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Investigation of Joint Deterioration in MnROAD Phase 1 Jointed Concrete Pavement Test Sections

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Minnesota Department of Transportation

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16. Abstract (Limit: 250 words)

A comprehensive forensic investigation was conducted at MnROAD in 2008. This investigation focused principally on joint performance, as little panel cracking had occurred. The most interesting observation was a unique distress phenomenon in the transverse joints. This distress occurred where jointed concrete pavements were built on undrained gravel bases. Cores showed that a significant amount of concrete material was missing from the middle section of the joint, with the area of greatest distress just below the saw cut, approximately at mid-depth.

To determine whether this distress was unique to MnROAD test sections, six other Minnesota concrete pavement projects, of similar age and materials, were examined. While similar types of distress were found, the extent of the damage was not as severe. This may be due to much less traffic loadings being applied to those sections compared to MnROAD. In all cases, though, sections with base layers that adequately drained water within the joints performed significantly better. A discussion of the potential causes of the distress revealed that it is likely a combination of freeze/thaw damage and erosion due to fast-traveling trucks that ultimately caused the distress. Findings show:

High Volume Traffic
- Undrained PCC on Class 5 base has resulted in significant joint distress (regardless of seal condition)
- Drained PCC on Class 5 base with edge drains and well sealed joints performed better than undrained PCC
- The combination of drainable base layers and edge drains worked best

Low Volume Traffic
- Undrained PCC on Class 5 base with well sealed joints performed excellently
- Undrained PCC on Class 5 base with poorly sealed joints exhibits significant distress

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Executive Summary

The Minnesota Department of Transportation has operated the Minnesota Road Research (MnROAD) facility since 1994. After over 13 years of live traffic, the original concrete pavement test sections on the interstate portion of the MnROAD facility have still exhibited very good performance. To extract all useful information, a comprehensive forensic investigation was conducted. This investigation focused principally on joint performance, as little panel cracking had occurred. The most interesting observation was a unique distress phenomenon in the transverse joints. This distress occurred where jointed concrete pavements were built on undrained gravel bases. Cores showed that a significant amount of concrete material was missing from the middle section of the joint, with the area of greatest distress just below the saw cut, approximately at mid depth.

To determine whether this distress was unique to MnROAD test sections, six other Minnesota concrete pavement projects, of similar age and materials, were examined. While similar types of distress were found, the extent of the damage was not as severe. This may be due to much less traffic loadings being applied to those sections compared to MnROAD. In all cases though, sections with base layers that adequately drained water within the joints performed significantly better. A discussion of the potential causes of the distress revealed that it is likely a combination of freeze/thaw damage and erosion due to fast-traveling trucks that ultimately caused the distress.

It was observed that Class 4 or 5 special base materials over a clay subgrade is a very slow draining pavement system. Based on the results of this study, it is recommended that a drainable base layer be used under jointed concrete pavements, with a properly maintained system to remove water. Drainable base layers and longitudinal drains significantly improve the condition of the transverse joints on high-volume roadways with drainable base layers providing better performance. If traffic volumes are low, drainable bases and longitudinal drains are not necessary as long as the joints are sealed. Drainage should always be provided as a precaution in case the joints are not adequately sealed. The main observations were:

High Volume Traffic

- Undrained PCC on Class 5 base has resulted in significant joint distress (regardless of seal condition)
- Drained PCC on Class 5 base with edge drains and well sealed joints performed better than undrained PCC
- The combination of drainable base layers and edge drains worked best

Low Volume Traffic

- Undrained PCC on Class 5 base with well sealed joints performed excellently
- Undrained PCC on Class 5 base with poorly sealed joints exhibits significant distress

It is also important to note that the gradation band for Class 5 aggregate is very broad, drainable and undrainable gradations can be made that fit the Class 5 specification. It was observed from the cores taken from highways around the state that where the Class 5 base was drainable, joint condition was significantly improved.

Chapter 1 INTRODUCTION

The Minnesota Department of Transportation has operated the Minnesota Road Research (MnROAD) facility since 1994. In 2008, substantial reconstruction of several of the test sections began the second phase of MnROAD research. With over 13 years of live traffic and exposure to the extreme climate of Minnesota, the original nine concrete pavement test sections on the interstate portion of the MnROAD facility still exhibited very good performance. This was despite having been designed to last either 5 or 10 years according to AASHTO pavement design standards in the early 1990's. Nevertheless, the time had come to investigate the performance of new test sections examining more current pavement design issues.

To fully extract all useful information from the original concrete pavement test sections before their removal, a comprehensive forensic investigation was conducted. This investigation focused principally on joint performance, as little panel cracking had occurred. Several useful and interesting observations on the real-world performance of concrete pavements in Minnesota were found. The most interesting observation was a unique distress phenomenon in the transverse joints. To test whether the observed joint behavior was unique to the MnROAD test sections, several other Minnesota concrete pavements built in the same time frame were investigated.

1.1 Objectives

The objective of this paper was to report interesting findings of the forensic investigation of the MnROAD Phase 1 concrete test cells. Specific focus was given toward identifying possible causes of the observed joint distresses, and whether they were unique to the MnROAD test sections.

1.2 Research Strategy

Forensic activities at MnROAD took place during three time periods. The first efforts in October 2007 consisted of extracting core samples of the concrete layers only. Additional core samples and more destructive investigation practices, like test pits and PCC panel lifting, took place in spring 2008. Then in the fall of 2009 additional core samples were taken from the MnROAD Low Volume Test loop.

To determine whether the joint distress observed at MnROAD was occurring in other jointed concrete pavements in Minnesota, six PCC pavement segments of similar age and design from around the state were cored. At each site, five six-inch diameter cores were taken over the transverse joints at approximately 12 to 18 inches from the outside edge of a panel. The cores were spaced evenly over 300 ft, in order to get a representative sample of the typical transverse joint condition at each site.

Chapter 2 MnROAD FACILITY

MnROAD is an outdoor pavement research facility located along Interstate 94 in Albertville Minnesota, forty miles northwest of Minneapolis/St. Paul. Initially constructed between 1990 and 1994, MnROAD consists of two primary roadway test segments; an interstate traffic loaded "mainline" segment, and a controlled traffic loaded "Low Volume Road (LVR)" segment. Each segment contains numerous test sections or "cells" designed to study the performance of various pavement structures and materials. MnROAD has an extensive infrastructure supporting automated sensors configured to record dynamic and environmental pavement response. Additional information on the MnROAD project can be found on the MnROAD website or numerous reports highlighting research findings and lessons learned (1).

The concrete test cells examined in this study were built in September 1992 (Mainline) and July 1993 (LVR) as part of MnROAD's original construction (Phase 1) with the exception of LVR cell 32 which was built in June 2000. Each cell was constructed with a jointed plain concrete pavement (JPCP) layer resting on various base and subbase layers constructed over a silty clay subgrade except for test cell 36 and 37 which were built on sand subgrades. Figures 1 and 2 show the various layers and thicknesses of the "Mainline" and LVR test cells considered in this study.

2.1 Mainline

Test cells 5-9 were designed to achieve an AASHTO terminal serviceability index of 2.5 after five years of traffic. Lane widths for these cells were 14 ft in the driving lane, and 13 ft in the passing lane, which was considered to be an extended edge or tied concrete shoulder design. Cells 10-13 were designed to achieve an AASHTO terminal serviceability index of 2.5 after ten years of traffic. Lane widths for these cells were 12 ft in both the driving and passing lanes. Except for test cells 8 and 9, the concrete test cells at MnROAD have bituminous shoulders on both sides. Cells 8 and 9 have a tied 13 ft wide concrete shoulder attached to the passing lane and a bituminous shoulder adjacent to the driving lane.

