

# **Recent Forensic Activities at MnROAD: Using Field and Laboratory Test Data to Determine the Cause of Pavement Failures**

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**ABSTRACT**

MnROAD consists of 53 pavement test sections on a Mainline and Low Volume Road. The test sections have shown varying degrees of distress over time, with some cells failing significantly. This warranted the initiation of several forensic activities in the spring of 2007. Forensic engineering is a valuable tool that can help determine the causes of pavement failure and therefore validate mechanistic-empirical design procedures. The failures investigated in 2007 included:

- Deterioration along and underneath transverse cracks on Mainline Cell 3 (HMA over gravel base) and Cell 4 (full depth HMA on clay)
- Rutting on Low Volume Road Cells 33-35
- General pavement structural failure on Low Volume Road Cell 28
- Faulting on Mainline whitetopping Cells 92, 96, and 97

Many analysis tools and techniques were used to determine the cause of each pavement failure. The investigations included a wide variety of field testing (forensic trenches, cores, dynamic cone penetrometer, and rod and level survey) and laboratory testing (unbound material moisture content and asphalt binder content and grade).

Through these forensic tools researchers were able to draw conclusions about the cause of each pavement failure. The problems solved include:

- The relative deterioration along transverse cracks between conventional and full-depth HMA pavements
- Primary location of rutting within the pavement structure
- A perfect storm of poor design and material parameters that led to a general pavement structural failure
- The cause of whitetopping faulting and the condition of the joints.

## INTRODUCTION

Forensic investigations have gained greater acceptance in the pavement engineering field in recent years. Forensic engineering is a valuable tool in an overall pavement management program. It can help engineers to determine the causes of early pavement failure, develop proper rehabilitation strategies of those pavements, and improve future pavement design and construction practices (1).

Several organizations have active forensic engineering teams that are deployed periodically to investigate the mechanisms that cause early pavement failures. For example, the Texas Department of Transportation (TxDOT) developed a forensic investigation procedure based on the Scientific Method, which organizes the investigation into problem statement, observations, hypothesis formation, hypothesis testing, data analysis, iteration, and conclusions (2). This team has been used extensively to investigate failures in the pavement surface, base, and subgrade materials (3-4). Caltrans uses forensic investigations as a final piece in their maintenance treatment experiments (5). The National Center for Asphalt Technology (NCAT) recently conducted a forensic investigation into the cause of early fatigue cracking in a perpetual pavement test section (6).

The Minnesota Road Research Project (MnROAD) has also been the location of several forensic investigations over the last decade to investigate the causes of early pavement test section failures. MnROAD is a sophisticated full-scale accelerated pavement testing facility operated by the Minnesota Department of Transportation. It contains 53 distinct test sections (cells) and is made up of a Mainline (ML) segment carrying live Interstate highway traffic and a Low Volume Road (LVR) carrying a Mn/DOT-operated standard 80,000 lb Class 9 truck (7). MnROAD staff have conducted several pavement forensic investigations to determine the causes of their test section failures, covering topics such as rutting of the HMA Mainline cells (8), shear failure in the aggregate base on LVR Cell 28 (9), shear failure in the reclaimed base on LVR Cell 26 (10), failure of three ML Whitetopping cells related to traffic volume, joint layout, and layer bonding (11), and top-down and thermal cracking failures in several ML HMA cells (12).

The purpose of this paper is to describe the efforts of four small forensic investigations performed at MnROAD in 2007 to determine the mechanisms of pavement failures in several cells. Each study is described in detail in the following sections. Refer to [Figure 1](#) for a schematic of each of the test sections investigated. References (13-16) contain information about the test section construction details and material properties.

## STUDY #1: DETERIORATION ALONG TRANSVERSE CRACKS IN CELLS 3-4

### Description of the Problem

The primary distress type seen in asphalt pavements in Minnesota is low temperature cracking. All of the original HMA cells at MnROAD have cracked due to low temperatures. Once a pavement cracks it allows moisture to infiltrate into the pavement structure. This free water causes a number of problems in the pavement materials including stripping of the HMA layers and pumping of the underlying base and subgrade layers. The combination of these phenomena lead to cupping across the transverse cracks and ultimately to a rough ride.

Cells 3 and 4 on the Mainline were chosen to investigate the deterioration along transverse cracks in HMA pavements. They represent “typical” asphalt pavements in Minnesota, with Cell 3 being a 6” thick HMA pavement over Class 5 aggregate base and Cell 4 being a 9” full-depth HMA pavement over clay subgrade. Both cells exhibited a number of transverse cracks that have deteriorated significantly over time. It has been said by several researchers that Cell 4 is the worst-performing cell at MnROAD.

Many of the MnROAD cells have received several maintenance treatments over time as the pavement has deteriorated. The transverse cracks on Cell 4 were filled in April 2000 and again in May 2003 with traditional hot-poured sealants. Later that summer the transverse cracks on Cell 4 were leveled with mastic materials followed by two layers of microsurfacing. All of these treatments were performed in order to reduce the roughness associated with the transverse cracks. Cell 3 has not received any

maintenance treatments over time; the researchers left this cell untouched to observe the rate of deterioration compared to treated pavements. These maintenance activities will come into play later in the analysis.

Figure 2 shows the profile of the transverse crack collected with Mn/DOT's Automated Laser Profile System (ALPS) (17). The plot clearly shows the amount of cupping across the transverse crack. The cupping in Cell 3 is twice as deep as that in Cell 4, but Cell 4 has a wider area of the cupped crack. The multiple maintenance treatments on Cell 4 account for the shallower cup, but they also have provided a more variable profile.

