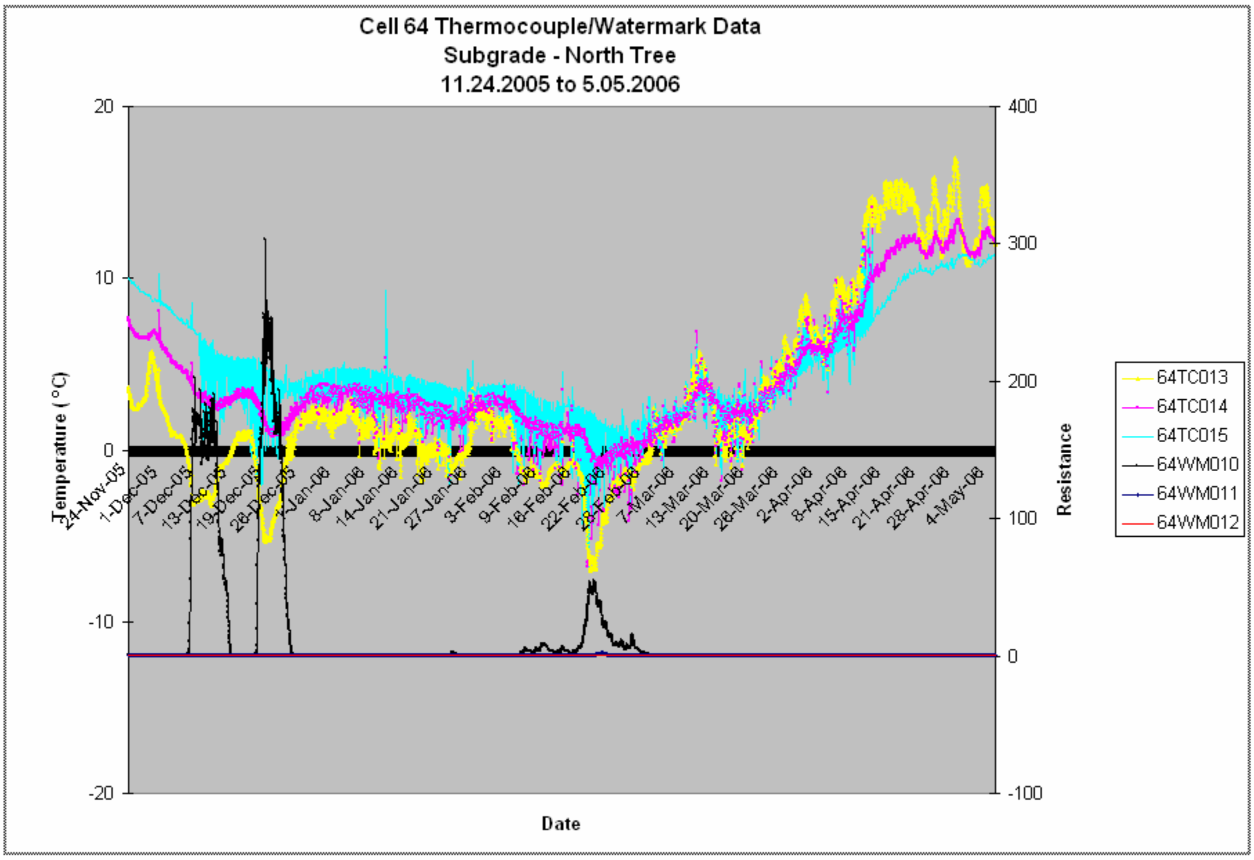


Figure 13. North Tree Thermocouple/Watermark Data, Subgrade

5 CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

The Cell 64 pervious concrete driveway shows apparent wear for its first season in service (see Appendix C for photos of cell64 from 9/21/06). However, it shows very little structural macro cracking, and varied raveling at the joints. The noted surface raveling may be due to excessive finishing during construction. It appears to be topical and is not expected to continue. However, this cell will be monitored for any changes in its condition. FWD deflection and strain data will continue on a quarterly basis, as will monitoring of the vibrating wire strain gauges and thermistors. Thermocouple and watermark data are continually logged by the MnROAD automated system, however, a more efficient means of measuring the flow from the drainage pipe is necessary to quantify the flow there.

The 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 modulus of rupture (2). However, FWD results showed larger deflection basins for the cell 64 pervious concrete than for normal concrete, 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 psi. The upper limit of this range is comparable to typical elastic moduli of normal concrete. However, as strength is not as critical as durability in transportation infrastructure, the distress mapping and petrographic information were critically examined to identify features that might affect durability.

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 the first year. In general, the mixture consisting of crushed aggregate performed better than the intermix of crushed and rounded aggregates. This corroborates the findings of the Iowa mix design report for Pervious Concrete by Schaefer et. al. (3).

Protocol for monitoring hydraulic conductivity is still being developed. In the interim, MnROAD uses a qualitative perveameter for periodic evaluation of clogging severity. So far there have been no overt changes in the hydraulic conductivity of the porous media. The Concrete Research team is designing a dynamic perveameter for quantitative hydraulic conductivity measurements.

5.2 Recommendations

Continued FWD deflection analysis and strain gauge data analysis are necessary to identify any new trends that may show from additional seasons. Continued, comprehensive collection of deflection and strain data will also be useful since FWD testing did not occur for the January 12, 2006 testing event, and thus deflection basin and strain data were not plotted for winter 2006. Furthermore, the October 26, 2005 FWD testing event only included 9000 lb. load drops because the concrete was only cured 30 days at that point. Continued collection of this data is key for future comparisons if any solid conclusions are to be drawn.