Test cells 5, 6, and 11-13 had traditional aggregate base layers specified as Class 3, 4, or 5 special materials. Table 1 shows design specification values for standard Mn/DOT and special MnROAD base material gradations. Except for cell 12, which had longitudinal edge drains located below the pavement/shoulder joint, these test cells were constructed without drains.

Test cells 7-10 had a permeable asphalt stabilized base (PASB). PASB consists of permeable hot mixed asphalt-coated aggregate, with 2-3% asphalt by total weight of mixture. This permeable base layer was connected to longitudinal edge drains located below the pavement/shoulder joint.

Test cells 5-9 had 1 inch diameter by 15 inch long dowel bars across each transverse joint (12 per lane). Test cells 10-12 had 1.25 inch diameter by 15 inch long dowel bars and test cell 13 had 1.5 inch diameter by 15 inch long dowel bars. All dowel bars were epoxy coated steel bars supported on baskets. Transverse joints were skewed 2 feet in a 12 foot lane, and were spaced at 15 ft intervals for test cells 6, 8, 9, and 12. Test cells 5, 7, 10, and 13 had 20 ft joint spacing, and cell 11 had 24 ft transverse joint spacing. All longitudinal joints and the concrete shoulder joints in cells 8 and 9 were tied with 0.50 inch diameter, 30 inch long deformed steel bars spaced every 30 inches.

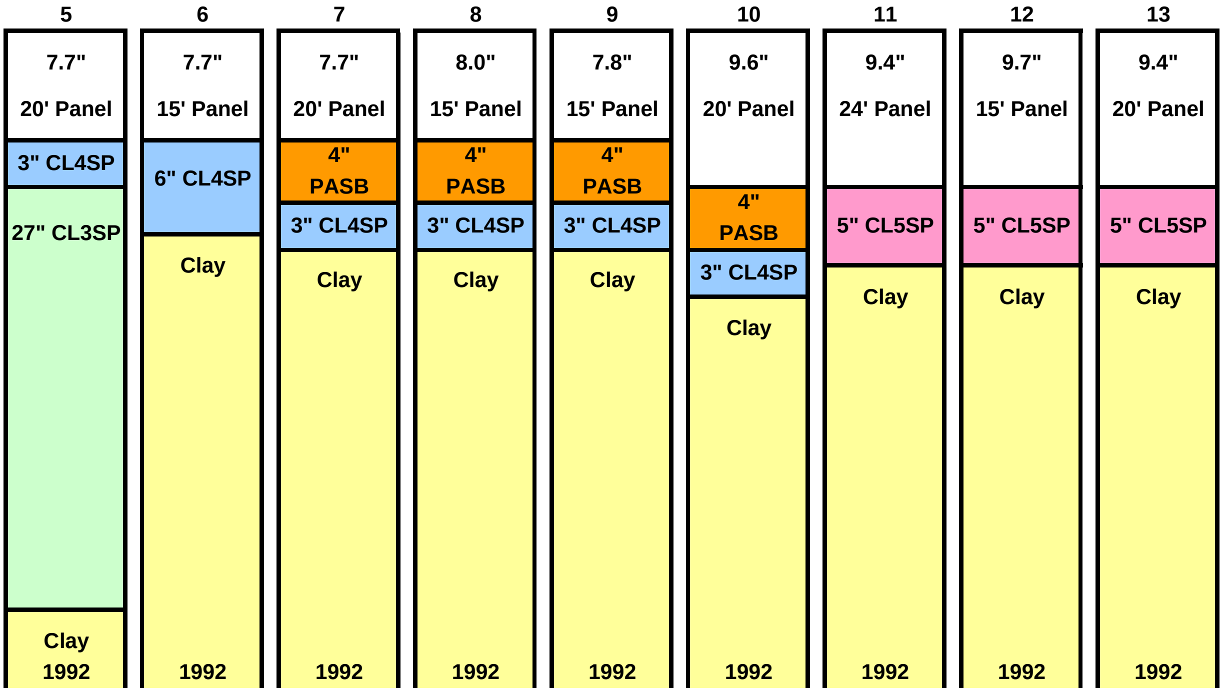

FIGURE 1 MnROAD Phase 1 interstate test cell design details.

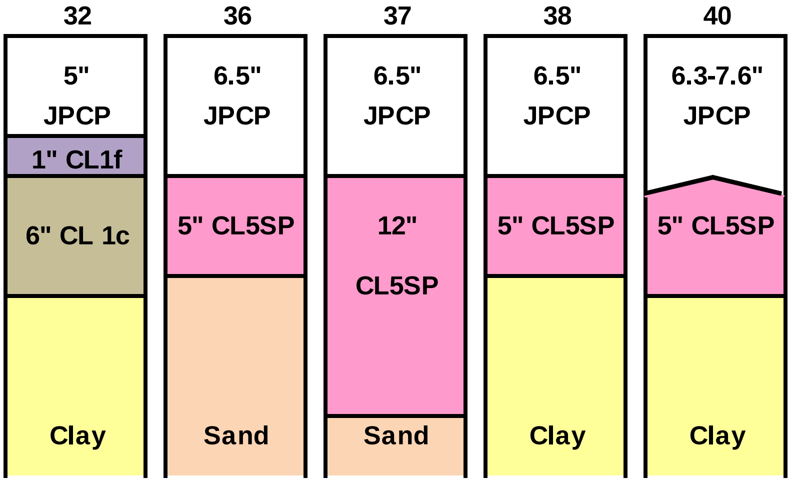

FIGURE 2 MnROAD Low Volume Road (LVR) test cell design details.

2.2 Low Volume Road

Test cells 36, 37, 38, and 40 were designed to achieve an AASHTO terminal serviceability index of 2.5 after 100,000 CESALs or approximately three years at the LVR traffic level. Initial pavement thickness calculations revealed a recommended slab thickness of 4.2 inches to meet the three year design life. The test cells design thicknesses were then increased to 6.0 inches (6.5 inch as built thickness) to reflect Mn/DOT's minimum concrete pavement thickness at the time that the test cells were built. With this increased thickness, it became apparent that these test cells would withstand significantly more CESAL applications than originally intended in the experimental time line of three years. Lane widths for these cells were 12 ft in both lanes with aggregate shoulders adjacent to each lane.

Test cells 36, 37, 38, and 40 had Class 5 special bases of variable thickness as shown in Figure 2. Test cells 36 and 37 were constructed over sand subgrades and test cells 38 and 40 were constructed over clay subgrades, all without drains. Test cells 36 and 38 had 1 inch diameter by 15 inch long dowel bars across each transverse joint (12 per lane). Test cells 37 and 40 were undoweled. Test cell 40 had a thickened edge design that was 6.3 inches at the centerline and 7.6 inches at the edge. All dowel bars were epoxy coated steel bars supported on baskets. Transverse joints were skewed 2 ft in a 12 foot lane, and were spaced at 12 ft intervals for test cell 37 and 15 foot intervals for test cells 36, 38, and 40. All longitudinal joints were tied with 0.50 inch diameter, 30 inch long deformed steel bars spaced every 30 inches.

Test cell 32 is a 5 inch thick jointed plain concrete pavement over 1 inch of Class 1f base and 6 inches of Class 1c subbase. Aggregate Classes 1c and 1f were developed by splitting Mn/DOT’s Class 1 into half with Class 1c following the coarse side of the gradation limits and Class 1f following the fine side.

Lane widths were 12 ft with 10 ft undoweled panels. Unlike the other MnROAD test cells in this study, the transverse joints were not skewed. Aggregate shoulders were adjacent to both lanes. Cell 32 was constructed using Mn/DOT’s concrete pavement mix specifications for 2000. Ground granulated blast furnace slag was used to replace 35% of the cementitious material in the mix.

