Final Report 1999-33

PB2000-105044

Minnesota Road Research Project Forensic Investigation 199701

MnROAD

Office of Minnesota Road Research

Technical Report Documentation Page

1. Report No. MN/RC - 1999-33	2.	3. Recipient's Accession No.
4. Title and Subtitle Minnesota Road Research Project FORENSIC INVESTIGATION 199701		5. Report Date July 1999
		6.
7. Author(s) Cassandra Isackson Shongtao Dai Dan Boerner		8. Performing Organization Report No.
9. Performing Organization Name and Address Minnesota Department of Transportation Office of Materials and Road Research Mn/ROAD Operations 1400 Gervais Avenue Maplewood, Minnesota 55109		10. Project/Task/Work Unit No.
		11. Contract (C) or Grant (G) No.
12. Sponsoring Organization Name and Address Minnesota Department of Transportation 395 John Ireland Boulevard St. Paul Minnesota, 55155		13. Type of Report and Period Covered Final Report 1997 - 1999
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This report focuses on the first extensive forensic excavation of a paved test cell at the Minnesota Road Research Project (Mn/ROAD). A trench was dug in Cell 28 of the Low Volume Loop at Mn/ROAD to investigate a localized failure of the roadway. This report documents the trenching process and serves as a historical record of the in situ conditions of Cell 28 in the early summer of 1997.

Data collected during this forensic excavation has contributed to the conclusion that mechanistic pavement design methods should include a maximum allowable stress criteria for aggregate base and subgrade. In addition, minimum hot-mix asphalt pavement thicknesses are required to prevent failures of aggregate base and subgrade.

The tests performed during the investigation, as well as the analysis of available data, are discussed. The conclusions of the forensic research team as to the historical performance and subsequent deterioration of Cell 28 also are included.

17. Document Analysis/Descriptors Mn/ROAD Forensic Investigations	Pavement Design Pavement Failures	18. Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 50	22. Price

Minnesota Road Research Project

FORENSIC INVESTIGATION 199701

Final Report

Prepared by:

Cassandra Isackson, PE
Dan Boerner, PE
Shongtao Dai, PE

Minnesota Department of Transportation
Office of Materials and Road Research
Mn/ROAD Operations

July 1999

Published by:

Minnesota Department of Transportation
Office of Research & Strategic Services
Mail Stop 330
395 John Ireland Boulevard
St. Paul, MN 55155

ACKNOWLEDGEMENTS

The authors would like to thank the Forensic Team, the Mn/ROAD operations staff, the Maplewood laboratory, and the Monticello maintenance crew for their contributions in the excavation process, the collection of samples and data, the testing of samples, and the analysis of results.

Forensic Team:

Dave Baker
Dan Boerner
George Cochran
Shongtao Dai
Jack Herndon
Cassandra Isackson
Dave Palmquist
Dave Rettner
Ruth Roberson
John Siekmeier
Dave Van Deusen
Ben Worel
John Zollars

TABLE OF CONTENTS

CHAPTER 1 – INTRODUCTION 1

Minnesota Road Research Project 1
Summary 1
Test Roadways 1
Objective of Forensic Excavation 2
Cell 28 History 3
Materials 3
Traffic Loading 4
Pavement Condition 4

CHAPTER 2 – DATA COLLECTION 9

Procedure 9
Forensic Trenches 9
Excavation 9
Surveyed Cross-Sections 11
Sampling and Testing 13
Sampling 13
Field Testing 14
Laboratory Testing 15

CHAPTER 3 – DATA ANALYSIS 17

Laboratory Test Results 17
Factors Influencing Strength 17
Elastic Rebound 17
Plastic Deformation 19
Analytical and Numerical Analysis 19
WESLEA Analysis 19
Finite Element Analysis 20
Required Minimum Pavement Thickness 22

CHAPTER 4 – CONCLUSIONS 23

Forensic Process 23
Sawing and Trench Excavation 23
Handling the Samples 23
Repair of Trenches 23
Cell Performance 24
Conclusions 24
Further Research 26

Appendix A Mn/ROAD Layout
Appendix B LVR Traffic
Appendix C Rod and Level Data
Appendix D Test Results

LIST OF FIGURES

FIGURE 1.1 – Mn/ROAD Truck Layout.. 2
FIGURE 1.2 – "Structural" Failure..3
FIGURE 1.3 – Rutting in Cell 28..5
FIGURE 1.4 – Cell 28 Rate of Rutting..5
FIGURE 1.5 – HMA Pavement Thickness..6
FIGURE 1.6 – Critical Event Locations in Cell 28.. 7

FIGURE 2.1 – Trench Layout.. 8
FIGURE 2.2 – Dry Sawing of Pavement..9
FIGURE 2.3 – Removal of Rectangular Pavement Sections..9
FIGURE 2.4 – Removal of Aggregate Base..10
FIGURE 2.5 – Taking Rod and Level Measurements..11
FIGURE 2.6 – Cross-section at "Failed" Trench Location.. 11
FIGURE 2.7 – Stacked Pavement Samples..12
FIGURE 2.8 – Aggregate Base Gradations.. 13

FIGURE 3.1 – Stress-Strain Curves.. 16
FIGURE 3.2 – Stress-Strain Curves.. 17
FIGURE 3.3 – Mohr-Coulomb Failure Envelope..17
FIGURE 3.4 – Method 1..18
FIGURE 3.5 – Method 2..19

LIST OF TABLES

TABLE 3.1 – Summary of ILLIPAVE Analyses..20
TABLE 3.2 – Summary of Minimum Thicknesses..21

EXECUTIVE SUMMARY

On July 1, 1997, the first comprehensive forensic excavation of a paved test cell at the Minnesota Road Research Project (Mn/ROAD) was conducted. The excavation took place in the 80K Lane of Cell 28 on the Low Volume Roadway. After receiving approximately 59,000 ESALs from the Mn/ROAD truck, the 80K lane of Cell 28 was exhibiting significant amounts of rutting with some ruts as deep as 1 inch. An evaluation of rut data beginning in 1994, reveals that rutting began almost immediately after the cell was opened to traffic. Rut depths, which had been increasing gradually, sharply increased during the spring of 1996 and the spring of 1997. Cross-sections taken during the excavation revealed deformation of both the aggregate base and the hot-mix asphalt (HMA) pavement. The majority of rutting was in the aggregate base with little or no observed deformation in the subgrade. Cross-sections and measurements made during the forensic confirmed Ground Penetrating Radar (GPR) pavement thicknesses. The pavement in Cell 28 varied in thickness from approximately 2.4 to 3.6 inches. Due to construction variability, the pavement thickness in Cell 28 varied significantly from the design thickness of 3 inches.

In the early spring of 1997, wheelpath cracking was reported along 40 linear feet of roadway. One month later this cracking had spread to 114 linear feet of roadway. The wheelpath cracking occurred in an area that GPR data indicated was the thinnest section of pavement in the cell. A "wedge" type structural failure then occurred in the 80K lane at Station 184 + 59 and prompted the forensic investigation. Two trenches were subsequently excavated. The purpose of this report is to document the forensic excavation and to record observations and conclusions as to the historical performance and subsequent deterioration of Cell 28.

Following the excavation, resilient modulus tests were performed on the Class 5 Special aggregate base and subgrade for use in analytical and numerical analysis methods. Triaxial tests were performed to establish a failure criterion for the aggregate base. Laboratory experiments illustrated that the shear strength decreased as the moisture content increased and suggested that a threshold for allowable stress exists for the aggregate base. If loading occurs up to the threshold, the material will fully rebound without permanent plastic deformation. However, loading that occurs beyond this threshold results in permanent plastic deformation such as that exhibited in Cell 28. The stress-strain curve established through testing revealed that plastic flow occurred after a peak stress was reached. This plastic flow implies that once stress exceeds the shear strength of the aggregate base, increased loading is not required for additional deformation. If the stress in the aggregate base is greater than its strength, a large plastic deformation occurs which, in the case of Cell 28, contributed to rutting and ultimately a structural failure.

"Failure" of Cell 28 began to occur soon after the opening of the roadway. The stresses induced in the aggregate base by the Mn/ROAD truck exceeded the shear strength of the material. This resulted in permanent deformation within the aggregate base, which contributed to rutting. The deformation of the aggregate base then stabilized due to the densification that accompanied the deformation. Finally, surface-initiated cracking in the thinnest area of pavement allowed moisture to flow into the aggregate base and subgrade during the spring of 1997. The additional moisture further weakened the aggregate base resulting in the wedge-type structural failure that prompted the investigation.

Data collected during this forensic excavation has contributed to the conclusion that mechanistic pavement design methods should include a maximum allowable stress criterion for aggregate base and subgrade. In addition, minimum HMA pavement thicknesses are required to prevent failures of aggregate base and subgrade.

CHAPTER 1 – INTRODUCTION

MINNESOTA ROAD RESEARCH PROJECT

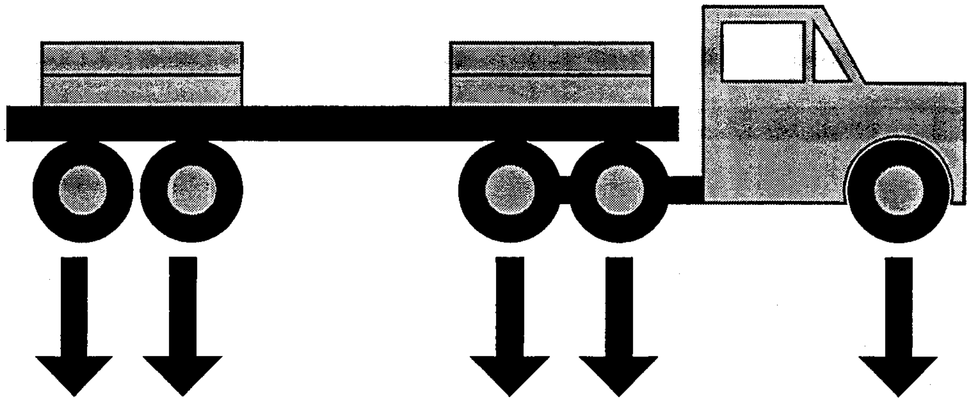
Summary

The Minnesota Department of Transportation (Mn/DOT) constructed the Minnesota Road Research Project (Mn/ROAD) between 1990 and 1994. Mn/ROAD is an extensive pavement research facility consisting of two separate roadway segments containing 48 distinct test cells. Each Mn/ROAD 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. Daily information is gathered via a computerized data collection system that monitors more than 4500 mechanical and environmental sensors. All data presented herein, as well as historical sampling, testing, and construction information, can be found in the Mn/ROAD database and in various publications. Appendix A contains a layout of Mn/ROAD test cells and a brief description of each cell.

Test Roadways

Located 40 miles northwest of Minneapolis/St. Paul, the 3½-mile Mainline Test Roadway (Mainline) is part of westbound Interstate 94. The two-lane facility contains 31 test cells and carries an average of 20,000 vehicles daily. Parallel and adjacent to the Mainline is the Low Volume Roadway (LVR). The LVR is a 2-lane, 2½-mile-closed loop that contains 17 test cells.

Traffic on the LVR is restricted to a Mn/ROAD operated vehicle, which is a typical 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). The axle load for each load configuration is illustrated in Figure 1.1. 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.



80K Configuration (MN "Legal" Load)				
18,400 lb	15,600 lb	16,600 lb	16,900 lb	12,000 lb

102K Configuration				
23,900 lb	21,200 lb	22,200 lb	22,900 lb	12,400 lb

Figure 1.1 - Mn/ROAD Truck Layout

Objective of Forensic Excavation

One of the primary research objectives of Mn/ROAD is to collect data for use in the development of mechanistic-empirical pavement design procedures. The ongoing analysis and evaluation of pavement performance is an important part of this process. On July 1, 1997, the first comprehensive forensic investigation of a paved cell at Mn/ROAD was conducted. A structural failure, as seen in Figure 1.2, occurred at Station 184 + 59 in the 80K lane of Cell 28 on the LVR. Wheelpath cracking, thermal cracking and significant amounts of rutting were present throughout the cell. The localized failure, in addition to the continued deterioration of pavement performance, prompted the investigation.

The purpose of this report is to document the forensic excavation. This report details the trenching process and the data collected during the investigation. This paper also records the observations and conclusions related to the historical performance and subsequent deterioration of Cell 28. The evaluation of this cell is based on data collected before and during the forensic excavation. The history of Cell 28 is summarized in this report, however, detailed information can be found in the Mn/ROAD database and various Mn/ROAD publications.

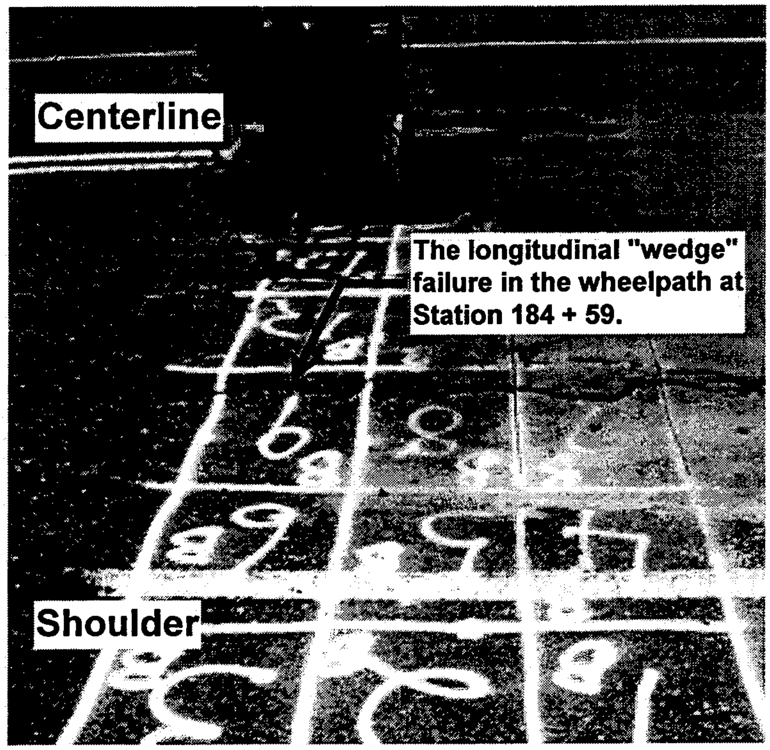


Figure 1.2 - "Structural" Failure

CELL 28 HISTORY

Materials

Cell 28 extends from Station 180 + 75 to Station 186 + 25 on the LVR. The cell, one of eight LVR HMA test sections, was designed to have 3 inches of HMA pavement over 13 inches of Class 5 Special aggregate base (CL 5S). The HMA has a Marshall Hammer design of 50 blows and uses an AC 120/150 penetration grade asphalt binder. Laboratory testing has shown that the 120/150 asphalt binder used at Mn/ROAD has a Performance Grade (PG) of 58-28.

CL 5S is a Mn/DOT designation that describes an aggregate base or surface material containing a minimum of 10 percent crushed particles. The maximum particle size is 25 mm and 3-10% of the material must pass the 75-µm sieve. CL 5S, utilized in many cells at Mn/ROAD, varies from Mn/DOT's Standard Specifications for Construction in that it follows stricter grading criteria.

Traffic Loading

In June of 1994, the Mn/ROAD vehicle began travelling on the LVR. By June 1997, the 80K lane of Cell 28 had received 59,000 Equivalent Single Axle Loads (ESALs). This corresponds to approximately 25,000 passes of the Mn/ROAD truck in the "legal" load configuration seen in Figure 1.1. Appendix B contains a summary of monthly and cumulative load cycles for the LVR up to the time of the excavation. Detailed traffic information can be found in the Mn/ROAD database.

Pavement Condition

Condition surveys have been conducted on all of the cells at Mn/ROAD from the time of initial construction using the Strategic Highway Research Program (SHRP) distress identification manual. The Mn/ROAD database contains additional information pertaining to performance data collected with the Pavetech van and the details of individual condition surveys. The database also contains information about the timing and location of pavement repairs. Information is available in various reports and memorandums that contain visual observations and measurements made by Mn/ROAD research staff. The pavement condition information that describes the most important events relating to the excavation in Cell 28 is summarized below.

After receiving approximately 59,000 ESALs from the Mn/ROAD truck, the 80K lane of Cell 28 was exhibiting significant amounts of rutting. An evaluation of rut data beginning in 1994, reveals that rutting began almost immediately after the cell was opened to traffic. The rutting seen in Figure 1.3 is at Station 183 + 50. Rut measurements taken during the spring of 1997 show that there was substantially more rutting in Cell 28 than in other cell at Mn/ROAD. Cell 28 had 0.2 inches of rutting as early as July of 1994 (almost immediately after being opened to traffic). Rut depths increased gradually then experienced a sharp increase from September of 1995 to June of 1996. Another dramatic increase occurred in the spring of 1997. By mid-July of 1997, ruts in Cell 28 were as deep as 1 inch. Figure 1.4 shows rut measurements taken at Station 183 + 00 and Station 184 + 00 throughout the life of the cell. Additional rut data for Cell 28 can be found in Appendix B.