Drainage flow data from the pipe exiting the CA-50 base material should be gathered to further analyze the hydraulic properties of the Cell 64 driveway. Collecting water flow data has been an issue due to lack of rainfall events coupled with limited man-hour resources to collect rainfall event data. Furthermore, the flow from the drainage pipe is much lower than expected, even after a rainfall event. The flow meter currently available for measuring the flow is less than ideal and does not provide reliable flow data. Other flow meter devices will be considered, such as a tipping bucket setup, to more accurately quantify the flow.

Gathering water block, thermocouple, and flow data from the driveway should continue. In the future it may be possible to connect the flow meter to the MnROAD automated data collection system such that collection of comprehensive flow data would not be limited by equipment that requires significant personnel-hour resources to monitor.

There are current efforts to design a quantitative hydraulic conductivity measurement process for pervious concrete. It is imperative that an accurate model is developed to quantify the loss, if any, of the pervious concretes ability to pass water through its void structure.

Elastic modulus, E, should be extrapolated from cores tested in the laboratory as a supplement to the moduli calculated from strain values collected from FWD and MnROAD truck passes. This data will validate some of the modulus values calculated from the strain data in order to evaluate strain data validity or identify issues with the strain data.

Finally, a test cell in the MnROAD LVR is needed to explore the performance of pervious concrete in greater detail. The cell will be loaded by the MnROAD 80 kip/102 kip truck on a regular basis (as with the other cells in the LVR) as opposed to the loading that cell 64 receives currently, in which the frequency of loading has not strictly been recorded. Furthermore, having a pervious concrete cell in the LVR loop at MnROAD will make it feasible to collect data on a continuous basis. This will help to provide a seamless dataset from each of the sensors so that the values can be compared, correlated, or corroborated. Ultimately, the performance of the pervious concrete under regular loading conditions will provide information toward the utility of the material for low volume roadway applications.

7 References

1. Izevbekhai, B.I., et. al. 2005 MnROAD – Pervious Concrete Project, Cell-64 Driveway Construction Report. 2005 Mn/DOT.

2. Burnham, Tom. Load Proximity Correlation of Dynamic Strain Measurements in Concrete Pavement. Proceedings from the 2nd International Conference on Accelerated Pavement Testing. Minneapolis, MN. September 26-29, 2004.

3. Schaefer, V., et. al. Mix Design Development for Pervious Concrete in Cold Weather Climates. Iowa State University and Center for Transportation Research and Education. February 2006.