2.3 Traffic

Since the Mainline test cells are loaded with traffic diverted off the existing Interstate Highway 94, the sections were designed for the Heavy Commercial Average Daily Traffic (HCADT), measured in 1992, of 1620 vehicles in the design lane with an assumed 2.5% annual compound growth rate (2). From 1994 to 2001, traffic volumes on the MnROAD mainline test cells were measured using a Weigh-in-Motion (WIM) system that was first installed on I-94 near the MnROAD site in 1989 (3). Using load cells, it generated axle weights and axle spacing. A second WIM system, which uses the piezoelectric effect to generate axle weights and spacing, was installed in 2000. The annual average daily traffic (AADT) for the MnROAD mainline test sections when they were open to traffic in 1994 was 38,000 and there was an annual growth rate of 5.4% through 2006. The WIM system showed that 79% of trucks traveled in the driving lane. In 2008, the measured AADT on the MnROAD mainline was 61,000 with 12.1% trucks.

Parallel and adjacent to Interstate 94 and the Mainline is the Low Volume Road (LVR). The LVR is a 2-lane, 2½-mile closed loop that contains over 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. Beginning in the fall of 2008, the MnROAD vehicle operated only in the 80K configuration and only on the inside lane of the LVR. The outside lane was kept free of traffic to study environmental effects. As of December 17, 2009; the inside lane (80 kip lane) of test cells 36, 37, and 38 had received 381,435 ESAL's and the outside lane (102 kip lane) had received 320,042 ESAL's. The inside and outside lanes of cell 40 had received 374,888 and 317,453 ESAL's respectively and cell 32 (built in 2000) had receive 206,823 ESAL's on the inside lane and 160,749 ESAL's on the outside lane.

TABLE 1 Design Gradations for Mn/DOT and MnROAD Base Materials

Sieve Size	Mn/DOT Class 3	Mn/DOT Class 4	Mn/DOT Class 5	MnROAD PASB	MnROAD Class 1f	MnROAD Class 1c	MnROAD Class 3 Special	MnROAD Class 4 Special	MnROAD Class 5 Special
1.5 in (38.1 mm)	-	-	-	-	-	-	-	-	-
1.25 in (31.8 mm)	-	-	-	100	-	-	-	-	-
1.0 in (25 mm)	-	-	100	95-100	-	-	100	100	100
3/4 in (19 mm)	-	-	90-100	85-98	100	100	99.5	98	96
1/2 in (12.5 mm)	-	-	-	-	-	-	-	-	-
3/8 in (9.5 mm)	-	-	50-90	50-80	80-95	65-80	97.7	91	81
No 4 (4.75 mm)	35-100	35-100	35-80	20-50	65-85	40-65	90.5	80	69
No 10 (2 mm)	20-100	20-100	20-650	0-20	45-70	25-45	79.6	67	54
No 20 (800 µm)	-	-	-	0-8	-	-	61.9	46	34
No 40 (425 µm)	5-50	5-35	10-35	0-5	25-45	10-25	39.6	28	20
No 60 (250 µm)	-	-	-	-	-	-	26.2	-	-
No 100 (150 µm)	-	-	-	-	-	-	18.3	11	8
No 200 (75 µm)	5-10	4.0-10.0	3.0-10.0	0-3	10-15	8-10	13.2	7.3	5.7

2.4 Climate

The local average yearly precipitation at MnROAD is 27.4 inches, with 22.5 inches typically falling between the months of April and October. The average temperature in the winter is 16 °F and the average temperature in the summer is 65 °F. The average beginning air freezing date is November 11 and the average ending date is March 20 with an average freezing season length of 125 days. The 30 year norm freezing index (FI) is 1699 °F-days. At MnROAD from 1993 to 1996, the average maximum frost depth was approximately 60 inches (4).

2.5 2007 Test Cell Conditions

The last full year of service for MnROAD mainline test cells 5, 6 and 13 was 2007. The following describes the surface and ride quality conditions as of late 2007 for the MnROAD Mainline concrete test cells and as of summer of 2009 for the MnROAD LVR test cells.

2.5.1 Surface Distress

Other than cell 5, all of the other mainline Phase 1 concrete pavement test cells had no visible surface cracks. Cell 5 had some longitudinal cracks predominantly near the driving lane edge. Otherwise, minor spalling of transverse joints was also observed in all of the test cells, but not considered to be abnormal for the age of the test cells. The LVR test cells were also in very good condition except for cell 40 which had spalling of several of the transverse joints.

2.5.2 Joint Faulting Measurements

At MnROAD, transverse joint faulting measurements are typically taken three times per year with a Mn/DOT modified version of the Georgia Faultmeter (5). Faulting measurements during MnROAD Phase 1 were made at 1 ft and 2.5 ft lateral offsets from the fog line. By 2007, very low levels of joint faulting were being measured on the MnROAD mainline concrete pavement test cells, regardless of whether they were designed for five or ten years of service. As of October 17, 2007 the mainline cell with the greatest faulting was cell 9, a five year design cell with a PASB base and approximately 0.30 mm of faulting. The cells with the least faulting were cells 11 and 13; both 10 year designs with Class 5 bases. The test cells with PASB bases typically had greater faulting than the test cells with Class 4 or 5 bases, although faulting levels were very low for all mainline test cells.

The LVR cell with the greatest faulting was cell 40, an undoweled widened edge JPCP with 1.39 mm of faulting. Cell 32, a 5 inch thick undoweled JPCP on Class 1 base material, also had 1.19 mm of faulting. Test cells 36, 37, and 38 had faulting that ranged from 0.20 (cell 36) to 0.35 mm (cell 38).

2.5.3 RIDE Quality

At MnROAD, a Lightweight Inertial Surface Analyzer (LISA) profiler mounted on a utility vehicle is used to measure ride quality (RIDE) in term of International Roughness Index (IRI). RIDE is typically measured three times per year. The design terminal Present Serviceability Rating (PSR) for the MnROAD test cells was 2.5, which corresponds to an IRI of 150 in/mile. None of the Mainline test sections had reached their terminal IRI as of March 28, 2008. In the passing lane, IRI varied from 109 in/mile in cell 8 to 81.7 in/mile in cell 12. In the driving lane IRI varied from 118.5 in/mile in cell 11 to 77.9 in/mile in cell 13. There was no observed correlation between base type and IRI.

On the LVR RIDE was much worse with cell 32 having an IRI of 180.2 in/mile on the inside lane and 162.7 in/mile on the outside lane. Cell 40 had an IRI of 145.3 on the inside lane and 119.0 on the outside lane. Cell 38 had an IRI of 154.4 on the inside lane and 119.8 on the outside lane. The other two dowel test cells fared much better with IRI ranging from 73.4 on the outside lane of cell 37 to 87.4 on the inside lane of cell 36. The doweled test sections had the lowest IRI followed by cell 38 which was undoweled but had a much thicker base layer than the other test cells. Cell 40, undowel with the widened edge was the second worst with the worst being the thinnest undowelled test section (cell 32). The effect of dowels was apparent with base and slab thickness also influencing IRI.

2.5.4 Falling Weight Deflectometer Deflections

Joint load transfer efficiency (LTE) measurements are typically conducted each season for MnROAD test cells. By examining the load transfer and overall deflection history of joints, a sense of their performance with time can be observed. Table 2 lists the 1993 and 2007 LTE (driving lane, right wheel path) for the MnROAD mainline test cells. Clearly, LTE in the 5 year design cells had declined significantly by 2007, compared to the 10 year design cells. Overall, joint deflections also increase in a similar fashion. Test sections with PASB seemed to have noticeably higher LTEs by 2007. However for the 5 year design cells, test sections with PASB (7, 8, and 9) had about half the deflection at the transverse joints as the Class 4 sections (5 and 6). FWD deflections for 9000 lb drops are shown in Table 2 for the MnROAD test sections. The PASB and Class 5 base 10 year test sections all had similar transverse joint deflections.