## Methodology

Three longitudinal trenches were cut in the wheelpaths for this investigation – one in Cell 3 and two in Cell 4. A grid was laid out on the pavement surface prior to cutting beams (shown in Figure 3). The grid was arranged with four blocks downstream of the crack and four blocks upstream of the crack. Each block was approximately 2' square. A masonry saw was used to cut the pavement with as little water as possible so as to not contaminate the underlying layers of the pavement. Each block was lifted out of the hole and examined visually on the bottom side of the block and on the face of the crack.

The bottom ½" was sliced off as well as the next ½" of two blocks immediately downstream of the transverse crack in Cells 3 and 4. The asphalt binder was extracted from each of these samples to measure both the asphalt content and the resulting binder grade. It was hypothesized that the asphalt binder had stripped away at the interface as well as aged from exposure to air and moisture.

The dynamic cone penetrometer (DCP) was used to investigate the shear strength of the underlying layers in the pavement structure. Four locations were tested in each trench – two underneath the blocks immediately adjacent to the crack and two underneath the blocks farthest away from the crack. It was hypothesized that the base and subgrade layers would be weaker immediately downstream from the crack due to increased moisture contents and the pumping away of fine particles.

## Test Results and Discussion

Visual observation of the bottom of the pavement slabs as they were removed yielded some interesting information. Four blocks downstream from the crack and half of the first block upstream from the crack on Cell 3 had approximately 1.5" of aggregate base material stuck to the bottom of them (see Figure 4). The HMA was also ½" thicker away from the crack than it was near the crack. Similar to previous transverse crack investigations at MnROAD, a ridge of pumped fine material was left behind at the face of the crack, as much as 3" high in some cases (see Figure 5).

Table 1 shows the asphalt binder test results for Cells 3-4. The binders were extracted from the block immediately downstream from the transverse crack. For each cell, the bottom layer had approximately 1% less asphalt binder than the layer above it, and its high PG failure temperature was at least 3°C higher than the layer above it. This indicates that the bottom layer of the HMA deteriorated significantly near the transverse crack due to moisture and air that infiltrated through the crack. The deterioration was worse in Cell 3 where the transverse cracks were never sealed. Multiple maintenance treatments on Cell 4 led to extended time periods where no moisture was allowed into the pavement structure to cause further distress.

The DCP results yielded no significant indication that the base or subgrade was weaker near the transverse crack than away from the crack. The "depth per blow" was basically the same for each location. The results did show that the aggregate base was more than twice as strong as the clay subgrade, which was to be expected.

## Summary and Recommendations

Part of the motivation for undertaking this forensic investigation was to demonstrate the poor performance of full-depth HMA pavements. Several of these pavements around the state are over 20

years old and in need of repair. This investigation actually showed that the traditional HMA pavement over gravel base performed worse than the full-depth HMA on clay. However, one is cautioned from making a direct comparison between the two cells investigated because of the different maintenance treatments received over time. Nevertheless, significant deterioration was found along the transverse cracks in both cells, primarily due to the intrusion of water into the underlying pavement layers. This investigation yielded more evidence encouraging the proper sealing of transverse cracks in order to prevent moisture infiltration in HMA pavements.

## **STUDY #2: RUTTING IN LOW VOLUME ROAD CELLS 33-35**

### **Description of the Problem**

Permanent deformation (rutting) is another common distress in asphalt pavements. Previous studies on the MnROAD Mainline have indicated that the majority of rutting is limited to the upper lifts of the HMA surface and has not extended down into the granular base or subgrade materials (8). However, thinner pavements at MnROAD have exhibited rutting in the base and subgrade layers. The purpose of this study was to determine the primary layer responsible for rutting in Cells 33-35. [Figure 6](#) shows the progression of rutting over time for these three cells. All three cells have an average rut depth over  $\frac{1}{2}$ " , which is the trigger for rehabilitation. Cell 35 had the highest average rut depth, almost  $\frac{3}{4}$ " .

### **Methodology**

Four transverse trenches were cut across the entire 12' lane (from shoulder to centerline) for this investigation. Each cell contained one trench in the inside lane, and Cell 34 had an additional trench in the outside lane. A grid was laid out on the pavement surface prior to cutting beams. Each block was approximately 2' square. A masonry saw was used to cut the pavement with as little water as possible so as to not contaminate the underlying layers of the pavement. Only the HMA pavement was removed on Cells 33 and 35, and the base was also excavated on Cell 34.

A rod and level was used to survey the elevations of various pavement layers after the blocks were removed. The rod was held at several increments across the lane in order to get a representative picture of the surface of each layer.

The DCP was used to investigate the shear strength of the underlying layers in the pavement structure. Three locations were tested in each trench – one in each wheelpath and one between the wheelpaths. It was hypothesized that the DCP would indicate differences in the material stiffness between wheelpath and non-wheelpath tests.

### **Test Results and Discussion**

The rod and level survey yielded valuable information about the performance of each pavement material. We attempted to measure the rutting of individual HMA lifts, but that effort was abandoned because of the difficulty delineating one lift from the other. [Figure 7](#) shows the survey results from Cell 34; the figure is indicative of the other two cells. The top two lines indicate the transverse profile of the HMA and base surfaces. The 2% cross slope is evident, as is the rutting in the wheelpaths. The HMA and base curves are basically parallel, suggesting that very little (if any) rutting is occurring in the HMA layers. The bottom line shows the subgrade profile, which is practically straight across. This would indicate that the majority of the rutting occurred in the aggregate base layer.