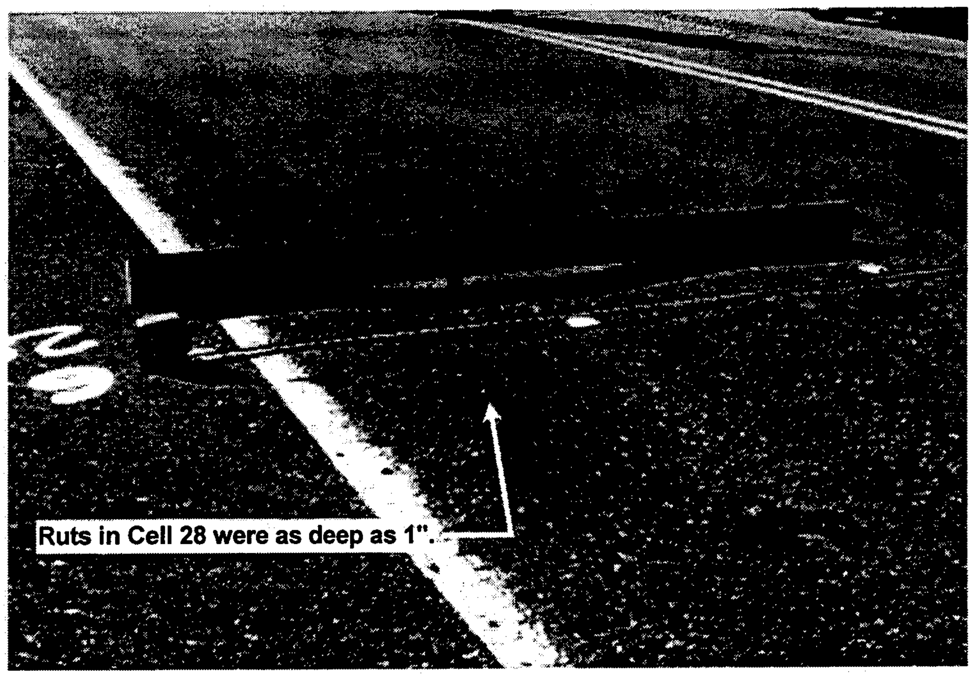


Figure 1.3 - Rutting in Cell 28

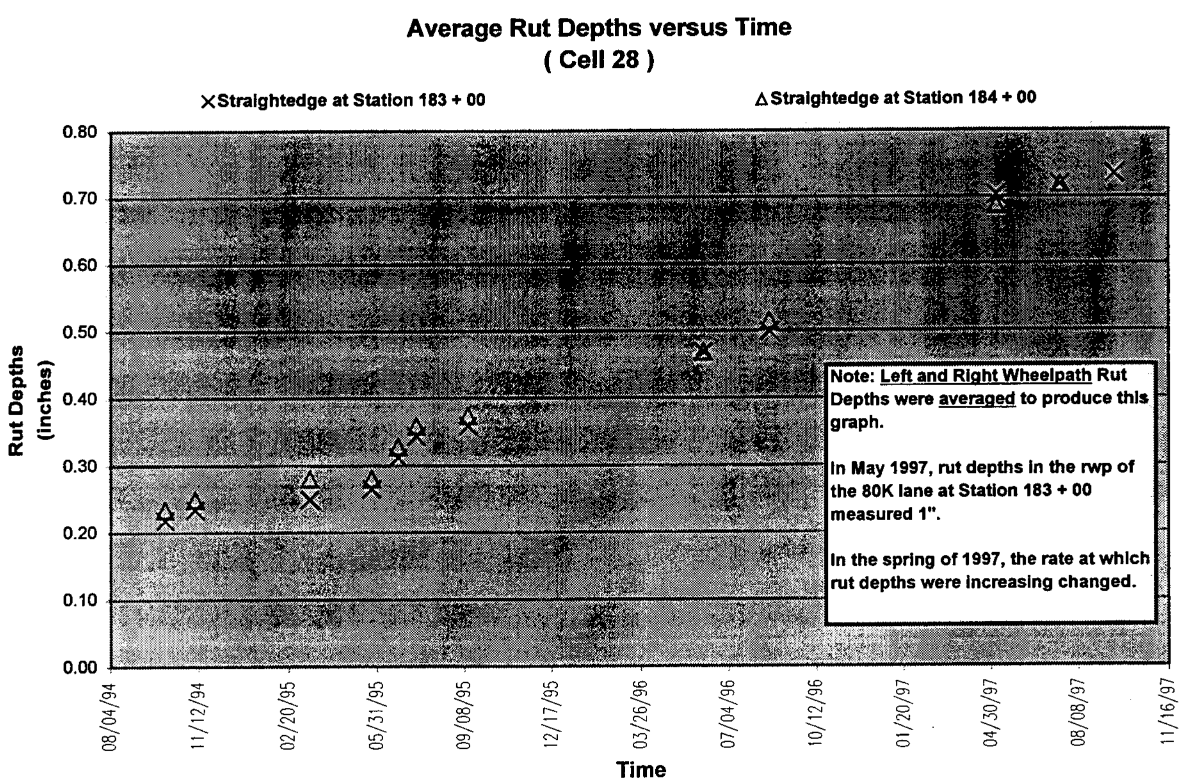


Figure 1.4 - Cell 28 Rate of Rutting

Ground Penetrating Radar (GPR) tests were performed at Mn/ROAD in July of 1994. Due to construction variability, the pavement of Cell 28 ranges in thickness from 2.39 inches to 3.57 inches. Figure 1.5 illustrates the range of pavement thickness in the right wheel path of the 80K lane of Cell 28. The thinnest portion of pavement, from Station 184 + 47 to Station 184 + 67 (2.39 inches to 2.56 inches), corresponds to the area of initial wheel path cracking. The pavement thickness in the remaining portion of the cell was generally greater than 3.0 inches.

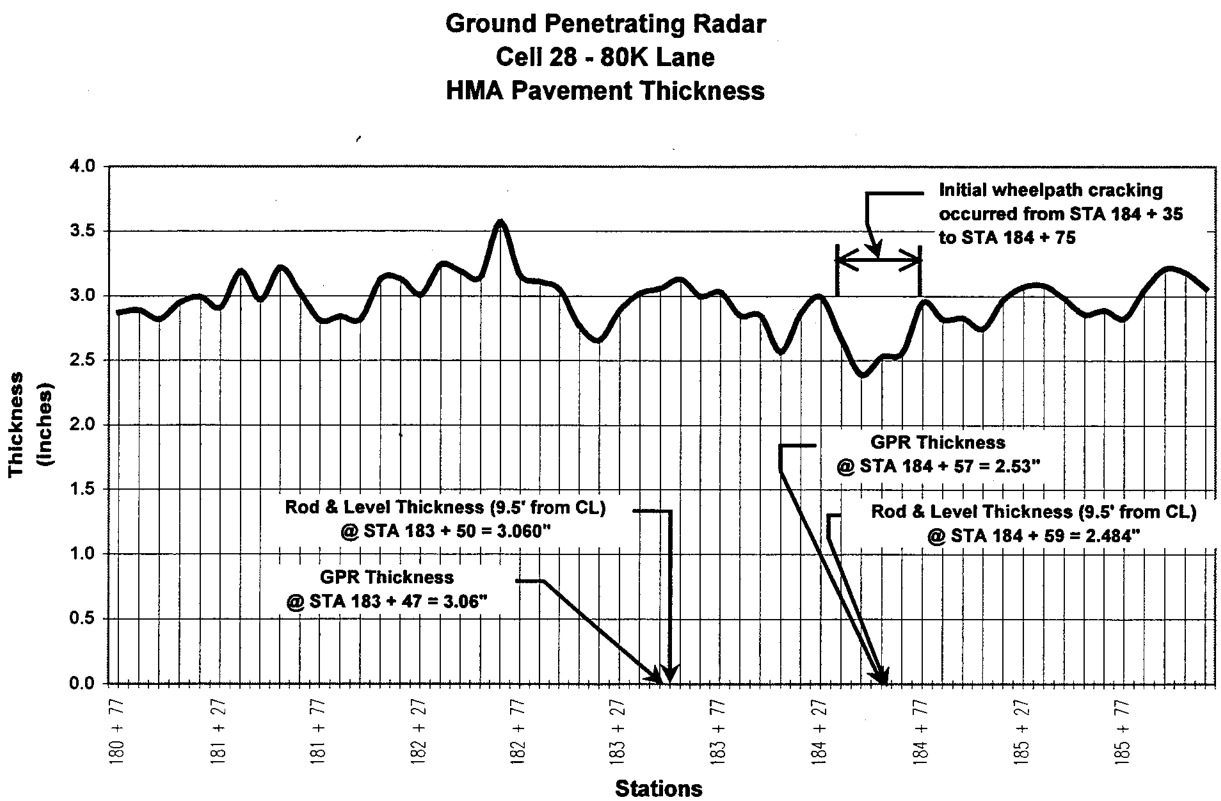


Figure 1.5 - HMA Pavement Thickness

The Forensic Team confirmed GPR data by measuring the HMA course during the forensic investigation. Calculations made using rod and level data established that the pavement at Station 184 + 59 was on average 2.64 inches. This is 0.36 inches less than the initial design thickness of 3 inches. The average pavement thickness at Station 183 + 50 was 3.10 inches. Appendix C contains the rod and level data taken during the forensic excavation and includes the pavement thickness from centerline to shoulder of both trenches and a cross-section of each trench. The measured CL 5S thickness ranged from 10.9 to 12.0 inches at Station 183 + 50, which is less than the initial design thickness of 13 inches. At Station 184 + 59, the CL 5S thickness was 12.0 to 13.8 inches.

From early February to mid-March of 1996, the amount of thermal cracking in Cell 28 increased from 1 to 28 total cracks. In May of 1997, there were 36 thermal cracks in Cell 28 with a total length of 491 feet. Six of these cracks were full-width transverse cracks. All 491 feet of cracking was rated as low severity (mean crack width < 0.25 inches) using the SHRP definition of thermal cracking. The severity and quantity of thermal cracking was comparable to that exhibited by other HMA LVR cells.

In the early spring of 1997, "fatigue" cracking was reported in the right wheel path of the 80K lane of Cell 28. On March 10, cracking was evident in the wheelpath for 40 linear feet from Station 184 + 35 to Station 184 + 75. By April 15, wheelpath cracking was observed along 114 linear feet of roadway from Station 183 + 88 to Station 185 + 02. This was the first report of fatigue cracking at Mn/ROAD. Figure 1.6 indicates the location of this cracking, the thinnest area of pavement, and the location of the forensic trenches.

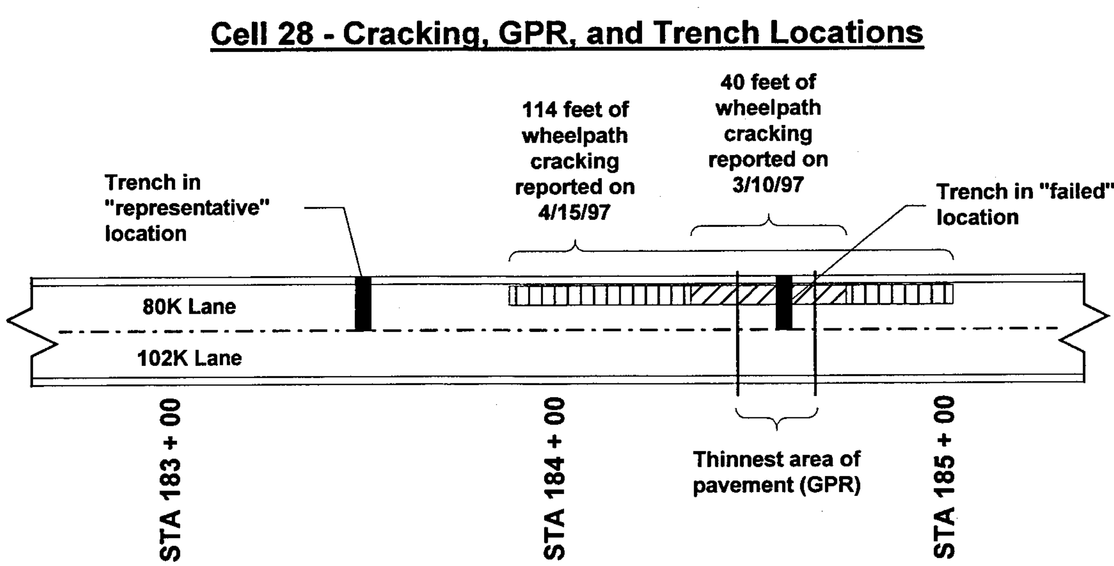


Figure 1.6 – Critical Event Locations in Cell 28

CHAPTER 2 – DATA COLLECTION

PROCEDURE

Forensic Trenches

In early July of 1997, two trenches were excavated in the 80K lane of Cell 28. The first trench was dug at Station 183 + 50, in an area that was representative of the majority of the test cell. The second trench was excavated in the area of concentrated failure, Station 184 + 59. A chalk line and white spray paint were used to identify the two trench locations. The pavement was dry sawn and removed using hand tools; the aggregate base and subgrade were removed with a backhoe. Both trenches were 14 feet by 4 feet. The 14-foot dimension encompassed the twelve-foot lane plus two feet of the shoulder. The 4-foot dimension accommodated the size of the backhoe bucket. The cutting was laid out with a chalkline and white spray paint. Each trench was subdivided and each subdivision numbered as shown in Figure 2.1. Each of the 21 individual rectangular subdivisions was 16 inches by 24 inches.

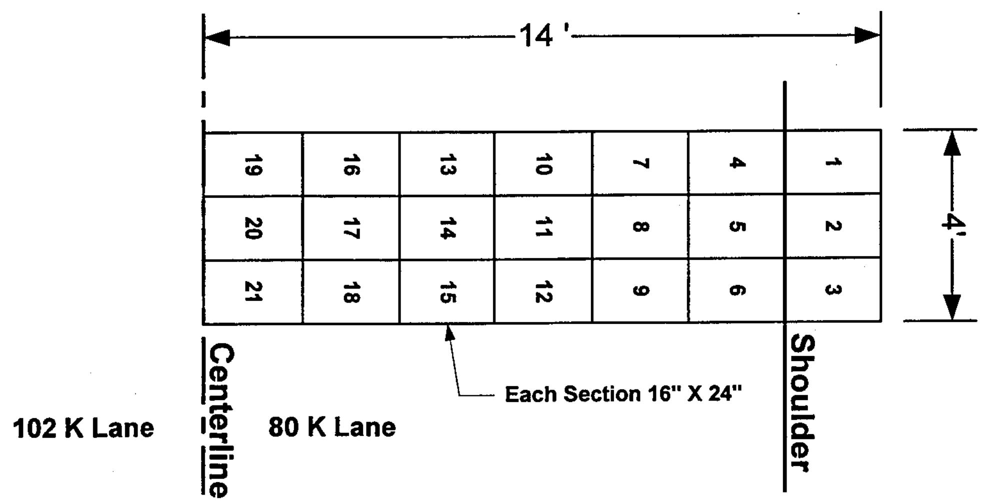


Figure 2.1 - Trench Layout

Excavation

Sawing of the pavement commenced at 9:00 AM on Tuesday July 1, 1997. A diamond circle saw was used to dry saw the pavement from the centerline across the 80K lane and into the shoulder as seen in Figure 2.2. A dry saw was used to prevent the introduction of moisture into the aggregate base that could effect test results. The sawing went quickly, taking approximately 60 minutes per trench to cut the pavement in the layout illustrated in Figure 2.1. After sawing, the Forensic Team removed the HMA pavement using hand tools as seen in Figure 2.3.

Figure 2.2 - Dry Sawing of Pavement

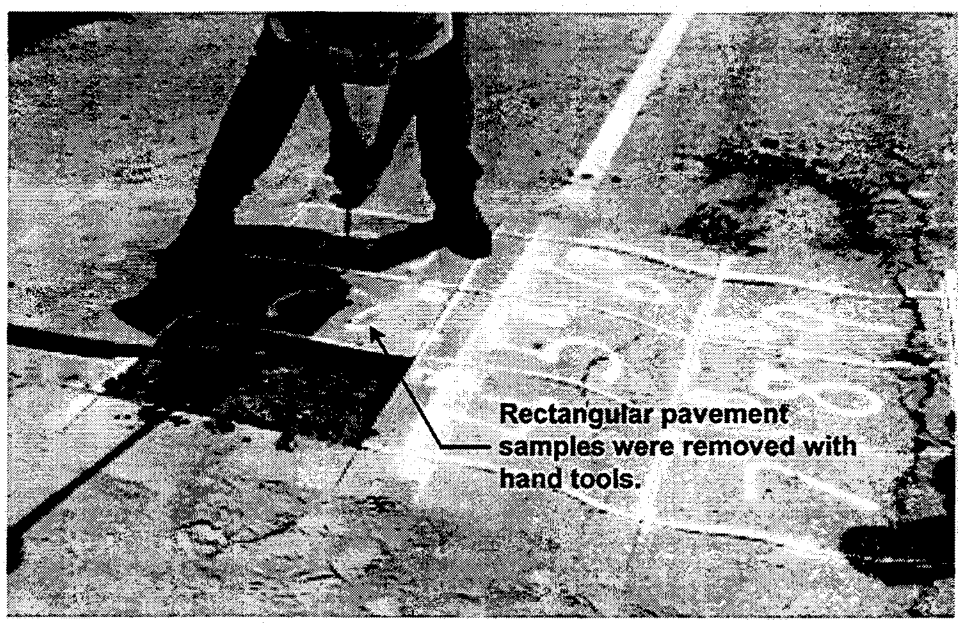


Figure 2.3 - Removal of Rectangular Pavement Sections

After removal of the HMA pavement, the backhoe operator removed the layer of CL 5S and 6 to 12 inches of subgrade in both trenches. A distinct separation between the subgrade and aggregate base layers was observed on the vertical faces of the trenches. Aggregate base was gently removed by hand from a vertical face in each trench to uncover a ledge of subgrade. Figure 2.4 shows the removal of the aggregate base.

Figure 2.4 - Removal of Aggregate Base

Surveyed Cross-Sections

Before excavation of the trenches, elevations of the pavement surface were established with a rod and level. As the trenching progressed, elevations were taken at the top of the aggregate base and at the top of the subgrade. As seen in Figure 2.5, a piece of lath was inserted into the interface between the HMA pavement and the aggregate base in order to determine the thickness of the pavement. The ledge created in the face of the trench was used to take cross-sections of the top of the subgrade. Figure 2.6 illustrates the layer deformation evident in both the HMA pavement and the CL 5S at Station 184 + 59. A surveyed cross-section at Station 183 + 50 can be found in Appendix C.

