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An Evaluation of Aggregate and Chip Seal Surfaced Roads at Mn/ROAD

Minnesota Local Road Research Board

Mn/ROAD
Office of Minnesota Road Research

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16. Abstract (Limit: 200 words)

A pavement testing facility, the Minnesota Road Research Project (Mn/ROAD) contains a two-lane Low Volume Road (LVR) loop with dedicated traffic supplied by a five-axle tractor semi-trailer truck that has maximum legal gross weight of 356 kN (80,000 pounds) when it travels in the clockwise direction and an overloaded 456 kN (102,500 pounds) in the counterclockwise direction. The LVR contains four 152.4 m (166 yard) sections with a 305 mm (12 inch) aggregate structure, two of which are surfaced with a double chip seal. These four sections include three main experimental variables: vehicle loads, graduations of aggregate, and surface types.

This study involved monitoring the performance of these four sections from June 1994 to May 1995. Study conclusions include the following:

- Aggregate gradations are not reliable predictors of performance as an aggregate wear.
- A simplified test is needed to evaluate aggregate wearing materials
- The performance of chip seals with respect to ride and rutting was better than the aggregate surfaced sections constructed with the same aggregate.

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AN EVALUATION OF AGGREGATE AND CHIP SEAL SURFACED ROADS AT Mn/ROAD

Final Report

Prepared by:

Erland O. Lukanen
Braun Intertec Corporation
6875 Washington Avenue, South
Minneapolis, MN 55439

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Published by:

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

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EXECUTIVE SUMMARY

Minnesota Road Research Project (Mn/ROAD) is a research facility operated by the Minnesota Department of Transportation (Mn/DOT) located on I-94, approximately 65 km (40 mi) northwest of Minneapolis. The facility includes two main components: A "Mainline" section which carries I-94 traffic plus a two-lane Low-Volume Road (LVR) loop that is approximately 4 km (2.5 mi) long. The traffic on the LVR is provided by a five-axle tractor semi-trailer truck loaded to 356 kN (80,000 lb) on the inside (clockwise) lane and 456 kN (102,500 lb) on the outside (counterclockwise) lane.

The LVR at Mn/ROAD contains 17 sections. Four sections, A-1 (Cell 33), A-2 (Cell 34), A-3 (Cell 35), and A-4 (Cell 32) are constructed with 305 mm (12 in.) of aggregate, two of which, A-2 (Cell 34) and A-4 (Cell 32), are surfaced with a double chip seal. Two gradations of aggregate were used to construct the sections, both conforming to the Mn/DOT Class 1 gradation. One aggregate, called Class 1C for this study, was on the course side of the allowable Class 1 gradation band and the other, Class 1F, was on the fine side of the gradation band. One aggregate surfaced section and one chip seal surfaced section was constructed with each of the two gradations. There are a total of eight aggregate evaluation sections on the LVR because of the different axle loadings on the inside and outside lanes.

The objective of this study was to identify or develop evaluation procedures for use in the evaluation of the performance of the aggregate and chip sealed sections, and to apply those procedures to evaluate the performance of those sections at Mn/ROAD. The traffic, as described above, does not represent the distribution of traffic on a typical low volume road; the LVR at Mn/ROAD is directly oriented toward a structural evaluation. The relationships developed, however, establish a baseline understanding of some of the critical performance characteristics of the sections. These relationships will be very useful in designing future experimental sections, or in establishing observation sections in other areas.

The results from this project allowed the development of several basic findings or conclusions that are summarized as follows:

1. Aggregate gradations alone are not reliable predictors of performance.

2. On the basis of rutting, the equivalent truck loadings (legal and overloaded) were approximately equal, indicating the ratio of the truck factors as calculated by the American Association of State Highway and Transportation Officials (AASHTO) method holds and that the accumulation of Equivalent Single Axle Loads (ESALs) on the legal and overloaded lanes were similar.

3. The most dominant deterioration modes for the sections were rutting or washboarding. Washboarding was much more dependent on the number of truck passes rather than the truck loadings.

4. Forensic studies showed that most of the rutting occurred in the aggregate, not in the subgrade.

5. Dynamic Cone Penetrometer, resilient modulus, and shear tests conducted in the laboratory at the University of Illinois predicted the course graded aggregate, Class 1C, would not perform as well as the fine graded aggregate, Class 1F, which was confirmed by the field performance.

The results of the study allowed several basic recommendations to be made as follows:

1. A simple test, such as a laboratory DCP test, should be evaluated for inclusion in the specifications for aggregate wearing materials.

2. Future research should include the use of different aggregates in Cells 32 through 34, and on existing aggregate surfaces roads, to broaden the experience regarding the structural performance of aggregate wearing materials and to provide a basis for the development of tests to be included as part of the specifications for aggregate surfacing materials.

CHAPTER 1
INTRODUCTION

Minnesota Road Research Project (Mn/ROAD) is a research facility operated by the Minnesota Department of Transportation (Mn/DOT) located on I-94, approximately 65 km (40 mi) northwest of Minneapolis. The facility includes two main components: A "Mainline" section which carries I-94 traffic plus a two-lane Low Volume Road (LVR) loop that is approximately 4 km (2.5 mi) long. The traffic on the LVR is provided by a five-axle tractor semi-trailer truck loaded to 356 kN (80,000 lb) on the inside (clockwise) lane and 456 kN (102,500 lb) on the outside (counterclockwise) lane.

The LVR at Mn/ROAD contains 17 sections. Four sections, A-1 (Cell 33), A-2 (Cell 34), A-3 (Cell 35), and A-4 (Cell 32) are constructed with 305 mm (12 in.) of aggregate, two of which, A-2 (Cell 34) and A-4 (Cell 32), are surfaced with a double chip seal. The LVR contains a number of other asphalt or concrete surfaced sections. Because of the different axle loadings on the inside and outside lanes of the LVR, there are eight aggregate evaluation sections on the LVR.

The objective of this study is to identify or develop evaluation procedures for use in the evaluation of the performance of the aggregate and chip sealed sections, and to apply those procedures to evaluate the performance of those sections at Mn/ROAD. Because of the design of the LVR, there will be eight individual sections in the evaluation made up of two aggregate surfaced sections and two chip sealed sections for each level of loadings. The traffic, as described above, does not represent the distribution of traffic on a typical low volume road; it is directly oriented toward a structural evaluation. The relationships developed, however, establish a baseline understanding of some of the critical performance characteristics of the sections. These relationships will be very useful in designing future experimental sections, or in establishing observation sections in other areas.

Chip seal surfaces are quite common in low volume applications in many of the areas surrounding Minnesota, but are not as common within Minnesota. They are particularly common in the sand hills of Nebraska, the upper peninsula of Michigan, and in South Dakota (Ref. 655)[1]. Even though the chip-sealed sections are to be evaluated along with the aggregate sections, they look more like a surfaced pavement to the user. Also, the maintenance techniques available for the sections are different. The unique characteristics of an aggregate surface and a chip-seal surface expand the domain of performance parameters beyond the traditional parameters of ride and distress indices commonly used for surfaced pavements. Performance may be definable from both the user's standpoint, such as ride, safety, and distress, and from the owner's standpoint in terms of maintenance requirements.

The performance of the sections was monitored for about ten months during this study. The most relevant performance indicators applied to this project included rutting, corrugation, and ride on all of the sections, and blading requirements for the aggregate sections. Truck passes were counted. Structural data, including deflection tests, dynamic cone penetrometer tests, and laboratory strength tests were collected. These data were then analyzed to determine the structural performance of the sections.

1.1 SITE DESCRIPTION

1.1.1 Location and Layout

Mn/ROAD is located in Wright County, Minnesota, about 65 km (40 mi) northwest of Minneapolis. The facility is within the right-of-way of Interstate 94 and consists of a new roadway constructed to carry westbound I-94 traffic which is called the mainline section and a Low Volume Road loop (LVR). The LVR is a two-lane, closed-loop roadway that is 4 km (2.5 mi) long with two tangent sections, about 1.3 km (0.8 mi) each, that parallel the mainline. The tangents are joined by banked loops at each end. The facility contains 40 test sections in all, 17 of which are on the LVR. The LVR consists of five concrete, seven asphalt, two chip seal, and two aggregate surfaced sections[2,3].

The sections were loaded with a 5-axle tractor semi-trailer truck driven by Mn/ROAD staff. The truck traveled at the legal 355.9 kN (80,000 lb) maximum load for Minnesota highways on the inside lane in a clockwise direction and at 455.9 kN (102,500 lb) overload on the outside lane in a counterclockwise direction.

1.1.2 Section Design and Specifications

This study deals with the four aggregate sections on the LVR, Cells 32 to 35, or LVR-A-1 through LVR-A-4. Cell 32 is on the southeast end of the southwest tangent of the LVR and Cells 33 to 35 are at the northwest end of the northeast tangent of the LVR. The sections are 152.4 m (500 ft) long and are separated from the other sections by a short transition zone.

Figure 1 shows the typical section of the four aggregate sections. All four have the same thickness. The experimental factors in this study are aggregate gradation, surfacing, and truck loadings. The different axle weights on each of the two lanes of the LVR resulted in eight evaluation sections as shown in Table 1.

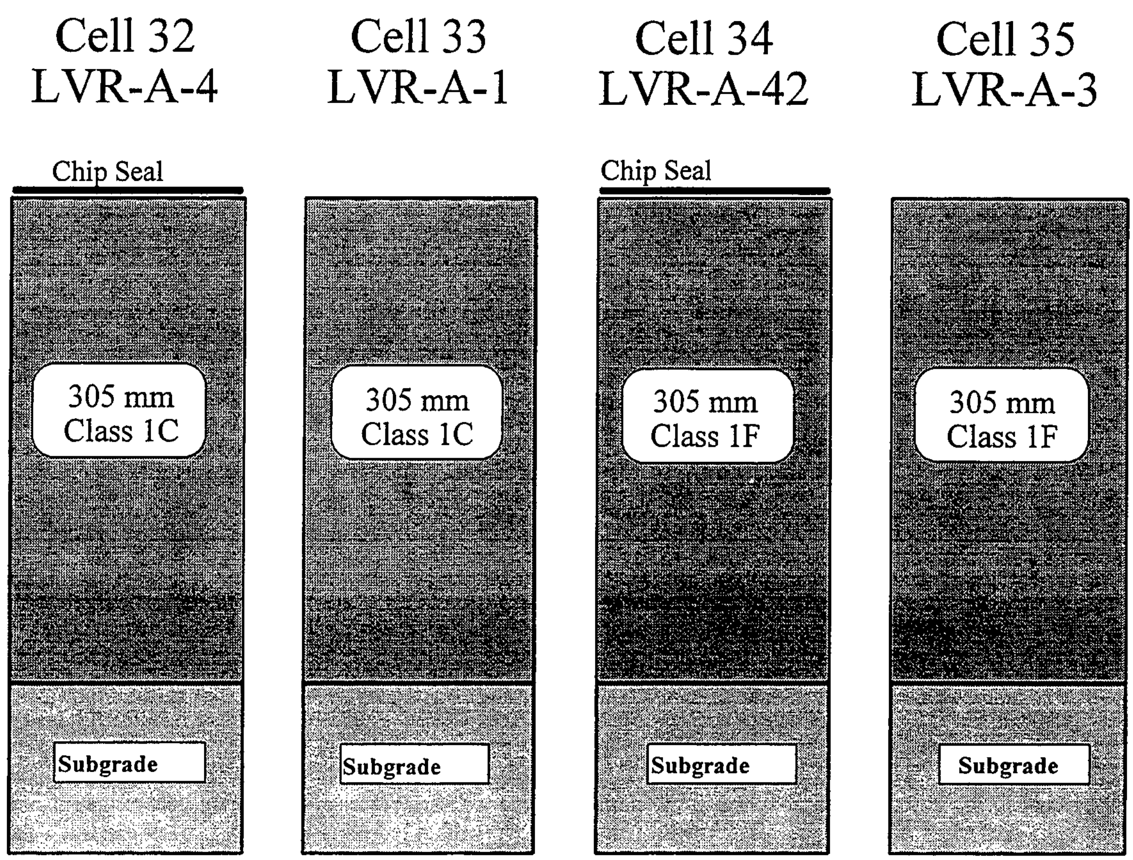


Figure 1. Low Volume Road loop aggregate sections.

Table 1. Aggregate sections experimental factors and cell assignment.

Aggregate		Class 1 Coarse		Class 1 Fine	
Surface Treatment		Chip Seal	None	Chip Seal	None
Truck Load	355.6 kN, Inside Lane	Cell 32	Cell 33	Cell 34	Cell 35
	455.9 kN, Outside Lane	Cell 32	Cell 33	Cell 34	Cell 35

The information that these sections can provide is:

- Whether or not performance is sensitive to aggregate gradations;
- What the benefit is of placing a chip seal on an aggregate road; and
- What the impact of truck loading is on performance.

Note that there are not enough sections to fully define the structural capacity of an aggregate-surfaced road. Aggregate thickness and subgrade are not experimental design factors, and two levels of loading are not sufficient to measure the nonlinear loading effects that are expected. There are sufficient sections, however, to determine if any of the three factors are significant, and if the performance checks with existing design procedures.

The soils at the Mn/ROAD facility are silty clay loams. Standard Proctor density and optimum moisture content (AASHTO T-99) is 1762 kg/m^3 (110 pcf) and 24 percent moisture content. The strength characteristics of the soil are an R-value of 12 and a resilient modulus of 75.8 MPa (11,000 psi). The specifications for the coarse and fine gradations of the Class 1 used for the aggregate sections is shown in the Table 2. The Mn/DOT specified gradation for Class 1 surfacing aggregate[4] is also included in Table 2 for reference. The gradations are also graphically shown in Figure 2.

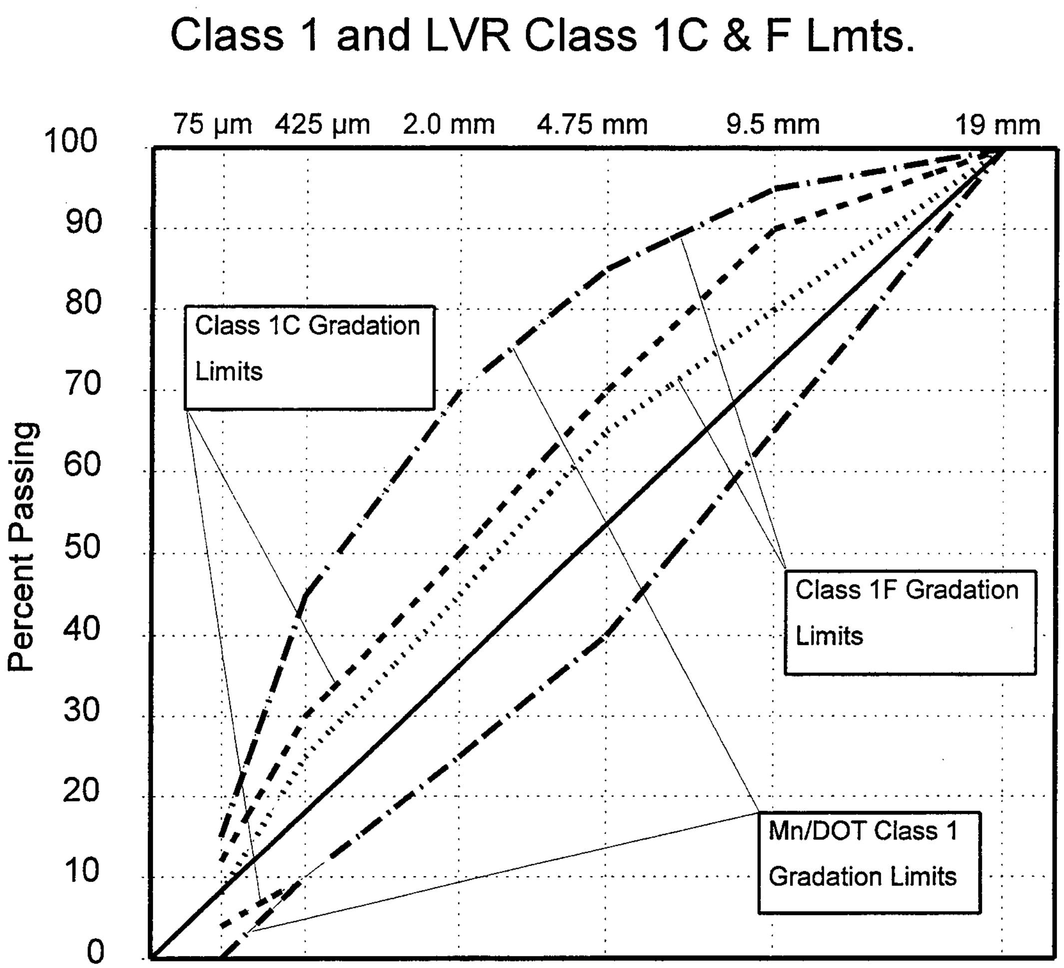


Figure 2. Gradation bands for Mn/DOT Class 1 and Mn/ROAD Class 1C and Class 1F.

1.1.3 Traffic

Traffic on the Low Volume Loop is provided by a 5-axle tractor semi-trailer truck that typically travels four days a week in a clockwise direction (inside lane) at the legal 356 kN (80,000 lb) load and one day a week in a counterclockwise direction (outside lane) at approximately 456 kN (102,500 lb) as shown in Table 3. The calculated Equivalent Single Axle Load (ESAL) truck factor for the 356 kN (80,000 lb) loading is 2.4 ESALs per pass and 7.88 ESALs per pass for the heavy side prior to April 1, 1995, and 7.55 ESALs per pass after April 1, 1995. This traffic has been applied to the LVR since June 15, 1994. By calculating the ESAL applications (calculations based on a SN of 1.8), the typical application rate on a calendar-day basis is about 45 ESALs/calendar day. The overall cumulative rate is about the same for both lanes because the truck travels one day a week on the heavy side and four days a week on the legal load side.

Table 2. Gradation Specifications for the Class 1 aggregates.

Sieve Size	Mn/DOT Class 1		Mn/ROAD Class 1 Coarse		Mn/ROAD Class 1 Fine	
	Min.	Max.	Min.	Max.	Min.	Max.
19 mm	100	100	100	100	100	100
9.5 mm	65	95	65	90	80	95
4.75 mm (#4)	40	85	40	70	65	85
2.0 mm (#10)	25	70	25	50	45	70
425 μm (#40)	10	45	10	30	25	45
75 μm (#200)	0	15	4	12	8	16

A 5-axle tractor semi-trailer truck with a flat bed trailer is used for applying the loads. The driver axles on the tractor are equipped with air suspension and the tandem axles on the trailer are equipped with spring suspension. Both truck and trailer are fitted with dual 11R24.5 tires. The trailer is equipped with a hydraulic crane for loading and unloading the 4.45 kN (1000 lb) steel blocks used to load the truck and the tires were generally inflated to about 800 kPa (115 psi). Axle loadings varied slightly during the study. Table 3 lists the weights of each of the tires or dual-tires, axles and axle sets. The adjustments made to the heavy load configuration on April 1, 1995, resulted in a better balance between the tandem axles on the tractor and trailer.

1.2 LITERATURE SEARCH

A literature search was performed for low-volume research reports conducted since the completion of Investigation 655[5] in 1982. The search included a search of the Transportation Research Information Service that is part of the Transportation Research Board. The search resulted in limited new information relevant to the structural capacity of aggregate-surfaced roads. Two reports of interest are included in an annotated bibliography at the end of this report.

Table 3. Axle loads in kilo-Newtons for heavy side of LVR.

Axle loads prior to April 1, 1995, on Heavy Configuration				
	Lt.	Rt.	Total Axle	Axle Set
Steering Axle	30.2	28.5	58.7	58.7
Front Driver	43.6	49.6	93.2	
Rear Driver	47.6	43.8	91.4	184.6
Front Trailer	48.7	52.3	101.0	
Rear Trailer	56.0	55.6	111.6	212.6
Total "Heavy" Vehicle Weight			455.9	
Axle Loads as of April 1, 1995, on Heavy Configuration				
Steering Axle	30.9	29.6	60.5	60.5
Front Driver	46.7	52.3	99.0	
Rear Driver	46.9	48.0	94.9	193.9
Front Trailer	52.7	53.6	106.3	
Rear Trailer	44.9	50.9	95.9	202.2
Total "Heavy" Vehicle Weight			456.6	

Aggregate surfacing specifications from the surrounding states were obtained for comparison. Several of the adjoining states had a minimum Plasticity Index requirement for their aggregate surfacing materials in addition to the typical gradation and soundness requirements.

1.3 CALENDAR OF EVENTS

In June 1990, Mn/DOT began construction of the Minnesota Road Research Project (Mn/ROAD), a new roadway test facility.[6] Grading was completed during the summer of 1993 and the aggregate material was placed. The aggregate was in-place without any traffic over the winter of 1993-1994. The chip seals were placed on July 18 and 19, 1994. All of the aggregate sections were reshaped by the contractor before the chip seals were placed. Traffic loadings started June 15, 1994. Note that this is before placement of the chip seals; however, the truck was providing structural loadings of the aggregate and subgrade. Monitoring began on July 25, 1994, and continued through April 1995.

CHAPTER 2

SELECTION OF A MONITORING PROCESS

Existing evaluation procedures for rating aggregate-surfaced roads were reviewed to determine if any of them are applicable for the monitoring phase of this project. Two rating methods, Unsurfaced Road Condition Index (URCI)[7] developed by the U.S. Army Corps of Engineers at the Cold Regions Research and Engineering Laboratory (CRREL) and the Gravel-PASER Manual[8] developed at the Transportation Information Center at the University of Wisconsin were evaluated. The URCI initially came about by work done at CRREL [9] with assistance from the University of Wisconsin. The URCI process was developed to be compatible with the Pavement Condition Index (PCI) that is part of the PAVER pavement management system developed by the U.S. Army Corps of Engineers[10].