The DCP results reinforced those found with the rod and level survey. [Figure 8](#) shows an example of DCP "depth per blow" (DPB) measurements from Cell 35; the figure is indicative of the other cells. The two curves toward the left of the plot show that the DPB is consistently about 0.5 cm/blow through the 12" aggregate base layer in each of the wheelpaths. However, the curve on the right shows that the DPB between the wheelpaths is significantly higher. This indicates that the wheelpaths are considerably stronger due to consolidation/densification underneath the truck tires.

## Summary and Recommendations

Both the rod & level survey and the DCP results show that the majority of the rutting in Cells 33-35 took place in the Class 6 aggregate base layer. This material is 100% crushed granite, which is more angular than many other aggregate base materials used around Minnesota. It was difficult to achieve adequate compaction during initial construction and therefore allowed for consolidation over time. This investigation underscores the importance of getting proper compaction on all layers in an asphalt pavement.

## STUDY #3: STRUCTURAL FAILURE ON LOW VOLUME ROAD CELL 28

### Description of the Problem

Cell 28 began showing signs of distress shortly after paving in August 2006. Some rutting became apparent, but the main concern was the appearance of slippage cracks toward the East end of the cell after Spring Thaw in 2007. At first the cracks appeared as small crescent-shaped cracks in the wheelpaths, but they quickly grew across most of the pavement lane. Within a few days the MnROAD truck further distressed the area to the point of severe fatigue cracking. It appeared that the top HMA lift had debonded from the bottom lift and was being shoved around with each pass of the MnROAD truck. The truck driver was able to push some of the deformed hot mix back into place by adjusting his travel pattern. [Figure 9](#) shows the area that was severely fatigued.

It was suspected that a combination of inadequate pavement structure, an extremely soft asphalt mixture, and moisture in the clay subgrade caused the localized failure. A forensic investigation was launched to investigate the cause of the distress.

### Methodology

A forensic pit was dug measuring approximately 12' wide by 30' long. A diamond blade saw was used to cut the pavement with as little water as possible so as to not contaminate the underlying layers of the pavement. In most of the distressed area the skid loader was able to scrape off the top 2" lift of HMA with minimal effort. Each layer (HMA, Class 5 aggregate base, and clay subgrade) was excavated with the skid loader and set aside.

Aggregate base and subgrade samples were taken to determine the moisture content of each material. It was obvious from the condition of the pavement that the underlying layers were quite wet, partially the result of a 2-inch rainfall over the previous weekend.

The DCP was used to investigate the shear strength of the subgrade soil. Several tests were performed in "bad" areas as well as several tests in relatively "good" areas.

### Test Results and Discussion

The investigation took place in mid-June when the pavement was rather warm. However, the HMA was so excessively soft (10 months after construction) that when removed and piled up next to the excavation, it flowed like HMA directly out of the plant. Previous laboratory tests performed shortly after construction showed the extracted binder grade to be PG 51.6-34.6. Asphalt Pavement Analyzer (APA) tests also indicated that the mixture was susceptible to rutting (i.e., highly soft).

[Figure 10](#) shows the results of DCP testing, similar to that in Cell 35. The plot shows two tests each in the "good" and "bad" areas. The good areas have a DPB of less than 2", but some bad areas saw a DPB of more than 12". The middle of the clay layer seemed to be softer than right at the surface.

The moisture content of the aggregate base and subgrade materials was about 6% and 18%, respectively. The clay at MnROAD becomes excessively soft at just past optimum moisture content.

## Summary and Recommendations

It seems a perfect storm of poor design and material parameters came together to cause the failures seen on Cell 28, as shown by the DCP and moisture results:

- A soft asphalt binder (PG 52-34) with no recycled asphalt pavement (RAP)
- A thin (6") base layer of marginal Class 5 material (it failed gradation tests during construction)
- The inclusion of wet, sticky clay as a subgrade layer. This layer seemed to catch the water flowing downhill (east to west) from the Cell 29 base material. The water had no place to go, so it just sat there and softened the pavement structure.

## STUDY #4: FAULTING ON MAINLINE WHITETOPPING CELLS 92, 96, & 97

### Description of the Problem

Faulting of concrete pavements is a significant factor in contributing to pavement roughness. Faulting is the difference in elevation of adjoining slabs at the transverse joint, initiated when load transfer through dowels or aggregate interlock is no longer adequate. In most concrete pavements, faulting is caused by the buildup of loose fine material pumped in the presence of moisture. The location of the buildup is most commonly under the approach edge of the slab, due to the erosion of subbase material from under the leave edge of the slab. The magnitude of faulting is affected significantly by heavy traffic loads, the type of subbase material, and climatic conditions that the pavement is subjected to over the course of its lifetime.

Several whitetopping cells were built at MnROAD in 1997 (see [Figure 1](#) for the pavement structures). Over time Cell 97 has developed significant faulting, as shown in [Figure 11](#). This was not expected since each whitetopping cell consisted of a 6" concrete pavement over 7" of structurally sound asphalt pavement. It was hypothesized that the asphalt pavement had cracked through to the subgrade, and the entire pavement structure was faulting. A forensic investigation was initiated to determine the cause of the distress.

### Methodology

Several 6" diameter cores were drilled along the transverse joints in each cell. The cores were removed and inspected visually to determine the condition of both the PCC and HMA layer. A few cores were also drilled in the center of certain panels and visually inspected for the condition of the pavement materials at the interface.