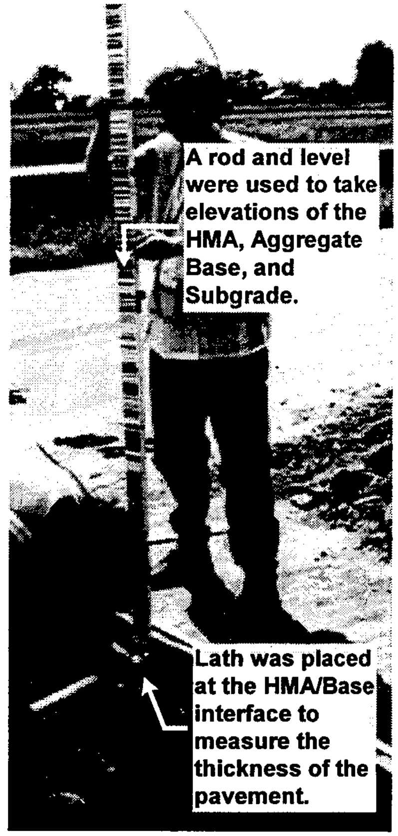


Figure 2.5 - Taking Rod and Level Measurements

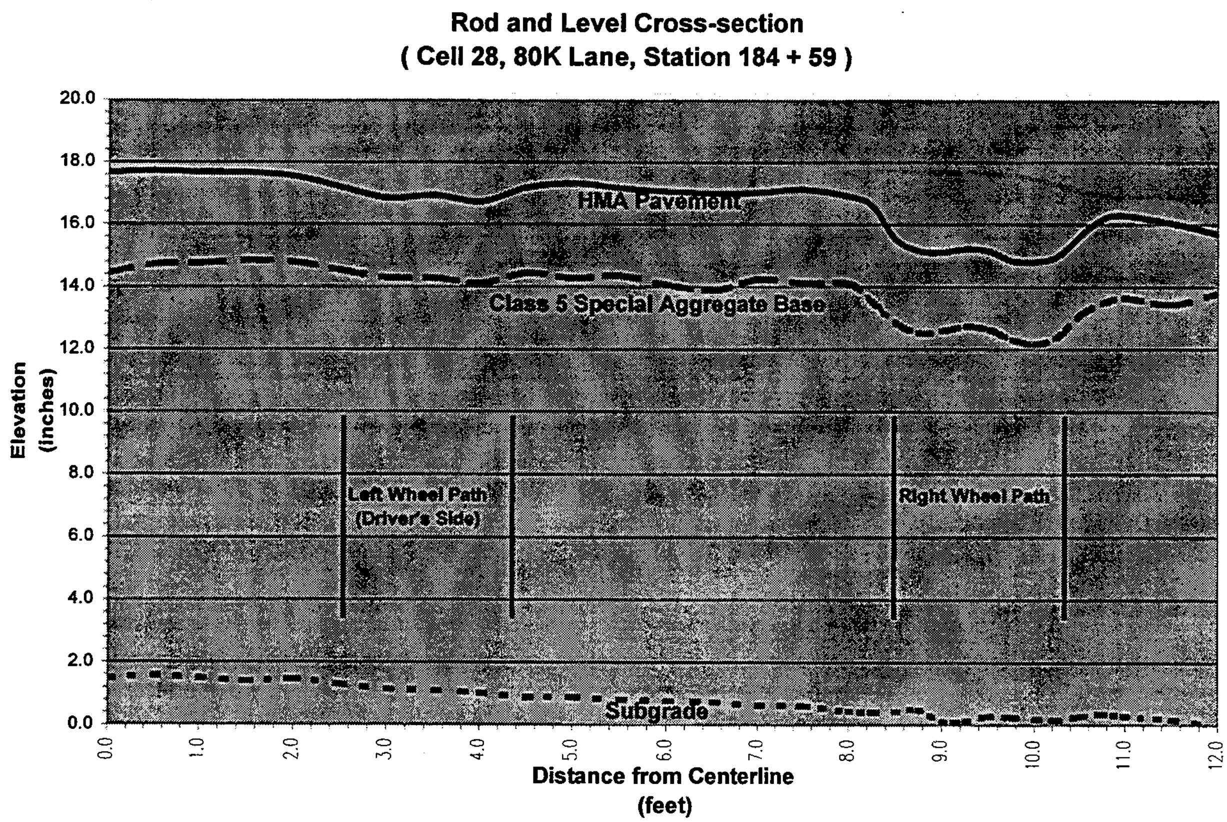


Figure 2.6 - Cross-section at "Failed" Trench Location

SAMPLING AND TESTING

Sampling

On the day of the excavation, air temperatures ranged from 77 °F in the morning to a high of 84 °F. Due to the previous days heating, pavement surface temperatures ranged from 97 °F to 109 °F. Investigators attempted to acquire twenty-one rectangular HMA pavement samples per trench; however, most of the samples sustained damage during removal and pieces that were removed intact quickly fell apart after they were stacked on the hot pavement. Figure 2.7 shows the stacked HMA pavement samples.

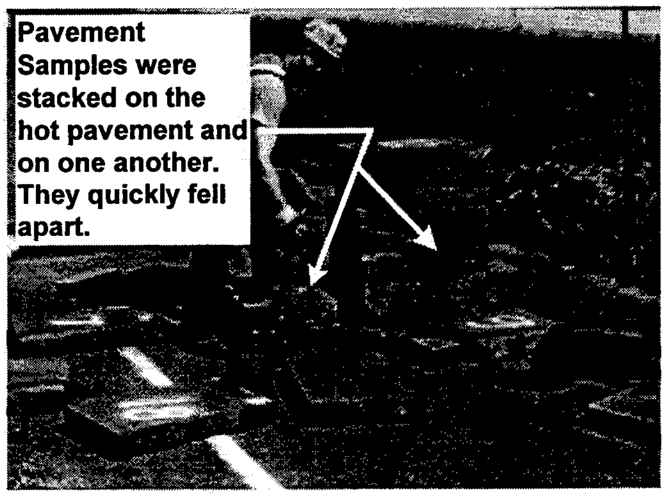


Figure 2.7 - Stacked Pavement Samples

At 16 inches by 24 inches, and roughly 140 lb/ft^3, each 3 inch thick rectangular piece weighed approximately 95 lb. The warm temperatures combined with the weight of the samples contributed to the damage of the individual rectangular HMA pavement samples. Overall, eighteen cores were cut from the rectangular pavement samples for laboratory measurement of inplace voids. Results of tests performed on these cores as well as HMA data collected during construction can be found in Appendix D.

Unbound samples of the CL 5S were taken to determine the in situ moisture content and gradation. During construction, the aggregate base was stockpiled for use in future testing. Six hundred pounds of CL 5S was obtained from stockpiles and used for resilient modulus and triaxial tests. The gradation of the CL 5S removed from the stockpile was determined and compared to the gradation of samples removed from the trenches. The gradations comparable and thus the stockpiled CL 5S was used for triaxial testing. Construction, stockpile, and forensic sample gradations are illustrated in Figure 2.8.

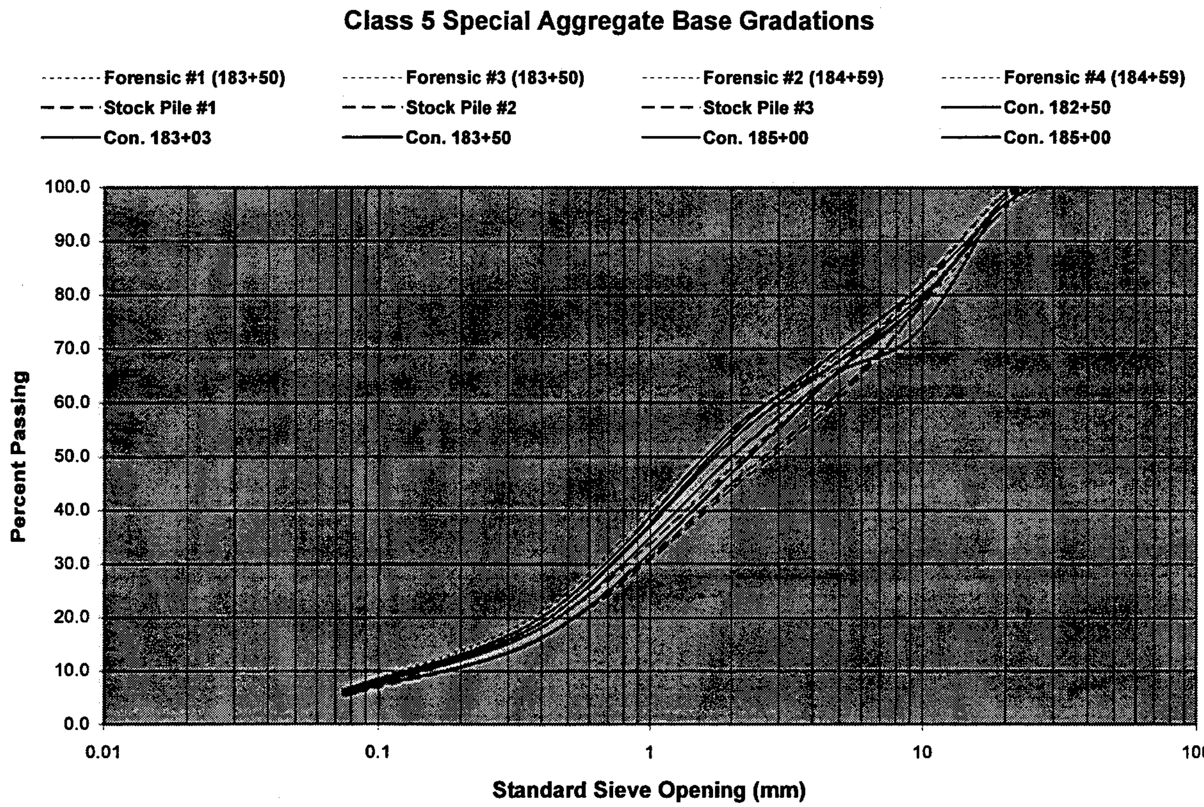


Figure 2.8 - Aggregate Base Gradations

Field Testing

Sand cone density tests were performed in the aggregate base and subgrade in the wheel path and between the wheel paths. The results of these tests can be found in Appendix D. Dynamic Cone Penetrometer (DCP) measurements were taken near the two trench locations in the aggregate base through holes cored in the HMA pavement. DCP Penetration Index (DPI) in the aggregate base was in the 4-6 mm/blow range at the time of the forensic.

Falling weight deflectometer (FWD) tests have been performed on Cell 28 since 1994. Based on this data, pavement layer moduli were back-calculated using the software EVERCALC (Washington DOT). This software utilizes linear elastic theory to determine modulus. The aggregate base modulus was back-calculated for 1994 through 1996. The aggregate base modulus in 1996 was found to be greater than the moduli in 1994 and 1995. The values for the aggregate base modulus were similar in 1994 and 1995. This indicates increased compaction of the aggregate base, which correlates with the increase in rut depth observed in the spring of 1996. The back-calculated subgrade modulus (wheelpath) decreased from 1994 to 1996 indicating that the subgrade soil was weakening. The decrease in subgrade modulus has been attributed to an increase in moisture in the subgrade. The deteriorating pavement surface allowed moisture to infiltrate the aggregate base and subgrade.

Although instrumentation was not located at the trench locations, strain gauges and thermocouples were located in other areas of Cell 28. Therefore, strain data and pavement temperatures have been recorded. Routine tests have been performed with the truck travelling at an average speed of 40 mph. The transverse strain measurements indicate that there was a significant increase in strain when the pavement temperature was greater than 77 °F with values as high as 900 $\mu\epsilon$ (micro-strain).

Laboratory Testing

Cross-sections and thickness measurements taken during the forensic suggest that the majority of the rutting/deformation observed in Cell 28 was from the aggregate base layer with minimal rutting in the subgrade. In order to study the failure using mechanistic principles, a failure criterion for the aggregate base needed to be established. Therefore, a series of triaxial tests were performed on the CL 5S.

During the excavation, moisture content samples were taken at the top of the aggregate base. The moisture content and the dry density for the top of the aggregate base were found to be 5.5% and 137.4 lb/ft^3 respectively. In order to account for the moisture gradient that exists throughout the depth of aggregate base, the instrumentation present at Mn/ROAD was utilized.

Time Domain Reflectometry (TDR) moisture data exists for much of the aggregate base present at Mn/ROAD. However, Cell 28 only has one TDR probe in the CL 5S. Therefore, data collected from Cell 21, which is composed of the same aggregate base and has three TDRs, was used to estimate the moisture content throughout the depth of Cell 28. A ratio of the moisture content at the top of the aggregate base to that near the bottom was established. Applying this ratio to the measured moisture content at the top of the aggregate base of Cell 28, 5.5%, the moisture content at the bottom of the aggregate base was determined to be about 8%.

Samples of the CL 5S were prepared at the target moisture contents, 5.5% and 8%, and the target density, 137.4 lb/ft^3. For each moisture condition, Mn/DOT laboratory personnel performed at least two tests using confining pressures of 4 lb/in^2 and 8 lb/in^2 respectively. Each specimen was compacted into a split mold in six lifts using a vibratory compactor. Moisture content samples were taken during the compaction of each lift to ensure that the target moisture contents were achieved. Triaxial tests were then performed on each specimen. Additional samples were prepared to determine the resilient modulus of the CL 5S and subgrade for use in numerical analysis.

CHAPTER 3 – DATA ANALYSIS

LABORATORY TEST RESULTS

Factors Influencing Strength

The laboratory tests performed illustrated that the moisture content of the aggregate base is an important factor in controlling strength. The shear strength decreased as the moisture content increased. In Cell 28, moisture content increased with depth. Another factor influencing strength is confining pressure. As the confining pressure increased, the strength of the material increased. The stress-strain curves are shown in Figures 3.1 and 3.2. After obtaining the stress-strain curves the Mohr's circles were constructed and can be found in Appendix D. The Mohr-coulomb failure envelopes (assuming a linear failure criteria), 5.3% and 8.2%, are shown in Figure 3.3.

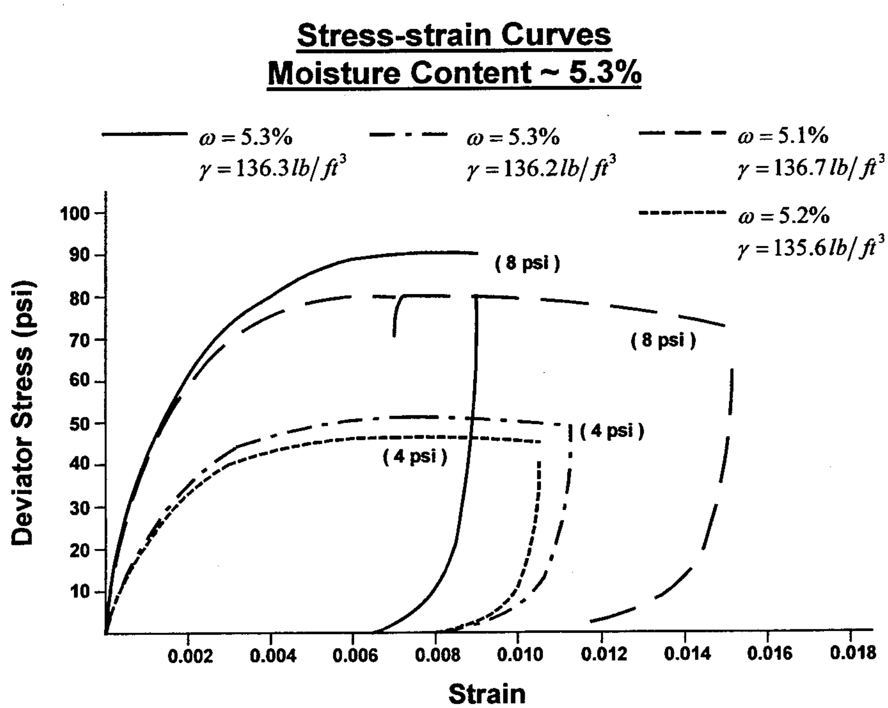


Figure 3.1 - Stress-Strain Curves

Elastic Rebound

As seen in Figures 3.1 and 3.2, a small amount of elastic rebound was apparent after unloading. This suggests that a threshold for stress exists in the aggregate base. If the aggregate base is loaded up to this threshold, and then unloading occurs, the aggregate base can fully rebound without permanent plastic deformation. Loading that occurs beyond this threshold results in permanent plastic deformation such as that exhibited in Cell 28.