The distresses of the two systems are similar, but have different methods of developing a numerical rating score. The distresses identified in both systems are:

Improper Cross Section (Crown);
Inadequate Roadside Drainage;
Corrugations (Washboard);
Dust;
Potholes;
Ruts; and
Loose Aggregate (Float).

PASER includes one additional item for rating: Gravel Layer.

2.1 USE OF URCI OR PASER AT Mn/ROAD

Of these distresses, Corrugations, Ruts, Loose Aggregates, Potholes, and Dust are relevant to Mn/ROAD. Crown and Drainage are not rating variables that can be used to differentiate the performance between the sections. Crown, although, is an important factor that will be discussed later in the report.

In addition to the distresses that are relevant to Mn/ROAD, one other performance factor, blading, was considered very important for the aggregate surfaced sections. At Mn/ROAD, blading was scheduled whenever the condition of one of the sections required the truck driver to slow down for safety reasons. The development of excessive washboarding and/or rutting would cause the driver to slow down to prevent damage to the truck, shifting of the steel load blocks, or loss of vehicle control. Whenever either of these conditions required the driver to slow down, the section would be bladed. The target operating speed of the truck is 50 to 60 kph (30 to 35 mph). Low severity washboarding [less than 25 mm (1 in.)] would introduce a severe resonance in the vehicle at the target speed, causing the ballast weights to shift. Localized rutting would result in longitudinal profile distortions of 50 to 75 mm (2 to 3 in.) and would require the driver to slow down to avoid vehicle damage caused by "bottoming" the suspension.

Many agencies that are responsible for maintaining aggregate-surfaced roads schedule blading to be somewhat consistent with demand. If a road is allowed to get too rough, the agency will begin to get complaints, prompting a revision to the blading schedule. We would expect that the frequency of blading is mostly dependent on the amount of traffic on the road, but we also expect that the structural capacity and ability of the aggregate wear course to resist washboarding are significant factors.

The rating of each distress requires a method of measuring the severity. PASER does not provide a severity rating for the individual distresses. The URCI method contains specific severity rating ranges; however, the severity ratings are too coarse (or large) for use at Mn/ROAD. Washboarding is the most relevant example here. URCI has three severity levels: low, medium, and high. The dividing lines between the severity levels are 25 mm (1 in.) and 75 mm (3 in.). Washboarding became a vehicle control issue at about 25 mm (1 in.) because of the vibration resonance that would develop on the trailer bed. Washboarding was the controlling condition factor with a few rutting exceptions on the heavy side of Cell 33. Therefore, the worst condition that would exist before blading was scheduled when washboarding occurred in the low- to medium-severity transition area.

Ruts within the URCI are also assigned severity levels according to the rut depth. The severity levels are again, low, medium, and high; and the dividing lines between the levels are 50 mm (2 in.) and 75 mm (3 in.). These are, perhaps, acceptable levels for routine ratings; however, the Mn/ROAD case was complicated by the occurrence of localized rutting. In Cell 33 heavy, localized rutting would occur. The length of the rut was too large to be called a pothole, but short enough to have a similar effect on vehicle speed. The ruts typically were about 6 to 10 m (6.5 to 11 yd) long and would be 50 to 100 mm (2 to 4 in.) deep, depending on the method of measurement.

The measurement of rutting is explicitly described in the URCI manual. We chose a 1.22 m (4 ft) straightedge to measure the rut depth which was a sufficient length to span the wheel paths for this project. (Note: The driver did not wander laterally, resulting in a wheel path that was defined by the axle width and the dual tires.) A 2 m (7 ft) straightedge is the recommended length for general use.

Loose aggregate or float was also an issue regarding the measure of the severity of rutting and of float. The dividing lines between the three severity levels for float are 50 mm (2 in.) and 100 mm (4 in.). The text of the URCI does not explain how to deal with float when measuring rut depth, or the other way around for that matter. The figures in the URCI manual indicate, however, that rut depth is measured independent of float. The float is first removed to the level of the aggregate surface, and then the rut depth is measured. That is how the manual rut depth measurements were made at Mn/ROAD. The Pave Tech device, however, measured the combined effect of float and rut since there were no means of removing the float before measuring the rut. Figure 2 shows a schematic drawing of how the rut depths are measured.

As shown in Figure 3, the Pave Tech measures a greater rut depth than was measured with a straightedge. The difference is largely due to the amount of float. Also, because of the different approach in rut measurement, the Pave Tech values will be different from a measurement made from a straightedge. The two methods do correlate well when data is collected across a wide range of rutting.

2.1.1 Data Collection Used for Project

Monitoring of the aggregate and chip seal sections on the LVR utilized the general distress definitions of URCI; however, the severity levels were modified. The definitions used are as follows:

2.1.1.1 Washboarding (Corrugation) — The URCI definition of washboarding (. . . *closely spaced ridges and valleys (ripples) at fairly regular intervals. The ridges are perpendicular to the traffic direction.*) was used. The severity levels were modified for this project as follows:

Low 0 to 13 mm (0 to 0.5 in.)

Med. 13 to 25 mm (0.5 to 1 in.)

High 25 mm (1 in.) and over.

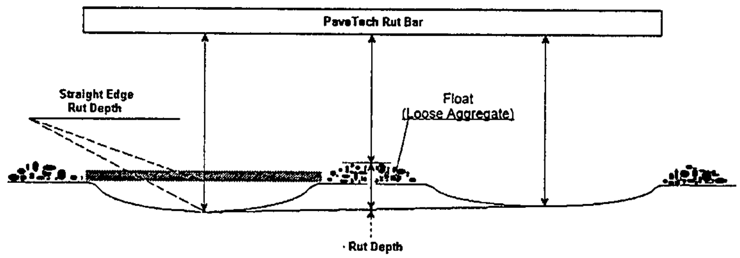


Figure 3. Rut measurements by Pave Tech and by straightedge.

2.1.1.2 Rut — The Mn/ROAD LVR facility has very distinctly established wheel paths. The rutting on the aggregate and chip seal sections was based on the 1.2-m (4-ft) straightedge. First, any loose aggregate or float was removed and then the straightedge was placed transversely across the wheel path. The rut depth measured is the largest distance between the surface and the bottom of the straightedge as shown in Figure 3. The severity limits were modified for this project as follows:

Low 0 to 6 mm (0 to 0.23 in.)

Med. 6 to 25 mm (0.23 to 1 in.)

High 25 mm (1 in.) and over.

These definitions were used as the basis of a visual survey that described the amount and extent of rutting. For instance, a section may be described as having low-severity rutting for the first 80.8 m (265 ft), medium rutting for 18.2 m (60 ft), and low severity for the remainder of the section. A straightedge was used to estimate where the severity levels changed.

Specific straightedge rutting measurements were also made at 15.2 m (50 ft) intervals during more active rutting times. In addition, the Pave Tech measured the rutting on each of the sections on an approximate monthly basis.

2.1.1.3 Dust — Dust relates to two specific and very different issues. One issue is health and safety. Dust obscures vision and may represent a health concern. The other issue is aggregate degradation and loss. Dust is difficult to effectively measure[11]. It requires collection devices at various offsets to the road, and these may only collect a fraction of the actual material loss. Another method of measure is based on opacity[12] and is oriented toward health and safety issues more than aggregate loss issues, although there may be some relationship to aggregate loss. Since Mn/ROAD is a structural experiment, we opted to sample the aggregate from the wheel paths rather than use dust measurements. This relates to the Gravel Layer attribute described in the PASER manual. The experiment did not run a sufficient length of time to get a measure of the change in thickness of the aggregate; however, changes in gradations could be investigated.

2.1.1.4 Potholes — The URCI definition of potholes was selected. Potholes never developed in Cells 33 and 35. If they had, the severity level may have been modified.

2.1.1.5 Loose Aggregate (Float) — The URCI definition of loose aggregate was used. No modification was made to the severity levels which used 50 mm (2 in.) and 100 mm (4 in.) depths as the boundaries between low, medium, and high severity. Float typically did not ever exceed the 50 mm (2 in.) depth on either Cell 33 or 35.

2.1.1.6 Blading — An indirect measure of the condition of an aggregate-surfaced road is the blading frequency required. In the Mn/ROAD experiment, it also impacts the other distresses, particularly potholes, rutting, washboarding, and float.

CHAPTER 3
MONITORING

Monitoring of the aggregate-surfaced and chip-seal surfaced sections on the LVR loop at Mn/ROAD included an inspection visit every two weeks along with occasional materials sampling and special testing at failure areas. Mn/ROAD staff collected deflection data, Dynamic Cone Penetrometer data, and Pave Tech data. Traffic data included a daily tabulation of the number of truck passes on each lane of the LVR. In addition, the sections contained instrumentation for temperature, soil moisture, soil pressure, and pore pressure. Limited data was collected from the instrumentation on these sections due to the workload of the Mn/ROAD staff and surfaced sections having a higher priority regarding the importance of instrumentation data.

Bi-weekly site visits were conducted by Ronald Urbach, Sr. Engineering Assistant at Braun Intertec Corporation. The visits were used to gather time-specific condition information of each of the eight observation sections and information was recorded in narrative form, which provided more flexibility to the monitoring process. The format of the narrative was based on a discussion of the conditions that were consistent within a specific length of the section. For this purpose, the severity definitions for rutting and washboarding were established as described above to provide more resolution to the ratings than existing rating systems would allow.

The narrative approach of rating the condition of a section consisted of describing the attributes of a consistent subsection within the overall section, including its limits. For instance, "The inner wheel path had low-severity rutting and medium-severity washboarding from station 0 to 265 and high-severity rutting with no washboarding from station 265 to 285; the washboarding was about 19 mm (0.75 in.) inch and the crests were 559 to 610 mm (22 to 24 in.)." This form of condition rating provides a more comprehensive description of the actual condition of the section; however, it is not as conducive to numeric quantification, such as an average amount of washboarding for the section. During several visits, eleven 1.22-m (4-ft) straightedge rut measurements were also taken at eleven evenly spaced intervals.

The narrative also included notes or comments relevant to the conditions at the site since the last survey. This included such items as unusual weather conditions, special concerns or observations made by the driver of the vehicle, and other relevant observations by the staff on site. Blading activity was noted whenever the information was available. Monitoring of blading activities was difficult to track. The blading was done by Ostego Township which was under contract to Mn/ROAD. Because the condition of the aggregate sections would affect the operation of the truck, the driver would initiate the request for blading, normally for excessive localized rutting in the heavy lane of Cell 33, or excessive washboarding on the legal lane of either Cell 33 or Cell 35. We requested that all blading activities would be recorded, by section and lane; however, we are not confident all blading operations were recorded. In addition to the narrative, photographs of characteristic conditions were taken.

The decision to use the narrative approach to the condition monitoring was made during the initial condition surveys. It was observed that the condition could, and did, vary significantly within each of the sections and measurements made at specific intervals may not fully reflect the condition of the section. Specific interval sampling is much more suitable for asphalt- and concrete-surfaced pavements because the processing and placement of the bound surfacing materials create a more consistent or uniform section.

A description of the data collected by Braun Intertec and by Mn/ROAD specific to the aggregate and chip seal sections is as follows:

3.1 INSTRUMENTATION

All of the sections at Mn/ROAD were instrumented. The instrumentation placed in the aggregate sections can be grouped into two basic categories by the data they provide: environmental and load.

The environmental sensors include:

- thermocouple to measure soil temperature;
- moisture sensors to measure the moisture content of the soil;
- resistivity probes to measure the depth of frost penetration and thaw penetration;
- static pore pressure cells to measure the static pressure of water in the soil;
- neutron probe access tubes to measure the moisture and density of the soil; and
- open standpipes to measure the watertable.

The load sensors include:

- soil pressure cells; and
- dynamic pore pressure cells.

Cells 33 and 35 were the most heavily instrumented. For example, Cell 33 included seven Kulite soil pressure cells, six Geokon 3500 soil pressure cells, nine Geokon 4800E soil pressure cells, five Geokon 3400S dynamic pore pressure cells, five Geokon static pore pressure cells, four thermocouple trees (a vertical shaft containing a number of thermocouples), four soil resistivity probes, two neutron probes, twenty-four TDR probes, twenty-four Watermark moisture blocks, and one open stand pipe for water table readings. Cells 32 and 34 had less instrumentation; they each had six Kulite soil pressure cells, one soil resistivity probe, one thermocouple tree, one neutron probe access pipe, six TDR probes, six Watermark moisture blocks, and one open standpipe. A detailed listing of the instrumentation for each section by type, location, and depth is shown on the sensor placement plan sheets which are included in the appendix. Note that the instrumentation in Cell 32 is in the legal load lane and in Cells 32 to 35, the instrumentation is in the heavy load lane.

Data from the load sensors in any of the aggregate sections are not available. Data from all of the environmental sensors except the TDR probes and the neutron access probes are available.

Moisture and thaw data are the most relevant to the evaluation of the performance of the aggregate and chip seal sections. The only moisture data available, however, are from the Watermark blocks installed in the subgrade; the highest sensors are 457 mm (18 in.) below the surface, or six inches into the subgrade soil. The TDR traces have been recorded, but the traces have not been evaluated to determine moisture content. The Watermark block readings are not considered to be very accurate according to the Mn/ROAD staff. The readings from the Watermark blocks during the spring thaw of 1995 do show the thawed readings to vary between cells.

Figures 4 through 7 show Watermark block readings during the spring thaw of 1995. The resistance values are high during the frozen period, and then drop quickly to a lower value. A comparison of the 0.46 m (1.5 ft) deep sensor in Cells 33 and 35 show a much higher reading in Cell 35. In fact, overall, the readings for Cell 35 tended to be higher after the thaw than the other sections which is consistent with the performance during the thaw period.

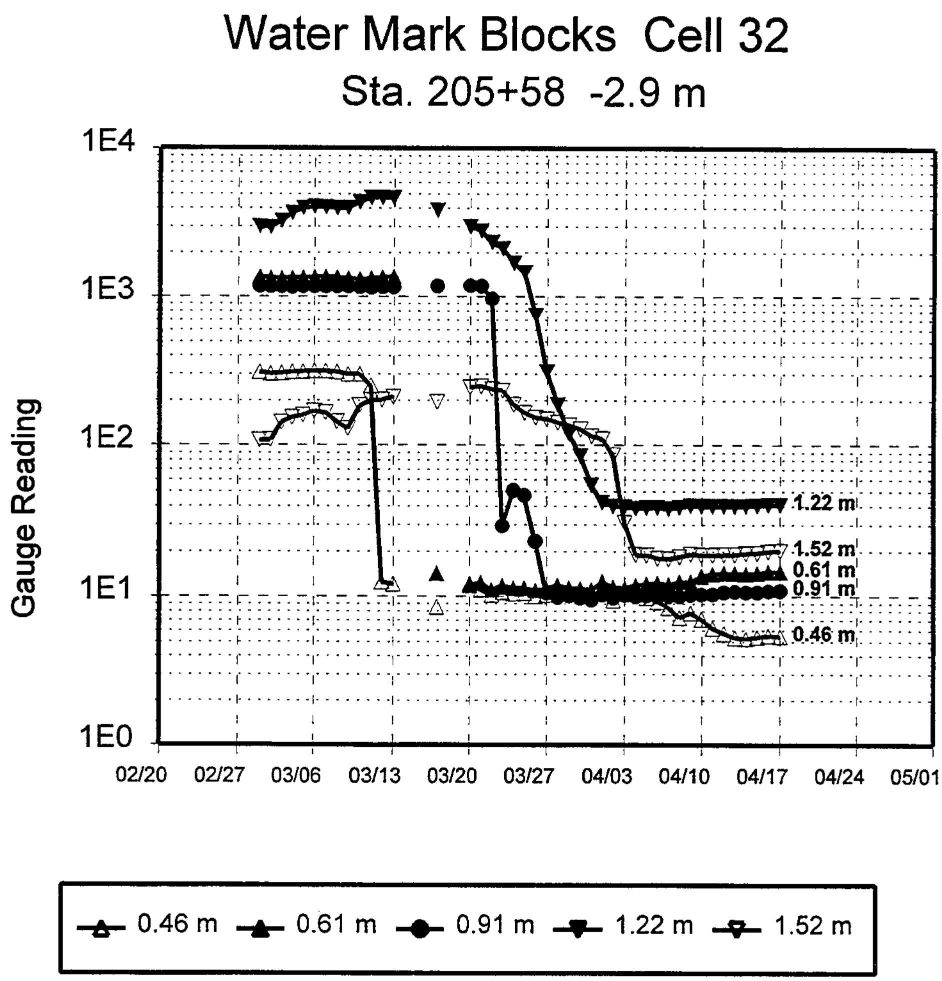


Figure 4. Watermark readings during spring thaw for Cell 32.

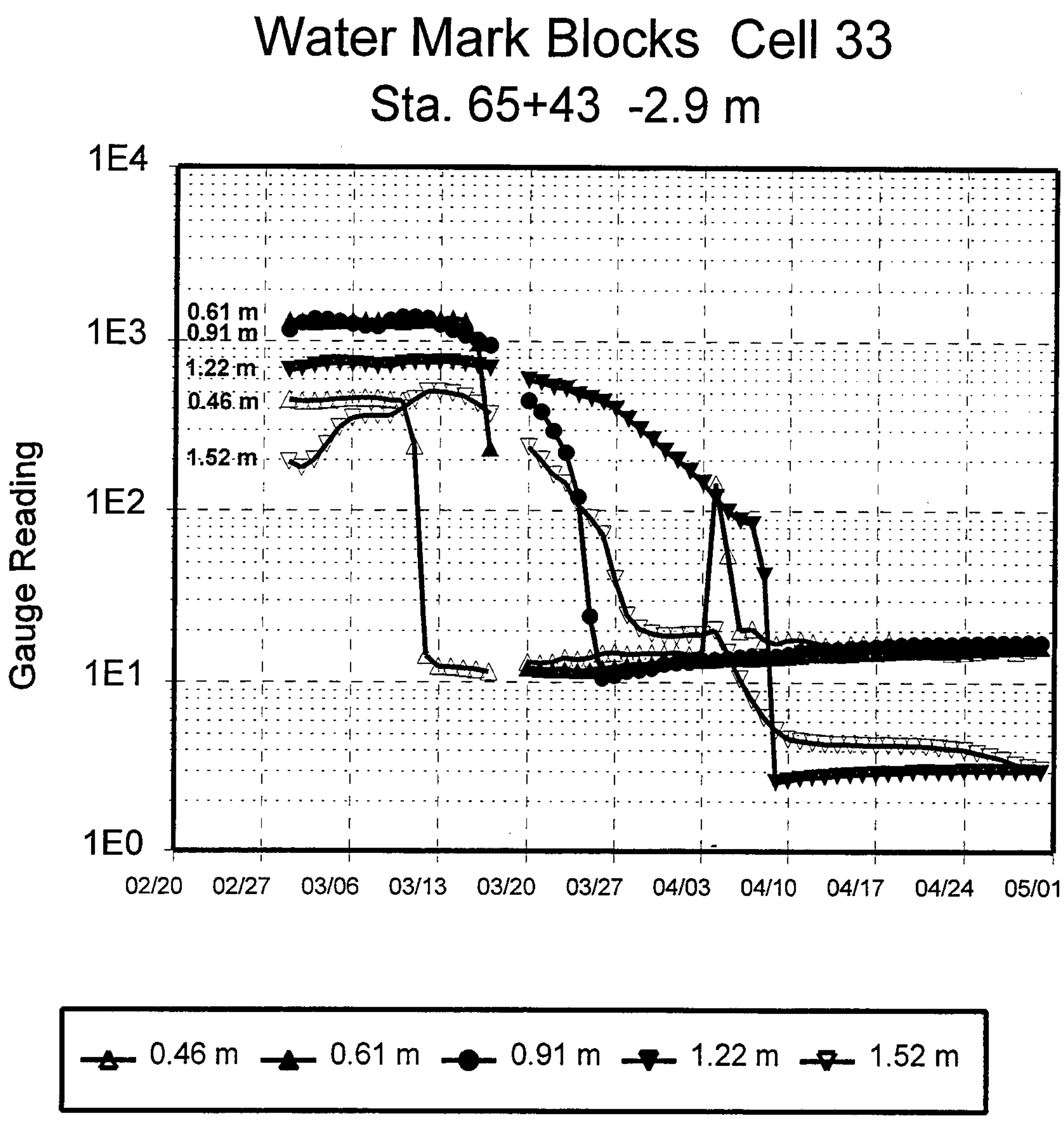


Figure 5. Watermark readings during spring thaw for Cell 33.

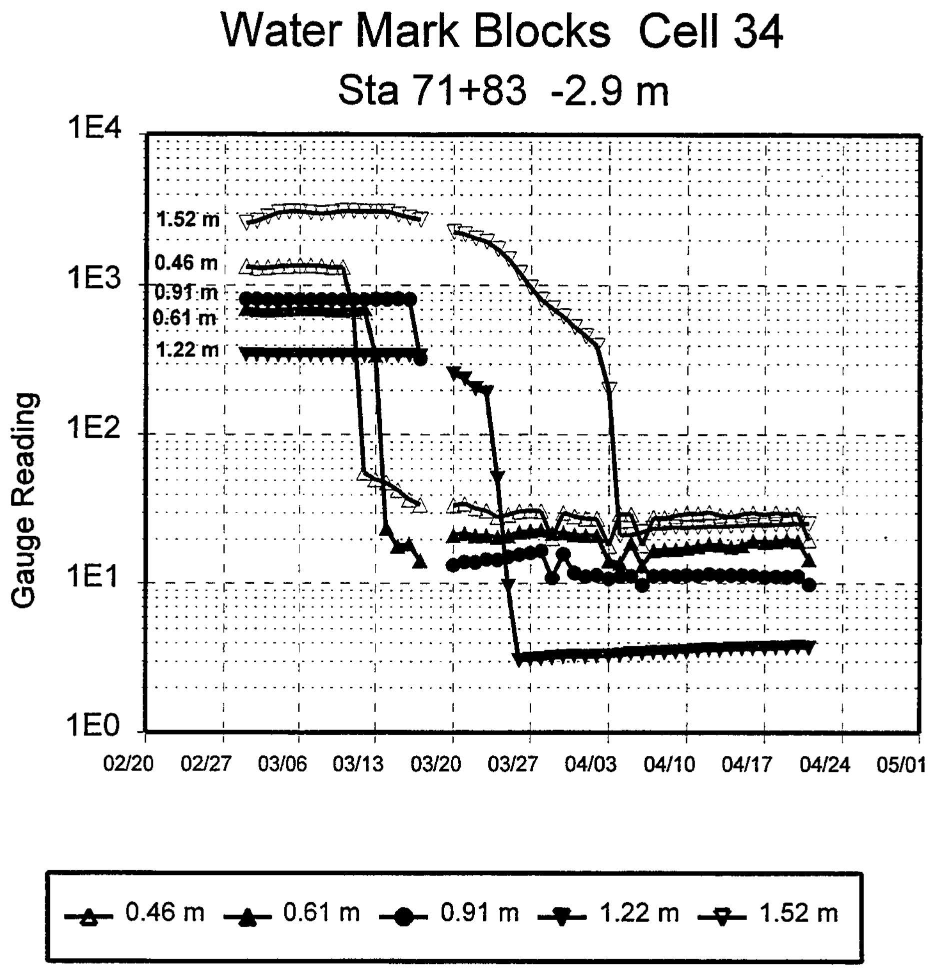


Figure 6. Watermark readings during spring thaw for Cell 34.