### Test Results and Discussion

The coring operation led to some surprises during the investigation. It was determined that the HMA layer was not faulted as previously assumed; instead it was the PCC layer that was primarily responsible for the faulting. The concrete debonded from the asphalt at each joint, allowing water to enter and erode the pavement materials. Because the concrete was not properly bonded to the underlying asphalt, the panels began rocking under heavy traffic, adding to the distress. Both the HMA and PCC materials were deteriorated, but the majority of deterioration was in the PCC. Polypropylene fibers were added to the concrete mix during construction, and these fibers were concentrated in clumps rather than dispersed uniformly. These fibers also likely contributed to the material deteriorating. It should be noted that these fibers are non-structural in nature, used primarily to mitigate the effects of plastic shrinkage cracking. This is in contrast to synthetic structural fibers that have been used in concrete pavements in recent years with great success. [Figure 12](#) shows the condition of several concrete cores at the bottom of the slab across the transverse joint.

## Summary and Recommendations

Adding dowels to concrete pavements for load transfer certainly improves the long-term performance, shown by the minimal faulting levels on Cell 92. Smaller panel sizes (6' x 5' on Cell 96) also lead to improved performance over time. Cell 97 had no dowels and large panel sizes (10' x 12'), a combination that led to the poor faulting performance. Subsequent whitetopping pavements built at MnROAD and elsewhere have arrived at a 6' x 6' x 6" panel being an optimum design for whitetopping pavements. Based on the data collected at MnROAD, the use of low modulus synthetic fibers in whitetopping applications provide little benefit to pavement performance.

## SUMMARY AND CONCLUSIONS

The four forensic studies discussed in this paper demonstrate that forensic investigations are valuable tools in determining the causes of premature pavement failures. Field testing methods such as DCP, cores, laser profiler systems, and visual observation are quite effective in measuring pavement material properties and performance. In the same way, laboratory testing methods such as asphalt binder grading, asphalt mixture performance testing, and aggregate property testing give useful additional information on pavement material properties.

Forensic engineering can be used to determine the proper pavement rehabilitation strategy as well as to better select pavement materials and designs in the future. Specifically, the lessons learned from the MnROAD forensic investigations include:

- It is ideal to prevent pavements from cracking in the first place. If cracking does occur, proper maintenance treatments can seal cracks in order to keep water out, thereby maintaining structural integrity and material durability.
- Proper compaction of all pavement layers during construction is crucial. Otherwise, consolidation can occur in the HMA, base, or subgrade layers and become manifest as rutting.
- The proper and careful selection of pavement materials and structural designs is of utmost importance. Even with a superior construction job, a pavement can fail if it was poorly designed.
- Whitetopping pavements have an optimal joint configuration that is able to withstand traffic as well as endure climatic conditions.

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## LIST OF TABLES AND FIGURES

### TABLE 1 Cells 3-4 Asphalt Binder Test Results

**FIGURE 1 MnROAD 2007 Forensic Cell Schematics.**

**FIGURE 2 Cupping Across Transverse Cracks in Cells 3-4.**

**FIGURE 3 Forensic Trench Grid (Top) and Sawing Operation (Bottom) on Cell 3.**

**FIGURE 4 Forensic Trench Exposed on Cell 3.**

**FIGURE 5 Ridge of Pumped Fine Material at Transverse Crack Face.**

**FIGURE 6 Average Rut Depths for Cells 33-35.**

**FIGURE 7 Rod & Level Survey Results in Cell 34.**

**FIGURE 8 DCP Results in Cell 35.**

**FIGURE 9 Condition of Cell 28 Before Forensic Investigation.**

**FIGURE 10 DCP Results in Cell 28.**

**FIGURE 11 Faulting of MnROAD Whitetopping Cells.**

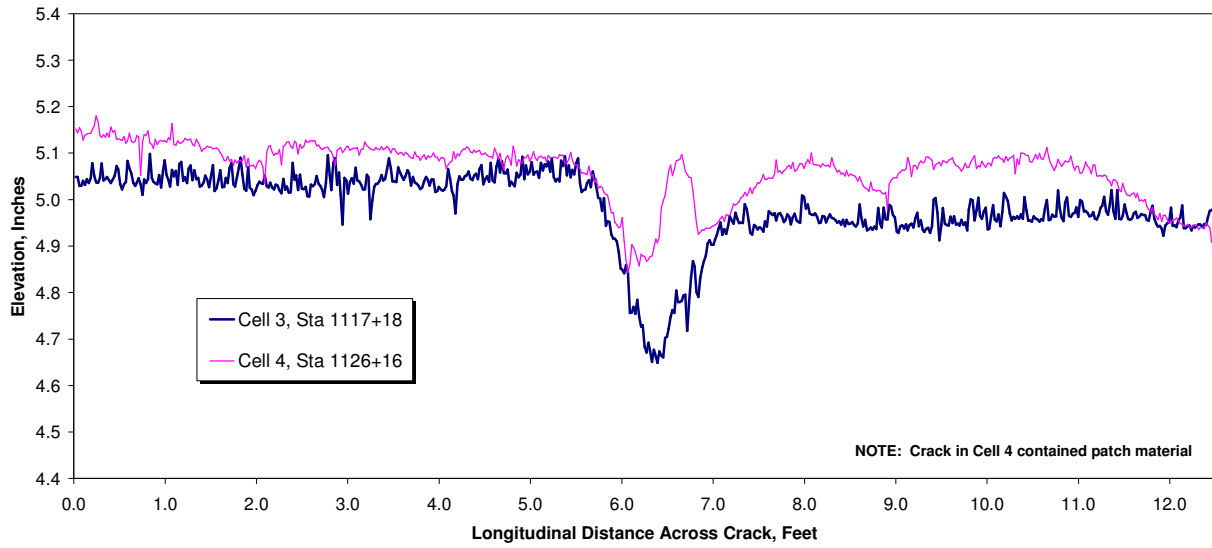
**FIGURE 12 Condition of Concrete Cores at the Asphalt Interface.**