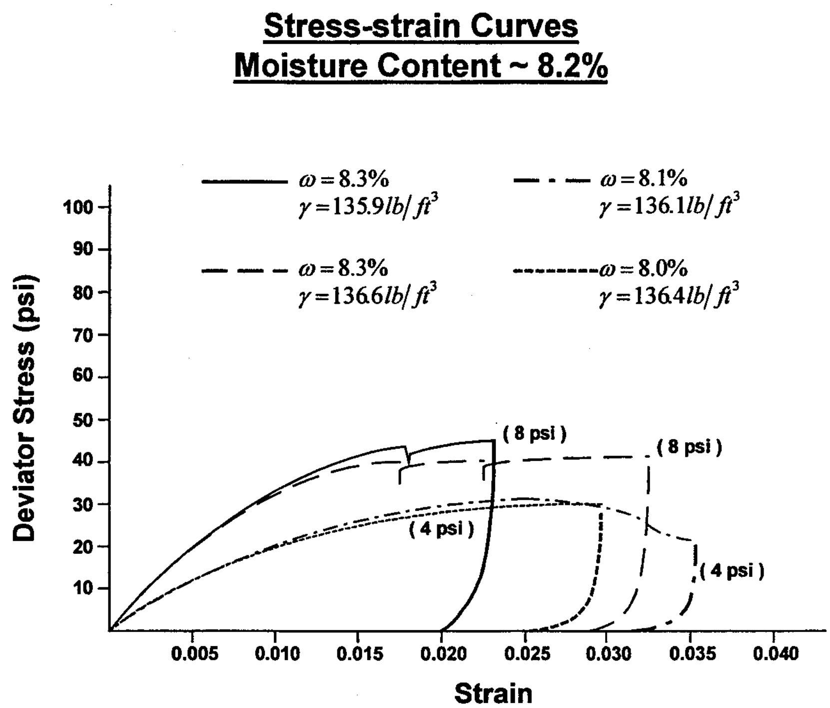


Figure 3.2 - Stress-Strain Curves

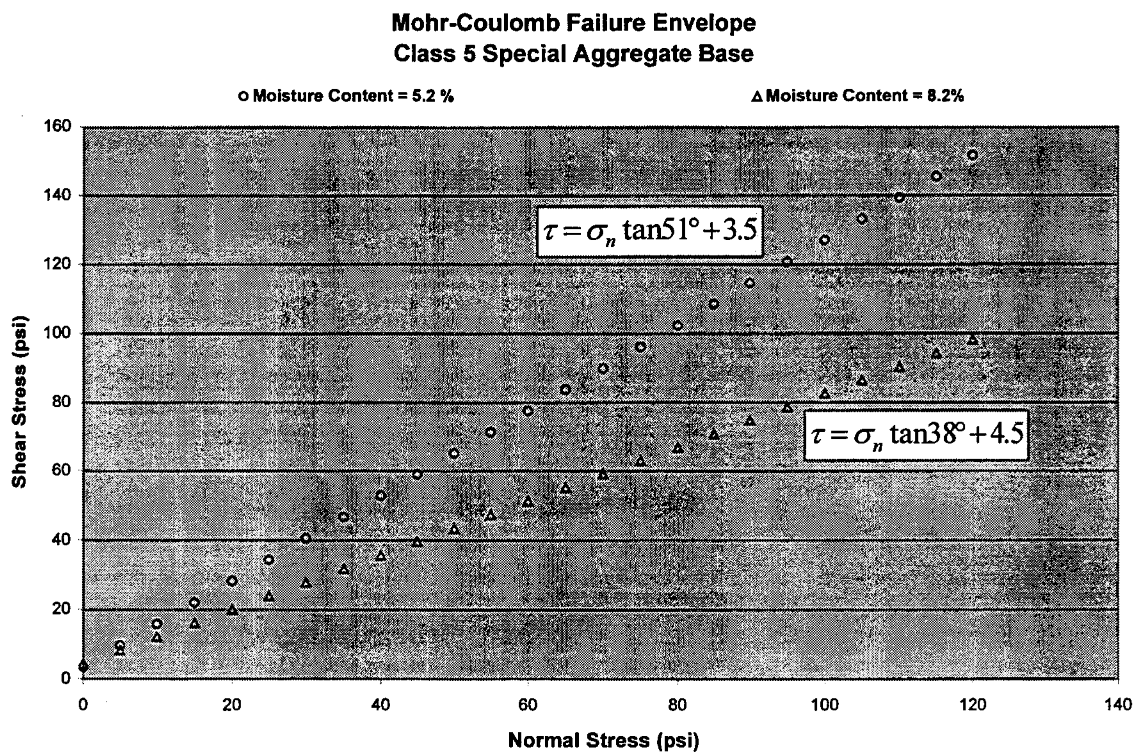


Figure 3.3 - Mohr-Coulomb Failure Envelope

Plastic Deformation

From the laboratory established stress-strain curves, plastic flow was evident once a peak stress was reached. This would indicate that once stress exceeds the strength of the material increased loading is not required for additional deformation. If the stress in the aggregate base is greater than its strength, plastic deformation occurs which, in the case of Cell 28, contributed to rutting.

ANALYTICAL AND NUMERICAL ANALYSIS

WESLEA Analysis

Analytical and numerical analyses were performed in order to examine the stress state and failure criterion. Figures 3.4 and 3.5 show comparisons between the laboratory developed failure envelopes and the calculated stresses in the aggregate base. The software WESLEA (Corp of Engineers) was utilized for the analytical calculations. Two different methods for pavement layer moduli determination were used.

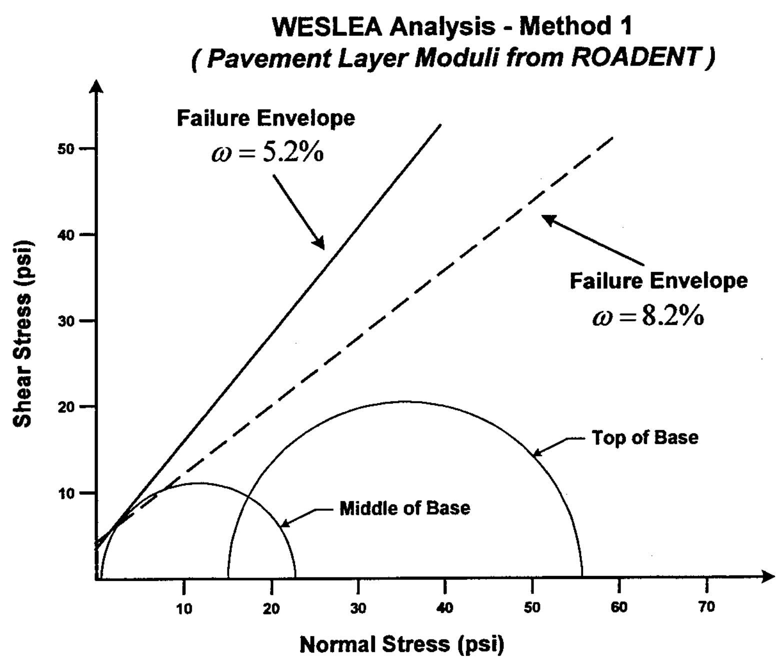


Figure 3.4 – Method 1

In the first method, the pavement layer moduli used in the WESLEA analysis were obtained from Mn/PAVE (University of Minnesota). The analysis revealed that the highest stresses in the aggregate base were generated by the steering axle not the tandem axles. Therefore, the steering axle load was used in the analysis. The portion of the Mohr's circle representing the stress in the middle of the aggregate base layer was above the failure envelope, indicating that failure likely occurred in the middle of the aggregate base layer.

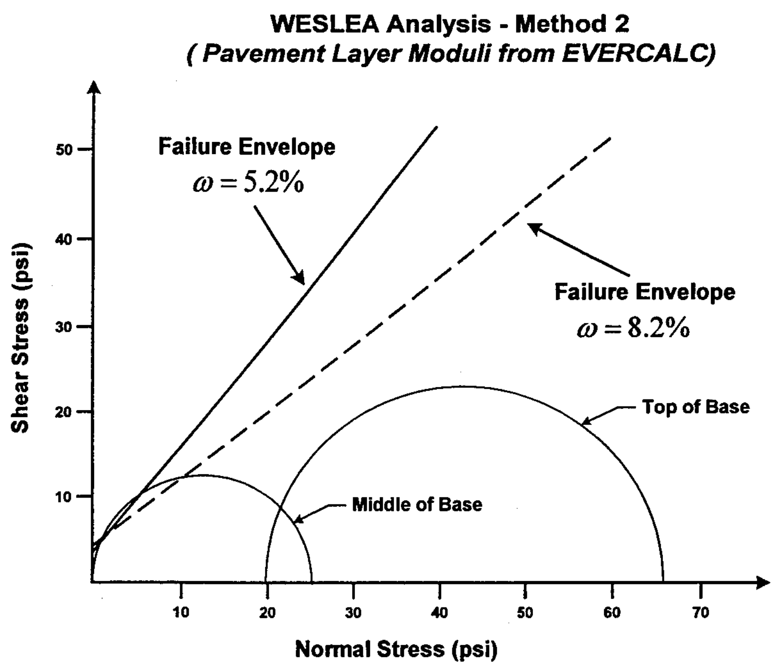


Figure 3.5 – Method 2

The second method used the pavement layer moduli calculated using EVERCALC (Washington DOT). The stress in the middle of the aggregate base layer was again above the failure envelope suggesting failure in the middle of the aggregate base layer.

Finite Element Analysis

Laboratory experiments have shown that the resilient modulus of aggregate base and subgrade soils is stress dependent. Normally, the resilient modulus of granular material increases with bulk stress, while the resilient modulus of fine-grained soils decrease as deviator stress increases. In order to assess the effect of stress dependency on pavement response, the software ILLIPAVE (University of Illinois), based on finite element methodology, was used to simulate pavement response. Four cases were considered in this analysis.

In Case 1, the laboratory determined aggregate base modulus at a low moisture content, 5%, was used. Mn/ROAD was initially opened to traffic in the summer. During the summer months, the

HMA modulus is low resulting in the highest aggregate base stress. Therefore, the Mn/PAVE (University of Minnesota) default pavement modulus for summer was used. It was found that the ILLIPAVE calculated modulus was similar to the laboratory determined aggregate base modulus. It was also found that the stress at the top of the aggregate base was quite high and, when compared to the failure criterion, indicates that failure occurred at the top of the aggregate base.

Case 2 utilized the aggregate base modulus at a high moisture content, 7%. The pavement and subgrade moduli were the same as those used in Case 1. Based on comparisons between the failure criterion and the calculated stresses, it was found that failure occurred in the aggregate base.

To further consider the effects of stress-dependency of subgrade soil resilient modulus on pavement response, a resilient modulus model as a function of deviator stress was used in Case 3. The resilient moduli for several deviator stress states was obtained from laboratory tests on a thin-walled tube subgrade sample. The moisture content of the subgrade specimen was 16.7%, which was close to the 17.5% measured during excavation. A comparison of the failure criterion and the calculated stresses again point toward failure in the top of the aggregate base, when this stress-dependent subgrade model was included in the analysis.

Case 4 utilized the pavement layer moduli back-calculated from FWD data. Comparisons of the stresses in the aggregate base to the failure criteria indicate, once again, that the aggregate base failed. Table 3.1 summarizes the ILLIPAVE analyses.

Table 3 .1 - Summary of ILLIPAVE Analyses

Material Properties	***Case 1***	***Case 2***	***Case 3***	***Case 4***
M_r HMA Pavement	290,471 psi	290,471 psi	290,471 psi	145,000 psi
M_r Aggregate Base	$4{,}554\Theta^{0.691}$	$1{,}581\Theta^{0.7592}$	$4{,}554\Theta^{0.691}$	$1{,}581\Theta^{0.7592}$
M_r Subgrade	11,600 psi	11,600 psi	$f(\sigma_d)$	11,600 psi
Aggregate Base MC	5 %	7 %	-	-
Subgrade MC	-	-	16.7 %	-
Location of Failure	Top of Agg. Base	Aggregate Base	Top of Agg. Base	Aggregate Base

Required Minimum Pavement Thickness

To prevent failures in the aggregate base, minimum HMA pavement thicknesses are required. Theoretically, these thicknesses are needed so that the stress at any depth in the aggregate base is below its shear strength. The pavement design of Cell 28 was evaluated based on data collected on the aggregate base and HMA pavement. This data was used to establish a minimum required pavement thickness using two different methods. WESLEA and ILLIPAVE were used to estimate four different minimum pavement thicknesses.

Two cases were considered for WESLEA. In Case A, the material properties were taken from Mn/PAVE. Case B utilized the in-situ aggregate base properties from back-calculated FWD data (EVERCALC). The minimum required HMA pavement thicknesses were found to be 3.5 inches for Case A and 4 inches for Case B. In both cases, the steering axle load of 6000 lbs was used as the applied load.

Case 1 and Case 3 of the ILLIPAVE analyses (Table 3.1) were used to calculate the minimum pavement thicknesses for Case C and Case D. The results of both cases indicated that approximately 6 inches of HMA pavement was required to protect the aggregate base from failure. Table 3.2 summarizes the input and results of the analyses. The HMA pavement in Cell 28 was designed to be 3 inches thick, which is less than the recommend thickness in all four cases.

Table 3 .2 - Summary of Minimum Thicknesses

Material Properties	***WESLEA***		***ILLIPAVE***	
	Case A	***Case B***	***Case C***	***Case D***
Taken From:	ROADENT	EVERCALC	ROADENT	Lab Tests
M_r HMA Pavement	209,471 psi	145,000 psi	290,471 psi	290,471 psi
M_r Aggregate Base	20,000 psi	18,850 psi	$4{,}554\Theta^{0.691}$	$4{,}554\Theta^{0.691}$
M_r Subgrade	12,000 psi	11,600 psi	11,600 psi	$f(\sigma_d)$
Calculated Minimum Thickness	3.5"	4"	6"	6"

CHAPTER 4 – CONCLUSIONS

FORENSIC PROCESS

Sawing and Trench Excavation

After the dry sawing was complete, the numbers painted on the pavement surface were difficult to read. In future forensic investigations, it is recommended that the pavement is swept and the numbers applied after completion of sawing. In addition, the backhoe should be equipped with rubber-footed outriggers, and a bucket without teeth. A smooth bucket will give a more even cut in the subgrade. For future forensic studies, a nuclear-density testing device should be used to test the density and moisture of the aggregate base and subgrade.

If sampling and testing of aggregate base materials is part of a forensic excavation, care must be taken to preserve the in situ moisture conditions of the aggregate base. The use of a dry pavement saw instead of a wet saw is recommended. The sawing will have to progress a little more slowly to prevent the saw blade from overheating. However, samples that are more representative of field conditions can then be taken. To reduce evaporation, tarps can be placed over the open trench when tests are not being performed.

Handling the Samples

The rectangular HMA pavement samples were too large to be easily handled without breaking. If it is desired to obtain pavement samples that remain intact, the forensic should be performed when the air temperature is no greater than 80 °F. Samples taken during the investigation should be stored in a cool flat area. The size of the pavement samples should be limited such that the sample weight does not exceed 70 lb. Thicker pavement sections may require heavier specimens. Regardless of size, HMA pavement samples should not be stacked upon one another, unless they are fully supported.

Repair of Trenches

At the conclusion of the sampling, testing, and measuring, the subgrade and aggregate base were replaced at Station 183 + 50 on the day of the excavation. Compaction was performed with the backhoe bucket; consequently, compaction in this trench was inadequate. The surface was not patched until two days later. Due to time constraints, the second trench was left open for two days, i.e. no materials were returned to the trench. There was a heavy thunderstorm and about 5 inches of rain fell the night following the forensic dig. The trench was covered with a tarp, but the tarp was ineffective at keeping out rainwater. The storm left about a foot of water in the bottom of this trench. The water was pumped out the following morning and the trench was left open to dry. The subgrade and aggregate base was then returned to the trench.

After both trenches were patched, loading from the Mn/ROAD truck caused failures almost immediately. The poor performance of the repair was attributed to insufficient compaction of the aggregate base and moisture infiltration into the aggregate base and subgrade. After two weeks, it was apparent that the repaired sections would no longer support traffic. The wet aggregate base and subgrade was excavated and the trenches were back-filled with Class 6 Special crushed granite aggregate base. The surface was then patched with hot-mix asphalt. This repair continues to perform satisfactorily. Finally, trenches should be reconstructed per the original design to avoid creating a "bath tub" in the granular material placed in the subgrade.

CELL PERFORMANCE

Conclusions

Using samples collected during the forensic process, laboratory failure envelopes of the CL 5S were developed. Analytical and numerical analyses were performed to determine the stresses induced in the aggregate base due to traffic loading and these were compared to the strength criterion. In addition, the back-calculated pavement moduli determined from FWD testing, along with historical cell data, were used to draw the following conclusions.

From the analyses, it was determined that the CL 5S in Cell 28 failed under traffic loading. The stress induced in the aggregate base was greater than its shear strength, which resulted in shear failure. The aggregate base experienced unrecoverable deformation early in the traffic loading cycle. Failure began in the summer of 1994 shortly after the roadway was opened to traffic. Rut depths increased during the spring of 1996 and 1997. The aggregate base modulus was greater in

1996 than in 1994 and 1995. This indicates an increase in compaction of the aggregate base, which correlates with the observed increase in rut depth.

The deformation of the aggregate base stabilized and then, due to surface-initiated cracking in the thinnest area of pavement, moisture began flowing into the aggregate base and subgrade. The additional moisture in the underlying strata weakened the already deformed aggregate base resulting in the structural failure that prompted the investigation. Laboratory testing, engineering analysis, and field observations support this assessment.

In order to prevent aggregate base failures, minimum HMA pavement thicknesses are required. The pavement design of Cell 28 was evaluated, based on data collected on the aggregate base and HMA pavement, to establish a minimum required thickness for the pavement using two different methods and four individual case studies. The recommended HMA pavement thicknesses ranged from 3.5 to 6 inches. The pavement in Cell 28 was designed to be 3 inches thick, which is less than the recommend thickness in all analysis methods. The construction variability that resulted in areas of HMA pavement that were actually thinner than the design thickness also contributed to failure.

In summary, data collected during this forensic excavation along with laboratory tests and engineering analysis suggest that:

1) Although there was some rutting present in the HMA pavement, the majority of rutting was in the CL 5S, with little or no rutting present in the subgrade. This indicates aggregate base failure, which was supported by the numerical analysis.

2) Observations made during the excavation indicate that the reported "fatigue" cracking in the wheelpath began on the pavement surface. This cracking occurred in the thinnest area of Cell 28.

3) Data collected during this forensic excavation has contributed to the conclusion that mechanistic-empirical pavement design methods should include a maximum allowable stress criterion for aggregate base and subgrade.