The effect of dowels on LTE is shown in Table 2 for the LVR test cells. Cell 32, the thinnest undoweled test cell had much higher deflection and lower joint transfer efficiency than the doweled mainline test cells of similar thickness (Cells 5-9). All three undoweled LVR test cells (cells 32, 37, and 40) had higher deflections and lower joint transfer efficiency than the dowel test cells.

TABLE 2 Joint Transfer Efficiencies and FWD Deflections

MnROAD			
Cell #	**Joint Transfer Efficiency 1993**	**Joint Transfer Efficiency 2007**	**Deflection at Joints [2007] mils** (μm)
5	85	63	13.3
6	85	66	14.0
7	87	67	7.1
8	83	73	6.4
9	90	78	7.0
10	90	83	8.2
11	91	77	9.0
12	87	84	8.4
13	88	83	8.0
32	44[1]	24[2]	33.0[2]
36	87	88	4.7
37	65	61[2]	16.0[2]
38	89	84[2]	18.5[2]
40	56	35[2]	22.1[2]

[1] Measured in 2000

[2] Measured in 2008

Chapter 3 FORENSIC OBSERVATIONS

3.1 MnROAD Mainline

As mentioned previously, forensic investigations of the MnROAD Phase 1 Mainline concrete test cells were conducted in 2007 and 2008, in preparation for the construction of several new test cells (Phase 2). In order to keep the test cells in service during the winter and spring of 2007-2008, only core samples were extracted during the fall of 2007. With the closing of the mainline cells in spring 2008, more destructive types of forensic activities were conducted, including trenches and slab removals.

The extraction of the first core samples in 2007 instantly revealed some interesting phenomena occurring within the transverse joint areas. In many of the core samples extracted from cells constructed with an undrained gravel base a significant amount of concrete material was missing from the middle section of the core. More specifically, it was noted that the area of greatest distress in those cores was just below the saw cut in the 7.5 inch thick design slabs, and approximately at the mid-depth for the 9.5 inch thick design slabs. This distress would not have been discovered in surface distress surveys, since the pavement surface looked very good (very limited spalling near the joints), there was very little faulting of the joints, and the silicone joint sealant remained intact. Figure 3 shows core samples from test cells 5 and 11 exhibiting the “hole” at the mid-depth of the core. Also shown in Figure 3 is the notable observation that core samples from test cells with a drainable (PASB) base (cells 7-10) did not exhibit similar distress.

As shown in Figure 4A, additional observations of the core samples revealed that test cells built on Class 4 or 5 bases typically had widening of the transverse joints from the bottom of the slab to just beneath the saw cut. Test cell 12 was a 10 year design test cell with a Class 5 aggregate base and longitudinal edge drain. As shown in Figure 4B, this test cell did not have deterioration of the transverse joints. The transverse joints in cell 12 were still in very good condition (but not as tight as the test cells with drainable bases). Figure 4C shows a pocket that formed around a dowel bar in test cell 13.

In 2008, larger slab-type samples were sawed and extracted from the test cells before they were removed in preparation for new Phase 2 test cells. Several interesting observations were revealed both immediately following the removal process, as well as from the large samples themselves. Figure 5A shows the remaining trench area in test cell 11 one day after removal of some slab pieces with a water cooled walk behind pavement saw. Note the amount of water, from sawing, still ponded in the trench area. It was observed that 3 days later, the base material was still considerably wet on top (though not ponded anymore). Clearly the Class 5 special base material over the clay subgrade is a very slow draining pavement system.

Additional forensic investigation of the larger pieces removed in 2008 recently confirmed the distresses discovered in the core samples. Several large pieces were lifted and dropped until they broke apart to reveal the condition of the joints near the dowel bars and the extent to which the “hole” distress occurred along the transverse joint. Figure 5B shows the pocketed areas near the dowel bars from a joint in cell 13. Note the deterioration of the epoxy coating on the dowel bar in the vicinity of the joint. Sandy material could be found packed into areas like this. The remaining distressed areas were lined with clean large coarse aggregates protruding from remaining sound areas of paste and aggregate. There was no cracking or delamination of the concrete observed near the dowels. As shown in Figure 5C and 5D, it was also observed that joint deterioration was more prevalent near the shoulder edge of the driving lane.

As mentioned previously, the forensic investigation of the MnROAD Phase 1 mainline concrete test cells also revealed the condition of the epoxy coated dowels after 14 years of traffic and severe climate. In the 9.5 inch thick pavement sections (ten year designs) the dowel bars were in very good condition, with the epoxy coating fully intact. In the 7.5 inch thick pavement sections (five year designs), the epoxy coating was worn away in the areas spanning the joint, and many dowel bars contained slight to moderate amounts of rust.