**TABLE 1 Cells 3-4 Asphalt Binder Test Results**

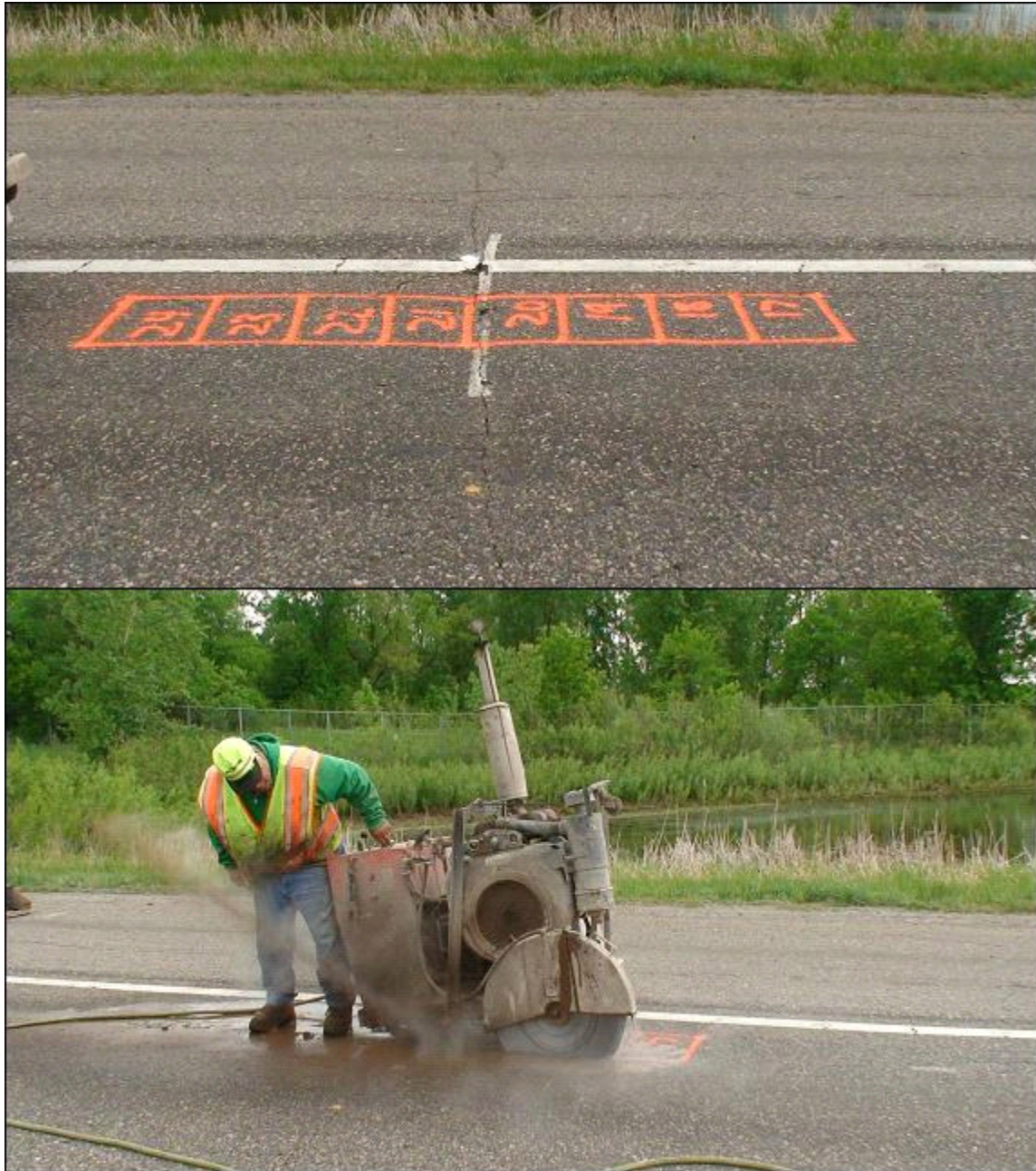
<b>Cell</b>	<b>Layer</b>	<b>Asphalt Content, %</b>	<b>High PG Grade</b>
3	Bottom 1/2"	4.4	74.6
	2nd layer from bottom	5.3	70.3
4	Bottom 1/2"	4.9	70.6
	2nd layer from bottom	5.3	66.8

<b>3</b>	<b>4</b>	<b>28</b>	<b>33</b>	<b>34</b>	<b>35</b>	<b>96</b>	<b>97</b>	<b>92</b>
6.3" 58-28	9.1" 58-28	2" 2"	4" 58-28	4" 58-34	4" 58-40	5.9"	5.9"	5.9"
4" Class 5	Clay	6" Class 5	12" Class 6	12" Class 6	12" Class 6	7" 58-28	7" 58-28	7" 58-28
33" Class 3		7" Clay				Clay	Clay	Clay
	Clay	Borrow	Clay	Clay	Clay			
	2003 Micro- surfacing	Clay				6'x5' panels	12'x10' panels	12'x10' panels
						Polypro fibers	Polypro fibers	Polypro fibers
						no dowels	no dowels	1" dowels