4) A minimum HMA pavement thickness is needed to ensure that the stress level in the aggregate base is below the its allowable stress to minimize deformation.

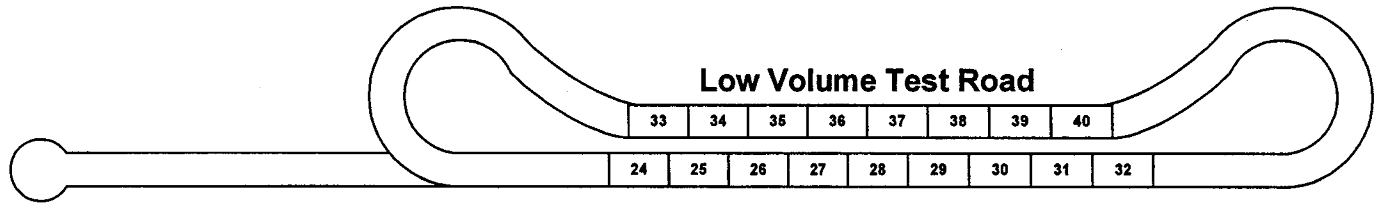
Further Research

This investigation confirms that stresses in the aggregate base must be below the threshold at which plastic deformation occurs. Further study is required to determine an allowable stress value for each material based on a percentage of the materials peak strength.

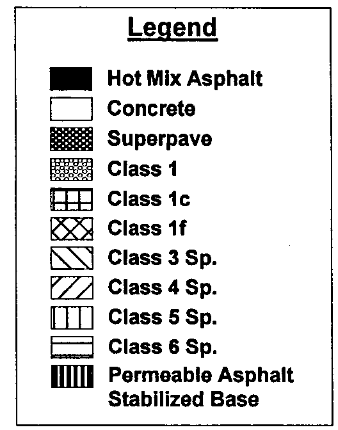
It should be noted that the area of greatest distress in Cell 28 (wheelpath cracking and structural failure) occurred in the thinnest area of HMA pavement. This area was approximately ½ inch thinner than the design thickness of 3 inches. Thus, construction variability has a significant impact on pavement performance. The effects of construction variability on pavement performance needs further study.

APPENDIX A

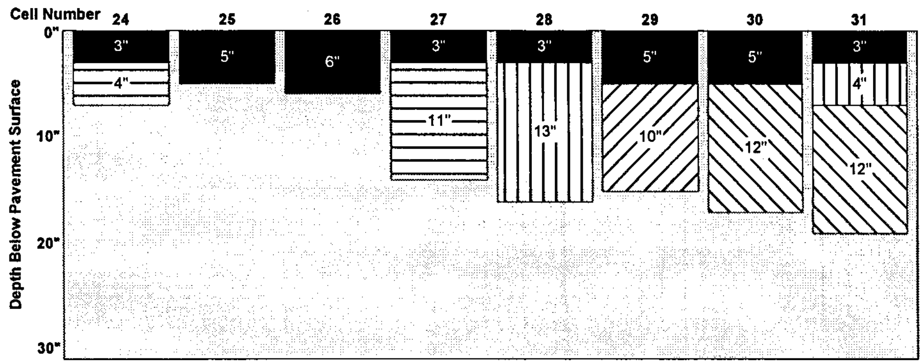
MN/ROAD LAYOUT



MnROAD
Office of Materials and Road Research

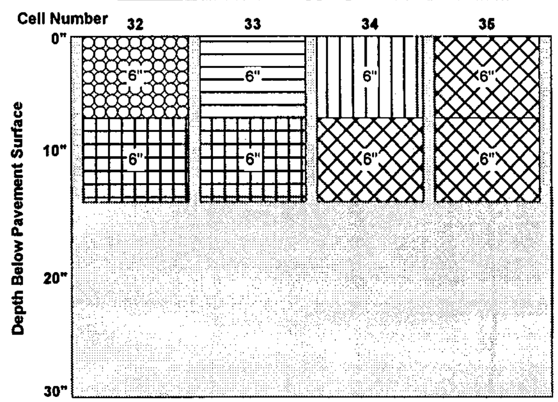


Low Volume Road Hot-Mix Asphalt Test Sections



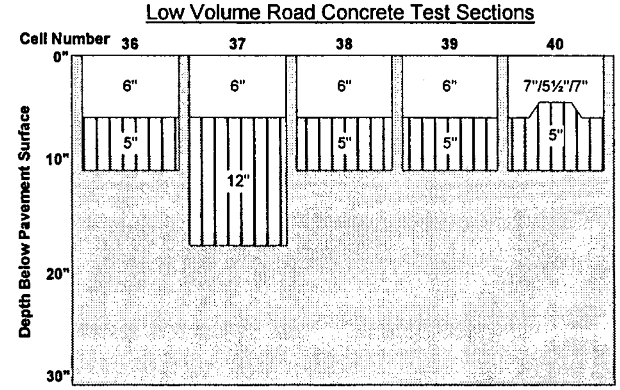
Cell Number	24	25	26	27	28	29	30	31
Asphalt Binder	AC 120/150	AC 120/150	AC 120/150	AC 120/150	AC 120/150	AC 120/150	AC 120/150	AC 120/150
Marshall Design	35	50	50	35	50	50	75	75
Soil "R" Value	70	70	12	12	12	12	12	12

Low Volume Road Aggregate Test Sections



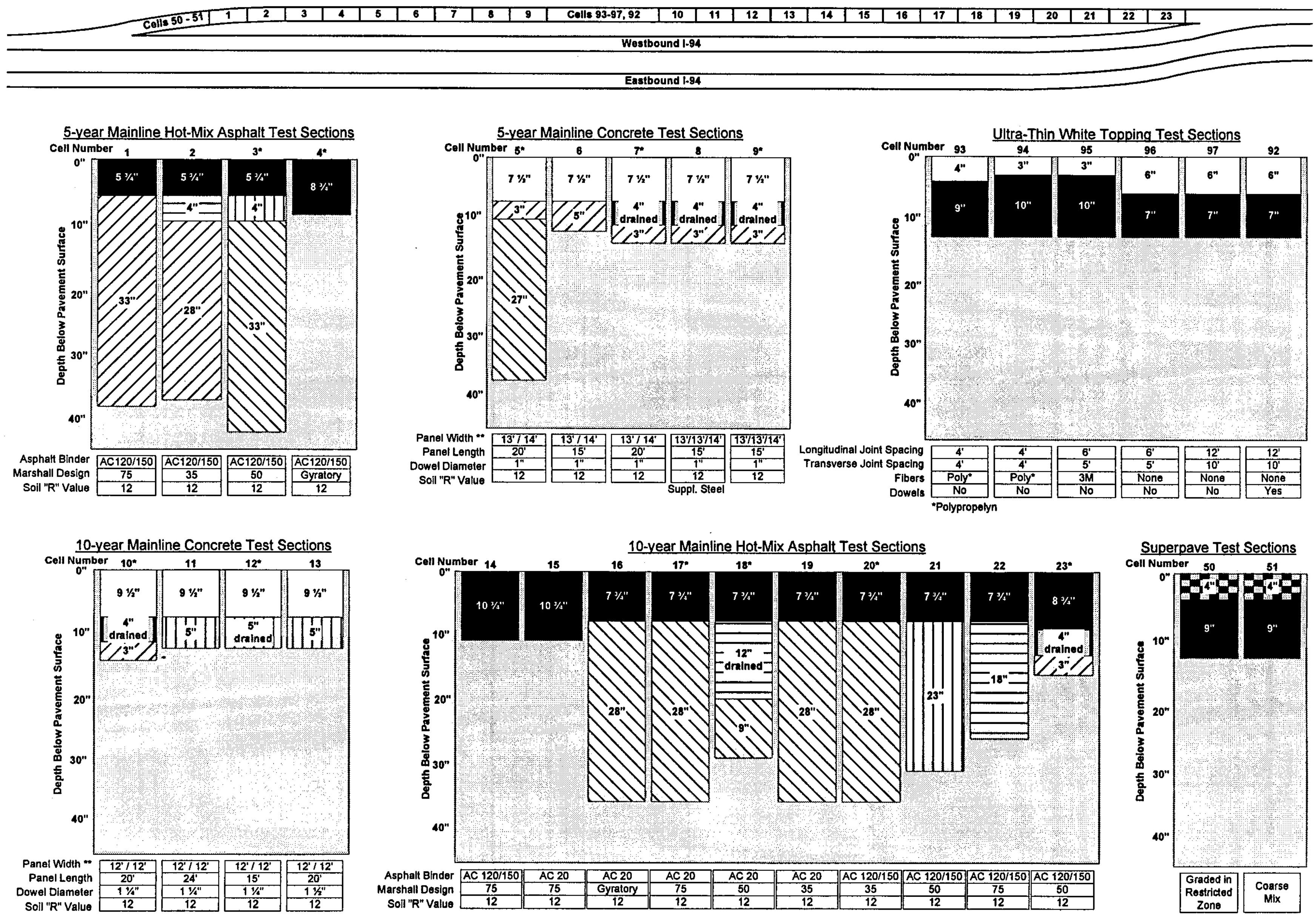
Cell Number	32	33	34	35
Soil "R" Value	12	12	12	12

Low Volume Road Concrete Test Sections



Cell Number	36	37	38	39	40
Panel Width **	12' / 12'	12' / 12'	12' / 12'	12' / 12'	12' / 12'
Panel Length	15'	12'	15'	20'	15'
Dowel Diameter	1"	None	1"	1"	None
Soil "R" Value	70	70	12	12	12

Mainline Test Road



5-year Mainline Hot-Mix Asphalt Test Sections

Cell Number	1	2	3*	4*
Asphalt Binder	AC120/150	AC120/150	AC120/150	AC120/150
Marshall Design	75	35	50	Gyratory
Soil "R" Value	12	12	12	12

5-year Mainline Concrete Test Sections

Cell Number	5*	6	7*	8	9*
Panel Width **	13' / 14'	13' / 14'	13' / 14'	13'/13'/14'	13'/13'/14'
Panel Length	20'	15'	20'	15'	15'
Dowel Diameter	1"	1"	1"	1"	1"
Soil "R" Value	12	12	12	12	12
				Suppl. Steel	

Ultra-Thin White Topping Test Sections

Cell Number	93	94	95	96	97	92
Longitudinal Joint Spacing	4'	4'	6'	6'	12'	12'
Transverse Joint Spacing	4'	4'	5'	5'	10'	10'
Fibers	Poly*	Poly*	3M	None	None	None
Dowels	No	No	No	No	No	Yes

*Polypropelyn

10-year Mainline Concrete Test Sections

Cell Number	10*	11	12*	13
Panel Width **	12' / 12'	12' / 12'	12' / 12'	12' / 12'
Panel Length	20'	24'	15'	20'
Dowel Diameter	1 ¼"	1 ¼"	1 ¼"	1 ½"
Soil "R" Value	12	12	12	12

10-year Mainline Hot-Mix Asphalt Test Sections

Cell Number	14	15	16	17*	18*	19	20*	21	22	23*
Asphalt Binder	AC 120/150	AC 20	AC 20	AC 20	AC 20	AC 20	AC 120/150	AC 120/150	AC 120/150	AC 120/150
Marshall Design	75	75	Gyratory	75	50	35	35	50	75	50
Soil "R" Value	12	12	12	12	12	12	12	12	12	12

Superpave Test Sections

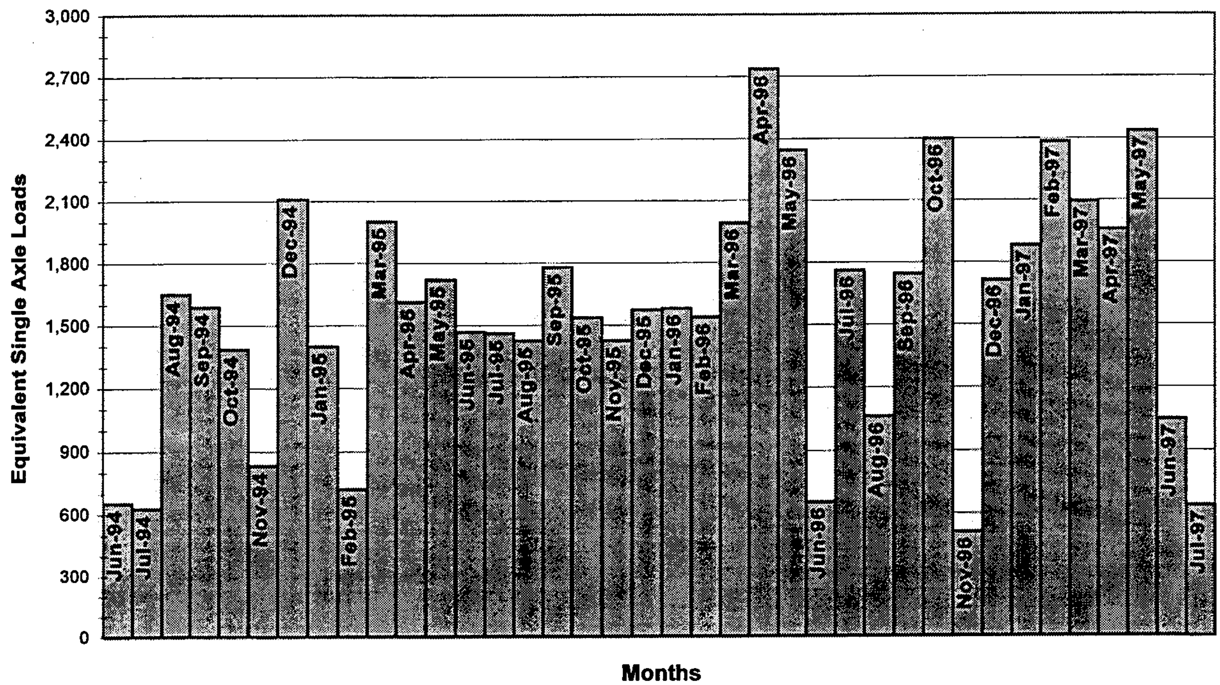
Cell Number	50	51
	Graded in Restricted Zone	Coarse Mix

*SHRP Sections - GPS Database
**Passing/Driving or Shoulder/Passing/Driving

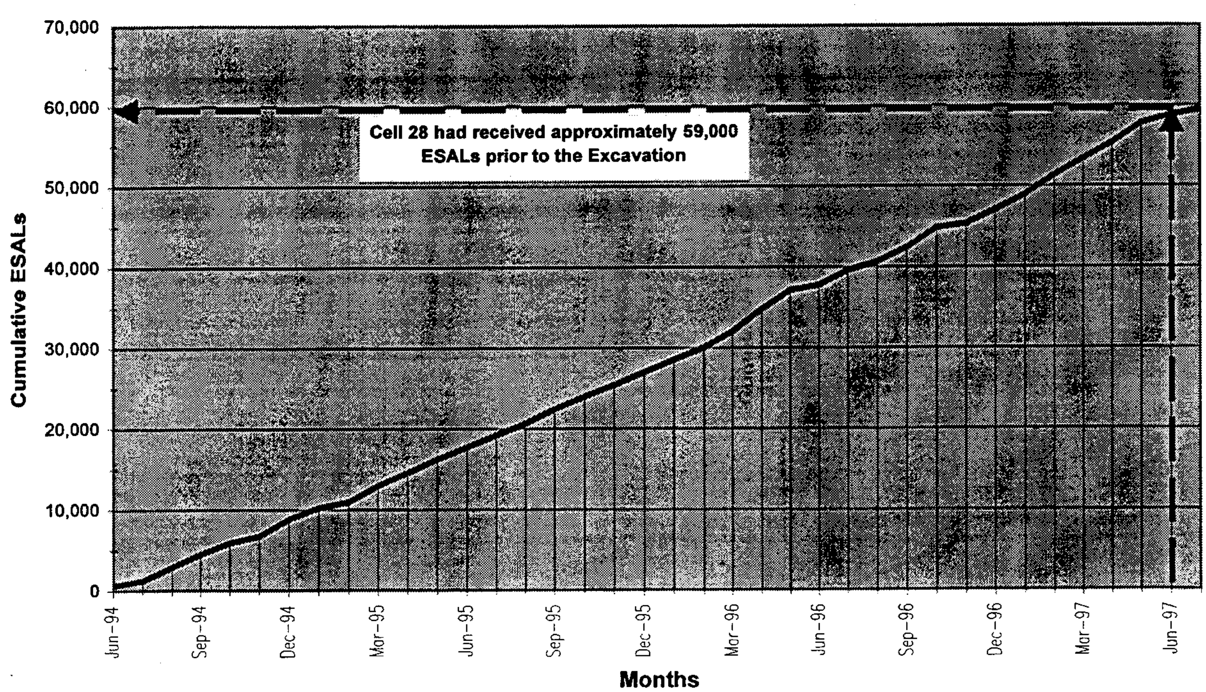
APPENDIX B

LVR TRAFFIC

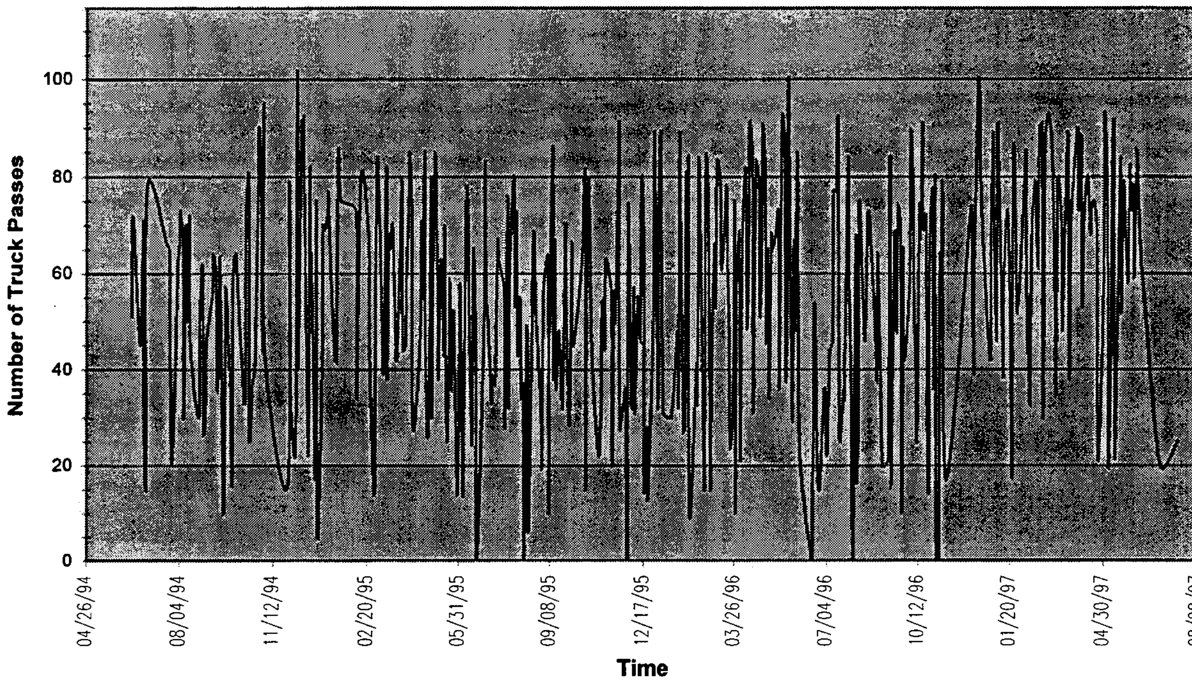
Low Volume Roadway - 80K Lane
Monthly ESALs