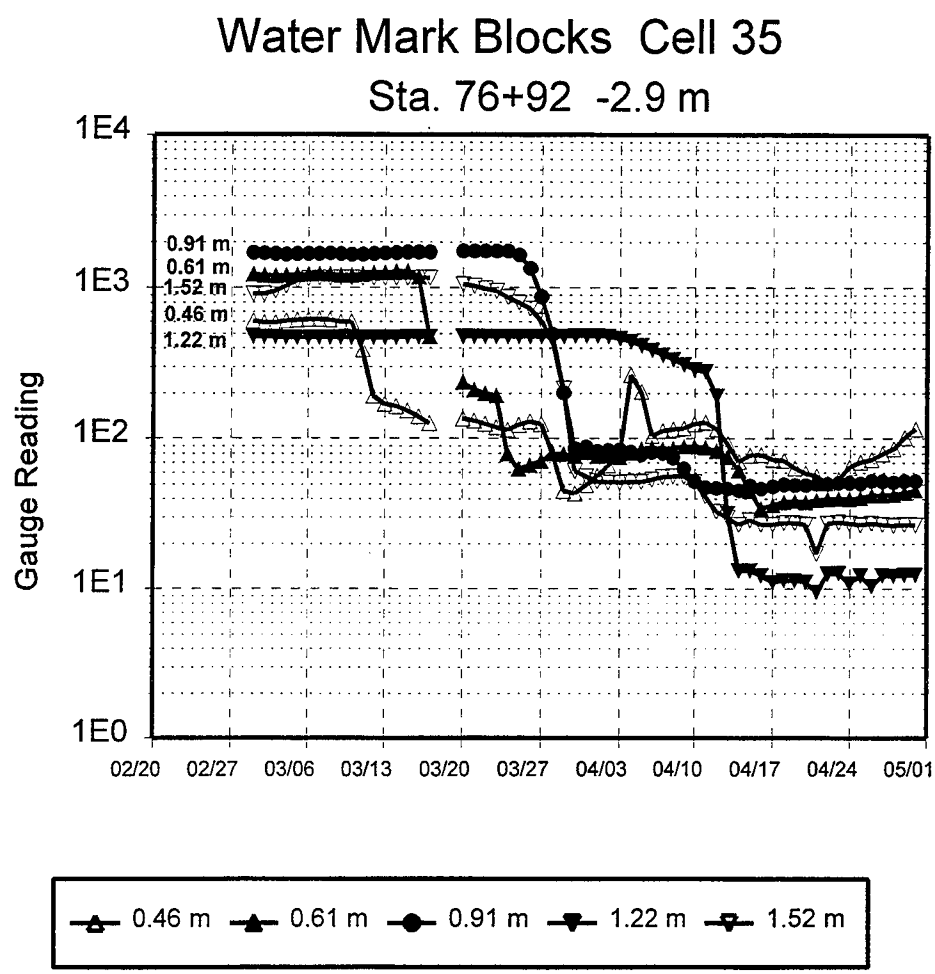


Figure 7. Watermark readings during spring thaw for Cell 35.

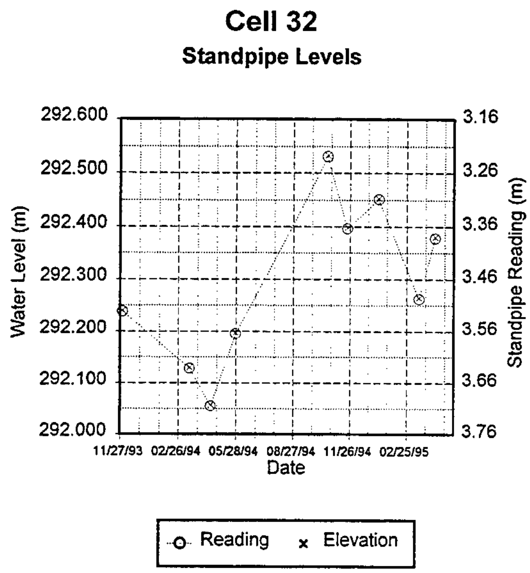


Figure 8. Standpipe readings for Cell 32.

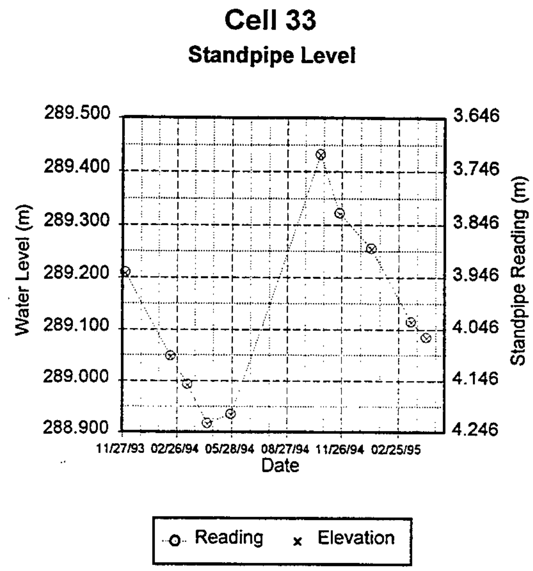


Figure 9. Standpipe readings for Cell 33.

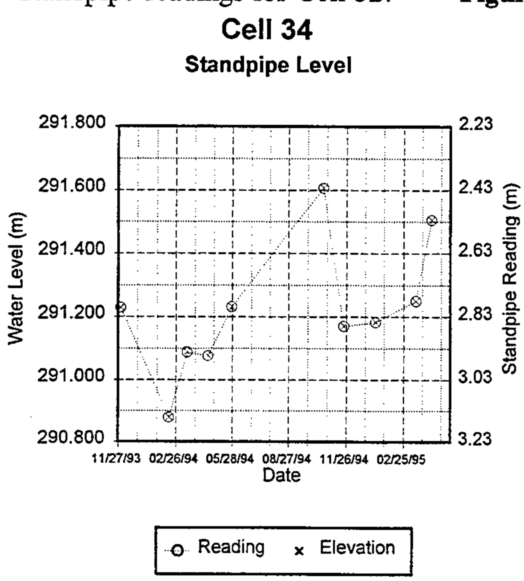


Figure 10. Standpipe readings for Cell 34.

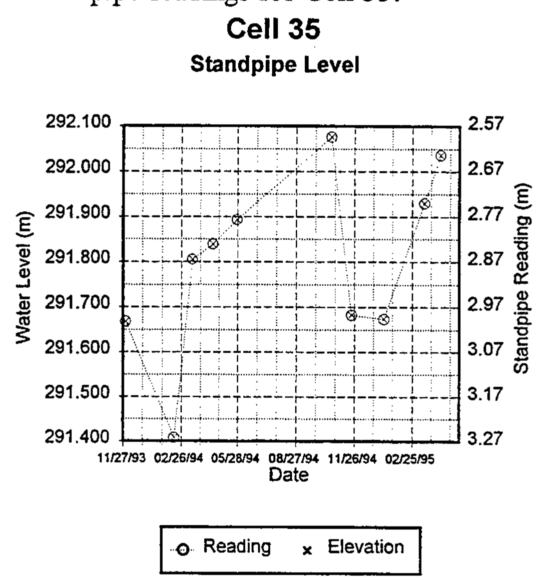


Figure 11. Standpipe readings for Cell 35.

The open standpipes, Figures 8 to 11, have been read nine to ten times over the course of the study and have shown a 0.5 to 0.6 m (1.6 to 2 ft) rise in water level from the summer of 1994 when traffic started on the sections. Moisture measurements in the sections during this time, however, did not indicate any general increase in soil moisture content.

The thaw in March of 1995 was quick as illustrated by Figure 12. The top thermocouple rose above 0 °C the morning of March 12 for all the cells except Cell 35 which crossed 0 °C late in the afternoon of the 11th.

(The actual freezing temperature of the materials may be below 0 °C.) The thermocouple at a depth of 610 mm (24 in.) rose above 0 °C on the afternoon of the 21st of March, except for Cell 35 which crossed over on the morning of the 22nd. It was during this period that Cell 32 failed due to severe rutting. The other sections also showed various degrees of deterioration during this period. Once the thaw occurred, no further freeze periods occurred.

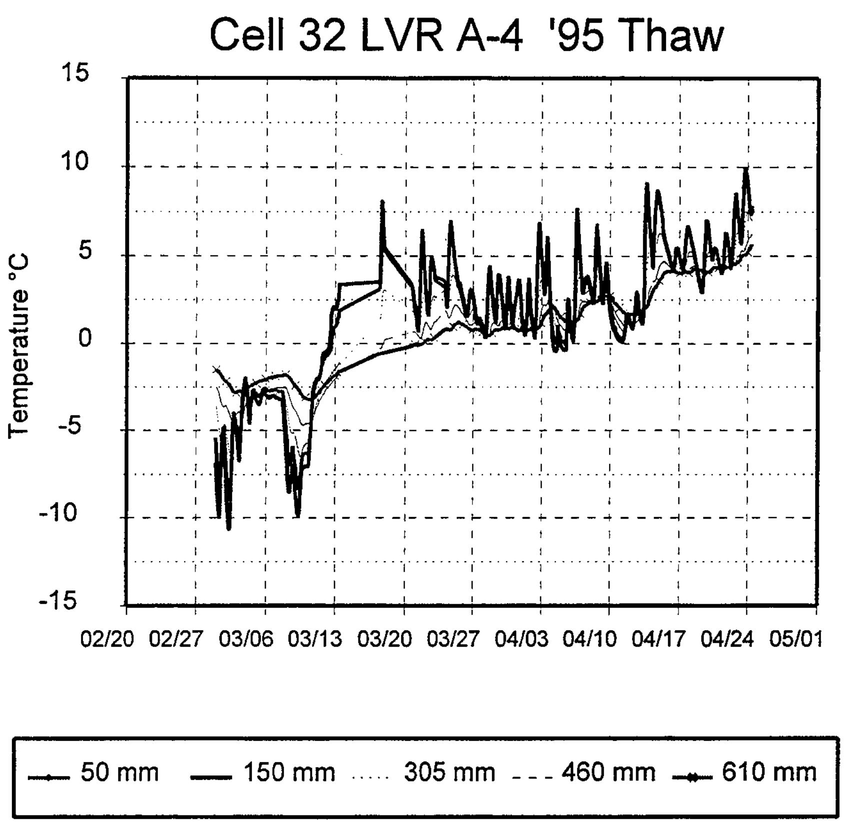


Figure 12. Soil temperature during the 1995 spring thaw.

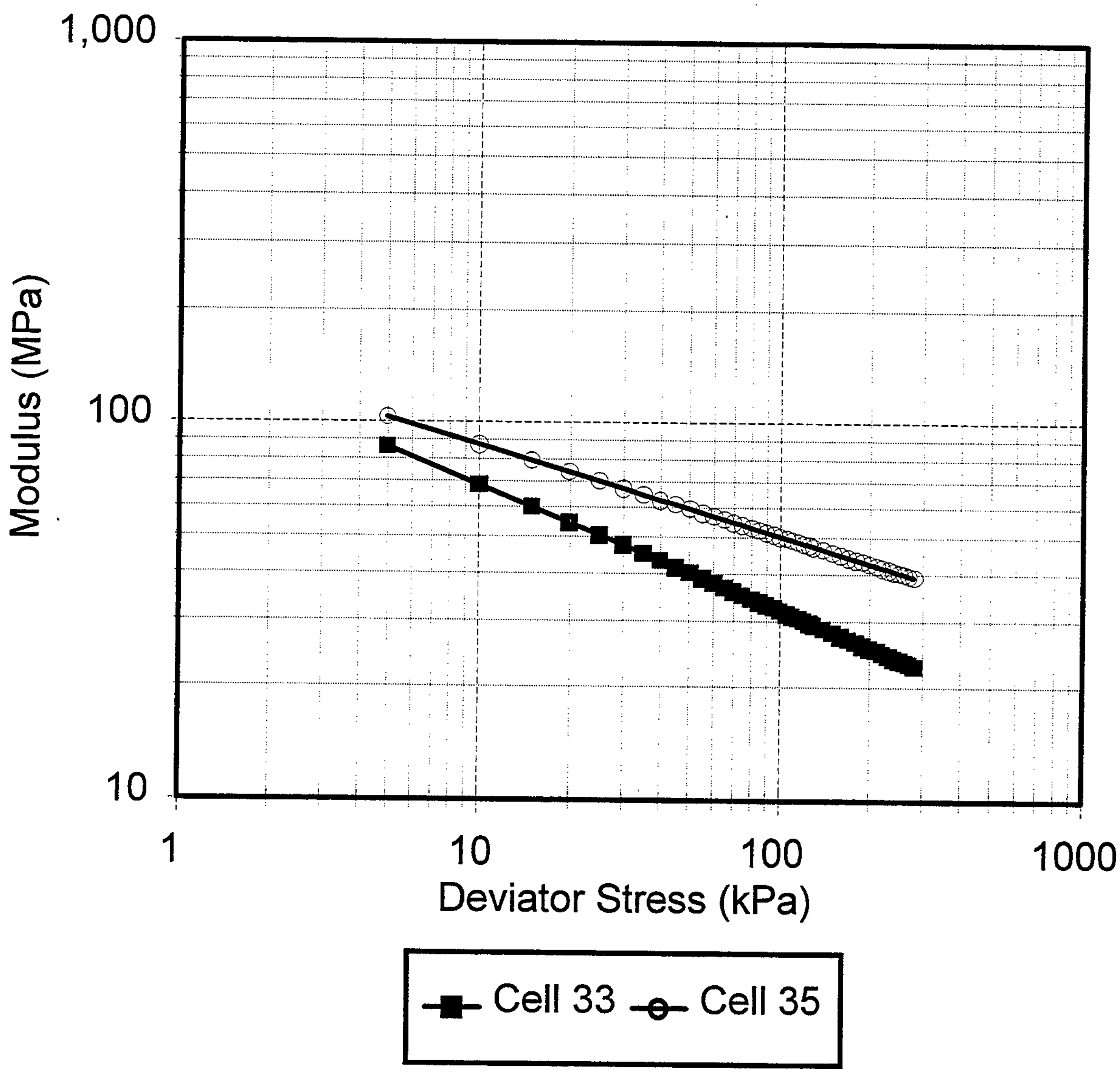


Figure 13. Subgrade Resilient Modulus from Recompacted Bag Samples.

3.2 MATERIALS

The structural component of the sections is made up of the aggregate and subgrade soils. The aggregate gradation specification used basically split the existing Mn/DOT Class 1 gradation into a coarse band and a fine band as shown in Figure 2. The subgrade consisted of a silty clay loam for all four sections; however, as with natural soils, variations existed. Laboratory resilient modulus results from recompacted bag samples are shown in Figure 13 and results from thin wall samples (Figures 14 to 17) show variation from cell to cell that show some consistency with other tests and with the performance of the cells as discussed later.

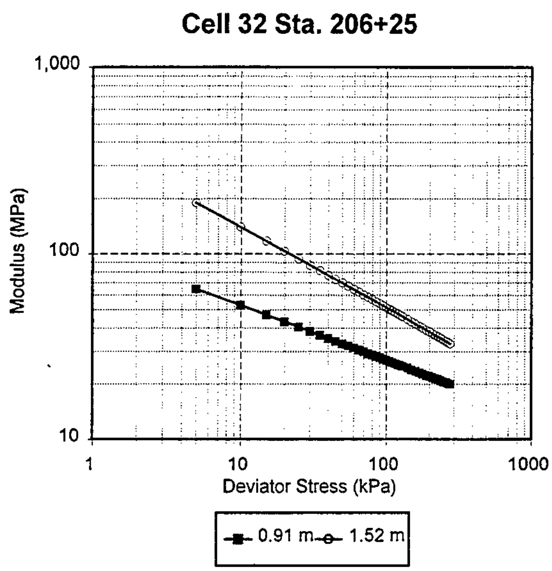


Figure 14. Resilient Modulus thin wall samples in Cell 32.

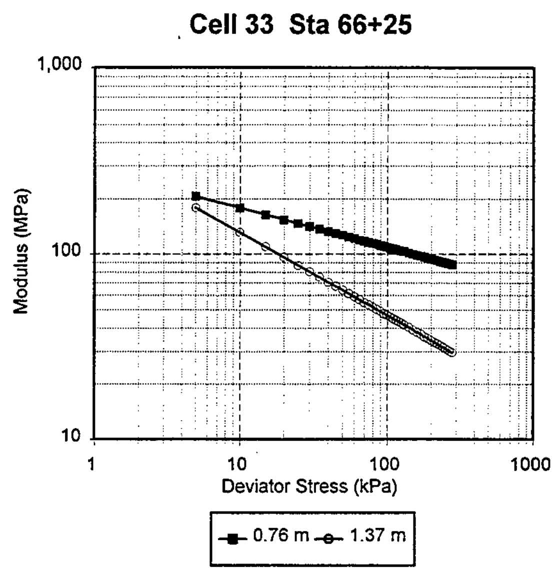


Figure 15. Resilient Modulus thin wall samples in Cell 33.

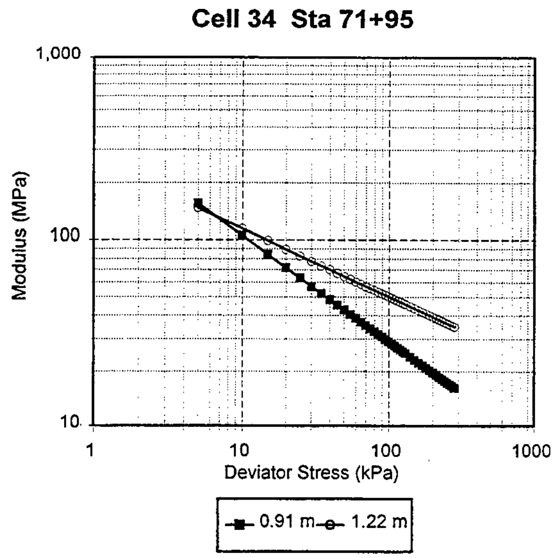


Figure 16. Resilient Modulus thin wall samples in Cell 34.

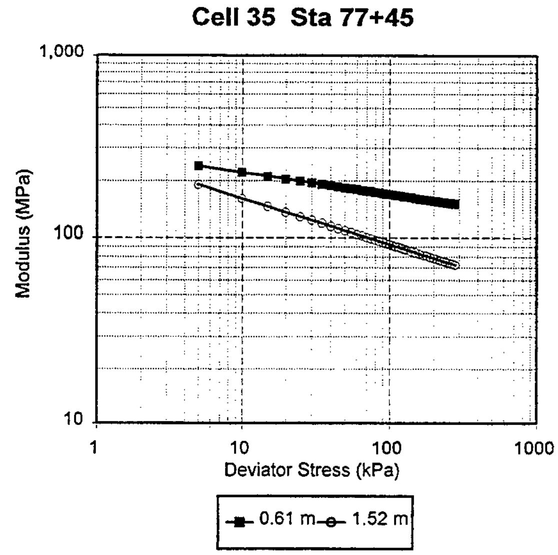


Figure 17. Resilient Modulus thin wall samples in Cell 35.

3.2.1 Aggregate

The Mn/DOT specifications for aggregate surfacing materials include a fairly broad gradation band and some controls on durability. The Class 1 gradations deal with pit run materials, and Class 2 are for 100 percent quarried materials. There are no gradation requirements (or any other type of requirement) for the minus 75 μm (#200) fraction of the materials. Figure 4 shows the gradation band of the Class 1 specifications and the fine and coarse gradations used at Mn/ROAD. Figures 18, 19, and 20 show gradation bands recommended by the Finnish Road Administration, South Dakota and Illinois. South Dakota and Finland require clay as a binder soil and South Dakota specifies what the plasticity index must be for the fines. There is no test data regarding the gradation or the Atterberg limits of the minus 75 μm (#200) material for the aggregates used in the aggregate sections Cells 32 to 35. Tests performed on the stock pile samples in June 1995 indicated that the minus 75 μm fraction of the Class 1F was 9.5 percent silt and 1.5 percent clay (11.0 percent passing the 75 μm sieve). The breakdown of the minus 75 μm fraction of the Class 1C aggregate is 6.6 percent silt and 1.2 percent clay (7.8 percent passing the 75 μm sieve).