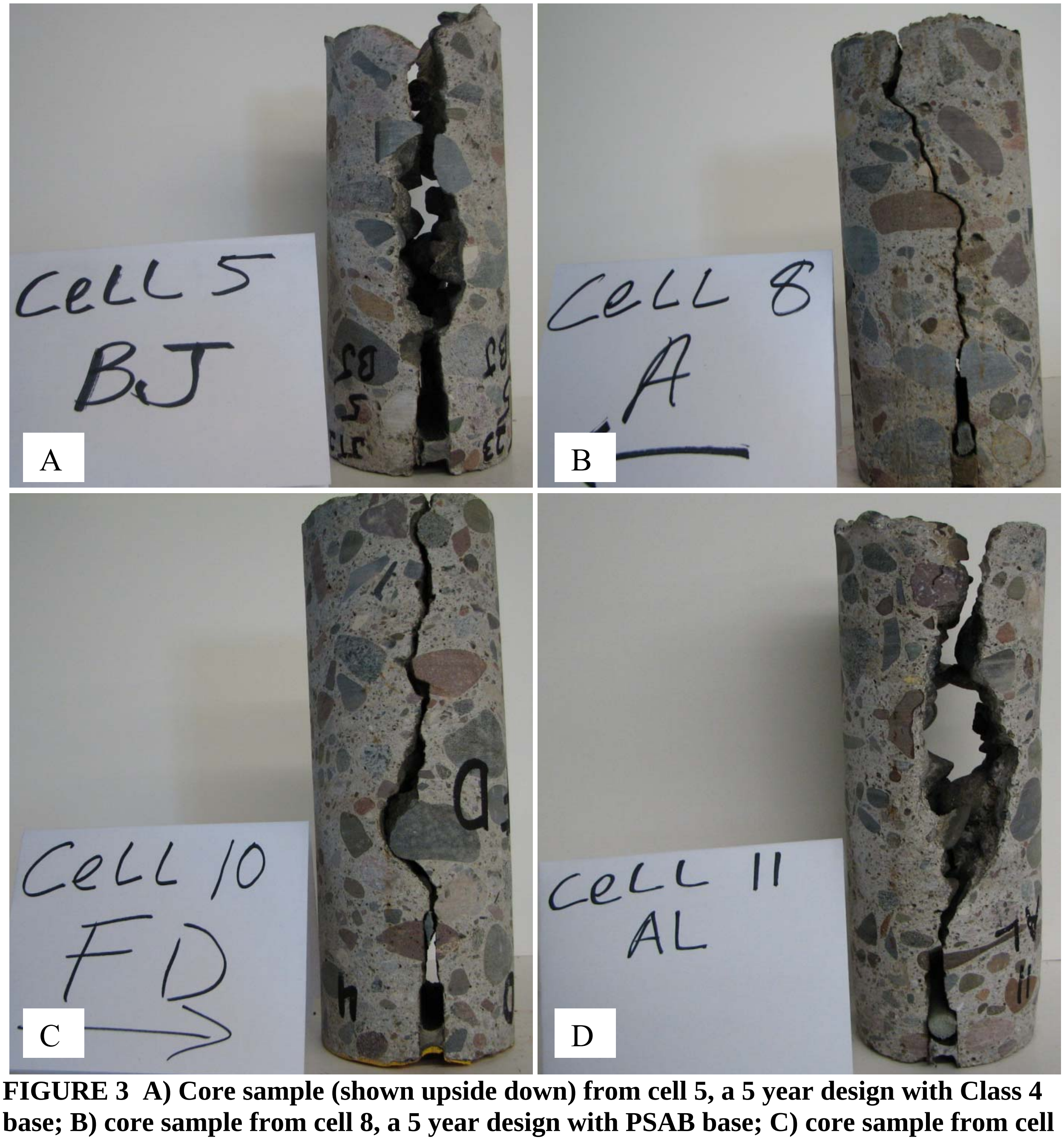

FIGURE 3 A) Core sample (shown upside down) from cell 5, a 5 year design with Class 4 base; B) core sample from cell 8, a 5 year design with PSAB base; C) core sample from cell 11, a 10 year design with Class 5 base; D) core sample from cell 10, a 10 year design with PSAB base.

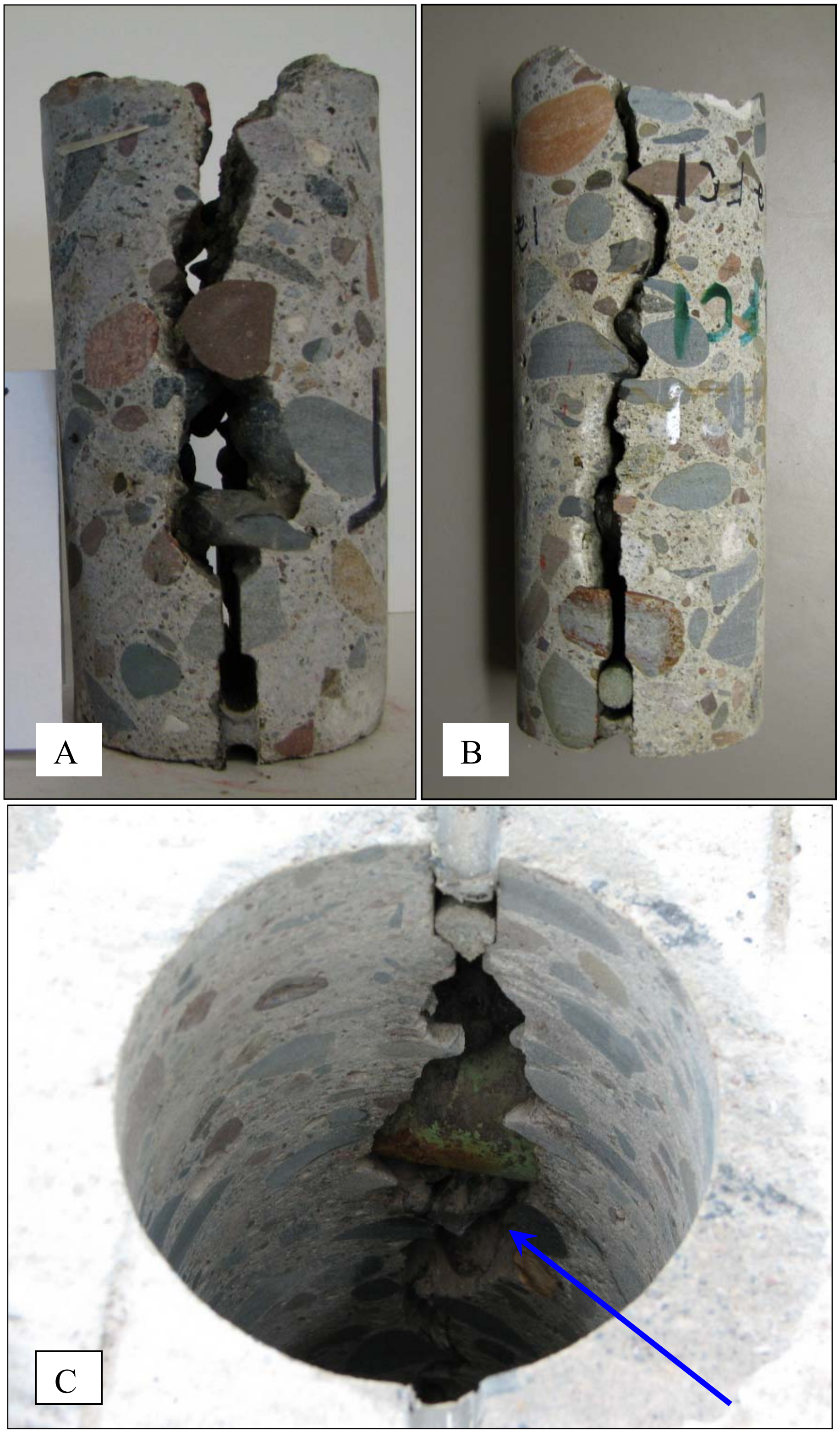

FIGURE 4 A) Widening of joint from top to bottom of core sample (shown upside down); B) core from cell 12 (longitudinal drains); C) pocket of missing material around dowel bar in test cell 13.