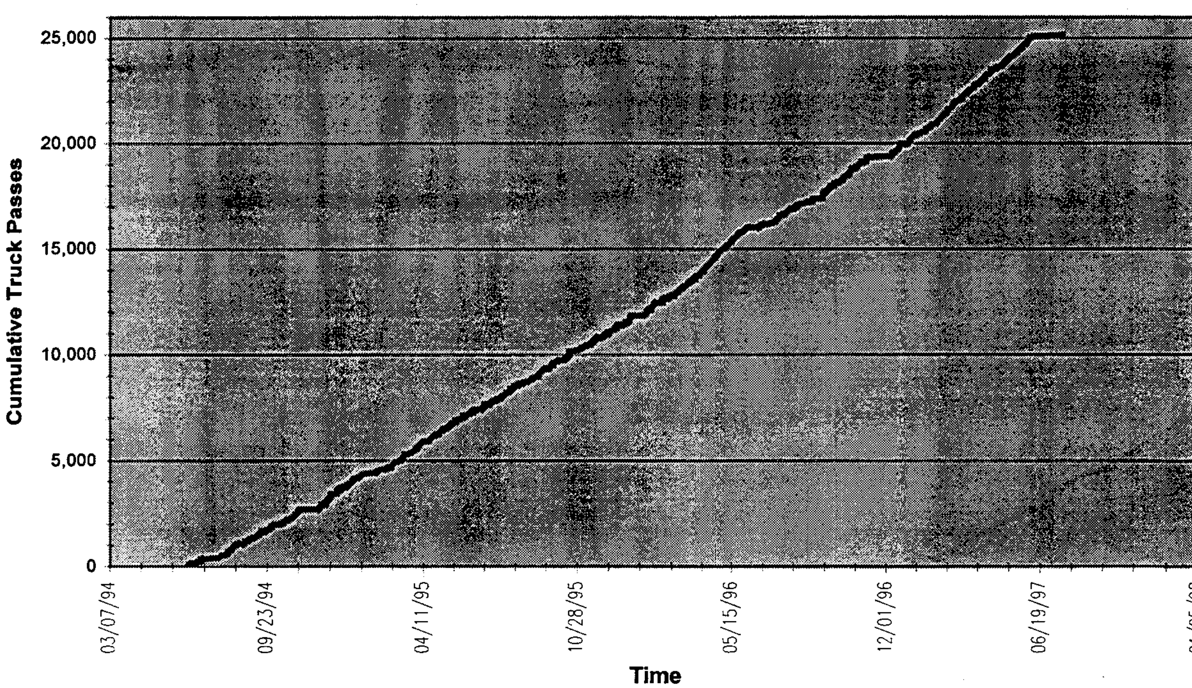
Low Volume Roadway - 80K Lane
Cumulative ESALs

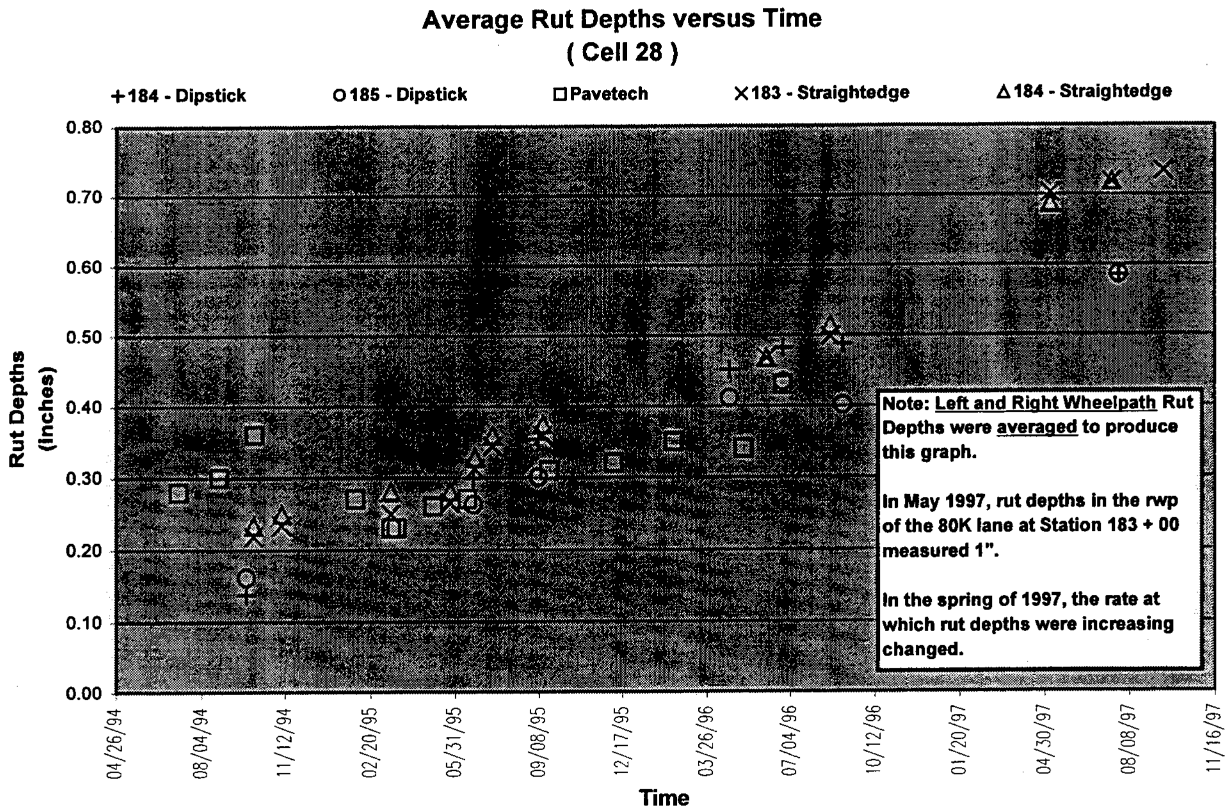


Low Volume Roadway - 80K Lane
Daily Loadings

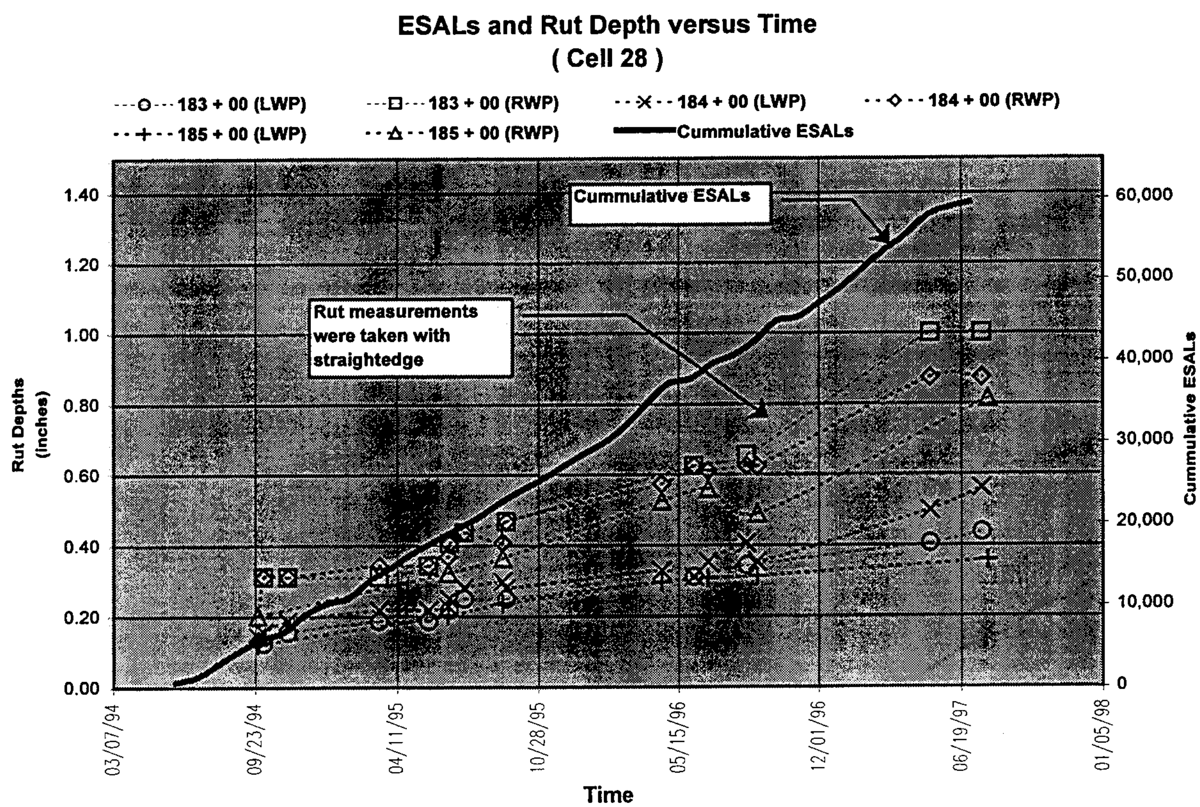


Low Volume Roadway - 80K Lane
Cumulative Loadings





Average Rut Depths versus Time
(Cell 28)
+184 - Dipstick
O185 - Dipstick
□Pavetech
×183 - Straightedge
△184 - Straightedge
Rut Depths (inches)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Note: Left and Right Wheelpath Rut Depths were averaged to produce this graph.
In May 1997, rut depths in the rwp of the 80K lane at Station 183 + 00 measured 1".
In the spring of 1997, the rate at which rut depths were increasing changed.
04/26/94
08/04/94
11/12/94
02/20/95
05/31/95
09/08/95
12/17/95
03/26/96
07/04/96
10/12/96
01/20/97
04/30/97
08/08/97
11/16/97
Time

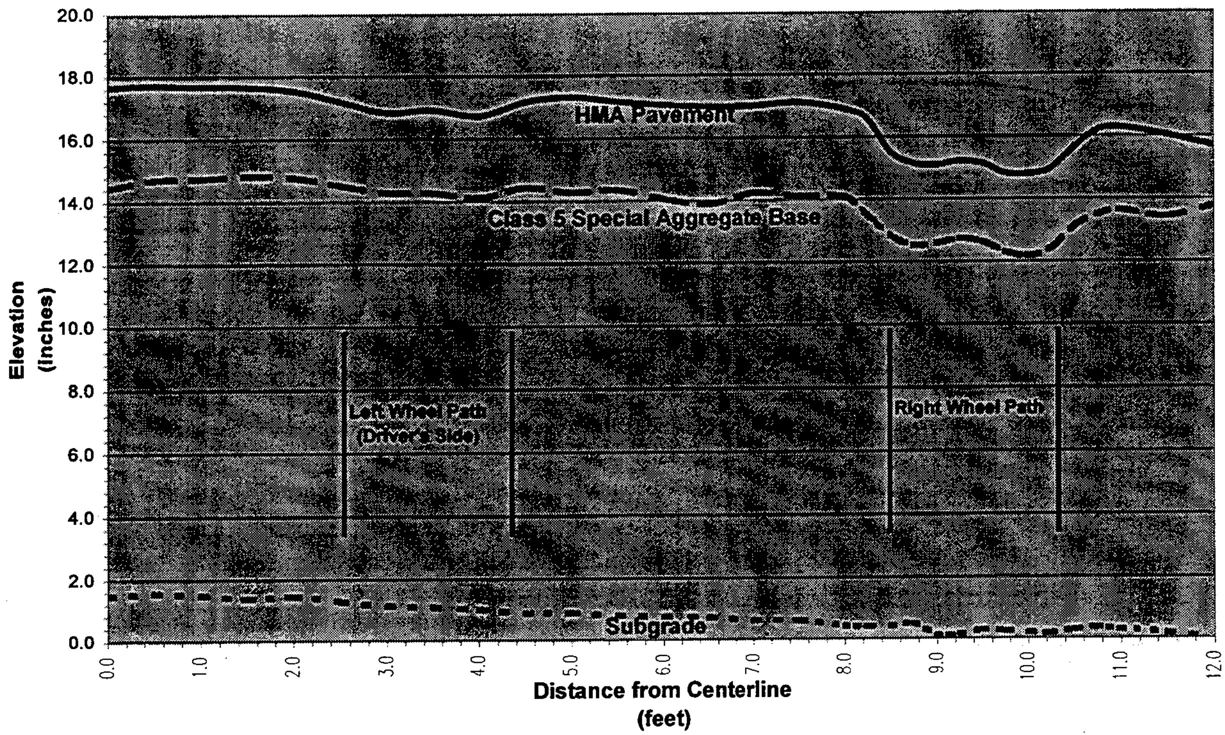


ESALs and Rut Depth versus Time
(Cell 28)
183 + 00 (LWP)
183 + 00 (RWP)
184 + 00 (LWP)
184 + 00 (RWP)
185 + 00 (LWP)
185 + 00 (RWP)
Cummulative ESALs
Cummulative ESALs
Rut measurements were taken with straightedge
Rut Depths (inches)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Cummulative ESALs
60,000
50,000
40,000
30,000
20,000
10,000
0
03/07/94
09/23/94
04/11/95
10/28/95
05/15/96
12/01/96
06/19/97
01/05/98
Time