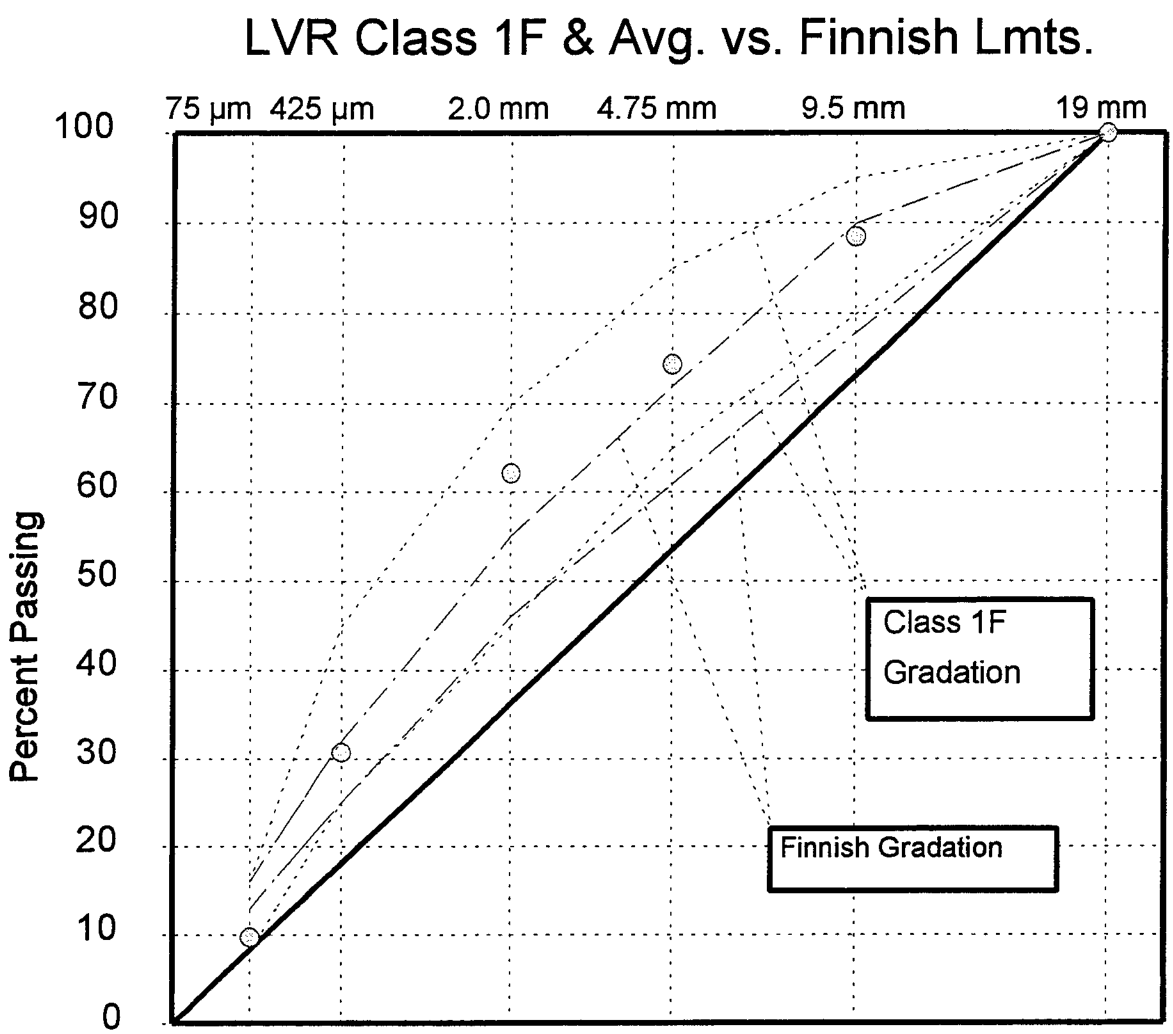


Figure 18. Finnish gradation band shown within Mn/ROAD Class 1F limits.

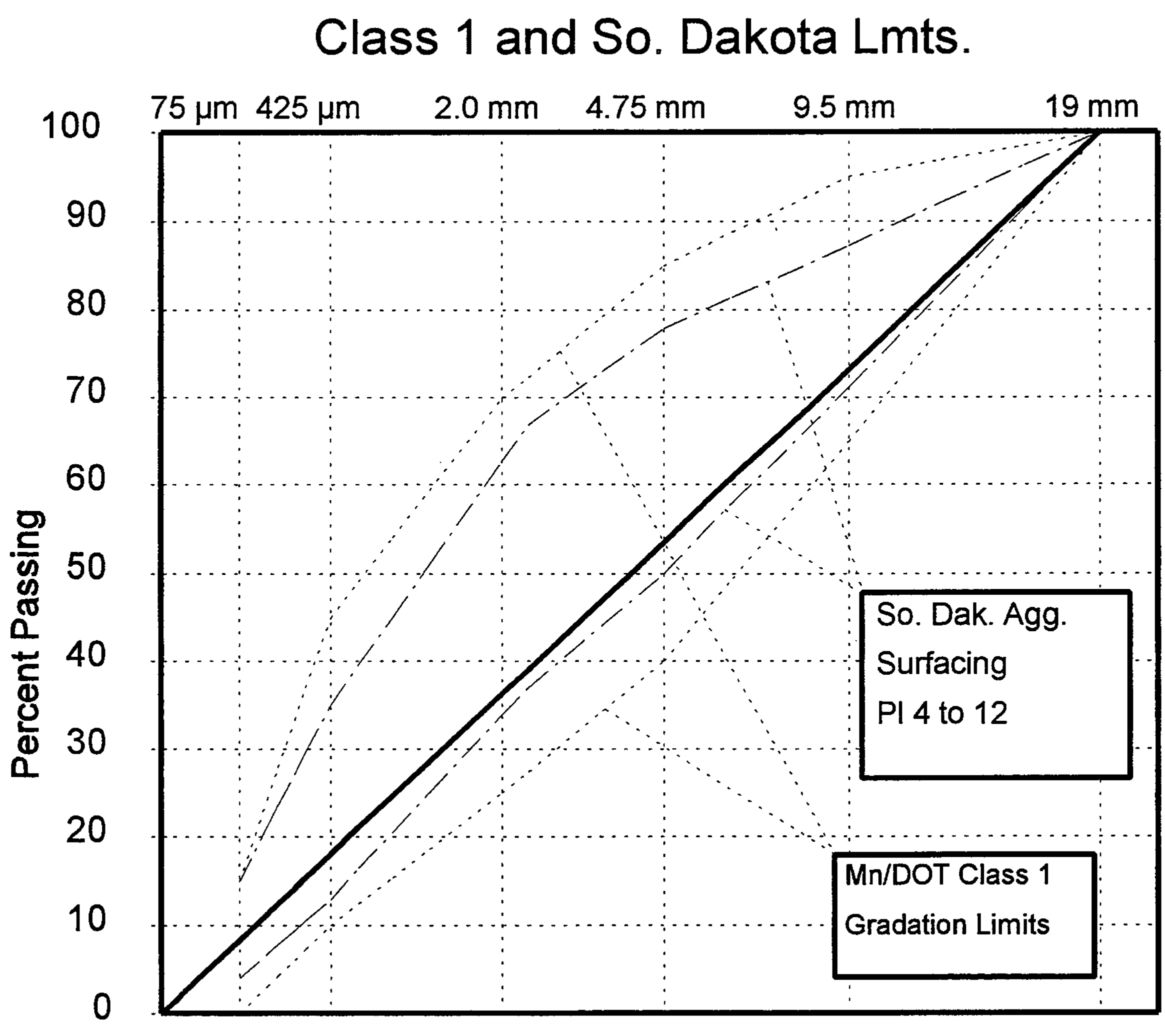


Figure 19. South Dakota surfacing aggregate gradation shown within Mn/DOT Class 1.

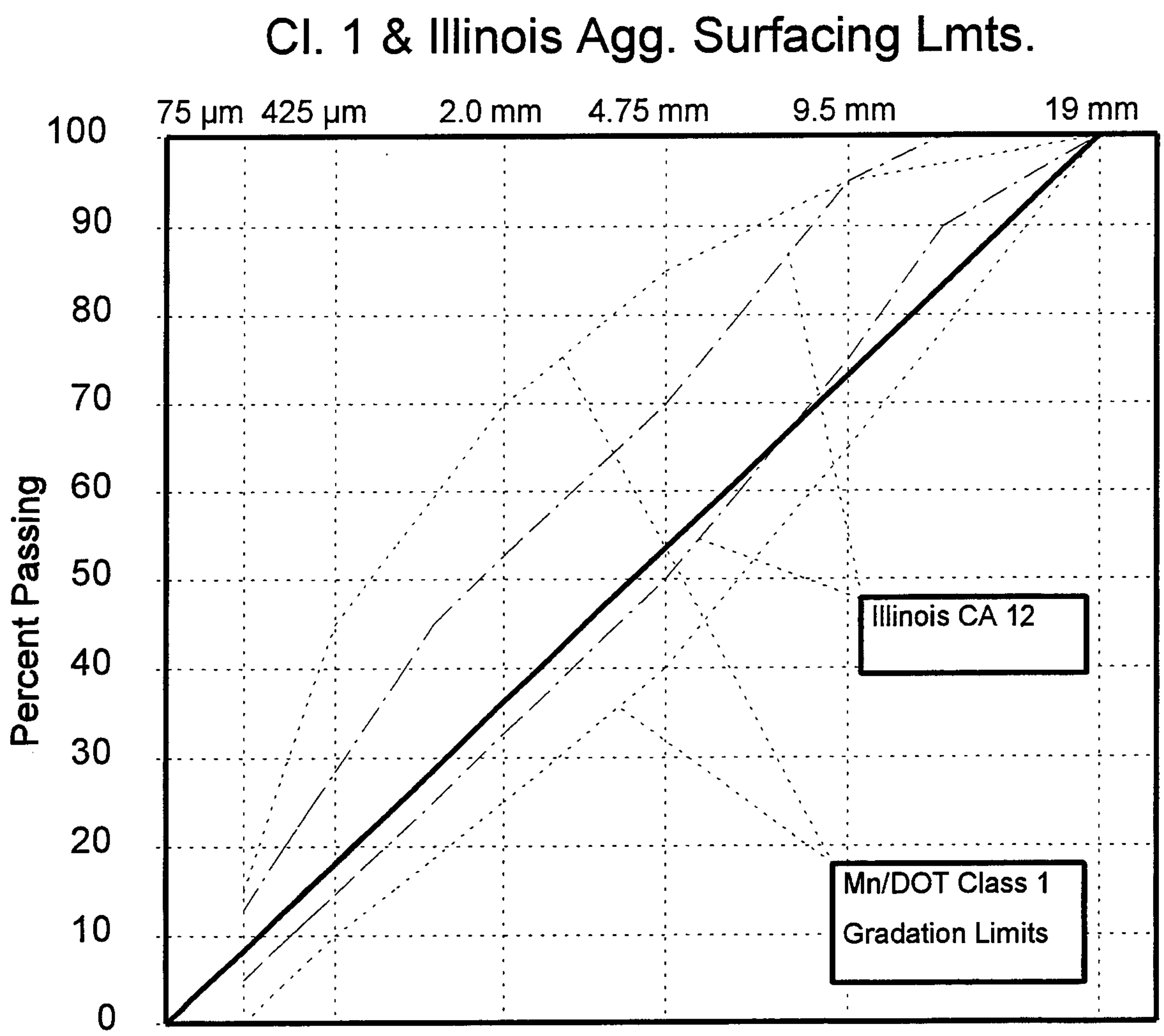


Figure 20. Illinois surfacing aggregate gradation shown within Mn/DOT Class 1.

From the gradation plots, it can be seen that Minnesota has a much less restrictive specification for aggregate surfacing materials than the others shown.

The intent of dividing the Class 1 gradation band into two bands, one on the fine side (Class 1F) and one on the coarse side (Class 1C), was to evaluate the effect this would have on performance. It was the expectation that the Class 1C would perform better than the Class 1F. From the performance of the test sections, it can be concluded from the laboratory tests and field performance that the Class 1C was much poorer than the Class 1F, contrary to the original thought. The source of the Class 1F material was from the "Buffalo Pit" and the Class 1C material was from the "Goetzky Pit." Since the sources are different, there may be other reasons for difference in performance of the two materials. Particle shape and texture are two items that may affect performance.

It is not readily apparent from the gradations that the coarse would perform worse than the fine, so other information is needed. Laboratory tests performed at the University of Illinois under the direction of Professor Marshall Thompson showed that the Class 1C was a poor material and was particularly moisture sensitive.[13] Professor Thompson's specific quote is:

> *"A separate set of observations and comments is included for CL-1Csp. It seems that this material is a LOSER!!"*

All of the test results, dynamic cone penetrometer and resilient modulus, were poorer for the Class 1C than for the Class 1F when run at 7 percent moisture and the tests could not be run at 9 percent moisture. No shear test results were given, and we are assuming that the test could not be run. It may be speculated that the performance was partly due to the nature of the minus 75 μm (#200) sieve material. The coarse had less minus 75 μm (#200) sieve material and a performance-based guess is that the fines in the Class 1C were more silt size and there were more clay size in the Class 1F. At least the behavior of the materials under traffic indicated that may be the case. The Class 1F seemed to knit together better and would form a significantly harder crust during dry times. (It was interesting to note that once the crust formed, it would form cracking in the wheel paths similar to alligator cracking except the crack orientation was more transverse and longitudinal.) If the minus 75 μm (#200) sieve material is low, and is silt size, the aggregate would have low cohesion and higher permeability. The low cohesion, along with low shear strength, would correspond with greater potential for washboarding. The higher permeability would lead to an overall reduction in strength of the aggregate, and subgrade, due to the possible buildup of water at the aggregate-subgrade interface.

Gradation changes occur over time due to the effects of traffic, rain, blading, and snow plowing. It appears that the gradation changes are greater for the Class 1C material than for the Class 1F material. In both the Class 1F and Class 1C, there is some material loss above the 2.0 mm (0.08 in.) sieve and some material gain below the 2.0 mm (.07 in.) sieve. This results in less material passing the 9.5 mm (0.37 in.) and 4.75 mm (#4) sieve. An article regarding the Finnish approach to gravel-road maintenance suggests that the gradation of the aggregate used for resurfacing be specially selected to counteract the effects of the shift in gradation due to traffic and weather, and that the new material be blended into the existing aggregate.

3.2.1.1 Gradation Shift — Figure 21 shows the shift in gradations for the Class 1F. This material did not shift as much as the Class 1C. This should be checked on other aggregates to determine if the gradation shift varies more on some aggregates than on others.

Figure 22 shows the gradations of Class 1C samples taken late in the summer of 1995. It shows that the gradation of the material has shifted from what was originally placed. The mechanisms at work on the gradations include an abrasion form of degradation, loss of fines as fugitive dust, loss of fines and sands carried by water splashed out of the corrugations and ruts by traffic, blading, and snowplowing. There may even be other mechanisms at work not listed. The measurement of material lost in the form of dust was included as part of the original work plan; however, it became evident that what was of interest was the thickness and gradation of the material left in place. The loss by dust transport is more of an environmental and safety issue. Additional material can be added, or blended in, to restore the gradations to their original values. This can be considered as the measure of aggregate loss, in terms of gradation. Another part of the aggregate loss is the total effective thickness of the aggregate at any point in time. The process recommended by the Finnish is to make the original gradation at time of construction along the coarse side of the band and to design the gradation of the aggregate to be added at a later time so that it would restore the gradation into the desired band after it was blended into the in-place aggregate. The gradations shown in Figures 21 and 22 are only one sample location from each lane of Cells 33 and 35; the results are expected to vary if other samples are taken; however, gradations of samples taken earlier are similar to that shown in Figures 21 and 22.

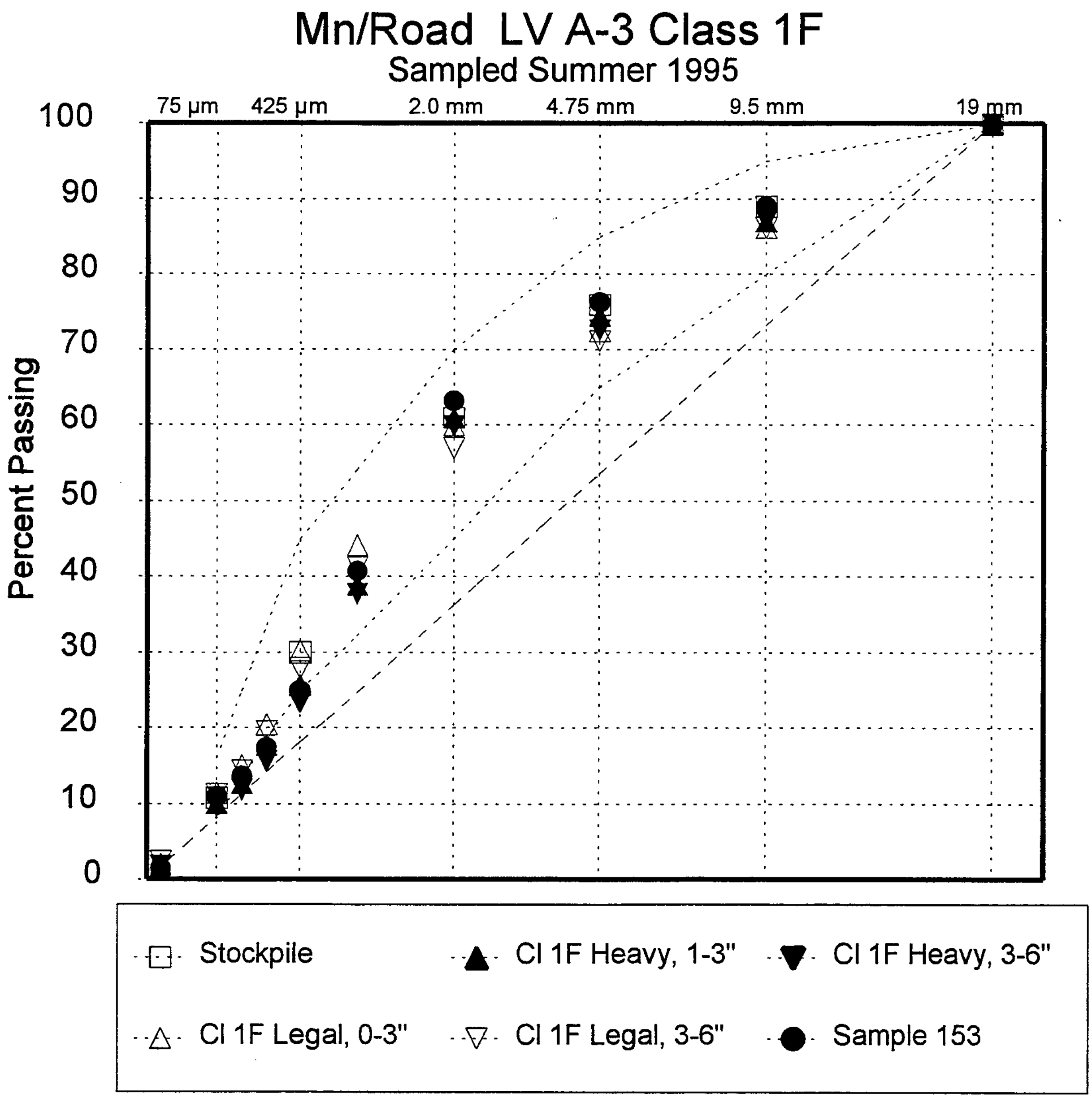


Figure 21. Gradations from Cell 35 after 1994 traffic.

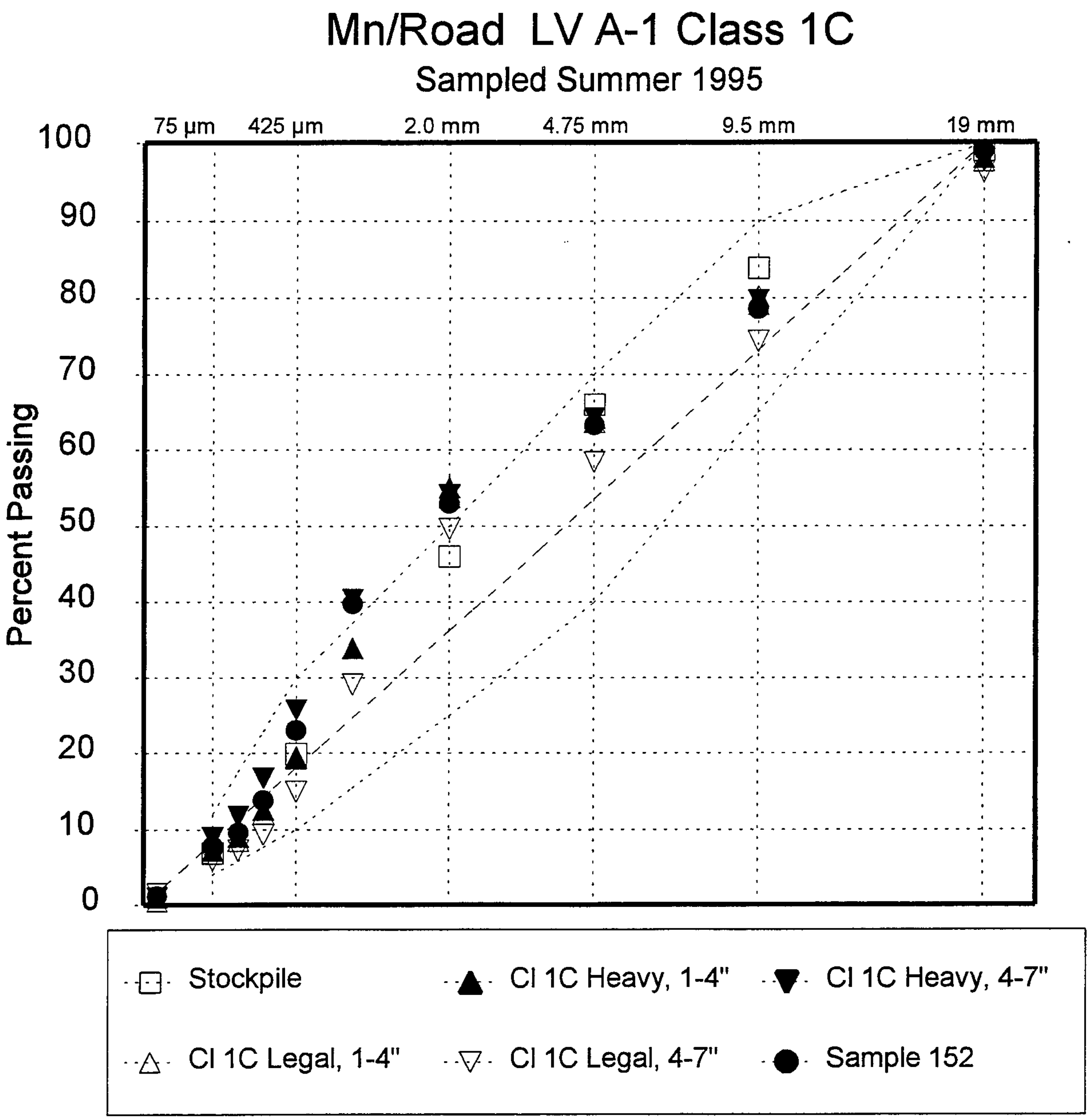


Figure 22. Gradations from Cell 33 after 1994 traffic.