**FIGURE 1 MnROAD 2007 Forensic Cell Schematics.**



**FIGURE 2 Cupping Across Transverse Cracks in Cells 3-4.**



**FIGURE 3 Forensic Trench Grid (Top) and Sawing Operation (Bottom) on Cell 3.**



**FIGURE 4 Forensic Trench Exposed on Cell 3.**



**FIGURE 5 Ridge of Pumped Fine Material at Transverse Crack Face.**

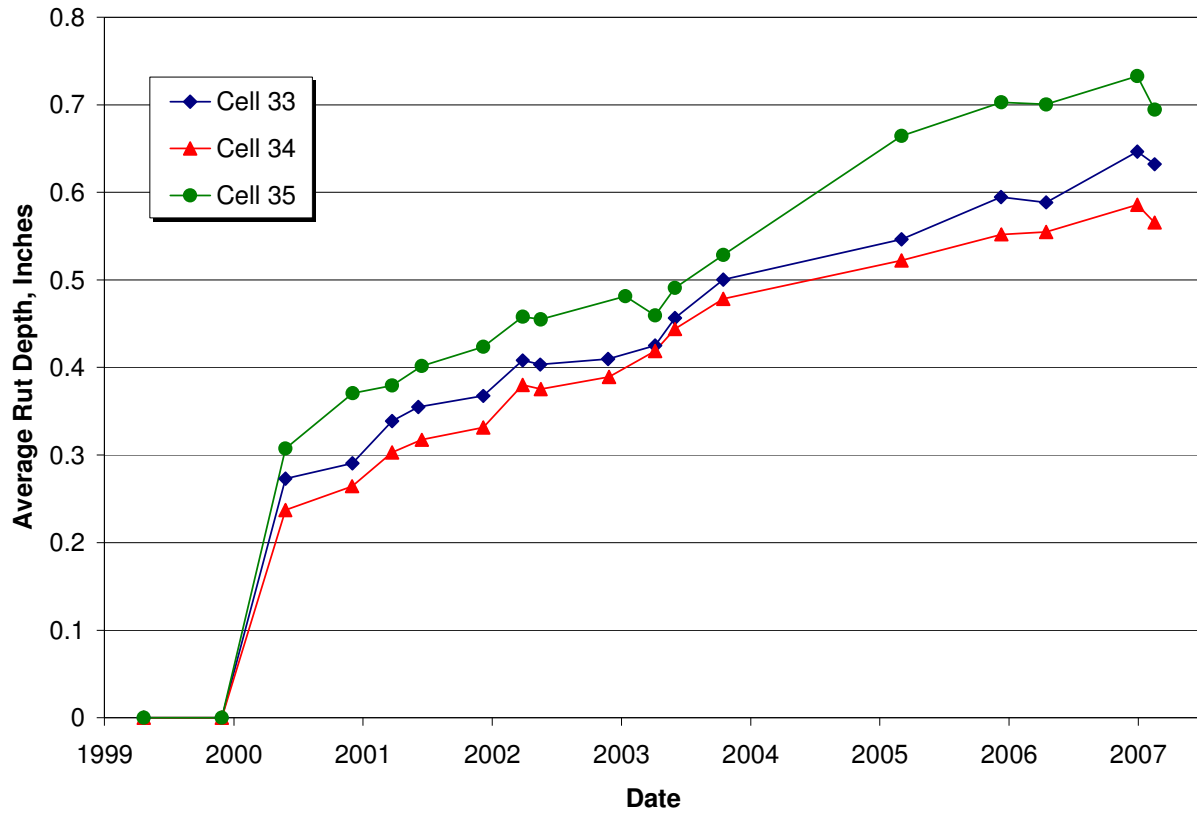


FIGURE 6 Average Rut Depths for Cells 33-35.