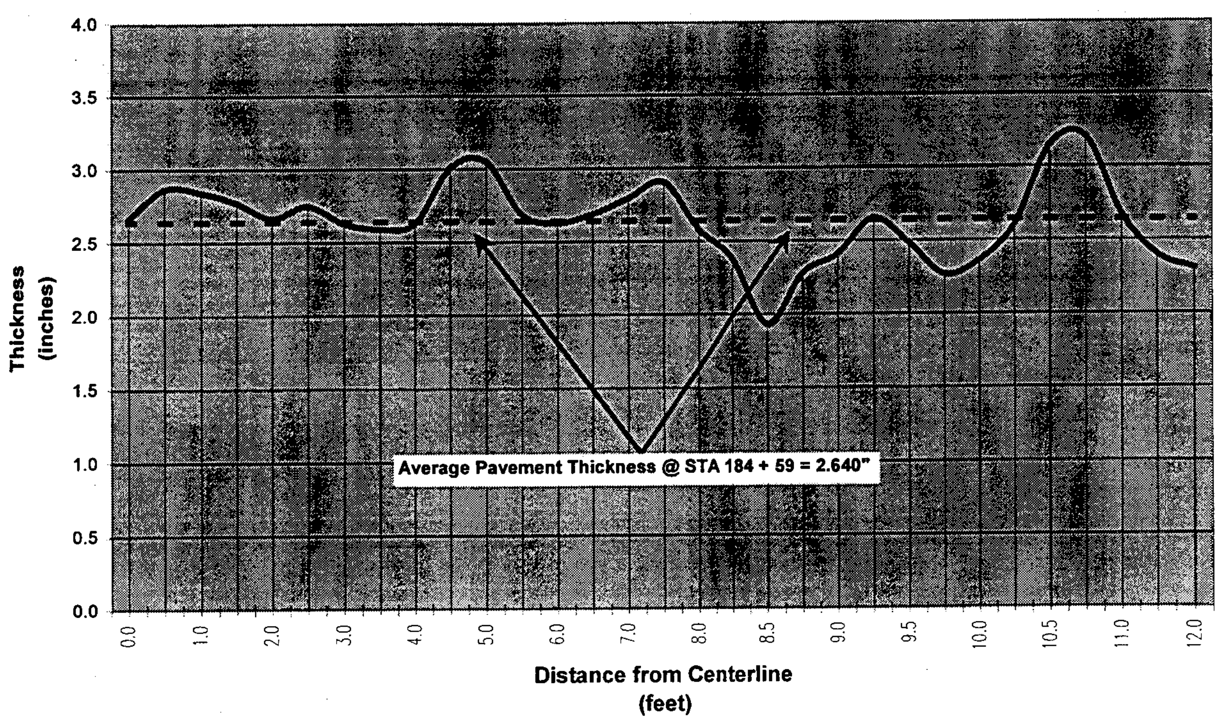
APPENDIX C

ROD AND LEVEL DATA

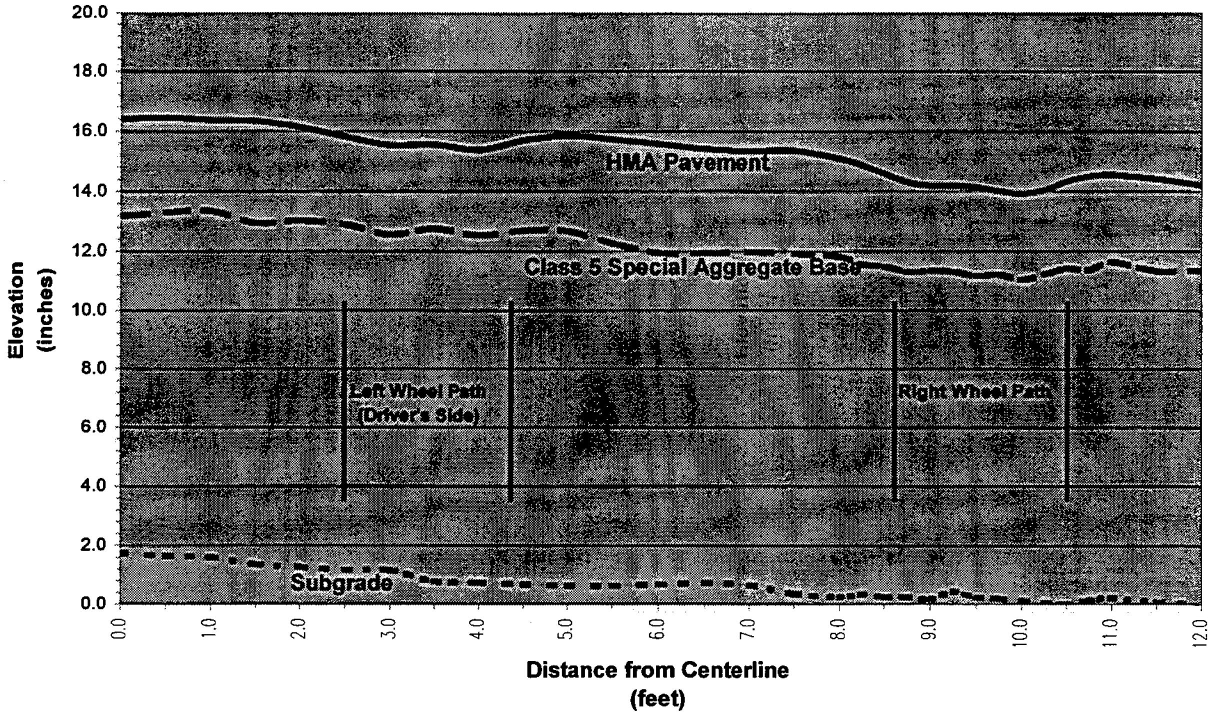
Rod and Level Cross-section
(Cell 28, 80K Lane, Station 184 + 59)



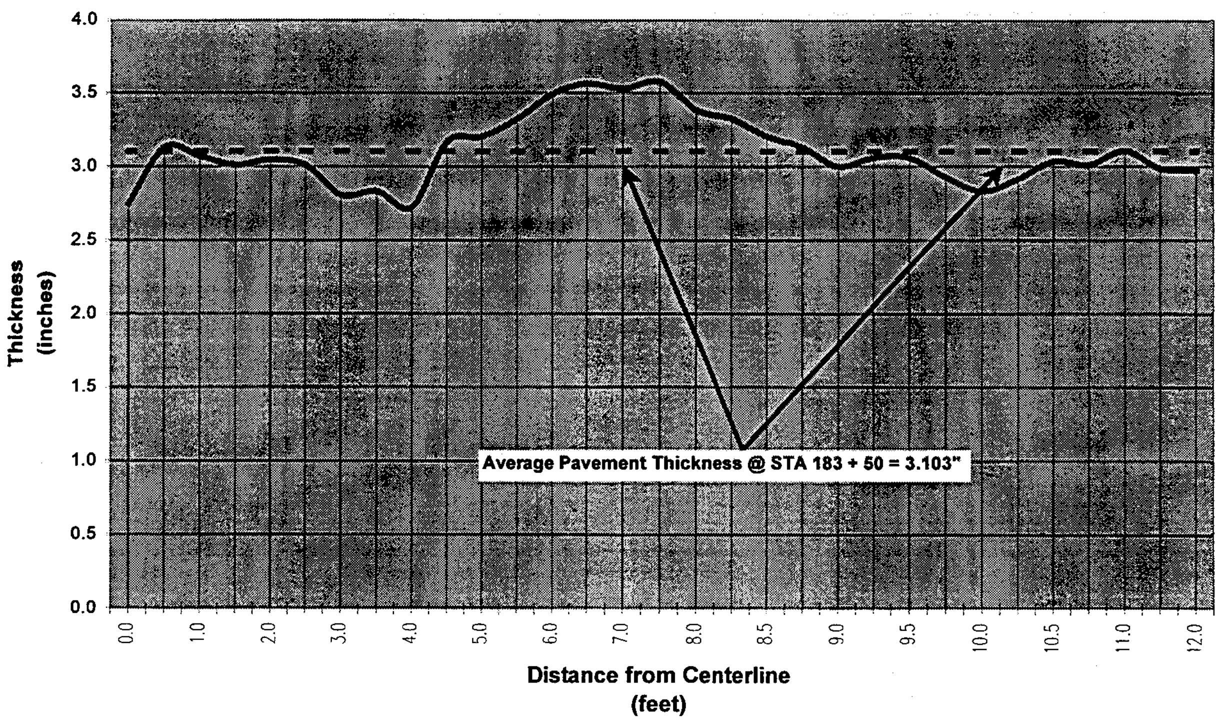
Rod and Level HMA Pavement Thickness
(Cell 28, 80K Lane, Station 184 + 59)



Rod and Level Cross-section
(Cell 28, 80K Lane, Station 183 + 50)



Rod and Level HMA Pavement Thickness
(Cell 28, 80K Lane, Station 183 + 50)



APPENDIX D

TEST RESULTS

Testing on Cores Removed from Rectangular Pavement Samples

Core Number	*Station*	*Location*	*Thickness*	*In-place Voids*
97101	183 + 50	Wheel path	3 "	5.5 %
97102	183 + 50	Wheel path	3 "	6.0 %
97104	183 + 50	Between wheel paths	3 ¼ "	6.8 %
97105	183 + 50	Between wheel paths	3 ½ "	7.5 %
97108	183 + 50	Between wheel paths	3 ¼ "	6.8 %
97109	183 + 50	Between wheel paths	3 "	5.5 %
97110	183 + 50	Wheel path	3 "	5.5 %
97111	183 + 50	Wheel path	2 ¾ "	5.1 %
97115	183 + 50	Between wheel paths	3 "	8.0 %
97116	183 + 50	Between wheel paths	3 "	8.1 %
97103	184 + 59	Wheel path	3 ⅝ "	6.1 %
97106	184 + 59	Between wheel paths	2 ¾ "	6.6 %
97107	184 + 59	Between wheel paths	2 ½ "	6.5 %
97112	184 + 59	Wheel path	2 ½ "	5.4 %
97113	184 + 59	Wheel path	2 ¾ "	5.0 %
97114	184 + 59	Wheel path	2 ¾ "	5.1 %
97117	184 + 59	Wheel path	2 ¾ "	8.4 %
97118	184 + 59	Wheel path	2 ¾ "	9.5 %

HMA Testing on Cell 28 - August 1993

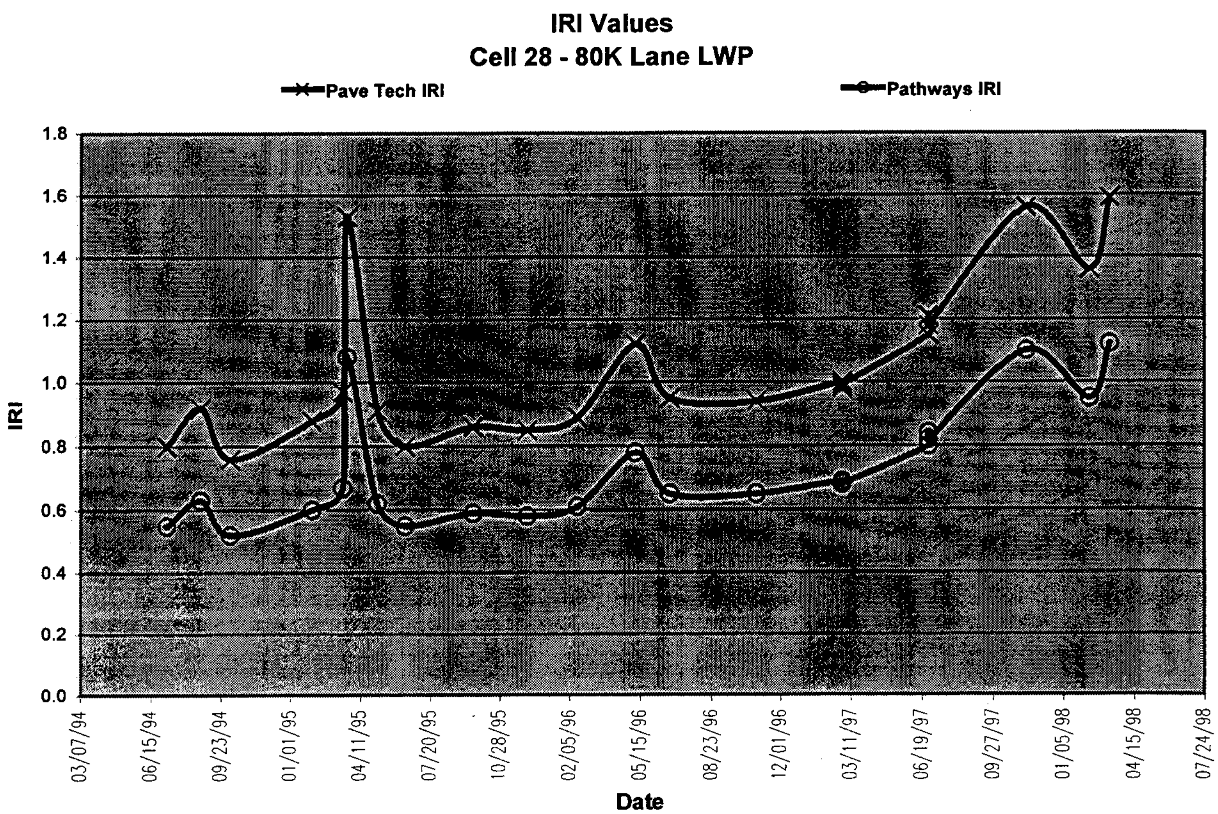
Station	*Thickness (Approx. from GPR)*	*Air Voids (%)*	*Marshall Specific Gravity*	*Rice Specific Gravity*	*VMA*	*Stability*	*Flow*	*Extracted Asphalt Binder*
181 + 11	3.0 "	4.10	2.349	2.449	15.7	1217	10.0	5.5
181 + 38	3.2 "	3.00	2.361	2.434	15.3	1510	10.3	5.7
182 + 30	3.1 "	2.80	2.356	2.424	15.5	1430	11.3	6.0
183 + 23	2.8 "	3.70	2.373	2.464	14.9	1433	10.0	5.3
183 + 83	2.9 "	4.00	2.349	2.447	15.7	1367	9.7	5.7
184 + 29	2.9 "	3.00	2.360	2.434	15.3	1420	10.7	5.7
185 + 76	2.8 "	3.40	2.363	2.447	15.2	1317	10.7	5.2
185 + 79	2.9 "	2.90	2.360	2.431	15.3	1233	10.7	5.9

Laboratory Determined Moisture Content of Class 5 Special Aggregate Base and Subgrade

Station 183 + 50				
Lab Number		***Offset from Centerline***	***Depth from Pavement Surface***	***Moisture***
SS97103	Subgrade	9' 6"	2' 6"	16.2
SS97104	CL 5S	11' 4"	-	5.5
SS97105	CL 5S	2' 0"	-	5.5
SS97106	CL 5S	6' 9"	-	5.5
SS97107	Subgrade	5' 10"	1' 0"	17.0
SS97108	Subgrade	2' 0"	-	17.1
Station 184 + 59				
Lab Number		***Offset from Centerline***	***Depth from Pavement Surface***	***Moisture***
SS97109	CL 5S	10' 0"	-	5.3 %
SS97110	CL 5S	11' 9"	-	5.7 %
SS97111	CL 5S	2' 6"	-	5.6 %
SS97112	Subgrade	7' 8"	2' 10"	17.3 %
SS97113	Subgrade	8' 11"	-	18.3 %
SS97114	Subgrade	11' 2"	2' 9"	18.5 %
SS97115	Subgrade	2' 6"	2' 8"	18.2 %

Sand Cone Density Test Results

Station 183 + 50				
Test Number		***Offset from Centerline***	***Depth from Pavement Surface***	***Density***
1	CL 5S	106.5"	3"	137.1 lb/ft^3
2	CL 5S	79"	3"	138.5 lb/ft^3
3	Subgrade	106.5"	30"	106.7 lb/ft^3
Station 184 + 59				
Test Number		***Offset from Centerline***	***Depth from Pavement Surface***	***Density***
4	CL 5S	112"	3"	136.5 lb/ft^3

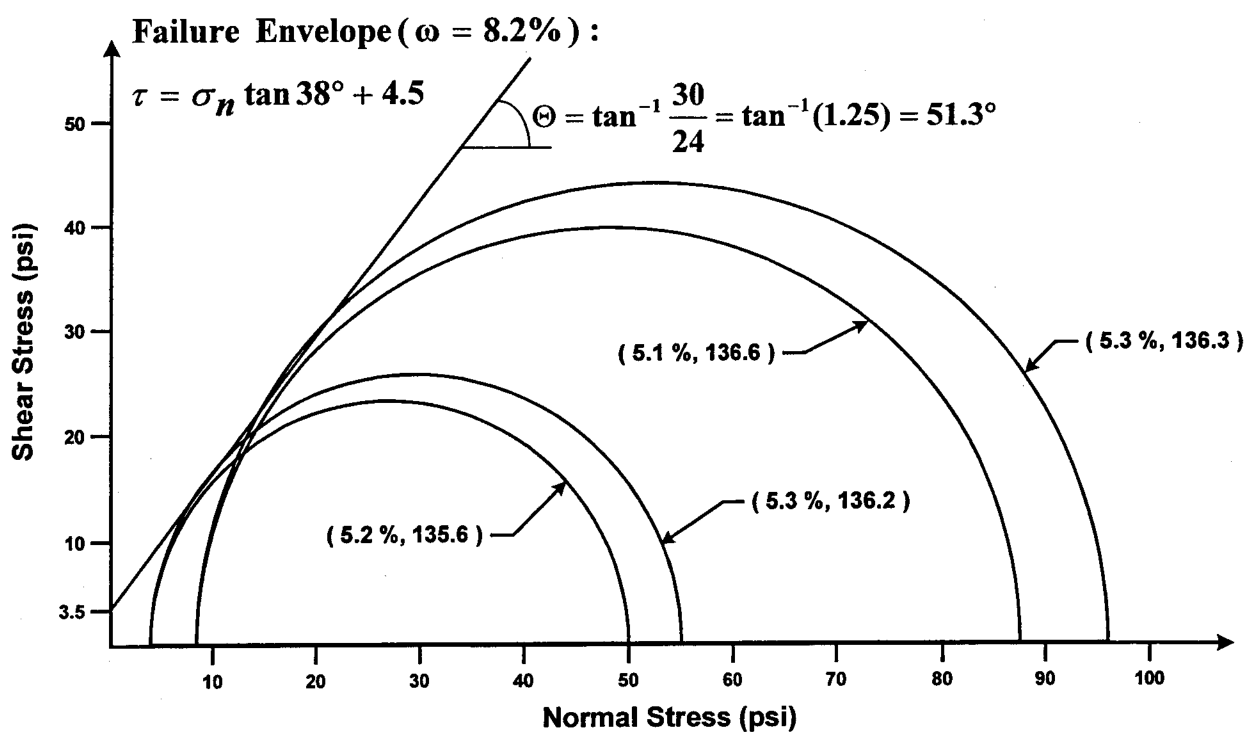


IRI Values
Cell 28 - 80K Lane LWP
Pave Tech IRI
Pathways IRI
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
IRI
03/07/94
06/15/94
09/23/94
01/01/95
04/11/95
07/20/95
10/28/95
02/05/96
05/15/96
08/23/96
12/01/96
03/11/97
06/19/97
09/27/97
01/05/98
04/15/98
07/24/98
Date