A factor that may have an effect on the gradations of the aggregate of these sections is the Class 1C and Class 1F aggregates were mixed at the surface when the sections were reshaped by Buffalo Bituminous in preparation for the chip seals. The blading operation involved the remixing of the top 50 mm (couple inches, no measure was made) of material to break the crust and, possibly, because of the localized rutting that developed in Cell 33. The material was windrowed and then bladed back and forth back into position. The blade operator traveled in the normal direction of traffic and intermixed the Class 1F from Cell 34 over the easterly third of Cell 33 and intermixed the Class 1C from Cell 33 over the westerly third of Cell 34 in the respective lanes.

3.2.1.2 Aggregate Thickness — The total effective thickness of the aggregate in Cell 33 and Cell 35 is the remaining aspect of aggregate loss. There are a number of research studies that relate aggregate loss to traffic. There may not have been sufficient time for measurable aggregate loss on this project. The results of the dynamic cone penetrometer tests before traffic began in the fall of 1994 can be evaluated to determine the depth to where the aggregate/subgrade interface is by the penetration index. This test can effectively measure the amount of effective remaining aggregate and will account for both the loss from the surface and also to any loss due to pumping of subgrade soil into the base, or base into the subgrade.

A case of a definite loss of effective aggregate thickness is in the severe rutting areas of the heavy lane of Cell 33. The effective aggregate thickness within the ruts ranged from 100 to 150 mm (4 to 6 in.), far less than the constructed thickness of 305 mm (12 in.).

3.2.1.3 Subgrade Soil — The subgrade soils for this section of the low-volume loop are a gray silty clay loam. The soil was sampled during testing and after construction. The target density of the soil was 100 percent standard Proctor density (T-99). The gradations, Atterberg Limits, R-value and other characteristics of the subgrade soil are described here.

The subgrade modulus from bag samples taken June 26, 1992, indicated the soil under Cell 33 was significantly weaker than the soils under Cell 35. Since the soil is plastic, the modulus is described by the deviator stress model as follows:

$$M_r = k_1 \delta^{k_2}$$

where:

M_r = Resilient Modulus (Mpa)

k_1 = Constant: 146.6 for Cell 33, 151.5 for Cell 35

δ = Deviator Stress, kPa

k_2 = Constant: -0.3314 for Cell 33, -0.2402 for Cell 35.

The graphical representations of the laboratory modulus from the bag samples are shown in Figure 13 which shows that the soil from Cell 33 is weaker than the soil from Cell 35.

Table 4. Resilient Modulus from Thin Wall Sample

Sample Location	Depth	Density % T-99	Moisture Content	Constants K_1	Constants K_2
Cell 32 Sta. 206+25	91.4 cm	108.8%	17.0%	103.5	-0.2924
	152.4 cm	109.0%	17.2%	380.0	-0.4338
Cell 33 Sta 66+25	76.2 cm	109.2%	14.1%	288.7	-0.2114
	137.2 cm	104.1%	17.3%	365.3	-0.4457
Cell 34 Sta 71+95	91.4 cm	101.3%	18.2%	383.4	-0.5609
	121.9 cm	105.3%	15.7%	260.1	-0.3573
Cell 35 Sta 77+45	61.0 cm	109.6%	13.1%	286.6	-0.1148
	152.4 cm	102.6%	16.9%	279.3	-0.2404

Thin wall samples taken from the grade in 1992 were tested in the laboratory for resilient modulus; the results are shown in Table 4 and in Figures 14 to 17. The results show seemingly random variation with both location and depth. The comparison of the results from Cell 33 and 35, however, are in the same order as results from the bag samples. Another characteristic of the thin wall samples is the remarkable high densities, ranging from 101.3 percent to 109.6 percent standard Proctor.

Proctor curves of subgrade soil samples were not available. The moisture density curve slope on the high side of the optimum moisture content would give an indication regarding the sensitivity of the soil to moisture.

3.2.1.4 Deflection Tests — Deflections were measured with a Dynatest Falling Weight Deflectometer several times during construction and after construction. Tests were taken on the prepared subgrade on June

26, 1992. After the base aggregate was placed, the sections were tested again on August 17, 1994, and three times during the spring thaw in 1995.

The deflection results can be analyzed in a number of different ways. One such way, and the way the data is presented here, is to calculate a surface modulus for all of the sensor positions. For comparison purposes, the minimum surface modulus value was selected to represent the modulus at each test location and drop. Frequency distribution plots of the "Minimum" surface modulus for each test location graphically show how the strength of the sections vary.

Figures 23 and 24 show the average surface modulus plots for Lane 1 of Cells 33 and 35. The plots all show a minimum surface modulus corresponding with the second or third sensor. The classical curve shape for a surface modulus plot is to have the highest modulus at the center of the load plate and decreasing to a horizontal asymptote for the outer two sensors. When there is a minimum, as in Figures 23 and 24, it indicates that there is an intermediate layer under the surface that is softer than the underlying layers. The increase in strength with depth may mean that there is layering within the subgrade, an apparent stiff layer (hard bottom) under the subgrade soil, or that the soil is stress weakening. Stress weakening is a condition where the soil weakens as the loading is increased; this is shown by the laboratory tests represented by Figures 13 to 17. To illustrate the structural difference between Cell 33 and 35, a comparison of the minimum surface modulus on August 17, 1995, shows Cell 33 to be 18.8 MPa (2727 psi) whereas Cell 35 is 140.9 MPa (20,400 psi), over a factor of seven greater.

Figures 25 through 28 show the frequency distribution of the surface modulus values for June 24, 1992 (tests on subgrade only); August 17, 1994; April 20, 1995; and April 25, 1995. As the graphs show, Cell 33 is by far the weakest. Once the aggregate was placed, Cell 35 was by far the strongest which ranks in consistent order with the performance of the sections. As discussed in the paragraph above, the average surface modulus for Cell 35 is 7.5 times greater than the surface modulus for Cell 33 on the same day. Cell 33 could carry no more than 40 passes of the heavy load before localized rutting failures would develop, whereas, the rutting on Cell 35 was insignificant over the course of the study.

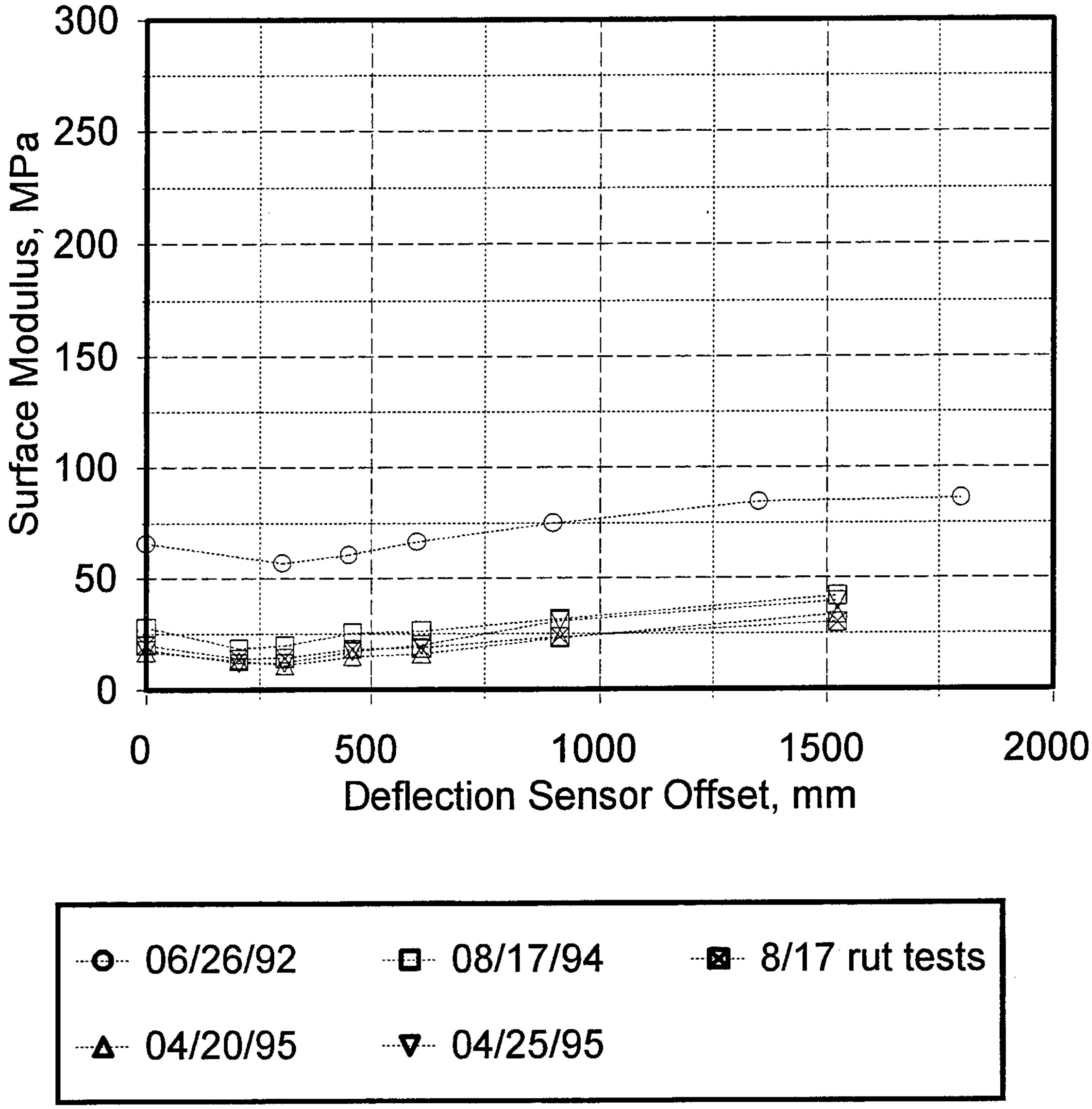


Figure 23. Average surface modulus for Lane 1 on Cell 33.

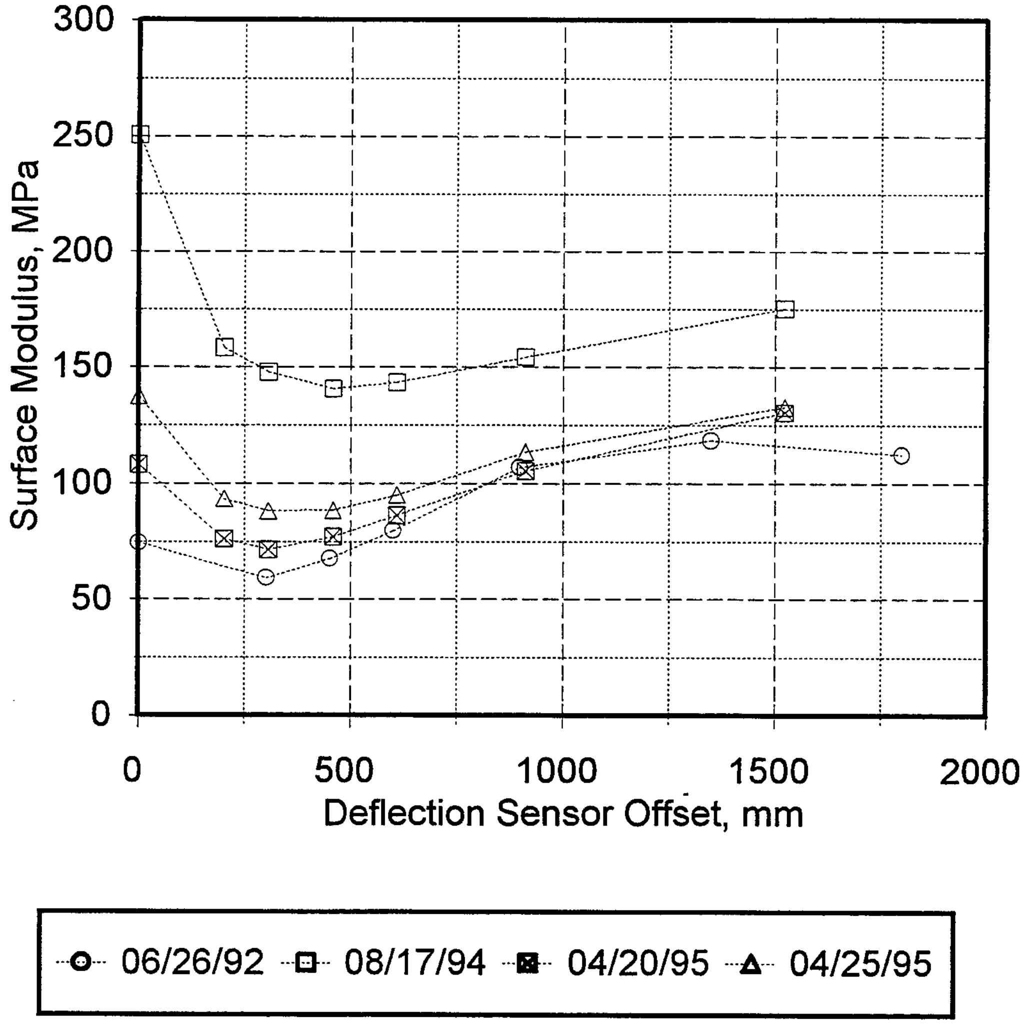


Figure 24. Average surface modulus for Lane 1 of Cell 35.

From the data available, there is no physical explanation for the large strength variations in the four Cells, particularly in 1994. The author may speculate as to potential reasons, including:

- The poor strength of the Class 1C aggregate may have contributed to the overall strength loss. The Class 1C was not a very good material as indicated by Professor Thompson from tests performed at the University of Illinois.

- The poor strength of the Class 1C would result in higher pressure on the subgrade soil, multiplying the effects of the load on a load softening subgrade soil. The subgrade soil laboratory resilient modulus test results do show the soil to be load softening as indicated by the negative exponent on the deviator stress in the non-linear deviator stress model.

- The Class 1C material may have been much more permeable than the Class 1F, allowing the top of the subgrade soil to become saturated. The subgrade soil was relatively impermeable so the zone of weak saturated subgrade material may have only been a few millimeters thick. There were no measurements of the moisture at the aggregate subgrade interface to substantiate this speculation.

The available data does not fully explain how such a large difference in strength could develop. The above discussion items may help select investigation methods to evaluate the performance of aggregate sections.

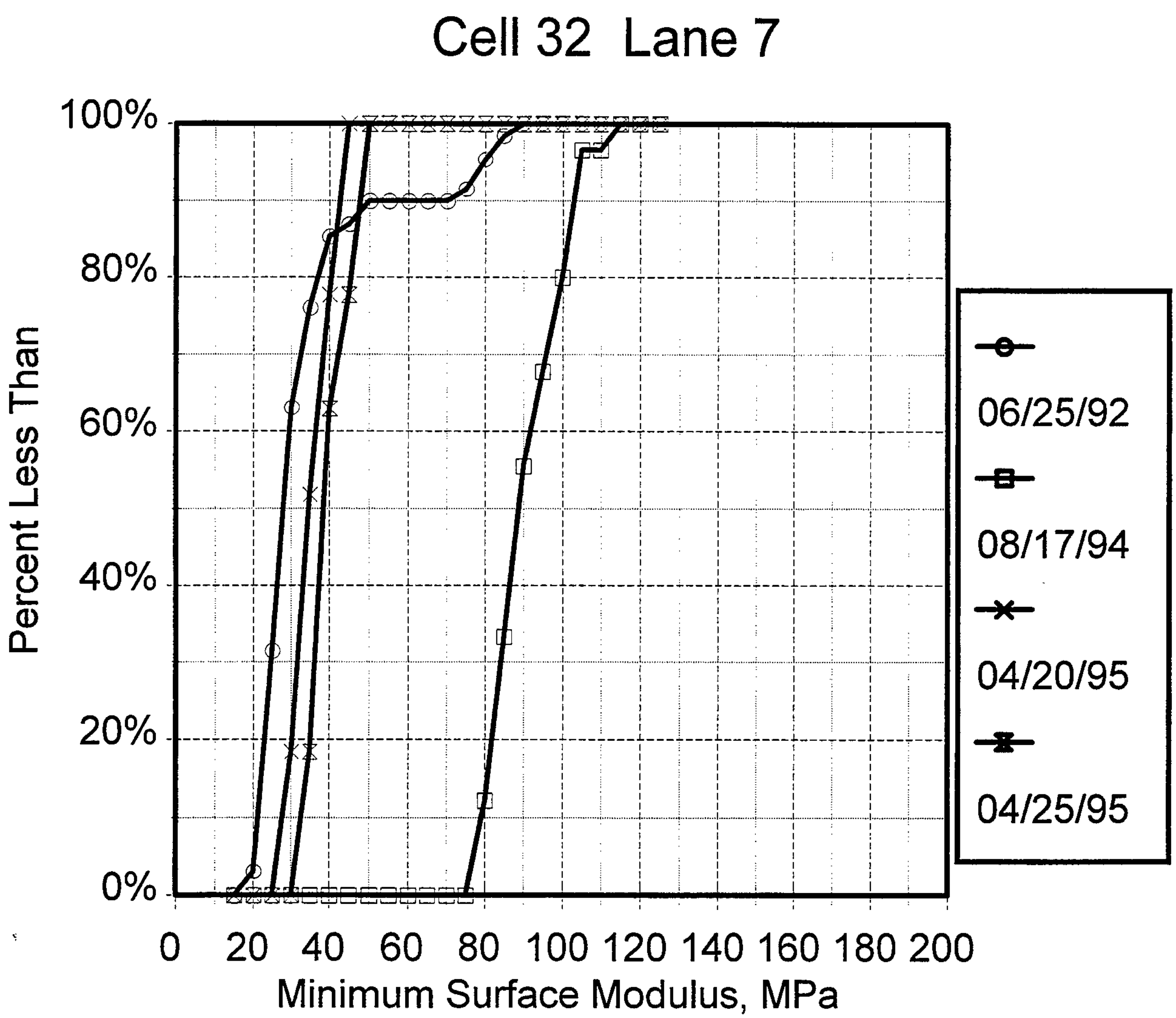


Figure 25. Cumulative surface modulus plots for Lane 7 in Cell 32.

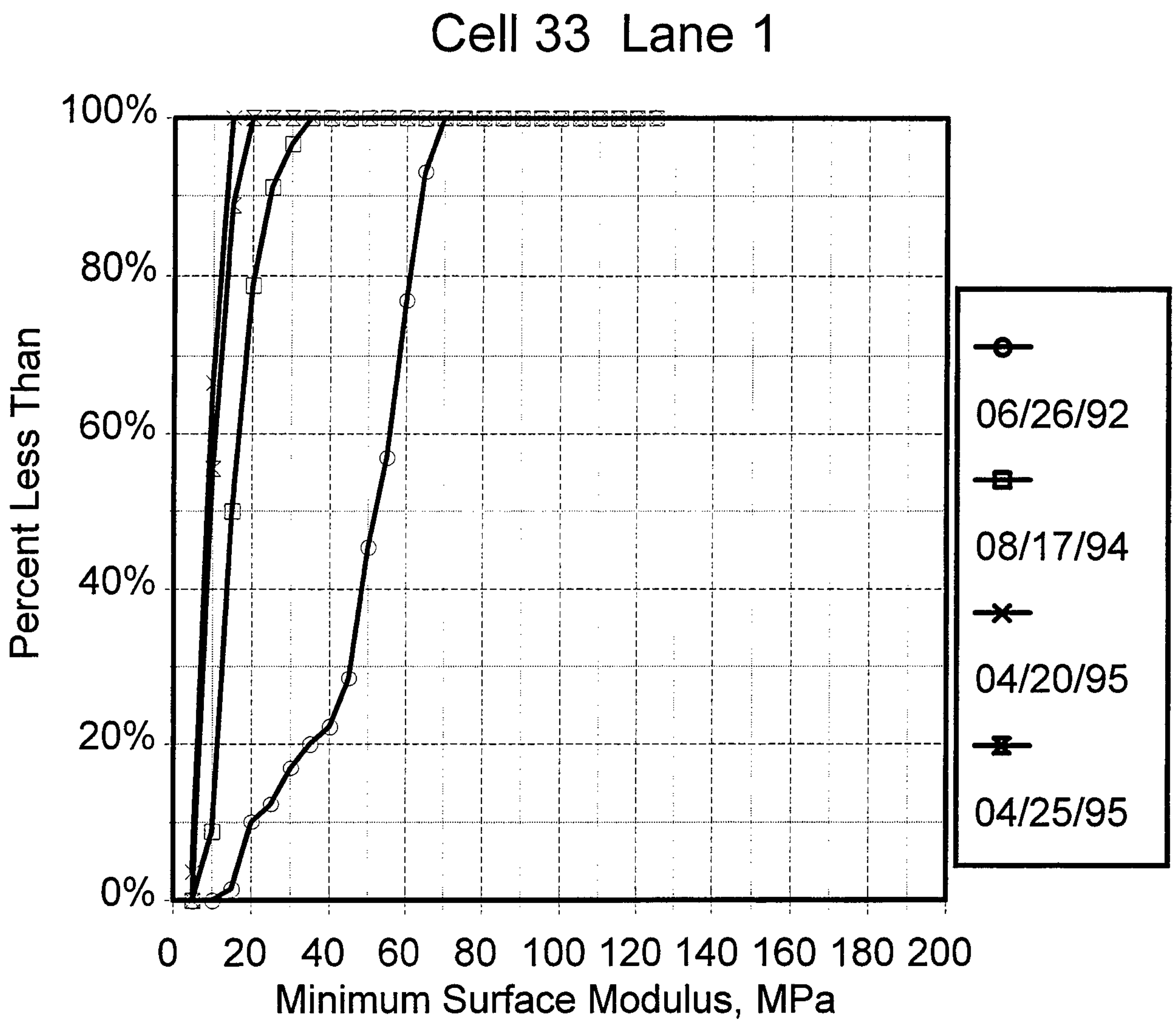


Figure 26. Cumulative surface modulus plot for Lane 1 of Cell 33.