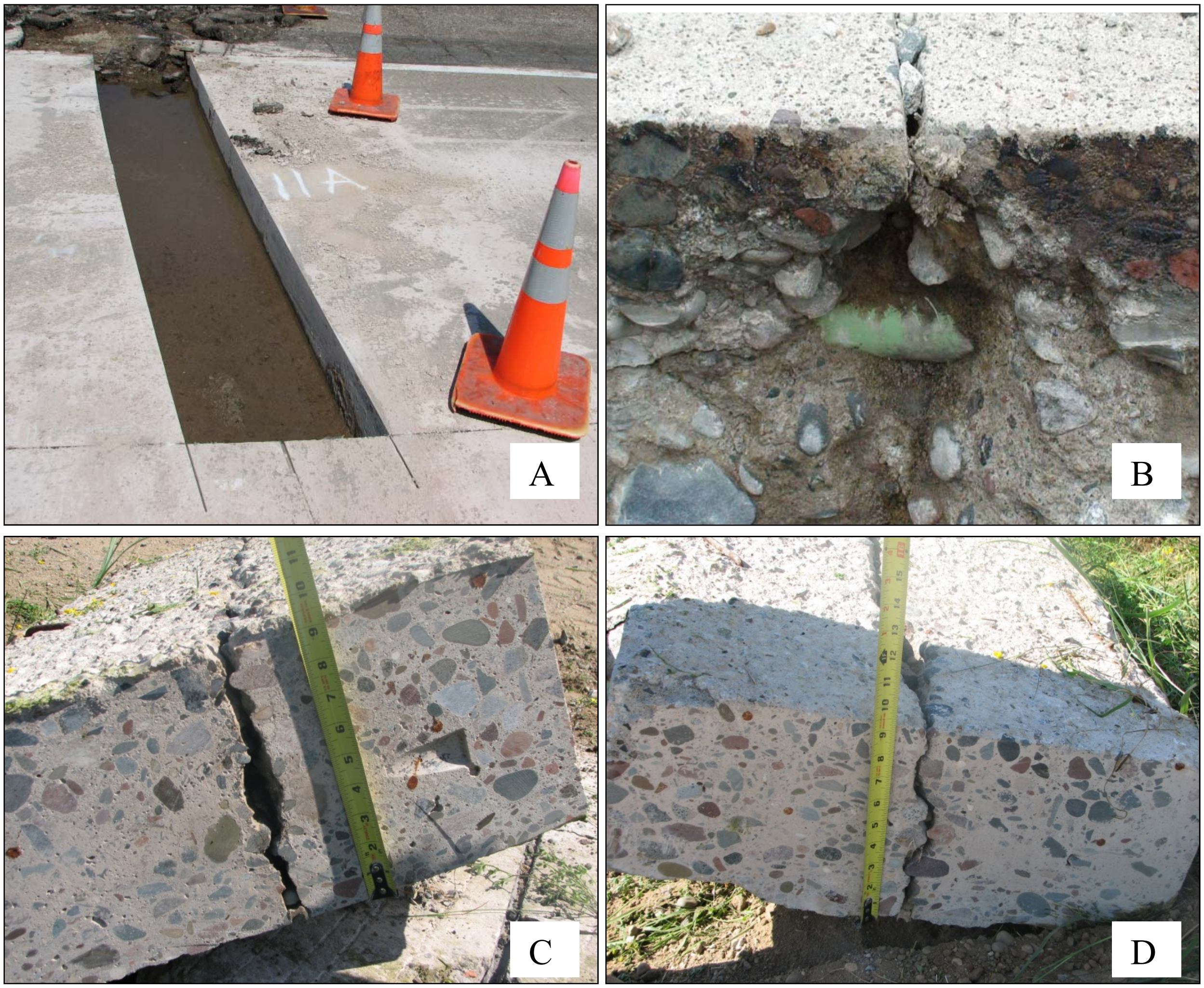

FIGURE 5 A) Photo of water from saw cutting sitting on Class 5 base one day after a panel was removed; B) Socketed areas near the dowel bars from a joint in cell 13; C) Joint deterioration at the shoulder; D) center line of the driving lane on Cell 13.

3.2 MnROAD Low Volume Road

Cores were taken along the transverse joints of the MnROAD LVR cells in the summer of 2009 to determine if the same distress that was occurring on the Mainline was occurring on the LVR. Test cells 36, 37, 38, and 40 had Class 5 aggregate bases and test cell 32 had a Class 1 base (all slow draining bases). None of the test cells has edge drains. Since the LVR test cells have similar thickness and base layers as the mainline test cells, the effect of traffic volume on joint distress could be determined from the condition of the LVR test cells.

Overall, the condition of the transverse joints in the LVR test cells was much better than on the MnROAD mainline. Transverse joints where the joints sealant was in good condition were still in good condition as shown in Figure 6 and 7. In areas where the joint sealant had failed (Figure 6B), joint deterioration similar to that observed on the mainline was present. Figure 6C shows that after 15 years the transverse joints were in very good condition if the joints were sealed and the amount of water able to enter the base layers was reduced. Where the joint sealant was in poor condition and did not prevent water from entering the base, the joints started to deteriorate and widen (Figure 6B).

3.3 Other Minnesota Highways

Given the unusual nature of the distress discovered in the MnROAD test cells, it seemed necessary to investigate whether this behavior was unique to MnROAD, or a function of the materials and methods used at the time when the test cells were designed and constructed. Certainly, the MnROAD test sections were designed to only provide a level of acceptable serviceability for 5 or 10 years. Their actual performance far exceeded those predicted design lives. This seems to be a function of the highly extrapolated design guide equations, still in use today, based on a limited amount of data gathered from the AASHO road test in the 1960's. At the same time, many of the MnROAD test cell designs would typically be built in places that experience much less than the interstate highway volumes they were exposed to. Therefore, in some ways one could say certain test cells were trafficked in an accelerated fashion. Either way, a comparison of the performance of Minnesota pavements built with similar designs, materials, and specifications was carried out to try to answer if MnROAD is typical or unique.

In order to determine if the same joint deterioration found at MnROAD was occurring in other pavements in Minnesota, core samples were taken from six different pavements throughout the state. Each of the chosen sections had similar slab thickness, age (within 6 years), subgrade and base type, and concrete mix design as the MnROAD Phase 1 sections. All sections were jointed plain or jointed reinforced concrete pavements with doweled joints. Five of the pavement sections had Class 5 bases, while the other had a drainable open graded (OG) base. Additional design features of each section are summarized in Figure 8 and Table 3. The following sections summarize the observations from the forensic cores taken in spring 2008. Refer to Figure 9 for photos of cores from each section.

FIGURE 6 A) Core hole from cell 32, a 5 inch JPCP with Class 1 base; B) core hole from cell 36 where joint sealant was in poor condition; C) core from cell 36 where joint sealant was in good condition; D) core from cell 37 where joint sealant was in good condition.

FIGURE 7 A) Core hole from cell 38, where joint sealant was in good condition; B) core hole from cell 38 where joint sealant was in poor condition; C) core from cell 40 where joint sealant was in good condition; D) core from cell 40 where joint sealant was in poor condition.

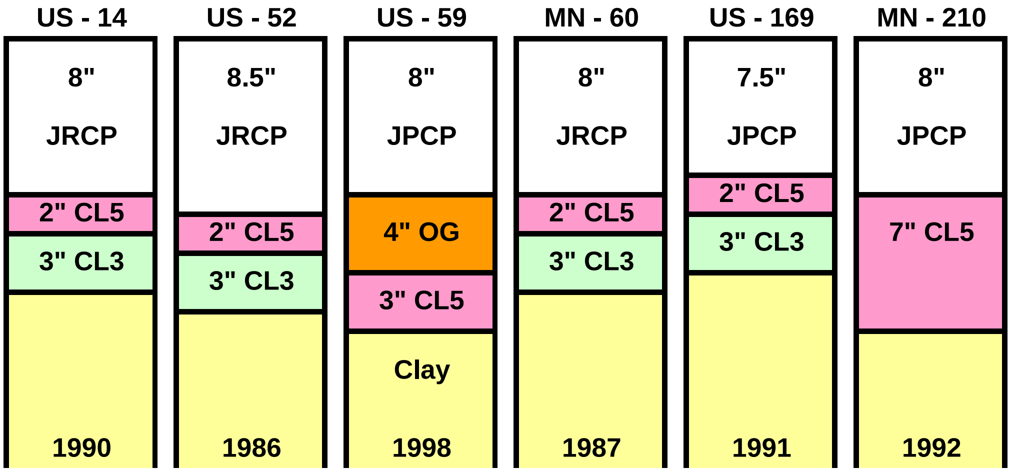

FIGURE 8 Minnesota concrete pavement sections chosen for comparison to MnROAD test sections.

3.3.1 US-14

US trunk highway 14 is a two lane, 8 inch thick JRCP with 1.25 inch diameter dowels and 27 ft long panels built in 1990. This pavement section has a Class 5 base. There was no observed distress on the concrete surface where the cores were taken. The water used during the coring of the joints did not drain through the base in four of the five core holes. The joint where the water did drain through was in good condition. Three of the five cores taken had widened joints, and cores that went through the dowel bars showed deterioration to the concrete near the dowel bar similar to what was observed at MnROAD. Deterioration was also greatest at the edge of the slab.

3.3.2 MN-60

Minnesota trunk highway 60 is a 4 lane divided, 8 inch thick JRCP, with 1.0 inch diameter dowels and 27 ft long panels. Eight core samples were taken, with five along an inclined portion of the route and three cores in a low area. There was some widening of the joint at the bottom of the slab at one core location in the low laying area but the other joints were in good condition. The surface of the concrete from the inclined section was in good condition, but in the low area there were transverse cracks at each midpanel. Even though the base layer in this pavement was Class 5, the water from coring drained through the base in some of the core holes.