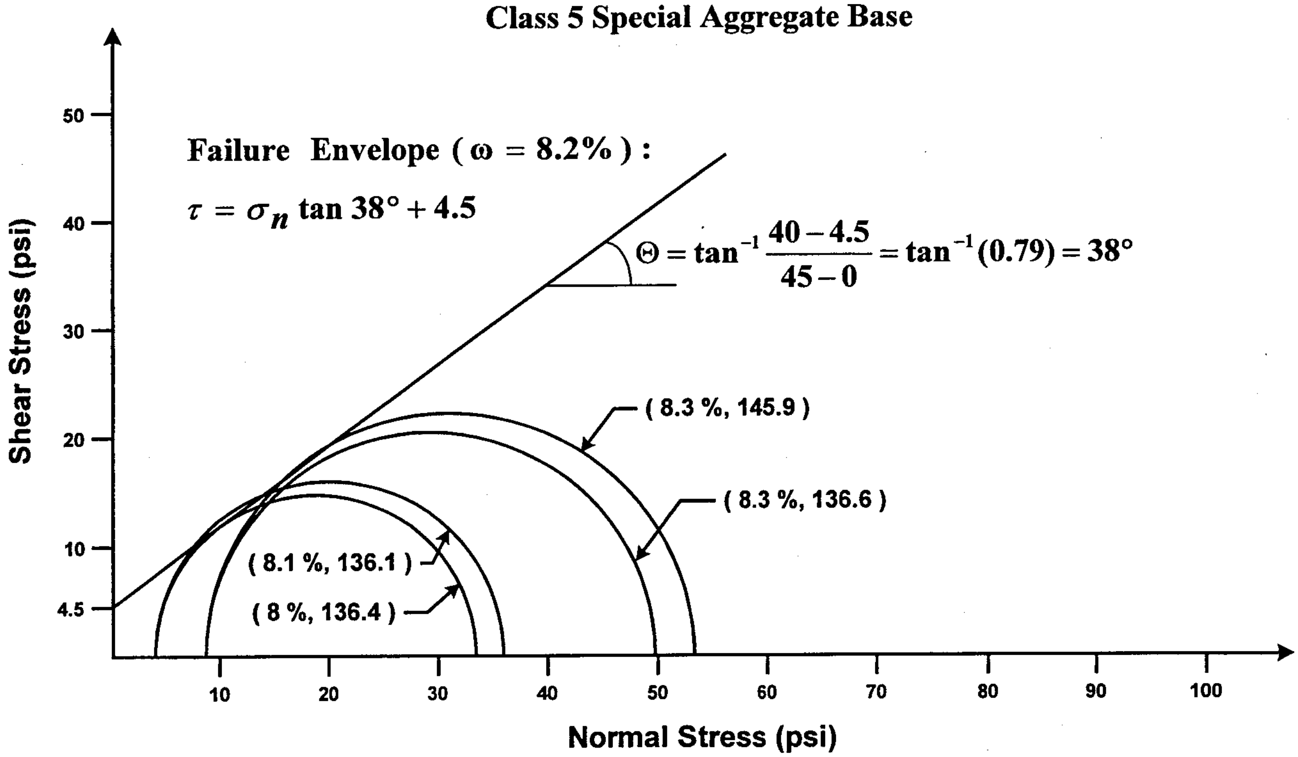
Gradation of Class 5 Special Aggregate Base

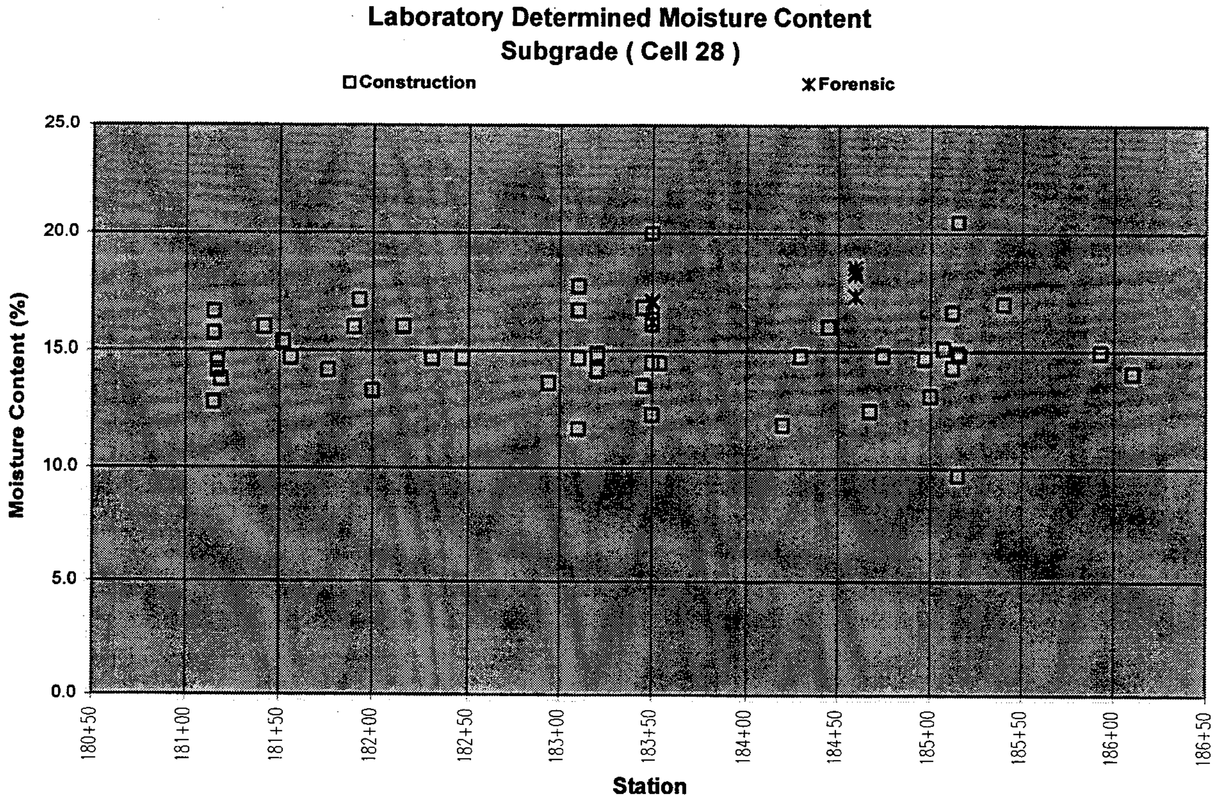
Sieve Size	Percent Passing											
	Station 183 + 50		*Station 184 + 59*		*Stock Pile Samples*			*Construction Gradations*				
	# 1	# 3	# 2	# 4	# 1	# 2	# 3	182+50	183+03	183+50	185+00	185+00
1 ¼”	100	100	100	100	-	-	-	-	-	-	-	-
1”	100	100	99	100	100	100	100	-	100	-	-	-
¾”	95	97	95	96	97	97	98	97	96	95	97	97
⅝”	91	91	90	92	92	91	95	-	-	-	-	-
½”	83	86	84	85	83	83	87	-	-	-	-	-
⅜”	77	80	79	79	77	77	81	73	81	79	78	78
# 4	66	68	67	67	61	60	65	65	69	67	65	67
# 8	-	-	-	-	47	46	50	-	-	-	-	-
# 10	55	55	55	57	45	44	48	50	54	53	47	55
# 16	-	-	-	-	36	35	40	-	-	-	-	-
# 20	37	36	37	39	-	-	-	-	34	-	-	-
# 30	-	-	-	-	23	22	25	-	-	-	-	-
# 40	21	21	22	22	17	17	19	19	20	20	17	21
# 50	-	-	-	-	13	13	14	-	-	-	-	-
# 80	10	10	10	10	-	-	-	-	-	-	-	-
# 100	8	9	9	9	7	7	8	-	8	-	-	-
# 200	6.1	6.6	6.4	6.5	5.2	5.4	5.5	6	5.7	6.5	5.8	6.2

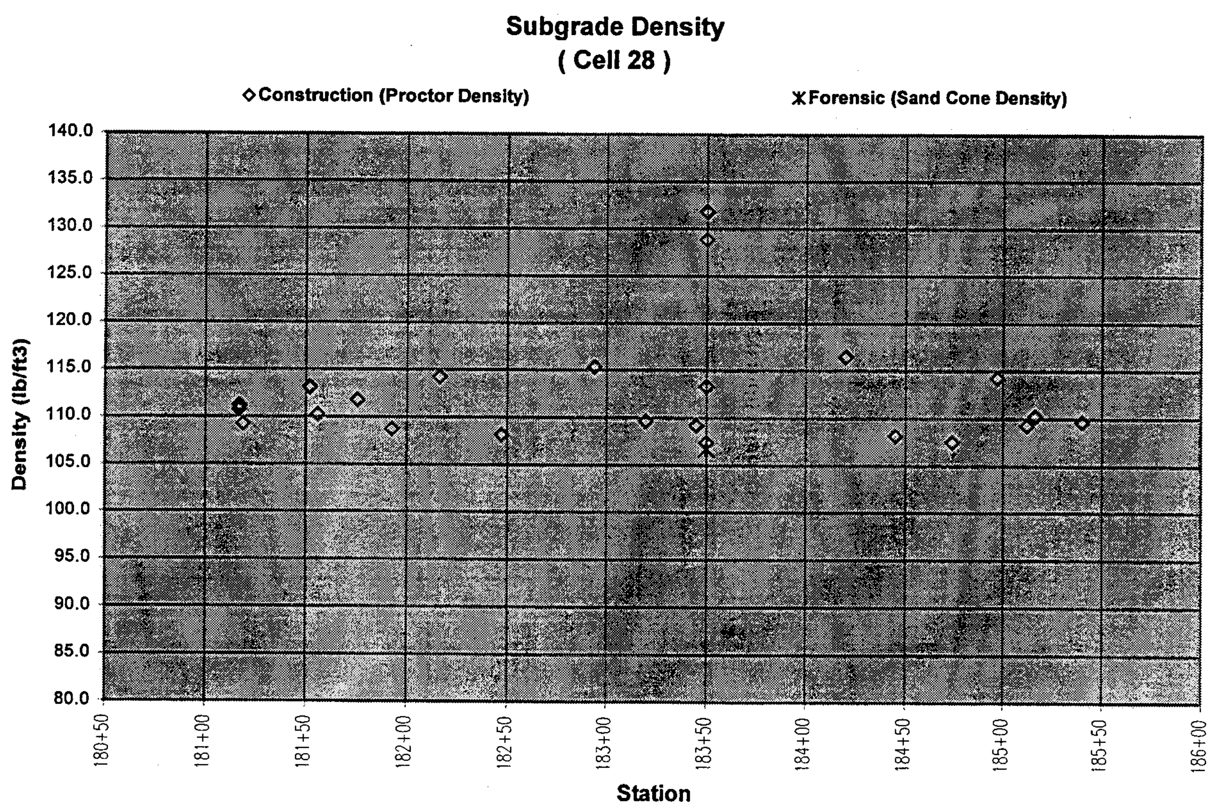
Mohr's Circles
Class 5 Special Aggregate Base

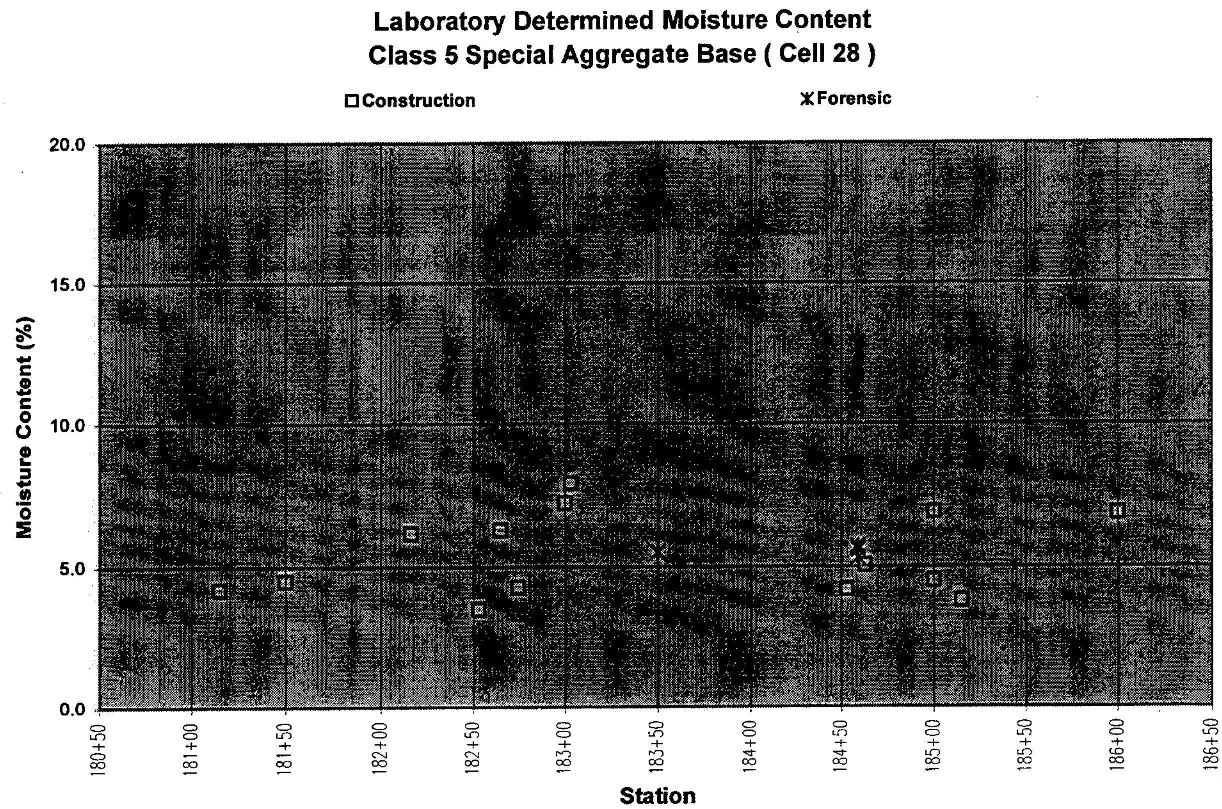


Mohr's Circles
Class 5 Special Aggregate Base

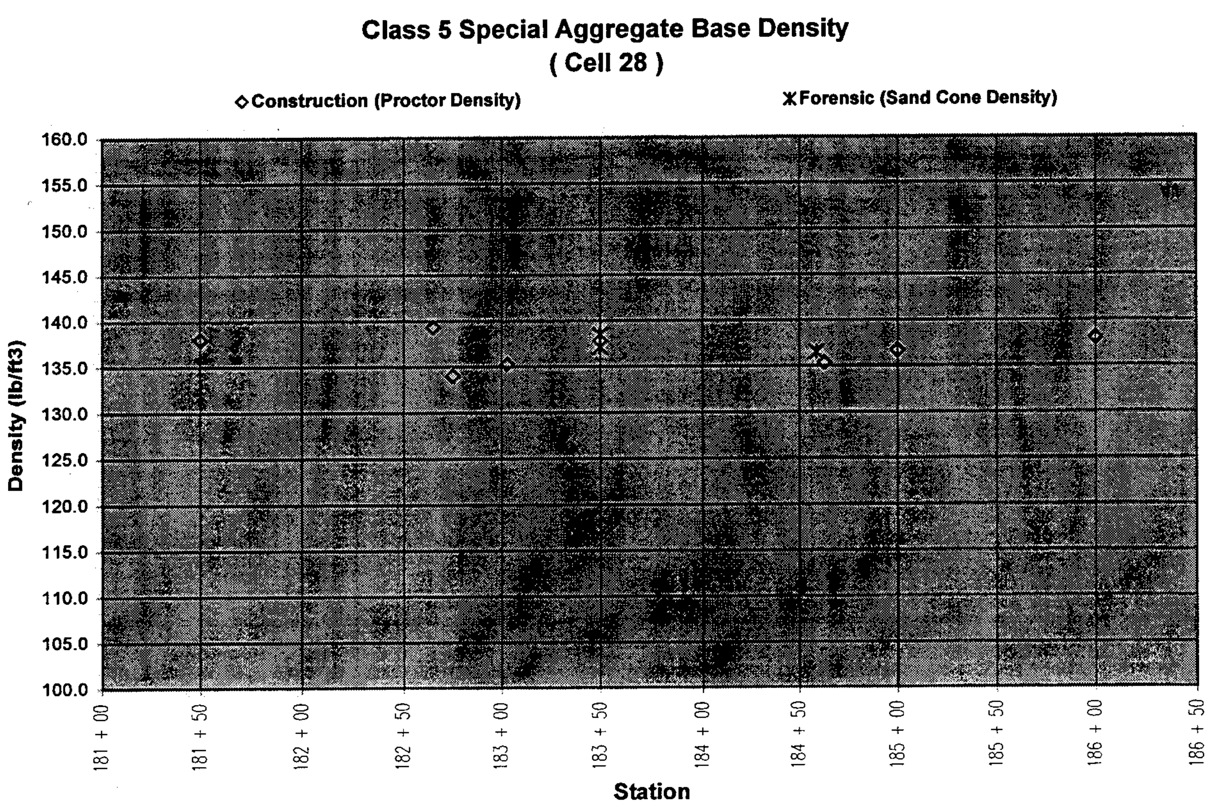



Laboratory Determined Moisture Content
Subgrade (Cell 28)
Construction
Forensic
25.0
20.0
15.0
10.0
5.0
0.0
Moisture Content (%)
180+50
181+00
181+50
182+00
182+50
183+00
183+50
184+00
184+50
185+00
185+50
186+00
186+50
Station


Subgrade Density
(Cell 28)
Construction (Proctor Density)
Forensic (Sand Cone Density)
140.0
135.0
130.0
125.0
120.0
115.0
110.0
105.0
100.0
95.0
90.0
85.0
80.0
Density (lb/ft3)
180+50
181+00
181+50
182+00
182+50
183+00
183+50
184+00
184+50
185+00
185+50
186+00
Station



Laboratory Determined Moisture Content
Class 5 Special Aggregate Base (Cell 28)
Construction
Forensic
Moisture Content (%)
20.0
15.0
10.0
5.0
0.0
180+50
181+00
181+50
182+00
182+50
183+00
183+50
184+00
184+50
185+00
185+50
186+00
186+50
Station



Class 5 Special Aggregate Base Density
(Cell 28)
Construction (Proctor Density)
Forensic (Sand Cone Density)
Density (lb/ft3)
160.0
155.0
150.0
145.0
140.0
135.0
130.0
125.0
120.0
115.0
110.0
105.0
100.0
181 + 00
181 + 50
182 + 00
182 + 50
183 + 00
183 + 50
184 + 00
184 + 50
185 + 00
185 + 50
186 + 00
186 + 50
Station