8 APPENDICES

Appendix A

FWD Deflection Basin Graphs

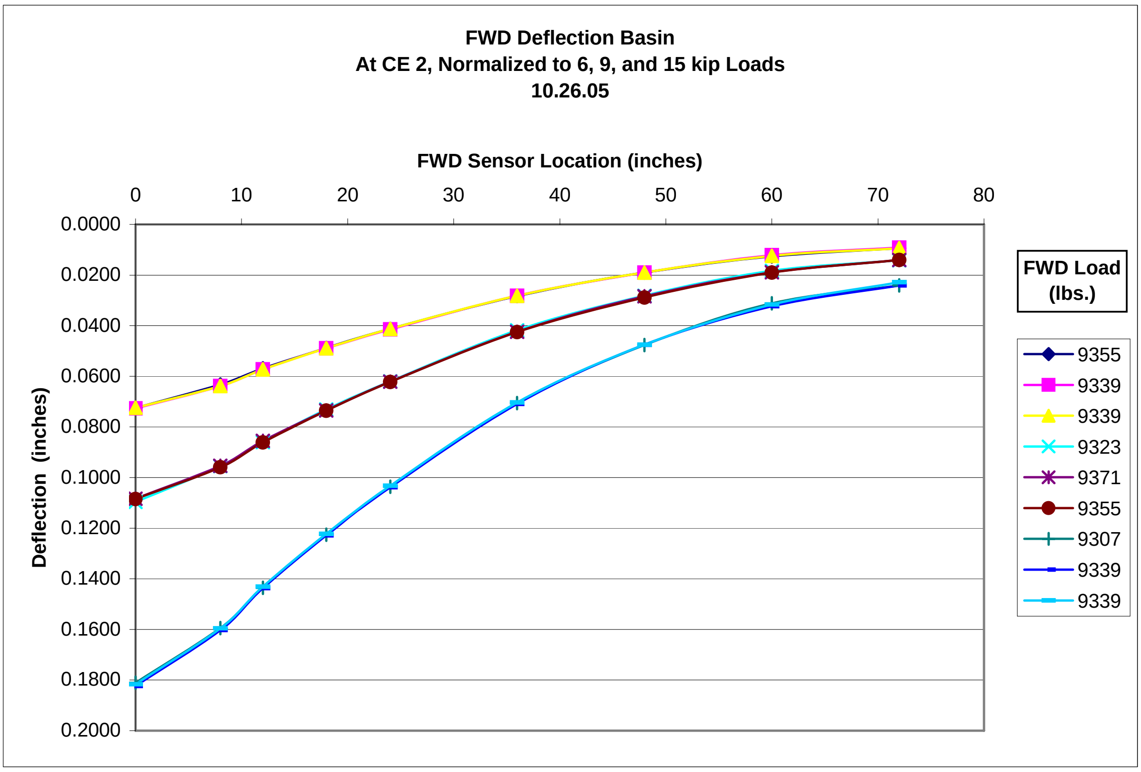


Figure A1. FWD Deflection Basin at CE-02, 1st Run, 10.26.05

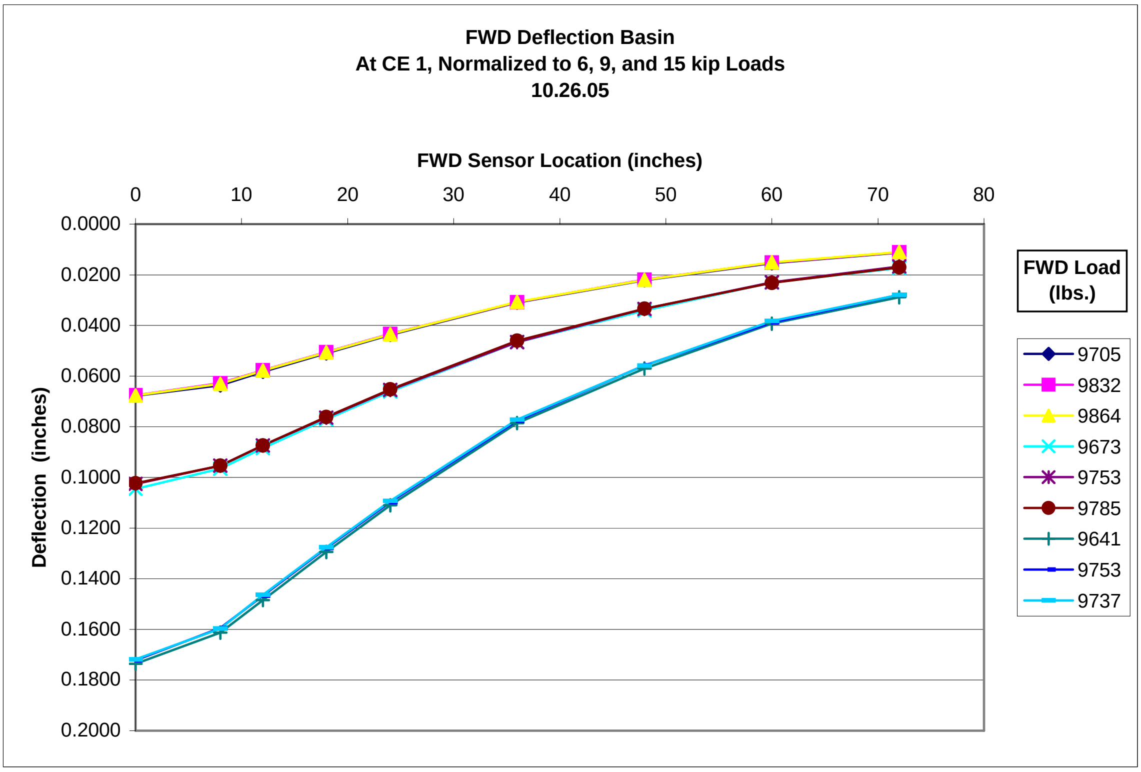


Figure A2. FWD Deflection Basin at CE-01, 2nd Run 10.26.05

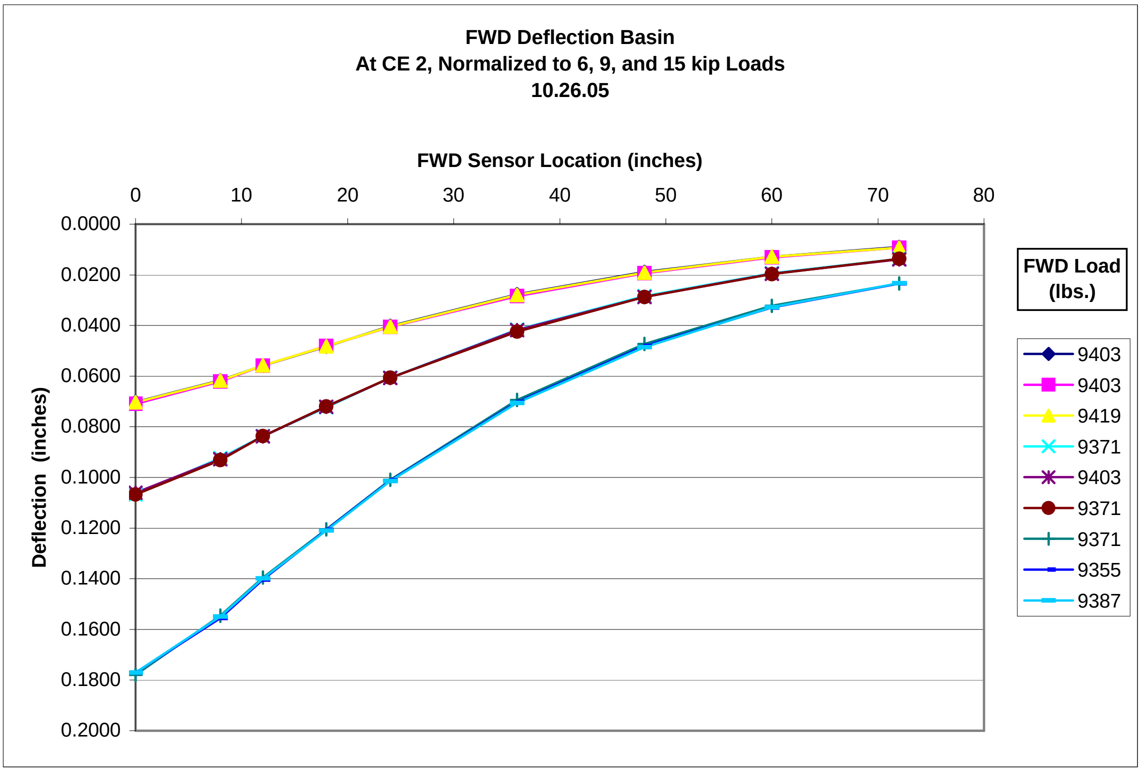


Figure A3. FWD Deflection Basin at CE-02, 3rd Run 10.26.05

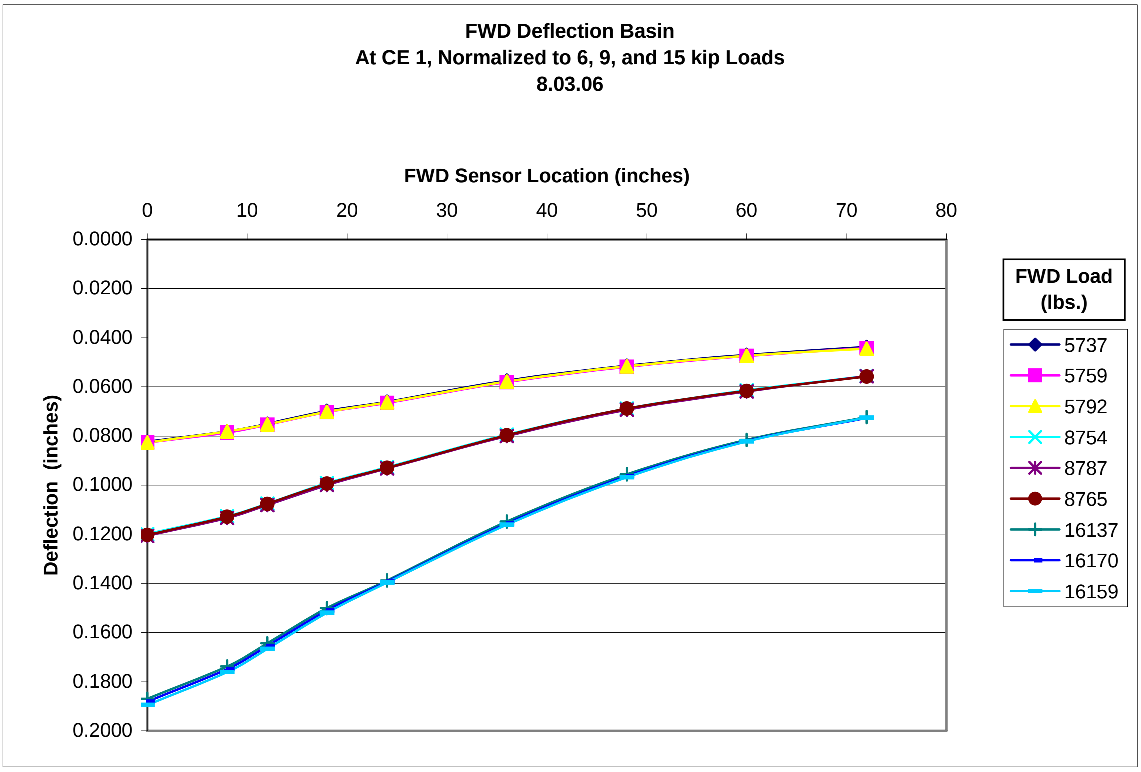


Figure A4. FWD Deflection Basin at CE-01, 1st Run 8.03.06

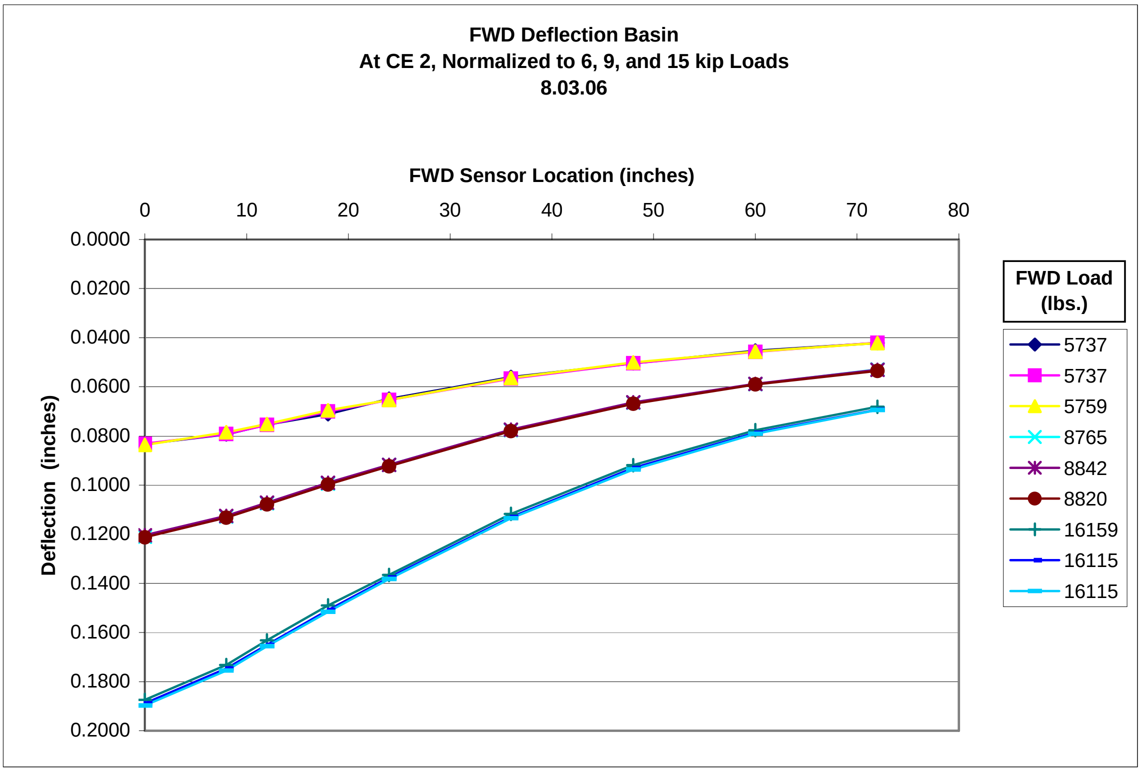