3.3.3 US-59

US trunk highway 59 is a two lane, 8 inch thick JPCP, with 1.0 inch diameter dowels and 15 ft long panels. This section has an open graded, drainable base. All of the joints in this section were in very good condition and there was no surface distress.

3.3.4 US-169

US trunk highway 169 is a two lane, 7.5 inch thick JPCP, with 1.25 inch diameter dowels and 15 ft long panels. In two of the five joints, directly beneath the widened saw cut, there was a deteriorated region in the cores. When taking these cores, the cooling water did not drain through the base. The other three transverse joints where in good condition, and the water drained rapidly during the coring process.

3.3.5 MN-210

Minnesota truck highway 60 is a 4 lane divided, 8 inch thick JPCP, with 1.25 inch diameter dowels and 15 ft long panels. Again some of the water from coring drained through the base in some locations. The joints were in good condition except for some slight deterioration immediately under the saw cut. In the joints where the base was not drainable, this deterioration was worse and the entire joint was widened, with the greatest deterioration at the bottom of the slab.

3.3.6 US-52

US trunk highway 52 is a four lane divided, 8.5 inch thick JRCP, with 1.0 inch diameter dowels and 27 ft long panels. The water from coring did not drain at any of the cored joints. None of the joints had the distress that was found at MnROAD. All of the joints were tight, but all of the cores were delaminated, either near the bottom or at the level of the dowels.

TABLE 3 Pavement Section Design Details

	MN-210	**US-52**	**US-169**	**MN-60**	**US-14**	**US-59**	**MnROAD Mainline (LVR)**
AADT	5900	30,000	2500	4150	1550	5500	61,000 (4160)
% Trucks	8.2	10.7	12.0	21.0	11.1	9.0	12.1 (100)
IRI (in/mile)	130.6	157.8	83.9	94.6	106.0	73.9	81-109 (73-180)
Completion Date	Jun-92	Nov-85	Jul-91	Oct-88	Sep-90	Sep-98	Sep-92 (Jul-93)
Lane Width	14 ft	12 ft	14 ft	12 ft	12 ft	13 ft	12-14 ft (12 ft)
Transverse Joint Spacing	15 ft	27 ft	15 ft	27 ft	27 ft	15 ft	15-24 ft (12-20) ft
Random Joints	No	No	Yes	No	No	Yes	No (No)
Skew	2.1	2	2.1	2	2	2.1	No (yes)
Joint Sealant	Silicone	Neoprene	Rubberized Asphalt	Neoprene	Silicone	Silicone	Silicone (Silicone)
Dowel Diameter	1.25 in.	1.0 in.	1.25 in.	1 in.	1.25 in.	1.0 in.	1.0-1.5 in. (1.0 in.)
Dowel Spacing	12 in.	12 in.	12 in.	12 in.	12 in.	12 in.	12 in. (12 in.)
Dowel Length	15 in.	15 in.	15 in.	15 in.	15 in.	15 in.	15 in. (15 in.)
Dowel Method	Baskets	Baskets	Baskets	Baskets	Baskets	Baskets	Baskets (Baskets)
Subgrade AASHTO Classification	A-1-B	-	A-7-6	-	-	A-1-A	A-6 (A-1-B)1[3]
Cement [lb/yd3]	-	552	468	462	451	450	451 (384)[2]
Fly Ash [lb/yd3]	-	0	109	83	79	130	79 (206)[2,3]
w/cm Ratio	-	0.46	0.44	0.48	0.46	0.36	0.46 (0.37)[2]
Coarse Aggregate [lb/yd3]	-	1999 Limestone/ Dolomite	1722	1791 Gravel/ Crushed Gravel	1906 Crushed Quartzite/ Granite	1840 Crushed Quartzite/ Granite	1938 (1725)[2] Gravel/ Crushed Gravel
Fine Aggregate [lb/yd3]	-	1079 Natural Sand	1200	1200 Natural Sand	1200 Natural Sand	1265 Natural Sand	1200 (1390)[2] Natural Sand
Compressive Strength [psi]	5250	6047	4748	5161	4851	5176	5270 (3987)[2]

[1] Sand subgrade
[2] Cell 32 only, cells 36, 37, 38, and 40 have the same mix designs as the Mainline test cells
[3] Ground Granulated Blast Furnace Slag

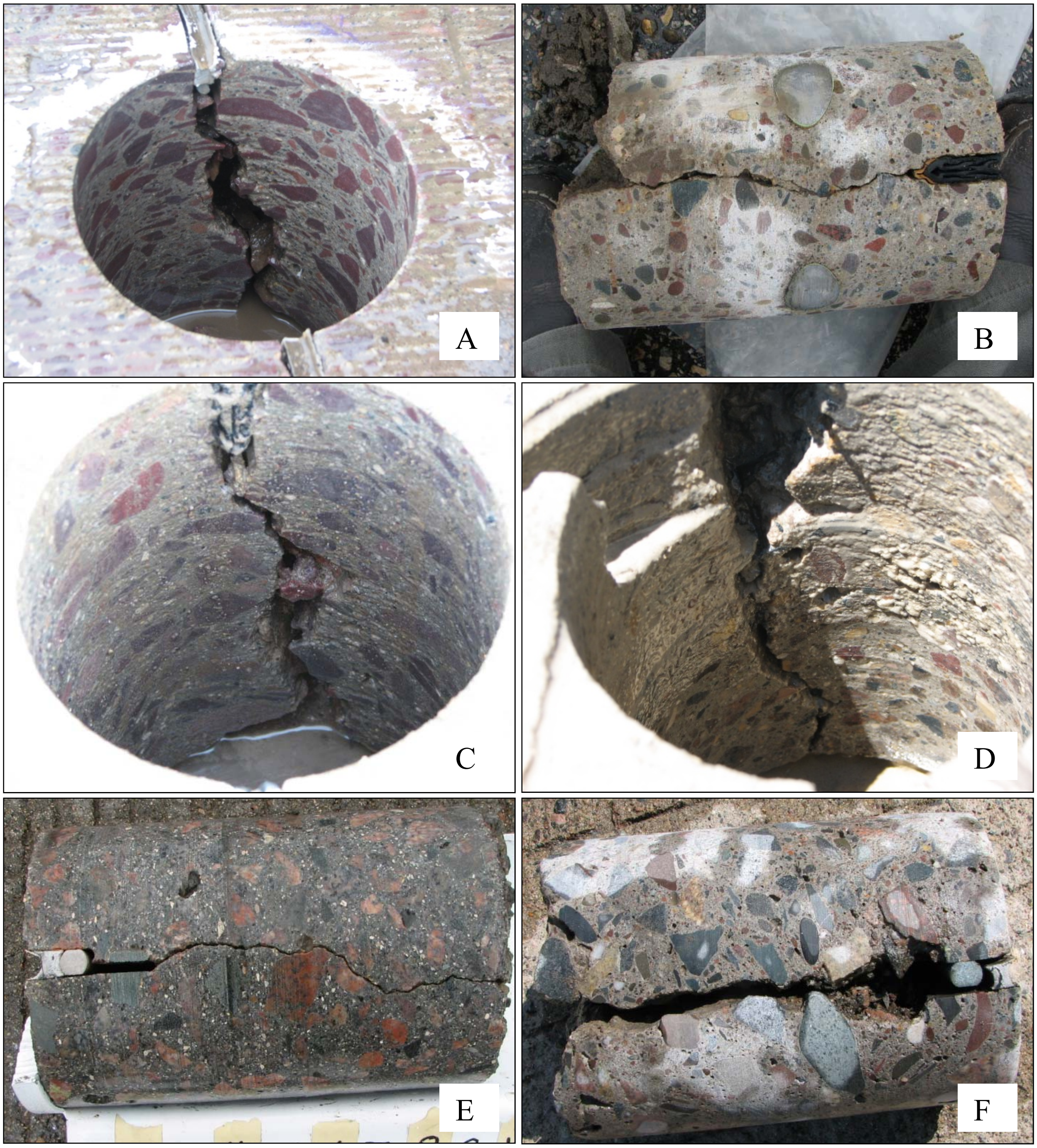

FIGURE 9 Core samples taken from: A) US-14; B) US-52; C) MN-60; D) US-169; E) US-59; F) MN-210.