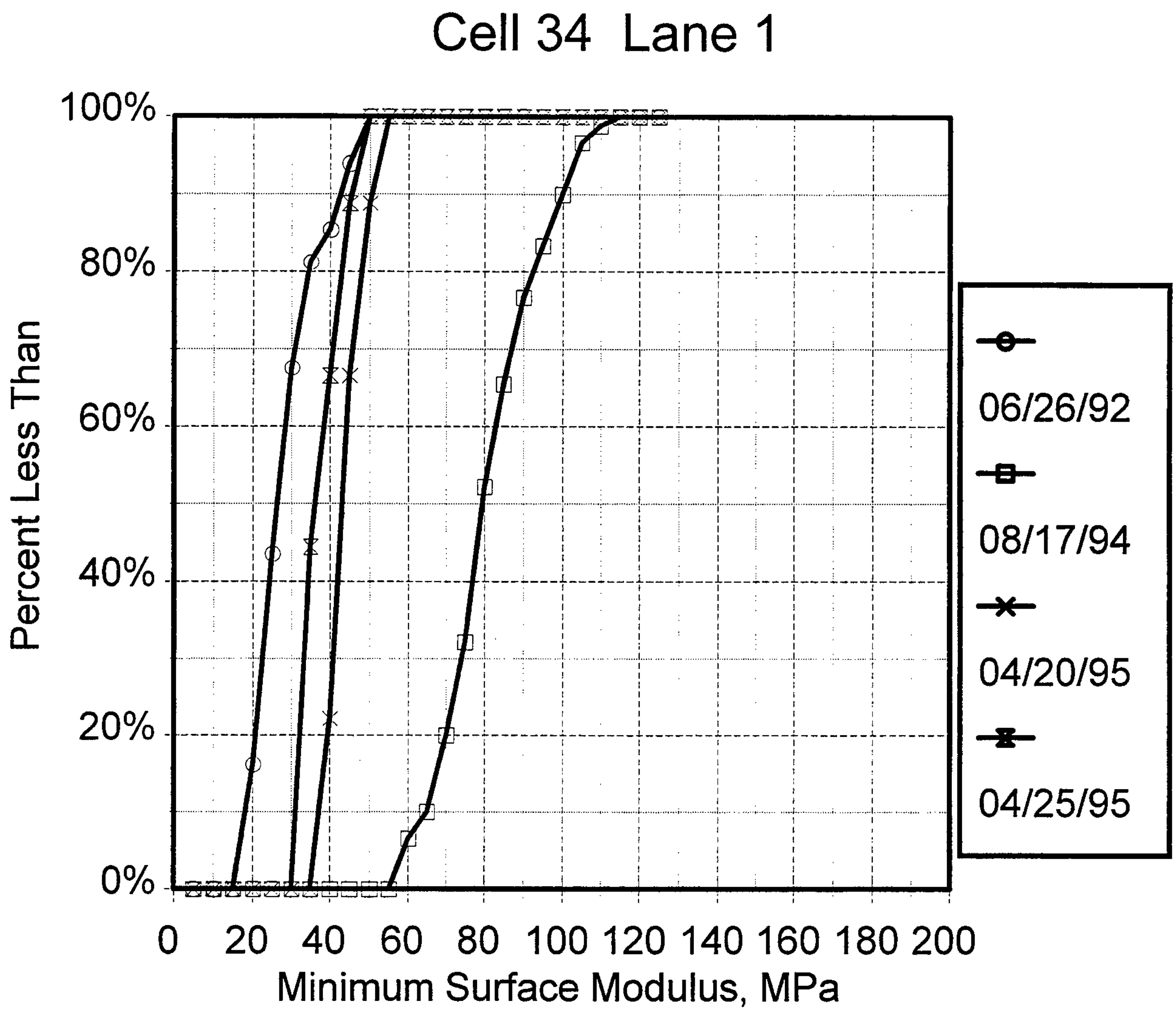


Figure 27. Cumulative surface modulus plots for Lane 1 of Cell 34.

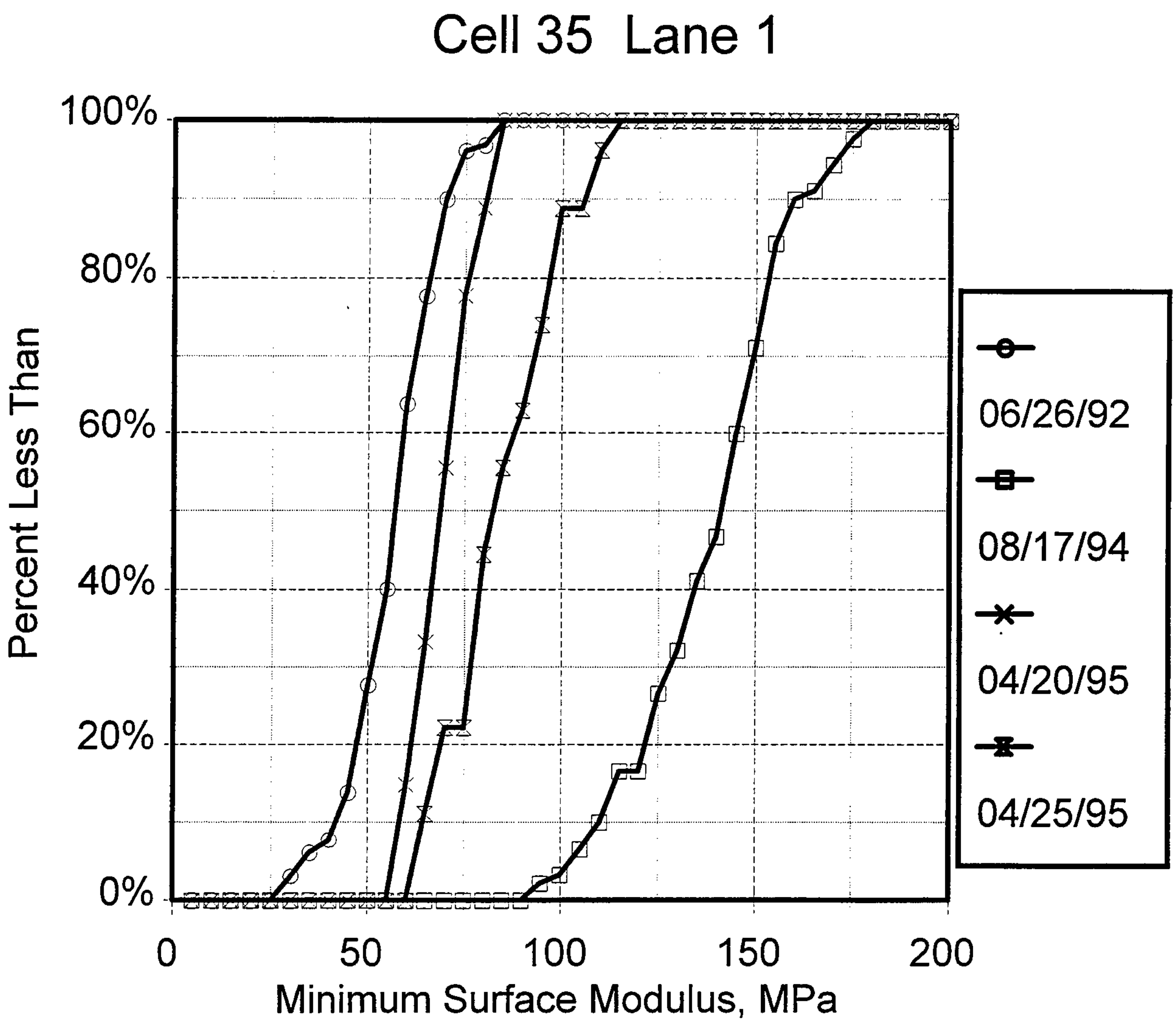


Figure 28. Cumulative surface modulus plots for Lane 1 of Cell 35.

3.3 DYNAMIC CONE PENETROMETER TESTS

Dynamic Cone Penetrometer (DCP) tests[14] were run on the aggregate sections in June 1992 and again in the fall of 1994. In addition, several other DCP tests were taken during the evaluation of the rutting failures that developed on the heavy load lane of Cell 33. The DCP is a very low cost but useful tool which can be used to evaluate aggregate base and subgrade soil support. It can be used to identify localized soft areas or localized soft layers. The device produces a Penetration Index (PI) that can be used to estimate a California Bearing Ratio, or resilient modulus. Figures 29 to 32 show the effective modulus of the sections by 150 mm (6 in.) thick layers as determined from the PI.

The results shown in Figures 29 to 32 are averages from about ten DCP test locations, except for Cell 34 which was based on six locations. The average values shown for Cell 33 are significantly higher than indicated by the surface modulus values calculated from falling weight deflectometer (FWD) deflection results. The minimum DCP-based subgrade modulus, however, is more consistent with the minimum surface modulus values.

The DCP test results do not show as large a difference between Cell 33 and 35 as would be expected based on the difference in performance. The DCP does show some difference, although small, between the stiffness of the Class 1C and Class 1F. The rutting failures in the heavy lane of Cell 33 were local and the DCP testing in the fall of 1994 may not have been located in the failure areas. DCP tests taken in the vicinity of the rutting failures on the heavy load side of Cell 33 show much higher PI values (lower effective modulus). The DCP results in the failure areas indicate that the failures may have been the result of small localized soft spots. One of the DCP test results had a PI of 210 mm (8 in.), indicating a very soft layer, but DCP tests within three meters on either side had much more typical values. The indication from the DCP testing is that very localized soft areas in the subgrade may have triggered the rutting failures.

Comparison of the DCP test results from the 1992 testing on the subgrade and the 1994 testing on the aggregate show that the subgrade soils generally increased in stiffness. This is consistent with the surface modulus calculated from the FWD results for all of the sections except for Cell 33 where the FWD showed a decrease in surface modulus. The surface modulus values referred to here are the minimum surface modulus obtained from all of the deflections within a deflection basin; the minimum surface modulus may not indicate subgrade stiffness.

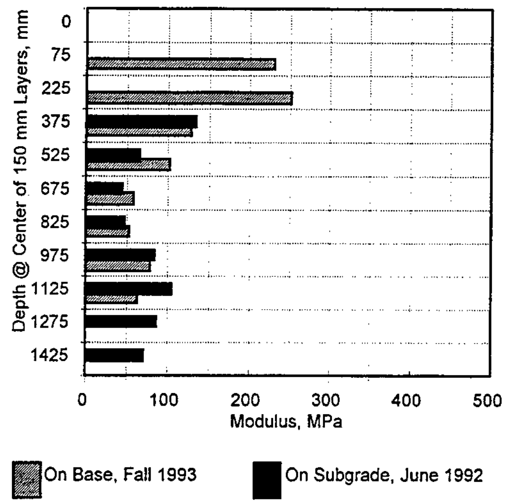


Figure 29. Average modulus values from DCP tests on Cell 32.

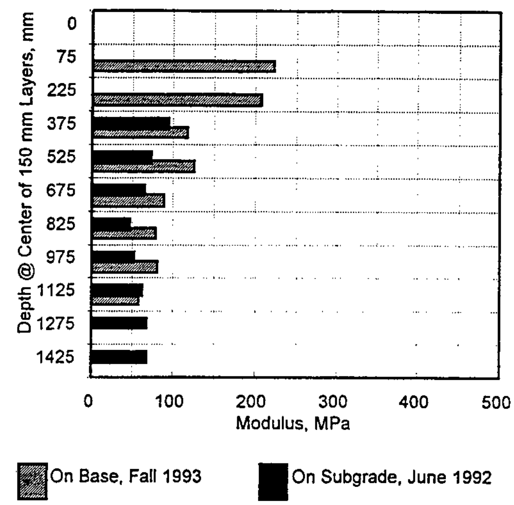


Figure 30. Average modulus values from DCP tests on Cell 33.

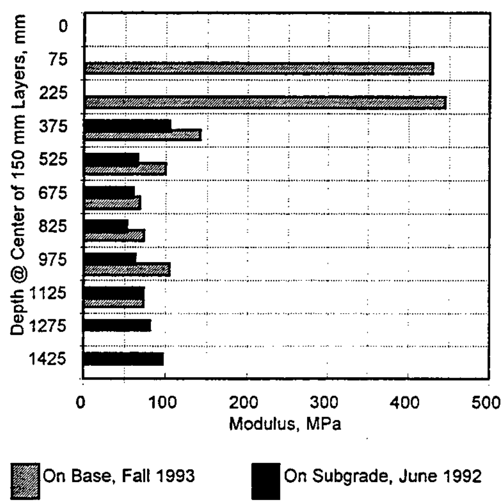


Figure 31. Average modulus values from DCP tests on Cell 34.

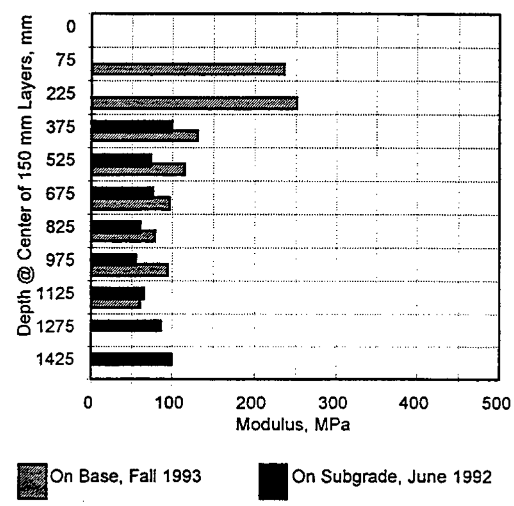


Figure 32. Average modulus values from DCP tests on Cell 35.

3.4 CLEGG IMPACT HAMMER

The Clegg Impact Hammer was used on the sections on April 7, 1995, to evaluate and demonstrate its use. The Clegg Impact Hammer is a 4.54 kg (10 lb) hammer that is dropped 457 mm (18 in.) onto the surface. An accelerometer is mounted in the hammer to measure the deceleration at impact which is displayed on a digital panel meter in gravities of deceleration divided by ten. That is, a Clegg Impact Value (CIV) of 1 corresponds to 10 g's of deceleration.

Figures 33 to 36 show the average of 10 or 11 test results from the outer wheel path of each of the cells, by lane.

The Clegg Impact Values (CIV) are always higher for the heavy side, except for Cell 32 which had failed; it is possible that the failure reduced the CIVs. The reason for the higher CIVs on the heavy lane may be due to the compactive effort from the heavier loads.

The two aggregate sections have higher CIVs than the chip seal sections. Both lanes of Cell 32 were considered failed at the time of test which may explain why it is low, but Cell 34 had not failed and has performed much better than Cell 33, but perhaps not quite as well as Cell 35. The chip seal may provide some cushioning, or may keep the aggregate moisture content higher. It is anticipated that the CIVs are very moisture dependent.

Cell 33, which has continually had problems due to several soft spots that did not go away, was considered to be the poorest performer of the four Cells, until Cell 32 failed. Aside from the soft spots, Cell 33 performed more poorly than Cell 35. The CIVs on Cell 33 are less than on Cell 35; however, they are in the adequate range. One thing to keep in mind is, at the time of the Clegg Hammer tests, Cell 33 had been repaired a number of times and had received a 50 to 100 mm (2 to 4 in.) Class 6 aggregate overlay.

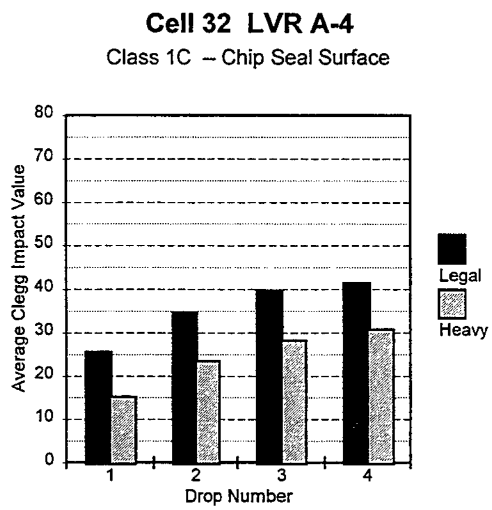


Figure 33. Average Clegg Impact Values for Cell 32.

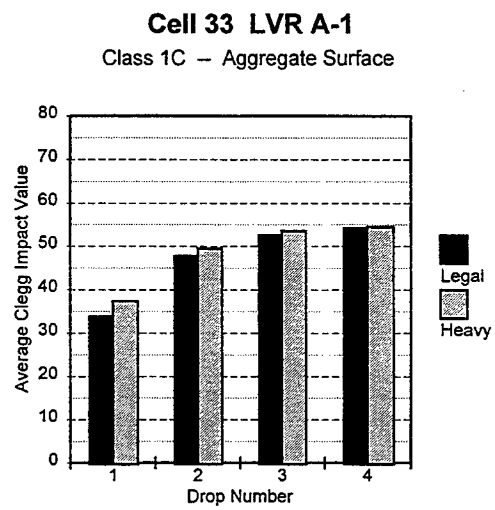
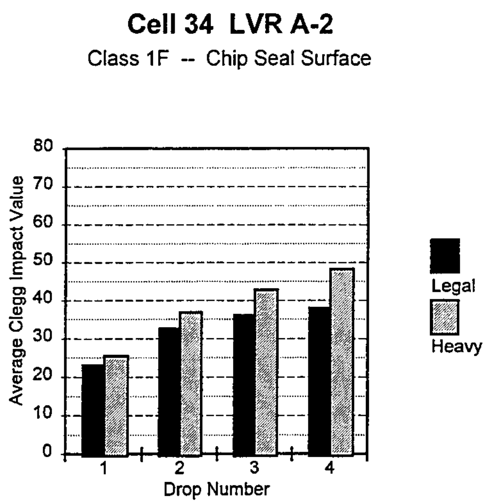


Figure 34. Average Clegg Impact Values for Cell 33.



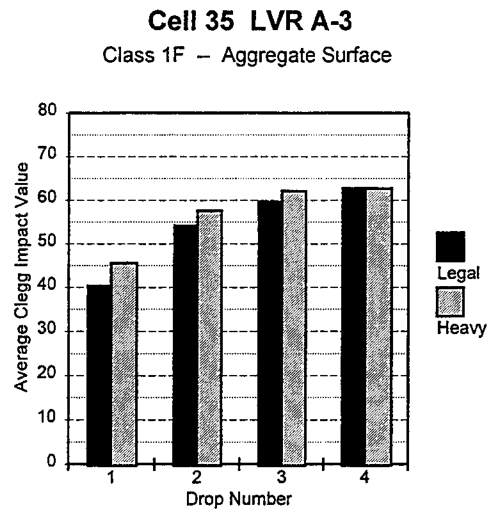


Figure 35. Average Clegg Impact Values for Cell 34.

Figure 36. Average Clegg Impact Values for Cell 35.

The CIVs can be related to other material characteristics such as the California Bearing Ratio (CBR) or the Resilient Modulus by the equation $E = 0.07(CIV)^2$, where E is in MPa[15]. This reference also states the same equation will give CBR; however, the modulus of a material in MPa is approximately the CBR times 10. The author's experience is that this relationship tends to over predict the CBR and under predict the resilient modulus.

A brief check of the CIV against the DCP also shows a correlation. This check was in the primary rutted area of the heavy lane of Cell 33 and the correlation was between the CIV and the largest PI measured with the DCP at the same location. Because the large PI values were at depth, and the CIVs are at the surface, the influence of the top layers on the CIVs should be significant.

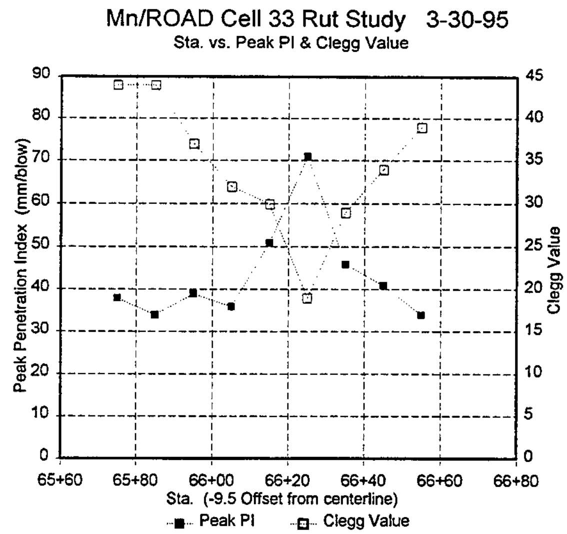


Figure 37. Comparison of PI and CIV.