Figure A5. FWD Deflection Basin at CE-01, 2nd Run 8.03.06

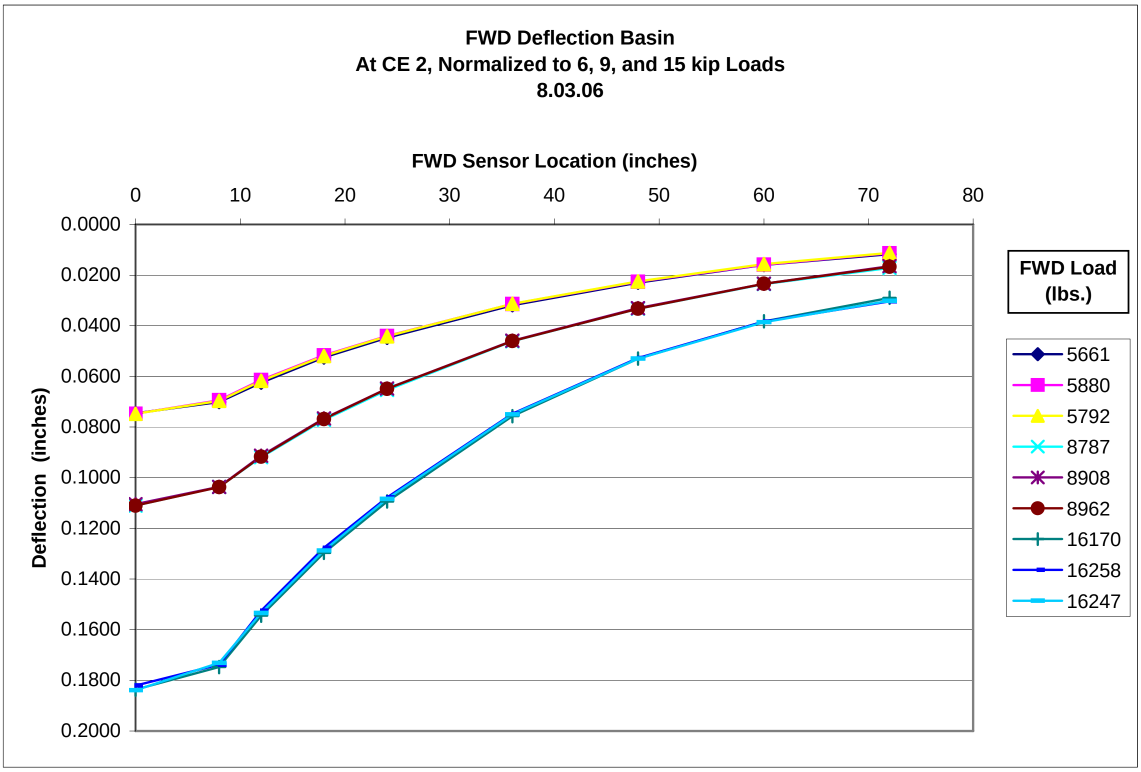


Figure A6. FWD Deflection Basin at CE-02, 3rd Run 8.03.06

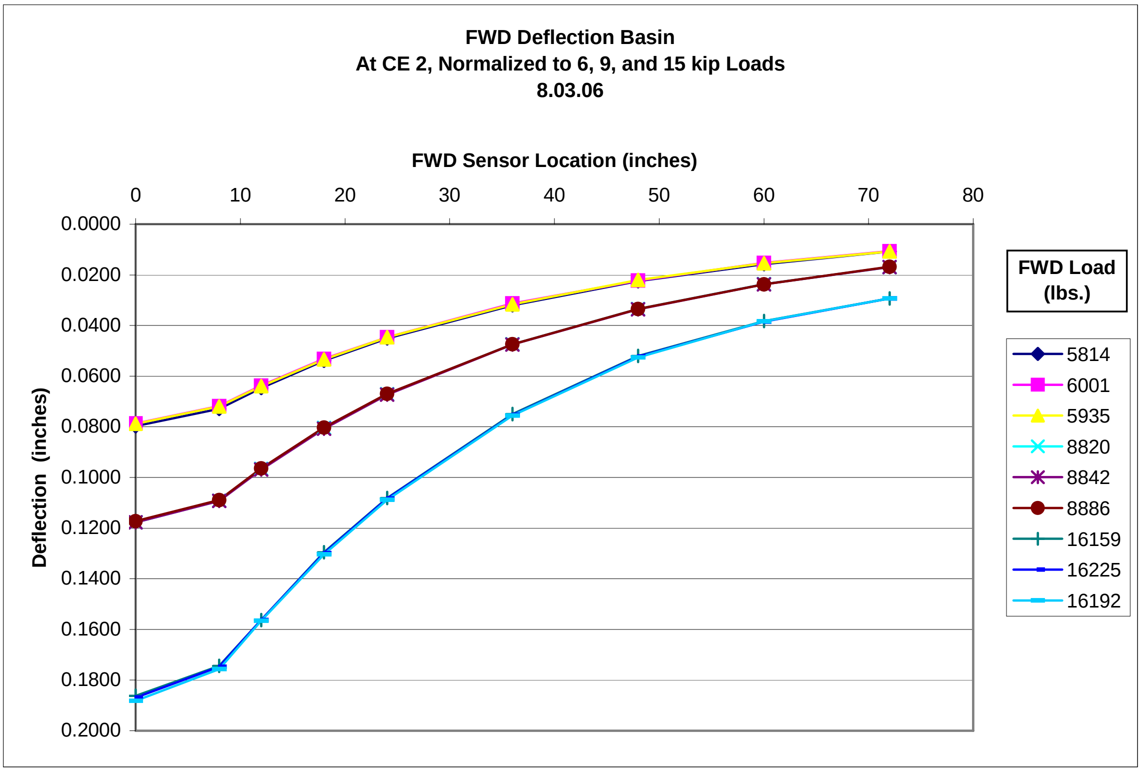


Figure A7. FWD Deflection Basin at CE-02, 4th Run 8.03.06

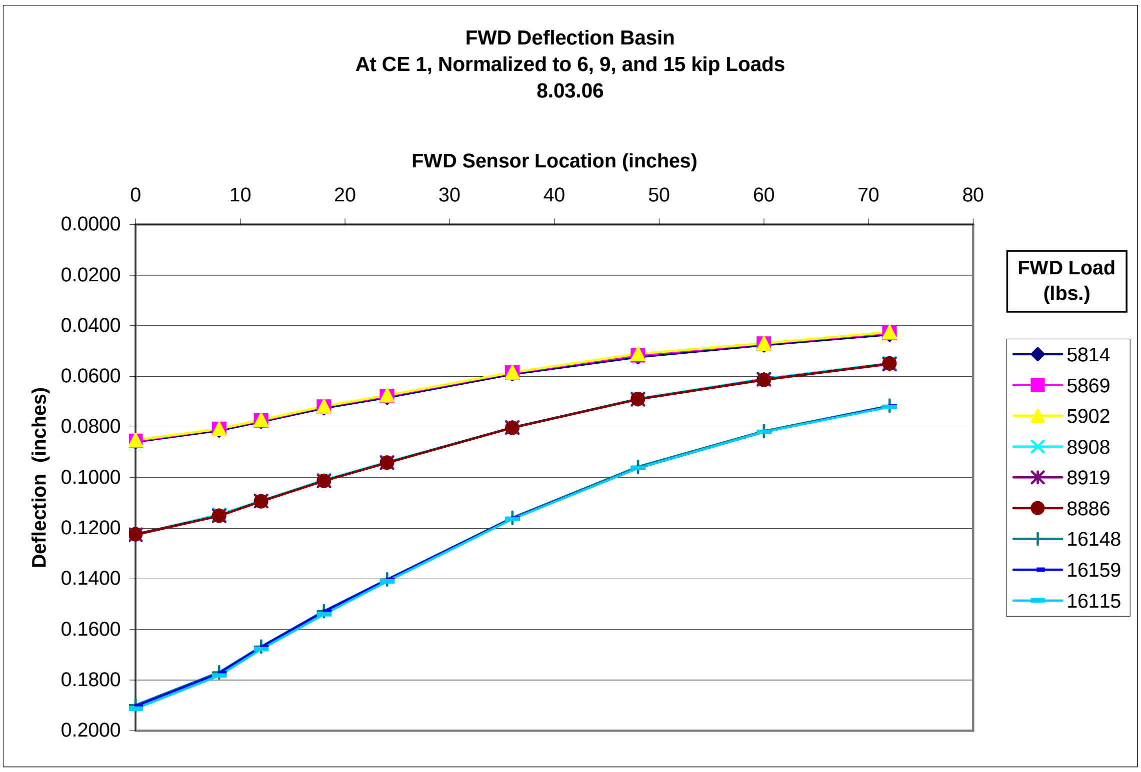


Figure A8. FWD Deflection Basin at CE-01, 5th Run 8.03.06

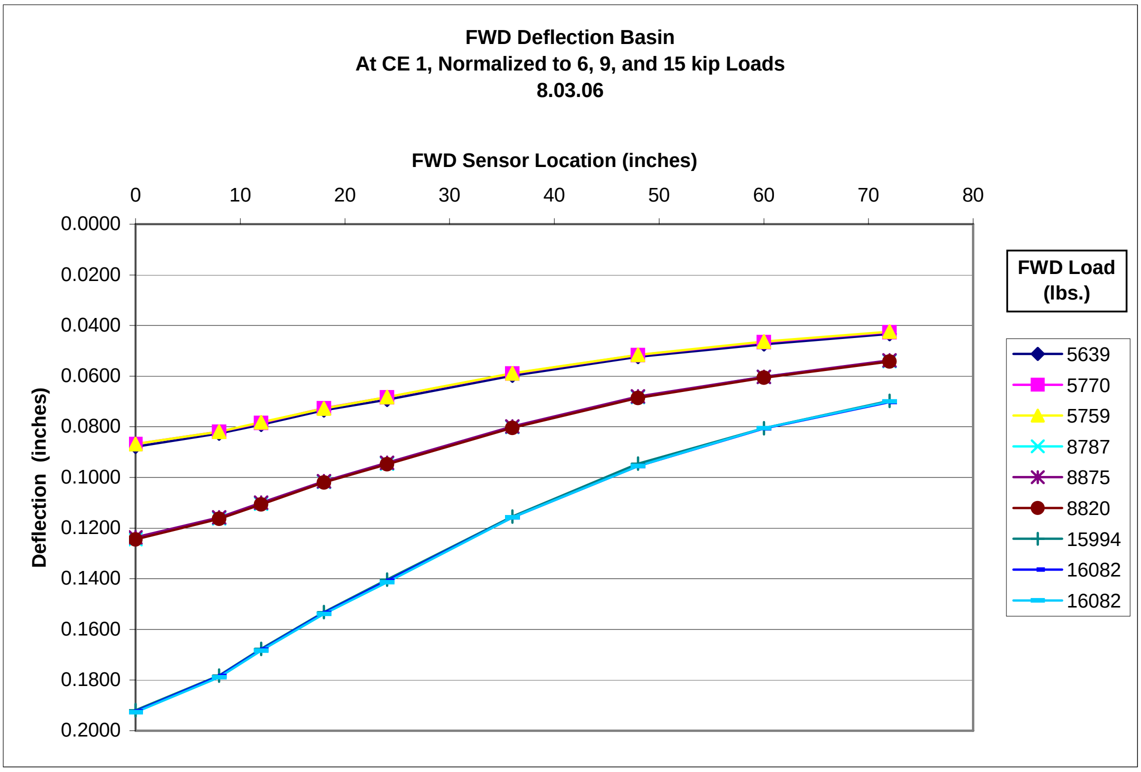


Figure A9. FWD Deflection Basin at CE-01, 6th Run 8.03.06

Appendix B
Strain Data Tables

CE-01 and CE-02 MnROAD Truck Roll Data								