Chapter 4 DISCUSSION

The results of the forensic investigations in this study indicate that the drainability of a base layer under a concrete pavement can have a significant effect on its performance. Both MnROAD and other similarly aged concrete pavements in Minnesota performed consistently better with a drainable base layer.

While it is unfortunate that the initiation and progress of the joint distress in the MnROAD test cells was not monitored, it is useful to discuss some of the potential causes for the distress. The following sections describe the plausible theories being considered as the cause for the observed MnROAD joint distress.

4.1 Freeze/Thaw Damage

As demonstrated in Figure 5A, any water that got into MnROAD joints over a dense graded gravel base layer tended to remain there for many days. Certainly these conditions would occur during the springtime thaw period, when the frost in the base and subgrade layers melts and creates saturated conditions within or above the base layer. Night time freezing temperatures certainly will cause ice to reform within the joints and cause expansive stresses that would damage any susceptible concrete material.

Due to slope of the base layer, efforts were made to see if a joint deterioration "hole" was located higher in the slab near the shoulder areas, where the water in the joint would have been deeper. No real correlation of water depth to distress depth was found with the limited number of cores taken across the joints.

Another theory related to freeze/thaw damage considers the possible deterioration of microcracks surrounding the crack cause by the initial saw cutting. Finite element modeling work by Raoufi *et al.* (6) demonstrated a bulb-shaped region of stress that forms just below the saw cut. Certainly if the stress in this area caused microcracking, the susceptibility to freeze/thaw damage would be increased. Verification of this theory is of course difficult, now that the material is gone. Earlier examination of core samples in MnROAD Phase 2 test cells may reveal the potential for such a mechanism.

4.2 Dowel Bar Stresses

Given that the distresses in the MnROAD joints typically occurred near the mid-depth of the slab, and that the distress did surround the dowel bars, one strongly feasible theory is that the dowel bars caused excessive stresses in the concrete due to the heavy interstate traffic loadings. Thinner slabs result in higher joint deflections if all other things are the same. This in turn, results in higher stresses in the concrete surrounding the dowel bars. If this was the cause for the observed distress in the joints, the stresses must have been tremendous, as the distress was found to occur equally near the dowel bars as between them.

High dowel bar stresses are most likely not the cause of the observed joint distress. Figure 10 shows cores from cells 6 and 8. Both pavements had similar slab geometry, but different base types. Both should have experienced the same dowel bar stresses over their lifetime. Certainly the socketing of the concrete material around the dowel bar in cell 6 is not prevalent in cell 8. High dowel bar stresses likely caused cracking in cell 38. As shown in Figure 7B, this resulted in tight cracks parallel to the pavement surface and not widening of the joints as was present on the MnROAD mainline.

FIGURE 10 Comparison of condition of joint in vicinity of the dowel bar in a test cell with an undrained (cell 6) and drained base layer (cell 8).

4.3 Pumping and Erosion

Given the clean, almost hydroblasted appearance of the joint distresses at MnROAD, one of the more plausible theories for a cause is that when any appreciable water ponded within the joints, it was pumped and swirled by each passing truck. Whether by the mechanisms of scour or cavitation, the fact is that very little of the missing material could be found during the forensic investigation. FWD testing showed that most of these joints had low load transfer efficiencies and high joint deflections. Past work by Hansen *et al.* (7), found that vehicle traffic produces high pressure beneath the leave slab and suction beneath the approach slab with induced water velocities beneath the pavement in the opposite direction of vehicle motion. Field tests revealed that pressure differences as high as 70 kPa (10 psi) and water velocities as high as 0.9 m/s (2.9 ft/s) are possible during pavement pumping. The pumping mechanism at MnROAD seemed to behave differently in that the erosion occurred higher up in the joints. Perhaps the concrete material near the dowel bars was loosened by high stresses and made more susceptible to the scouring forces.

Chapter 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

A forensic investigation of MnROAD Phase 1 concrete pavement test cells revealed an interesting type of joint distress. This distress occurred on high volume roads where jointed concrete pavements were built on undrained gravel bases but was not present when a drainable PASB base layer was used or where edge drains were present. On low volume roads this distress was present to a lesser extent where joint sealant was in poor condition and drainage was not provided. Cores along the transverse joints showed that a significant amount of concrete material was missing from the middle section of the joint, with the area of greatest distress just below the saw cut or approximately at mid depth. There was no accompanying surface distress, very limited spalling near the joints, little faulting, and the joint sealant was in good condition.

To determine whether the newly discovered distress was unique to MnROAD test sections, six other Minnesota concrete pavement projects, of similar age and materials, were examined. While similar types of distress were found in several other projects in Minnesota, the extent of the damage was not as severe. This may be due to much less traffic loadings being applied to those sections compared to MnROAD. In all cases though, sections with base layers that adequately drained water within the joints performed significantly better. On low volume roads, sections with joint sealant in good condition performed significantly better than sections where the joints were no longer sealed even if no drainage was provided. On high traffic volume sections, this distress occurred even if the joint sealant was in good condition. This observation provides further support of the work of Mathis, who found that properly designed and constructed permeable bases “virtually eliminated pumping, faulting, and cracking.” (8).

A discussion of the potential causes of the distress revealed many possibilities. It is likely a combination of freeze/thaw damage, erosion due to fast traveling trucks, and saturated base layers that ultimately caused the distress. While it was not possible to directly determine the cause of the distress, valuable lessons were learned that will improve the research being conducted on MnROAD Phase 2 concrete test cells. For high volume roadways such as the MnROAD Mainline, sealing joints is not enough; a drainable base layer is also needed. For lower volume roadways if the joints are sealed, a nondrainable base can be used but if the joint sealant became compromised, joint deterioration occurred. In summary:

High Volume Traffic

- Undrained PCC on Class 5 base has resulted in significant joint distress (regardless of seal condition)
- Drained PCC on Class 5 base with edge drains and well sealed joints performed better than undrained PCC
- The combination of drainable base layers and edge drains worked best

Low Volume Traffic

- Undrained PCC on Class 5 base with well sealed joints performed excellently
- Undrained PCC on Class 5 base with poorly sealed joints exhibits significant distress

It is also important to note that the gradation band for Class 5 aggregate is very broad, drainable and undrainable gradations can be made that fit the Class 5 specification. It was observed from the cores taken from highways around the state that where the Class 5 base was drainable, joint condition was significantly improved.

5.2 Recommendations

It was observed that Class 4 or 5 base materials over a clay subgrade is a very slow draining pavement system. Based on the results of this study, it is recommended that a drainable base layer be used under jointed concrete pavements, with a properly maintained system to remove water. Drainable base layers and longitudinal drains significantly improve the condition of the transverse joints on high volume roadways with drainable base layers providing the better performance. If traffic volumes are low, drainable bases and longitudinal drains are not necessary as long as the joints are sealed. Drainage should always be provided as a precaution incase the joints are not adequately sealed.

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