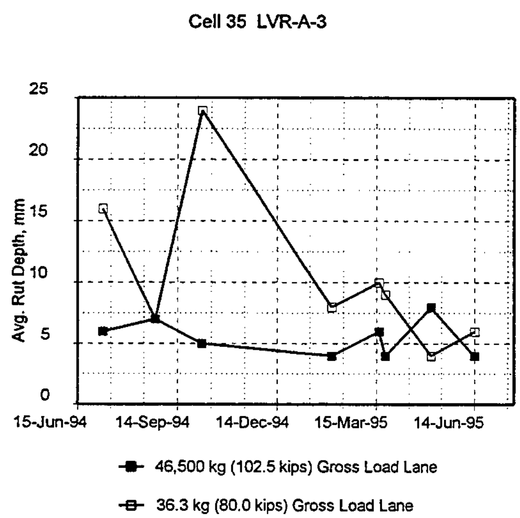


Figure 38. Pave Tech rut depths for Cell 35.

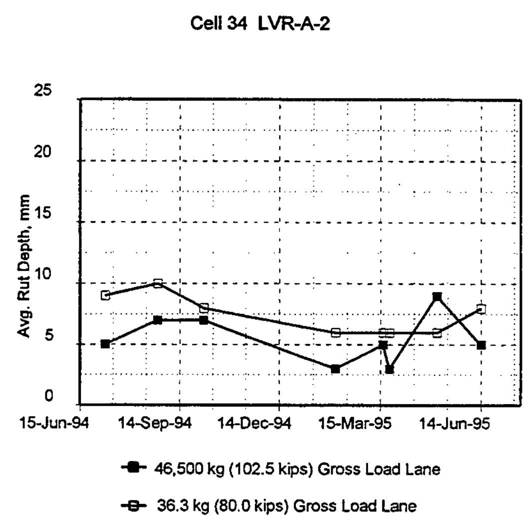


Figure 39. Pave Tech rut depths for Cell 34.

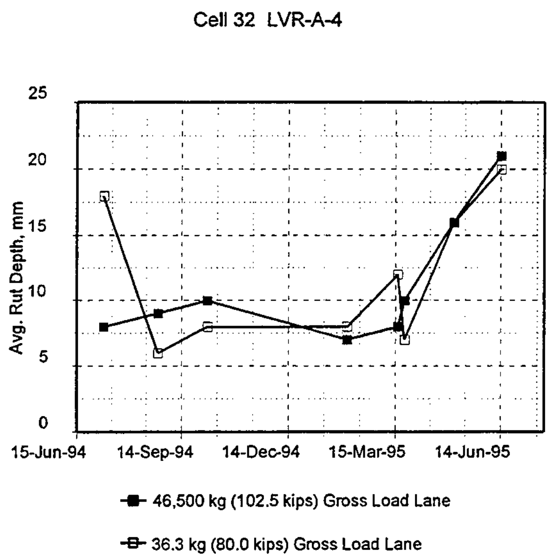


Figure 40. Pave Tech rut depths for Cell 32.

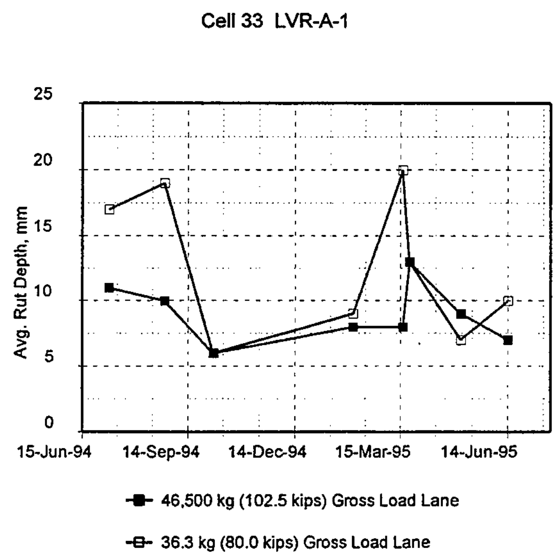


Figure 41. Pave Tech rut depths for Cell 33.

3.5 PAVE TECH

Mn/ROAD uses a Pave Tech vehicle monthly to measure the longitudinal profile, rut depth, and textural characteristics. The Pave Tech also records a visual image of the surface and shoulder area with high resolution video cameras (Super VHS), although the videos were not reviewed as a part of this project.

3.5.1 Ride (IRI)

The Pave Tech measures the longitudinal profile in both the right and left wheel path. The profile is measured from an inertial reference plane. Elevation measurements are taken at approximately 300-mm (12-in.) intervals by an ultrasonic sensor mounted on a bar on the front of the vehicle. The bar elevation is monitored by internal mounted accelerometers.

The profile measurement interval used by the Pave Tech device may present a problem for the aggregate sections. A common length between the peaks of the washboarding is about 600 mm (23 in.). If the Pave Tech measurement locations correspond with the crests and valleys of the washboarding, it will give the most accurate measure of the roughness. However, if the elevation measurements correspond with the quarter points of the washboard wave form, the measurements will indicate little or no roughness.

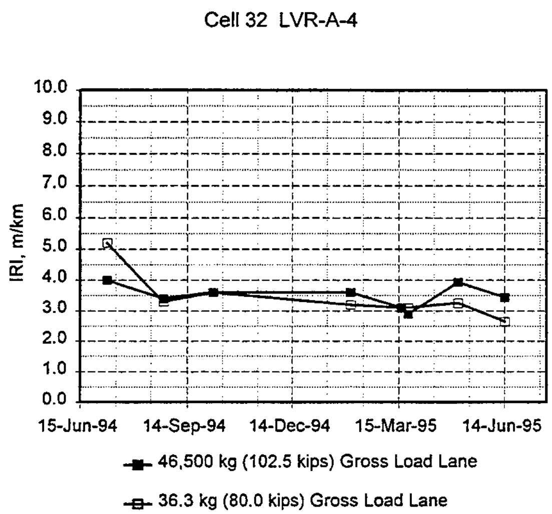


Figure 42. Pave Tech IRI for Cell 32.

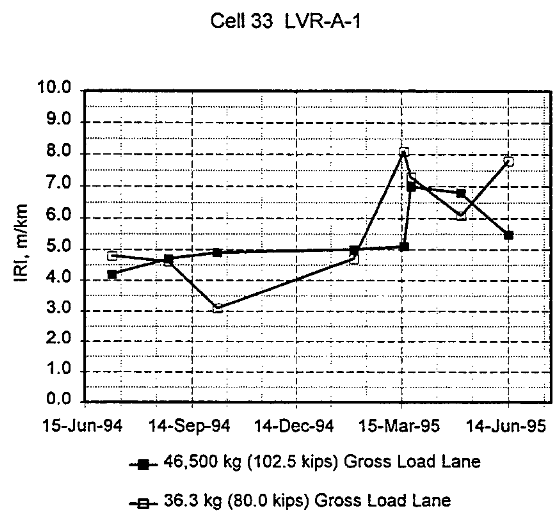


Figure 43. Pave Tech IRI for Cell 33.

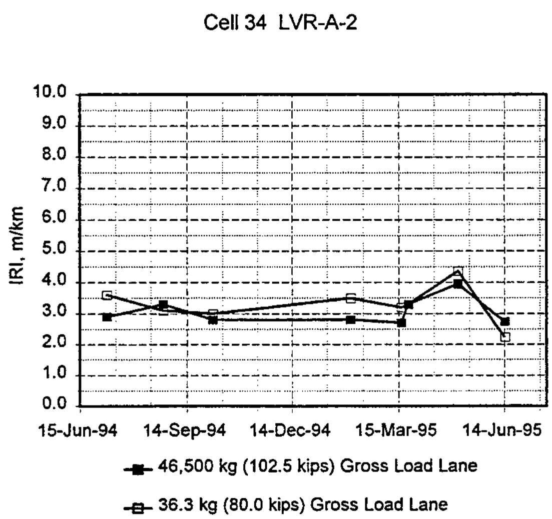


Figure 44. Pave Tech IRI for Cell 34.

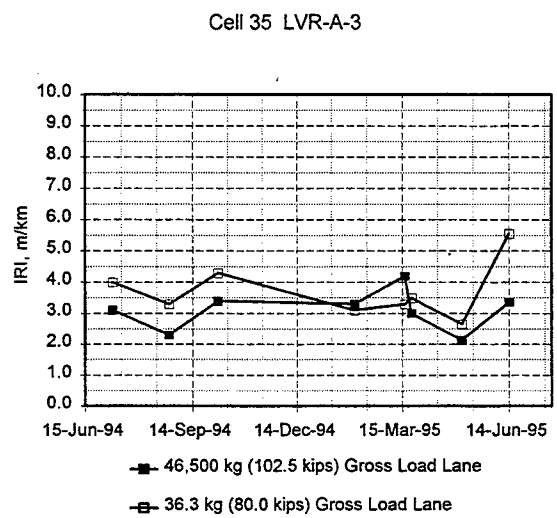


Figure 45. Pave Tech IRI for Cell 35.

3.5.2 Video

The Pave Tech vehicle is equipped with Super VHS video cameras. Two pair of down-looking cameras, one in front and one in back, record a close-up image of the road surface. Another camera is available that generally is directed toward the right shoulder/ditch area.

Each frame of each of the videos is referenced by frame number in a data base that associated the frame with a specific position on the road. This allows the video data collected in the field to be analyzed with the help of a specially designed work station to do condition surveys. The videos were not used for this project; however, they are available through the Mn/ROAD office.

3.5.3 Rutting

The Pave Tech vehicle also measures a cross slope characteristic that generally has a good correlation to rutting. A schematic drawing of the rut measuring process is shown in Figure 4 in the *Data Collection Used for Project* section in this report.

3.6 TRUCK PASSES

A five-axle tractor semi-trailer was used to apply the loading on the Low Volume Road loop at Mn/ROAD. The tractor was driven by a Mn/DOT staff employee during normal weekday hours. The driver traveled at about 50 to 60 kph (30 to 35 mph) and was able to complete about 80 laps on a typical day. The driver was very careful to follow the same wheel path. Based on our observations of the shape of the wheel ruts on the aggregate sections, the lateral wander was typically within 50 mm (2 in.) of the center of the wheel path. Specific measurements of lateral wander, however, were not made.

Each of the two lanes was loaded with different axle loadings and number of passes as explained earlier in this report. Figure 46 shows the accumulation of passes and AASHTO based equivalent single axle loads based on a structural number of 1.8. The legal load traveled clockwise on the inside lane of the LVR for four days per week and the heavy load traveled counterclockwise on the outside lane of the LVR one day a week, typically Wednesdays.

3.6.1 Traffic Relationship to Low Volume Roads

How does this relate to the traffic on a Low Volume Road? For a gravel road application, based on a ten-year design, no growth, and a typical truck factor of 0.58 ESALs per truck. Figure 47 shows the equivalent two-way HCADT volume required over a ten-year period to equal the ESALs accumulated on the LVR at any date up until March 15th. Note that the rate of ESAL application for the legal and heavy truck loads is about the same based on the four-to-one ratio of application rates. The ESALs per truck were based on the AASHTO equations for a structural number of 1.8.

The evaluation of the traffic versus surface condition on the LVR is greatly complicated by four distinct periods from the beginning of the load applications to June 1995:

- The summer and fall of 1994 represents the typical summer-fall conditions regarding moisture and soil and base strengths. The performance of Cells 34, 35, and 32 showed the sections to be reasonably stable. Rutting developed at reasonably consistent rates and washboarding began developing on the aggregate sections. Cell 33 developed localized severe rutting in the heavy lane nearly immediately and it continued to behave in a similar manner throughout the summer.

- The winter (frozen) period of 1994-1995 is a period of limited functional and structural activity since the pavement and subgrade are frozen and there were periods of partial snow cover.

- The spring thaw, starting about March 12, 1995, and continuing into and through most of April was a period of significant (and catastrophic) weakening of the base and subgrade materials, resulting in the complete failure of Cell 32, the coarse aggregate chip seal section, in a matter of days. The differences in the rate of failure between the heavy lane and the legal lane is not dramatic enough to address the possibility of equivalent axle load differences. The other sections suffered various levels of deterioration during the thaw, resulting in some significant rutting in the heavy side of Cell 34 and an aggregate "patch" placed on both lanes of Cell 33.

- A second summer-fall period begins sometime in late April to mid May, depending on the rate of recovery. Deflections were not periodically measured on these sections during the thaw, so the time when recovery was complete has to be estimated. Recovery is a gradual process, some times are more gradual than others; however, a definite time has to be developed for analysis purposes and May 1st may be a good date to use for the thaw of 1995.

At the end of the study, the sections had not yet experienced a full year of traffic (Cell 32 was removed from the study in March 1995 due to excess rutting), and the equivalent 80.1 kN (18,000 lb) single axle load concept really should be based on the multi-seasonal effects of traffic over the design years of the structure. In order to express the capacity of any of the sections, by lane, a process of weighting the loadings must be used. One can conclude that Cells 32 and 33 were done in about a week (or less) of traffic during the spring thaw. If this is put into design-based equivalencies, the ten-year, two-way HCADT capacity of Cells 32 and 33 is about 0.14, or one truck per week. Both Cells 32 and 33 may have been able to withstand one trip per day over the thaw period if buildup of pore pressure in the base was contributing to the fast rate of rutting. This illustrates that some subjectivity is necessary to process the results from the part of the LVR study and the application of the results and recommendations from this study should be made with this in mind.

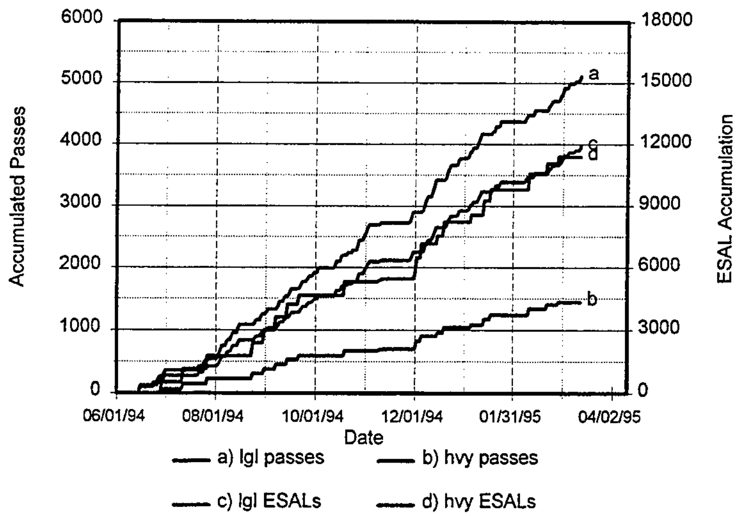


Figure 46. Truck passes applied to the Low Volume Road loop.

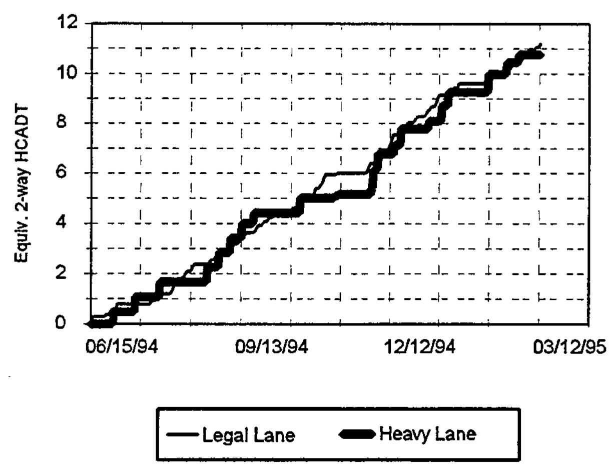


Figure 47. Equivalent ten-year accumulated two-way Heavy Commercial Traffic on a local road.

It should be noted that the AASHO Road Test had this same problem. There they noted, particularly for the thinner asphalt sections, that the rate of deterioration was much more pronounced during the spring thaw, and that some sections only went through one thaw where others went through more. The researchers there found it necessary to weigh the truck passes to equivalent rates of deterioration. A similar process is necessary here, except the deterioration on Cell 32 was so quick, it can be argued that short period alone is all that can be considered in developing the ESAL capacity of that section.

To complicate matters, nearly all of the gravel roads in Minnesota are under a 5-ton per axle load restriction during the spring thaw. If that is to be considered, the development of ESAL or HCADT capacity of the sections would need to be developed from the condition information for the previous summer and fall and an extrapolation is necessary to predict the capacity since it was not failed prior to freeze up.

3.7 SURFACE CONDITION

Much of the monitoring of the aggregate sections was done by manual section inspections once every two weeks. The inspections would collect condition information about the surface condition, recent events, plus periodic photos of the site. As part of the inspections, a narrative of the observed conditions and notes was developed. Although the narrative is not a numeric measure of performance criteria, it provided useful insight into the behavior of the sections.

Specific information regarding the sections that were manually observed was the severity and extent of rutting, washboarding (corrugation), and loose aggregate (float).

3.7.1 Rutting

The rutting observed on the sections was observed on the basis of the description in the section titled *Data Collection Used for Project*. Based on the early behavior of the sections, particularly the heavy load side of Cell 33, this approach was used to retain flexibility in recording the overall condition of the section. Figures 48 to 55 show the rutting behavior of the sections over the course of the study.

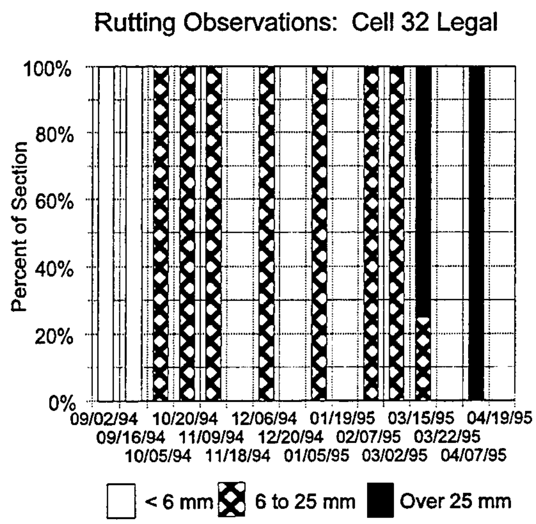


Figure 48. Rutting on legal lane of Cell 32.

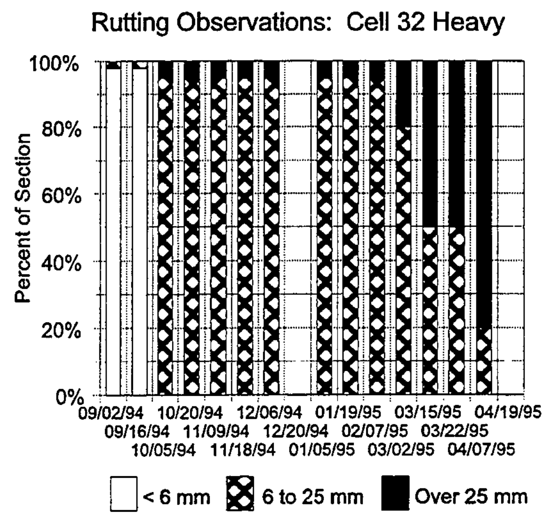


Figure 49. Rutting on heavy lane of Cell 32.

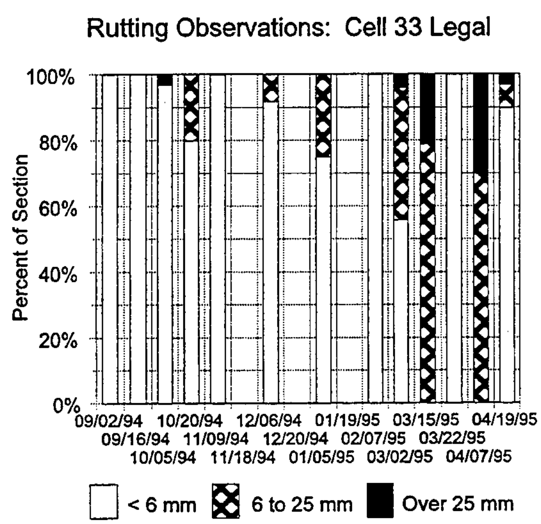


Figure 50. Rutting on legal lane of Cell 33.

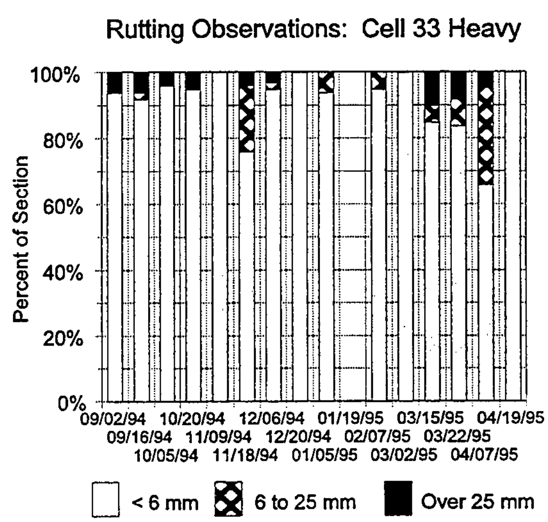


Figure 51. Rutting on heavy lane of Cell 33

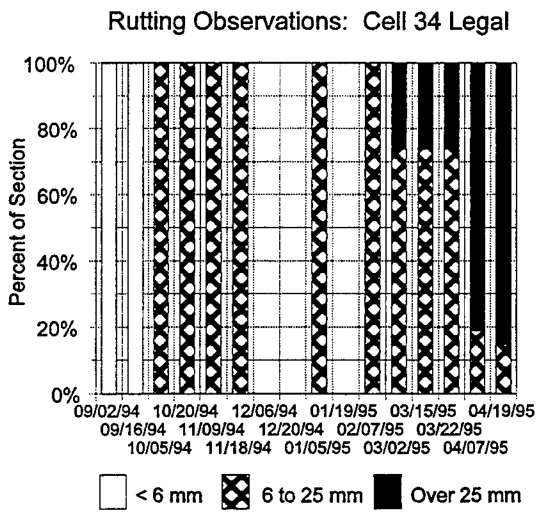


Figure 52. Rutting on legal lane of Cell 34

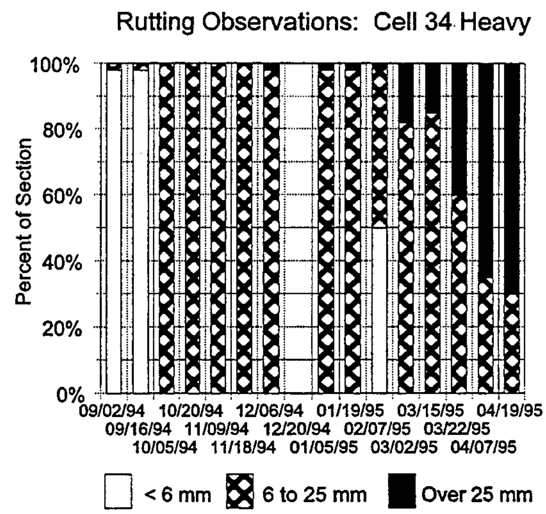


Figure 53. Rutting on heavy lane of Cell 34.