Sensor	Date	Time	Peak Strain (με) - Axle Set Number			Peak Strain Averages		
			1	2	3	1	2	3
CE-01	10/26/05	12:23	44	48	47	44	48	47
CE-02	10/26/05	12:23	98	99	no data	98	99	no data
CE-01	1/12/06	11:11	35	43	42	36	46	44
CE-01	1/12/06	11:12	46	47	48			
CE-01	1/12/06	11:13	27	47	44			
CE-01	1/12/06	11:14	35	47	42			
CE-02	1/12/06	11:11	48	42	50	62	59	63
CE-02	1/12/06	11:12	70	66	68			
CE-02	1/12/06	11:13	58	62	65			
CE-02	1/12/06	11:14	73	66	67			
CE-01	8/03/06	10:33	75	85	68	64	80	68
CE-01	8/03/06	10:35	61	86	74			
CE-01	8/03/06	10:36	56	70	61			
CE-02	8/03/06	10:33	62	66	85	70	74	75
CE-02	8/03/06	10:35	87	93	61			
CE-02	8/03/06	10:36	60	63	78			

Table B1. Truck Pass Maximum Strain Data

CE-01 and CE-02 FWD Data							
Sensor	Date	Time	Avg. Load (lbs.)	Peak Strain (με) - Blow Number			Avg.
				drop 1	drop 2	drop 3	
CE-01	10/26/05	15:12	9749	38	42	40	40
CE-02	10/26/05	15:06	9341	75	94	96	88
CE-01	8/03/06	9:56	5763	63	68	52	61
CE-01	8/03/06	9:56	8769	70	81	83	78
CE-01	8/03/06	9:56	16155	118	106	112	112
CE-01	8/03/06	10:09	5745	59	56	48	55
CE-01	8/03/06	10:09	8809	69	71	77	72
CE-01	8/03/06	10:09	16130	110	122	107	113
CE-02	8/03/06	10:16	5778	61	58	61	60
CE-02	8/03/06	10:16	8886	55	52	50	52
CE-02	8/03/06	10:16	16225	71	65	79	72
CE-02	8/03/06	10:19	5916	36	43	30	36
CE-02	8/03/06	10:19	8849	33	31	35	33
CE-02	8/03/06	10:19	16192	53	54	49	52
CE-01	8/03/06	10:26	5862	46	44	38	43
CE-01	8/03/06	10:26	8904	52	62	62	59
CE-01	8/03/06	10:26	16141	69	79	72	73
CE-01	8/03/06	10:29	5723	46	44	38	43
CE-01	8/03/06	10:29	8827	50	61	47	53
CE-01	8/03/06	10:29	16053	98	88	86	91