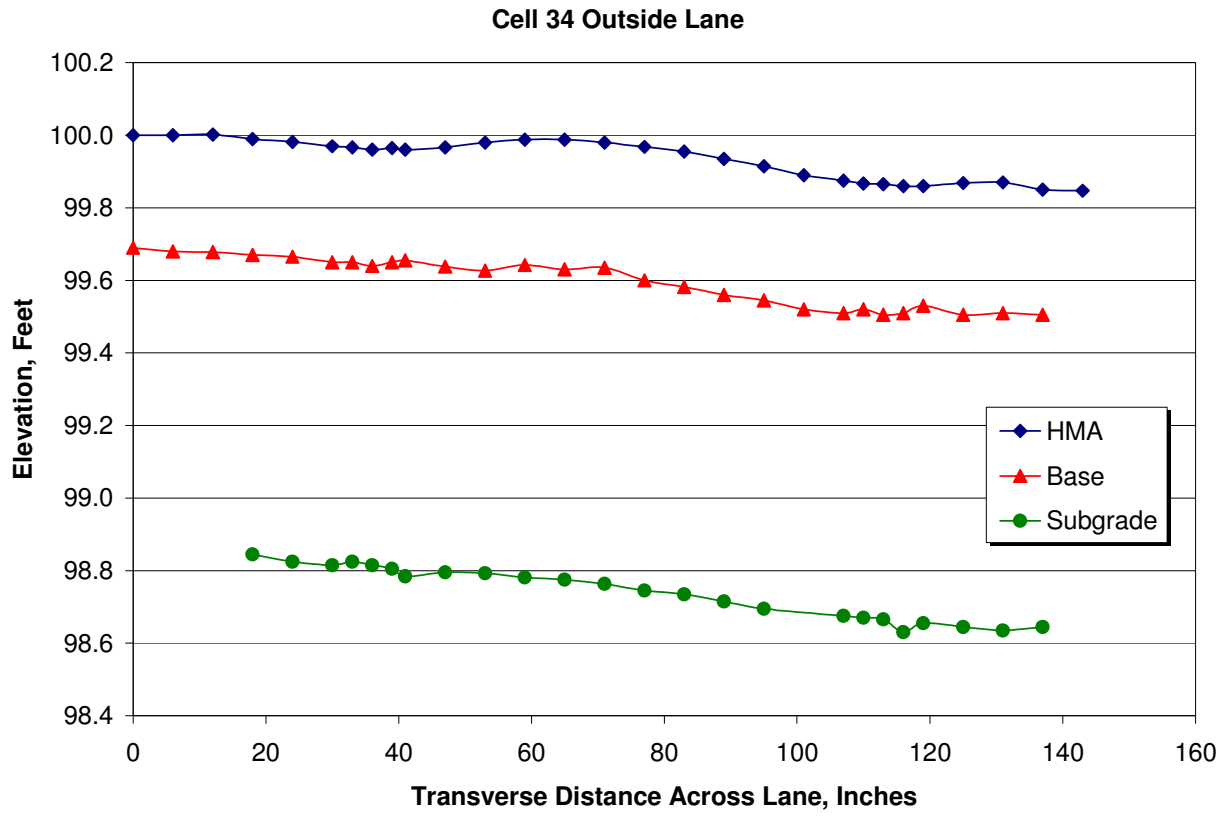


FIGURE 7 Rod & Level Survey Results in Cell 34.

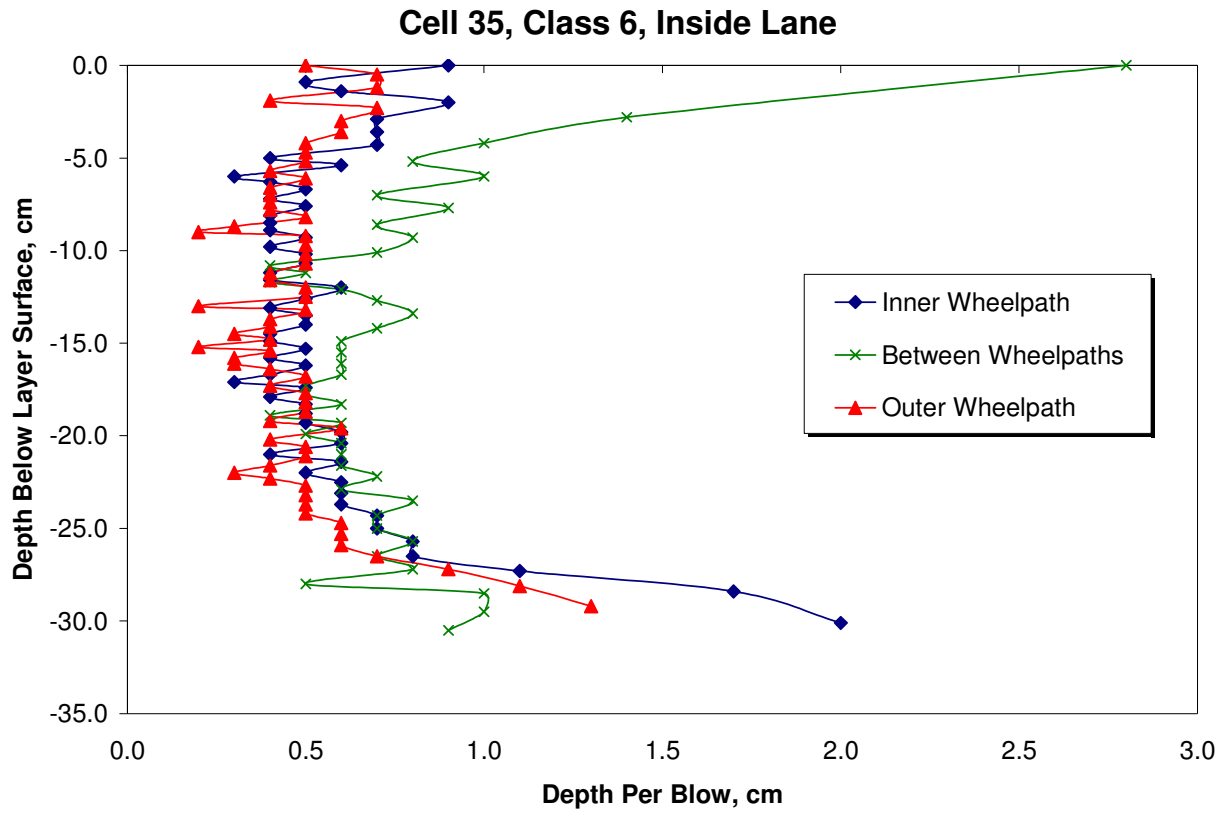


FIGURE 8 DCP Results in Cell 35.



**FIGURE 9** Condition of Cell 28 Before Forensic Investigation.

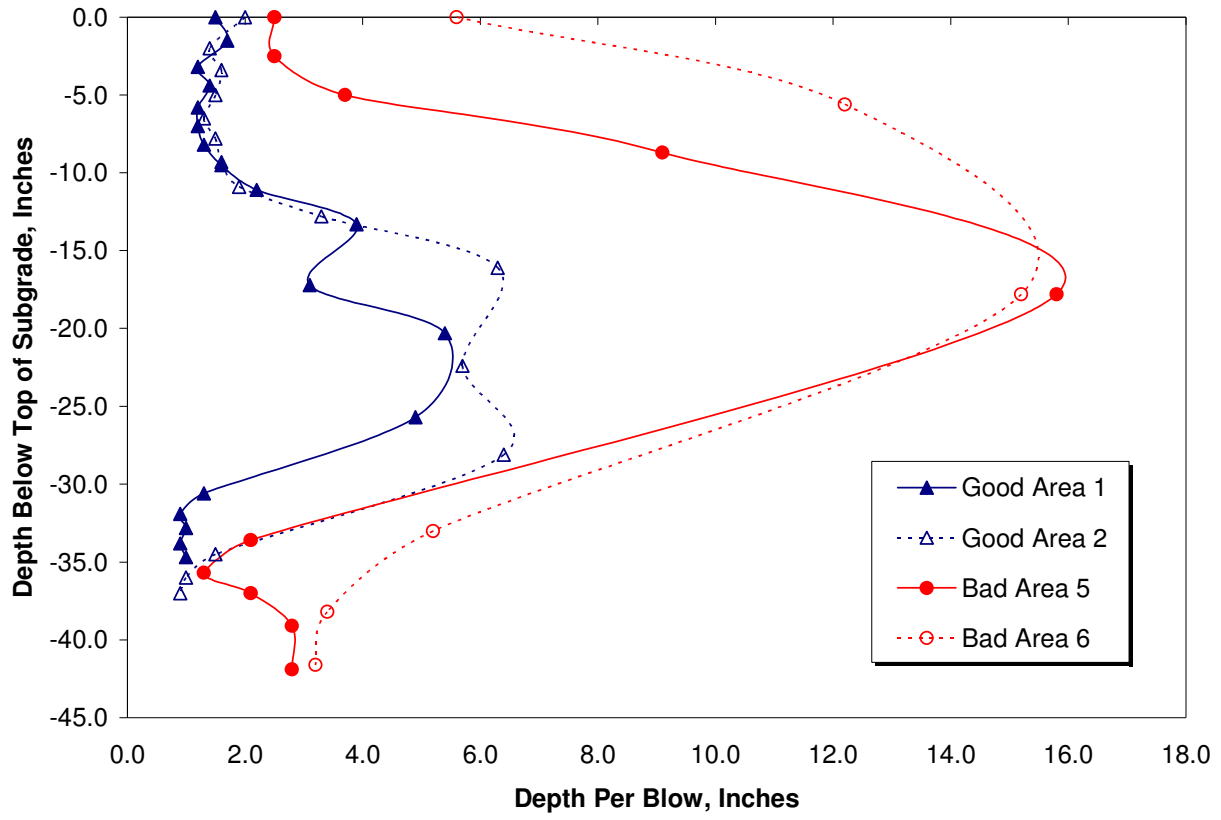


FIGURE 10 DCP Results in Cell 28.

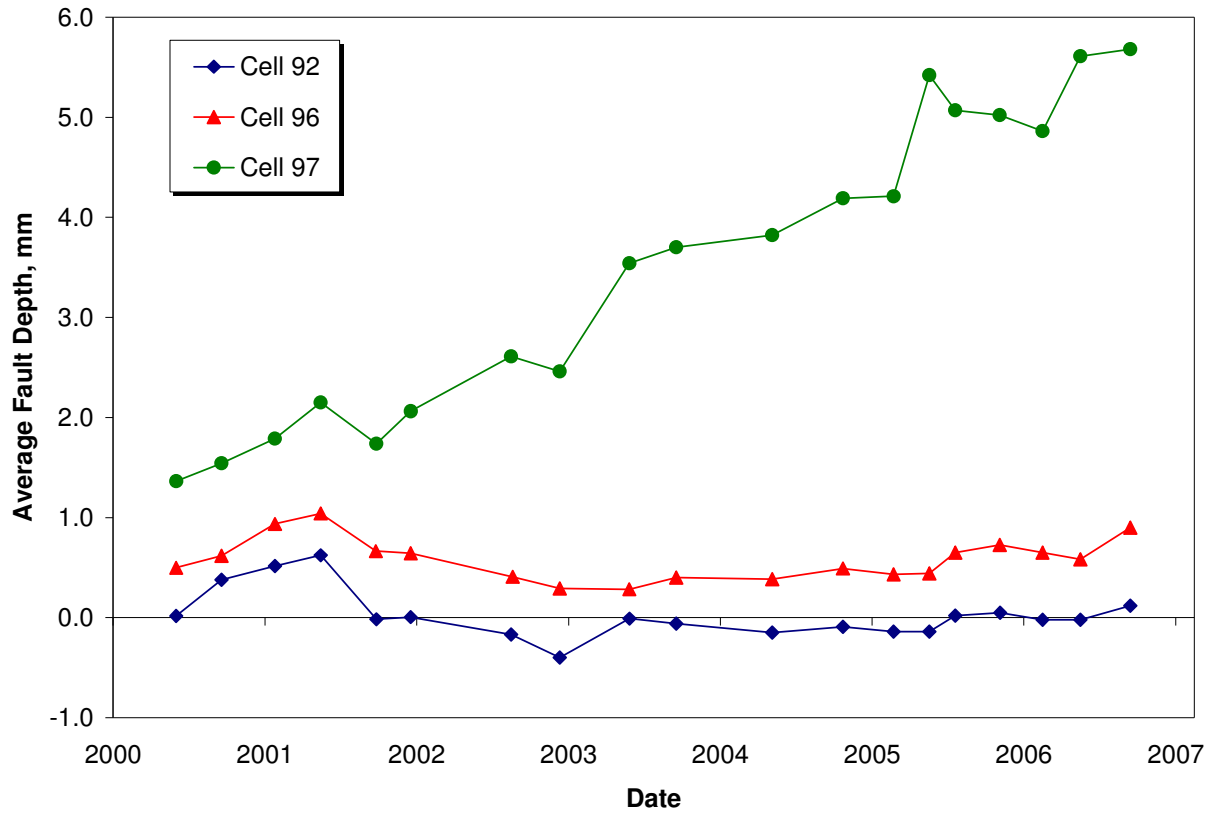


FIGURE 11 Faulting of MnROAD Whitetopping Cells.



**FIGURE 12** Condition of Concrete Cores at the Asphalt Interface.