Table B2. FWD Maximum Strain Data

Appendix C
Photos of Cell 64

Figure C1. Tooled Joint, Cell 64 Facing Southeast, 9.21.06

Figure C2. Header/Construction Joint, Cell 64 Facing Southeast, 9.21.06

Figure C3. Mix #2 Surface Raveling, West Edge Cell 64, 9.21.06

Figure C4. Mix #2, Surface Raveling, 01.04.06

Figure C5. Mix #2 & Mix #3 at South End of Cell 64 at Coterminous Joint, 9.21.06

Appendix D
MnROAD Test Sections

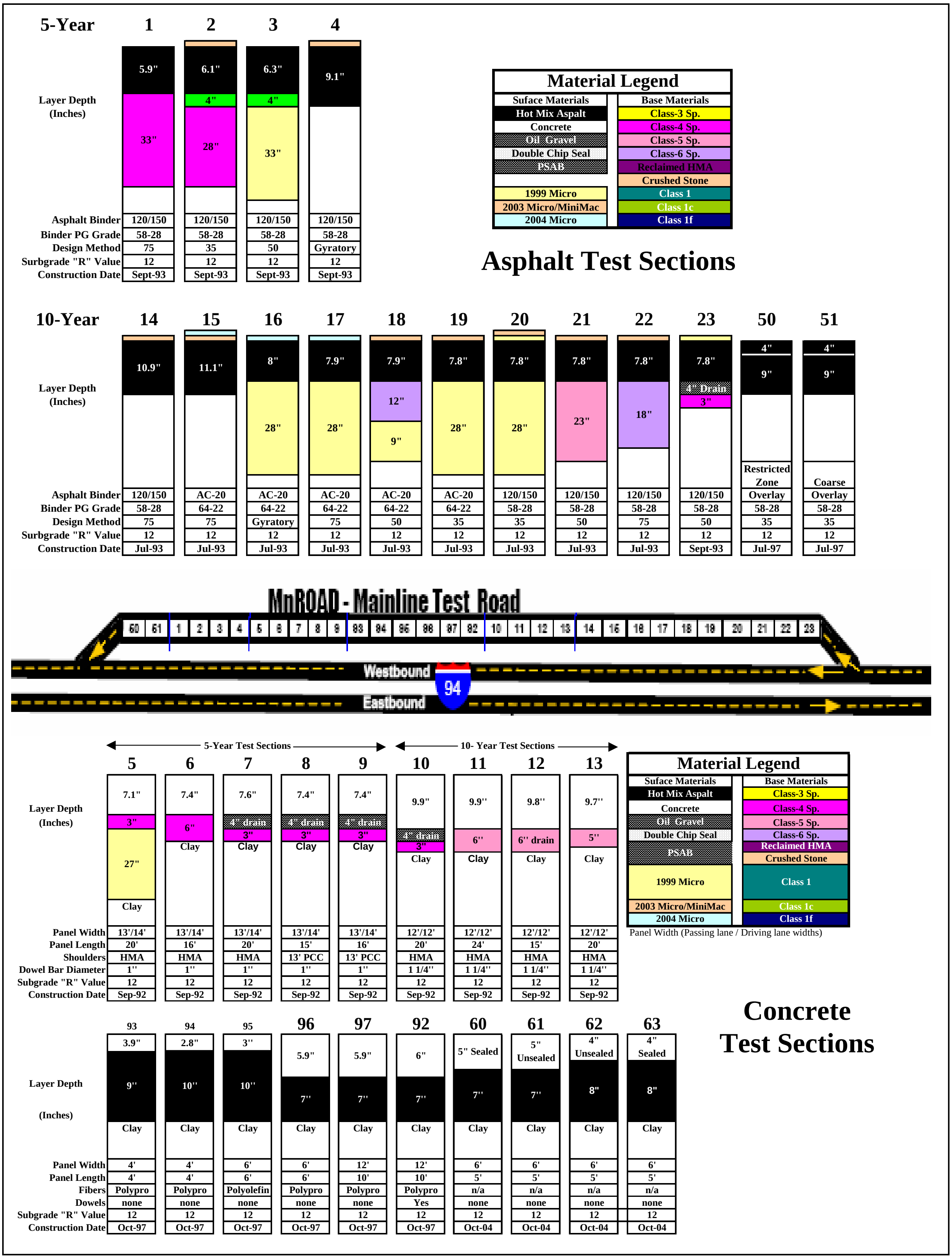


Figure D1. Mainline Test Sections

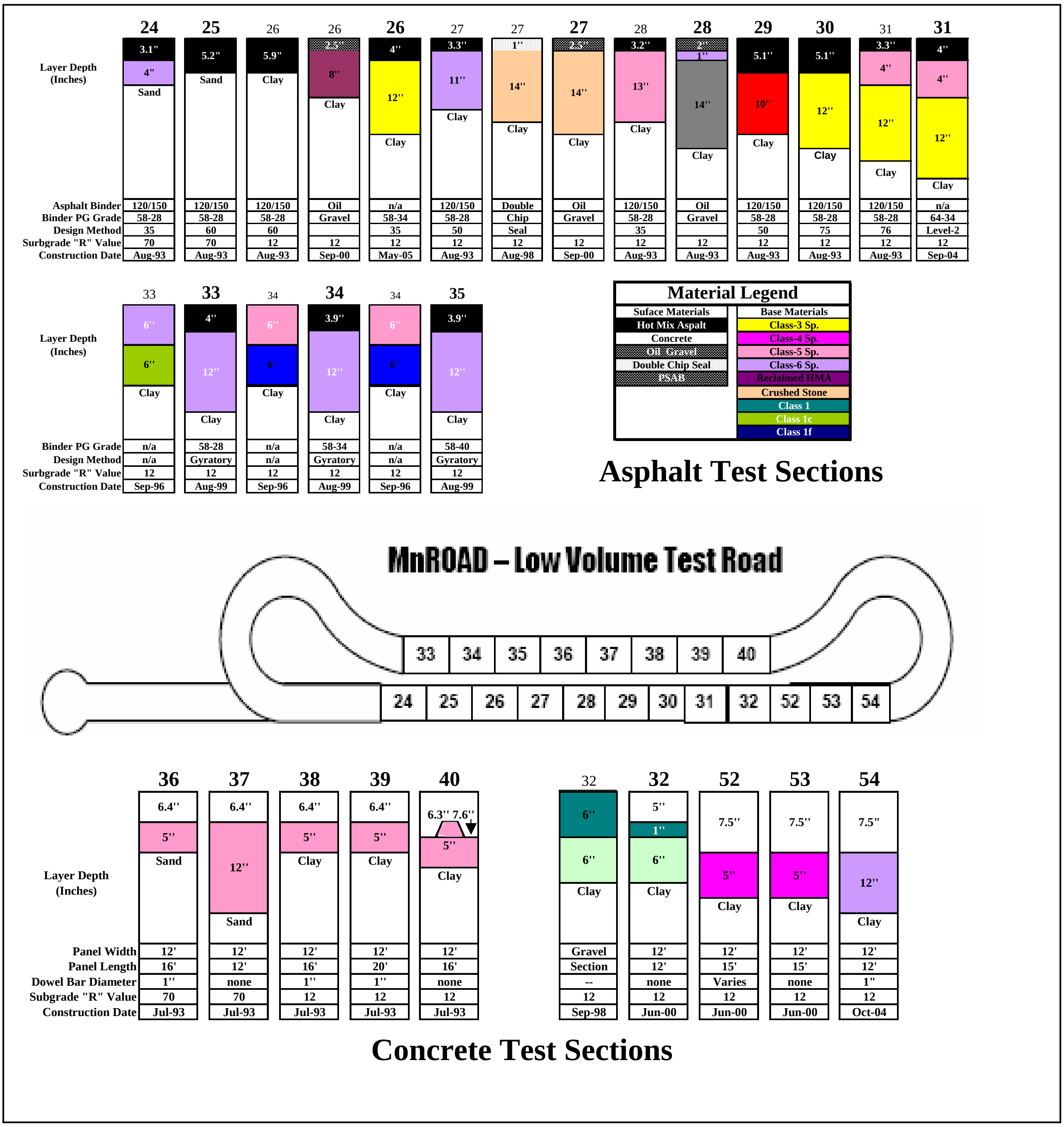


Figure D2. Low Volume Road Test Sections