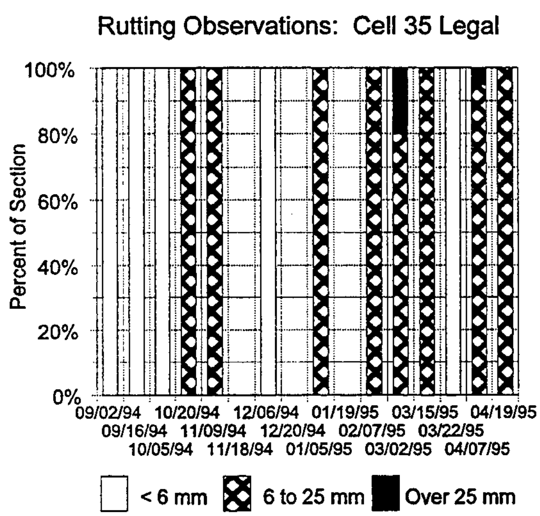


Figure 54. Rutting on legal lane of Cell 35.

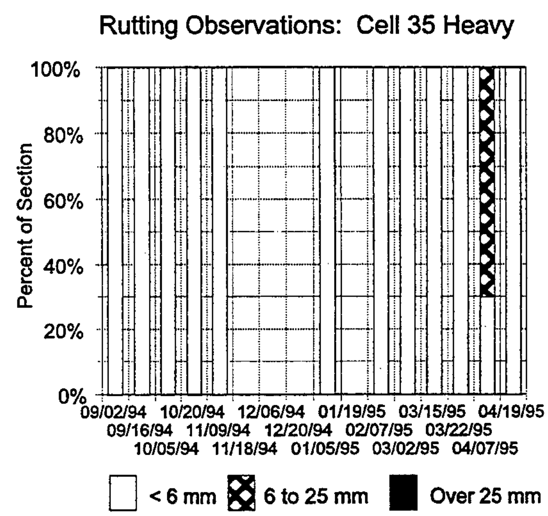


Figure 55. Rutting on heavy lane of Cell 35.

Figures 48 to 55 show a distinct difference in the rutting performance of the sections with Cell 35 performing the best. The observed rutting for the heavy lane of Cell 33 may be considered somewhat misleading because it does not show the performance to be very bad; however, the rutting on the heavy lane of Cell 33 was repaired quickly after the rutting developed. Also, the rutting on the heavy lane of Cell 33 was fairly localized and continued to reoccur at the same locations.

3.7.2 Washboarding

The washboarding observed on the sections was observed on the basis of the description in the section entitled *Data Collection Used for Project*. The use of the severity and extent concept for rutting seemed to fit for washboarding as well. Figures 56 to 59 show the observed washboarding on the sections.

The graphs in Figures 56 to 59 show that the washboarding that developed on the aggregate sections is much more a function of truck passes than load. Because of the interaction of the blading and load, an actual ratio of passes to washboarding cannot be established from these sections; however, it appears that the rate of washboarding is a function of passes.

The comparison of the performance of Class 1C versus Class 1F gives the performance edge to the Class 1F material. Cell 33 tended to develop more washboarding than Cell 35. A confounding factor in comparing the rate of washboarding is the difference in strength between Cell 33 and 35. It is not possible to evaluate the role two factors have on washboarding when only two sections are monitored. It may be possible that the rate of washboarding, for the same aggregate materials, may vary according to the overall strength of the section.

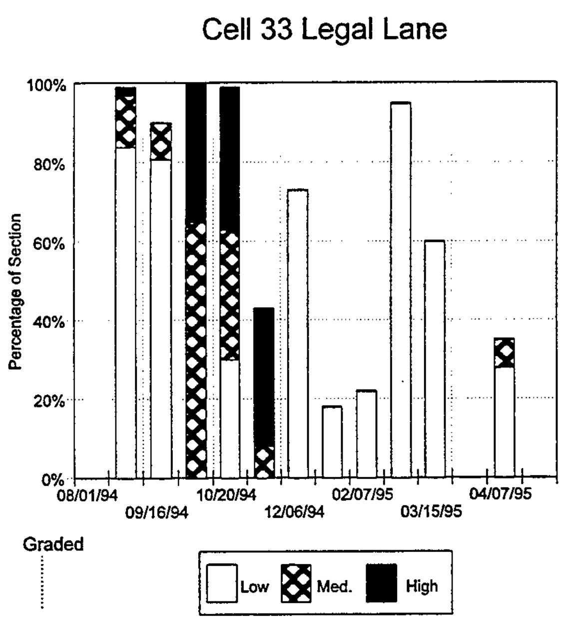


Figure 56. Washboarding on legal lane for Cell 33.

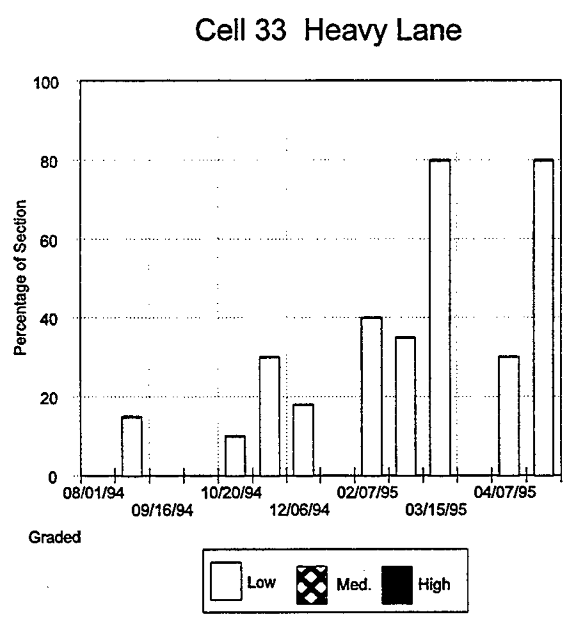


Figure 57. Washboarding on heavy lane for Cell 33.

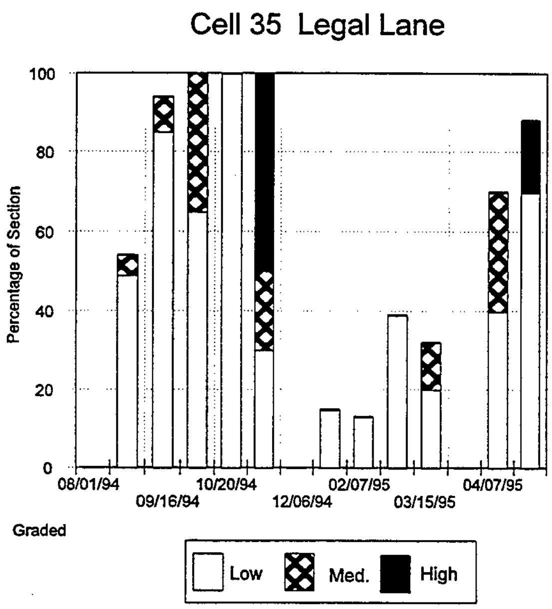


Figure 58. Washboarding on legal lane for Cell 35.

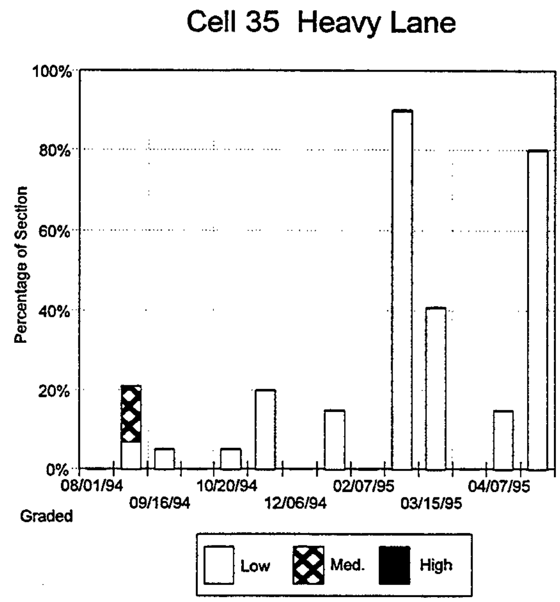


Figure 59. Washboarding on heavy lane for Cell 35.

The amount of washboarding that developed on the chip seal surfaced sections was significantly lower than it was on the aggregate sections as indicated by Figures 60 to 63. The difference in the amount of washboarding between Cell 32 and 34 was noted the first time the sections were evaluated after placement; this difference could not be explained. A comparison of the amount of washboarding between Cells 32 and 34 during the life of the test sections showed the difference to remain about the same.

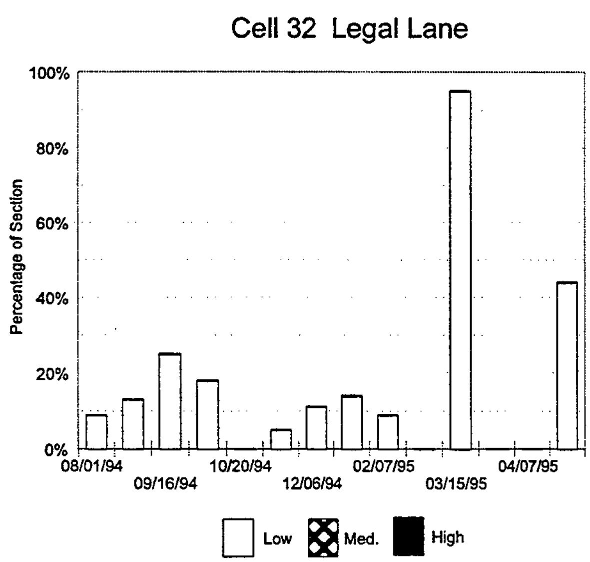


Figure 60. Washboarding on legal lane for Cell 32.

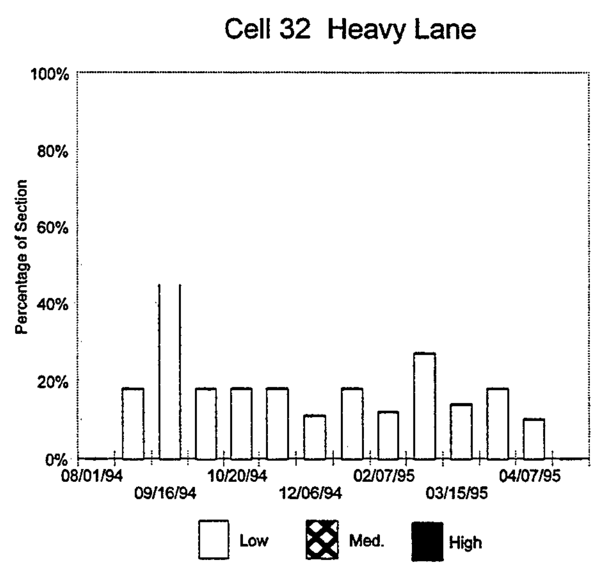


Figure 61. Washboarding on heavy lane for Cell 32.

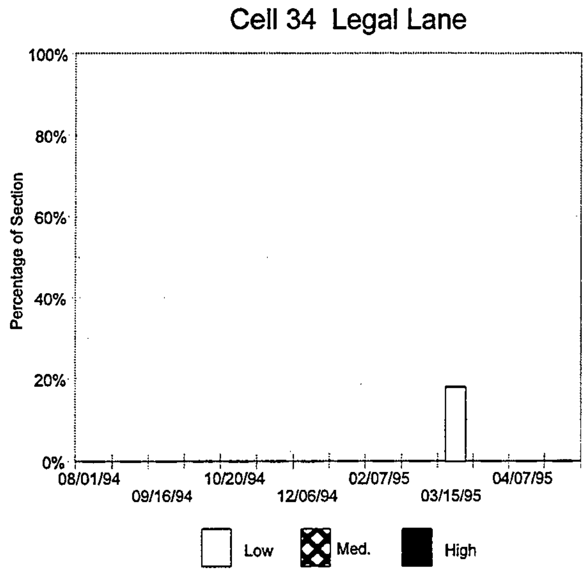


Figure 62. Washboarding on legal lane for Cell 34.

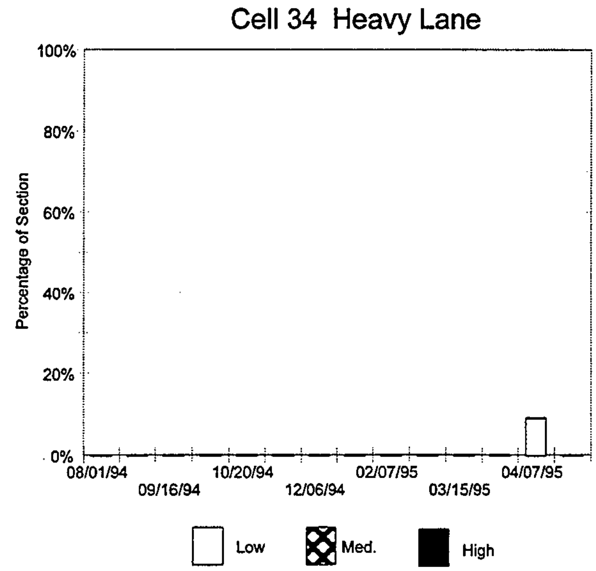


Figure 63. Washboarding on heavy lane for Cell 34.

3.7.3 Loose Aggregate (Float)

The development of loose aggregate, or float, on either Cell 33 or 35 was minimal. The float would develop to about 20 to 40 mm (one to two coarse aggregate layers thick) before blading would mix the float back into the aggregate.

3.8 BLADING

Blading is an indication of the performance of aggregate sections. Blading was called for whenever roughness would develop to a point where the truck had to slow down. When the truck could not safely maintain 50 kph (30 mph) on any section, all the aggregate surfaced sections were graded. Excessive local rutting on the heavy lane of Cell 33 or washboarding on the legal lane of either Cell 33 or 35 would trigger blading of the sections. The difficulty with judging the performance of the Mn/ROAD sections on the basis of blading is that when the grader would come in to blade a section, all of the sections would be bladed. Grading events are shown by the dashed vertical lines in Figures 56 to 59.

The chip seal surfaced sections did not require blading due to excessive roughness until the spring of 1995 when Cell 32 failed due to severe rutting and the chip seal on Cell 34 started to fail due to general cracking and degradation.

3.9 FAILURE EXAMINATIONS

Within about 40 passes of the heavy load, severe localized rutting developed in Cell 33. The local failure area had to be repaired by blading and reshaping the aggregate surface before the truck could continue at normal speeds. After several repeat failures, the section was repaired and a blister patch of Class 6 crushed granite was placed over the weak areas.

The nature of the rutting failures was a combination of rutting and shoving that would occur in localized areas about 7 to 15 m (8 to 16 yd) long. The ruts appeared to be in excess of 150 mm (6 in.) deep in the outside wheel path and over 100 mm (4 in.) deep in the inside wheel path; however, trench investigations as shown in Figure 64. The heavy line in Figure 64 is the cross section as measured with a string line level. The fine dashed line that crosses through the heavy line is a representation of the original cross slope which was estimated by connecting the ends of the heavy line. The end points were measured in areas that appeared to be undisturbed. The top dashed cross section line is the same data adjusted to show the distance from the cross slope. The dash-dot lines across the wheel path ruts illustrate how the ruts would look if measured with a straightedge reference. The rutting as measured from the original cross slope, therefore, is 75 to 80 mm (2.9 to 3.1 in.) rather than the 110 to 170 mm (4 to 7 in.) that a straightedge would show.

The significance of the rutting failure is that it relates to an interpretation of the failure mechanism. It is unclear as to the initial cause of the rutting, subgrade yielding, or poor aggregate shear strength. It may be a combination of both. What is evident, however, is that once the rutting started, the aggregate material would displace. Observations made by Lukanen and Urbach while the heavy-loaded truck crossed the rutted areas is that the surface deflection was visible, that there was upward movement in front of the axles, and that there was a slight forward movement [2 to 4 mm (0.08 to 0.16 in.)] of the surface on each truck pass. There was a mound of aggregate base material being pushed up on the downstream side of each of the rutting failure areas.

This movement of aggregate greatly reduced the effective thickness of the aggregate, thereby reducing the overall bearing capacity of the road in those areas which would result in larger displacements. The failure, once it started, was progressive.

Figures 65 and 66 are cross sections measured during a forensic study on Cell 33. Two trenches were cut across the outside wheel path of the heavy traffic lane. At each of these trenches, a string line was set across the roadway to use as a reference to measure the elevation of the surface and subgrade interface relative to the stringline. In both cases, there were two very distinct aggregate layers: the top layer had a natural brown gravel color and the bottom layer had a dark grayish color. The appearance suggests that some subgrade soil was mixed in with the base when initially placed; however, gradations run on the two layers did not indicate a significant difference between the light and dark layers.

The cross section shown in Figure 65 shows that there was 10 to 15 mm (0.4 to 0.6 in.) rutting at the base-subgrade interface. Also, there was only about 250 mm (10 in.) of aggregate at the trench instead of the 305 mm (12 in.) of Class 1C that was planned. The aggregate thickness at the low severity rut location shown in Figure 62 has about 280 mm (11 in.) of aggregate. DCP tests in the rutted area show that the effective thickness of the aggregate is much less than the original 305 mm (12 in.). Using a liberal PI of 10 mm (0.4 in.)/blow as effective aggregate, the DCP shown in Figure 67 has only about 130 mm (about 5.1 in.) of effective aggregate thickness. Our expectation is that continued passes of the heavy truck would continue to develop rutting at a rapid pace.

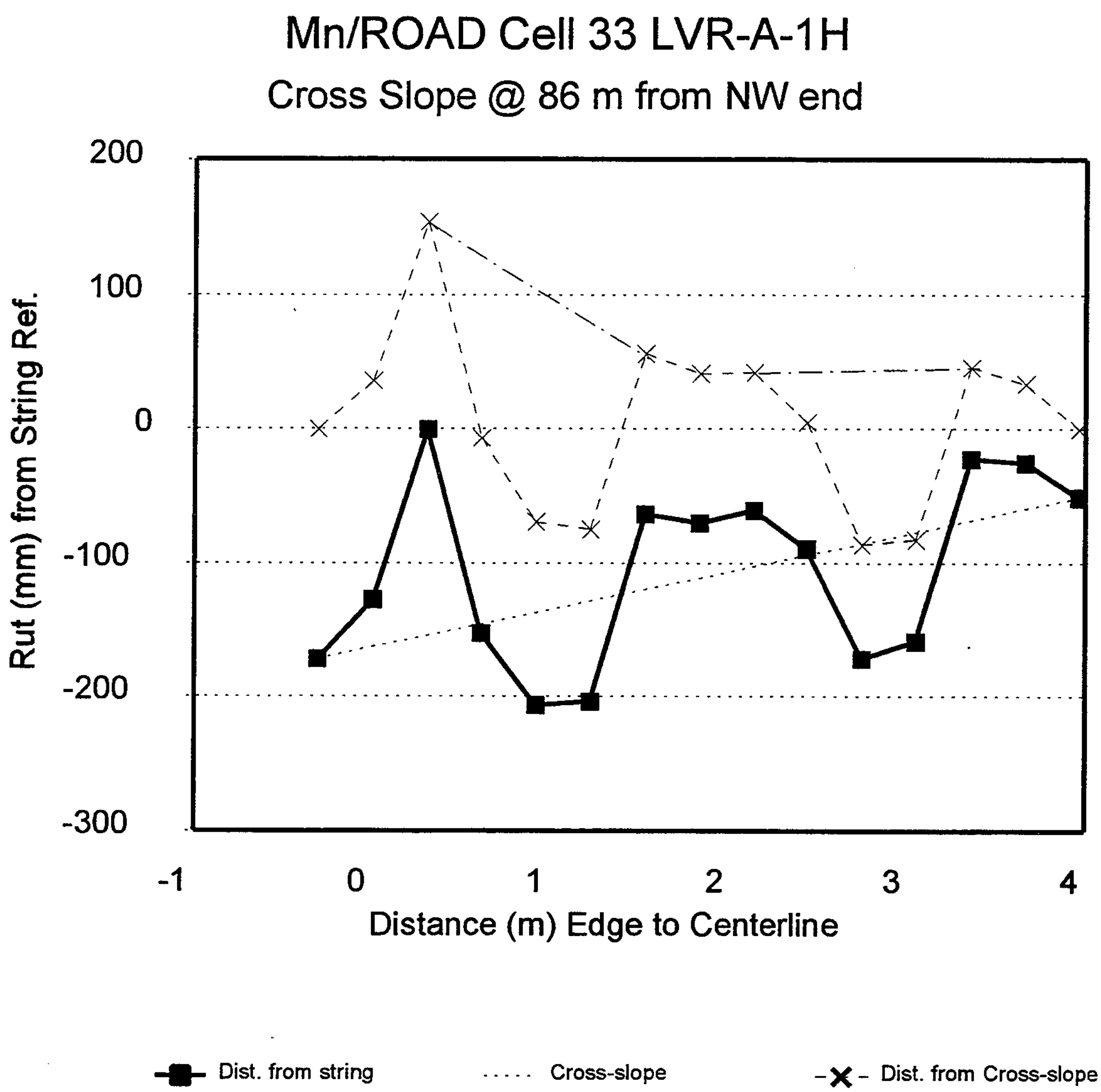


Figure 64. Cross section across rutted location to illustrate amount of shoving and actual rutting.

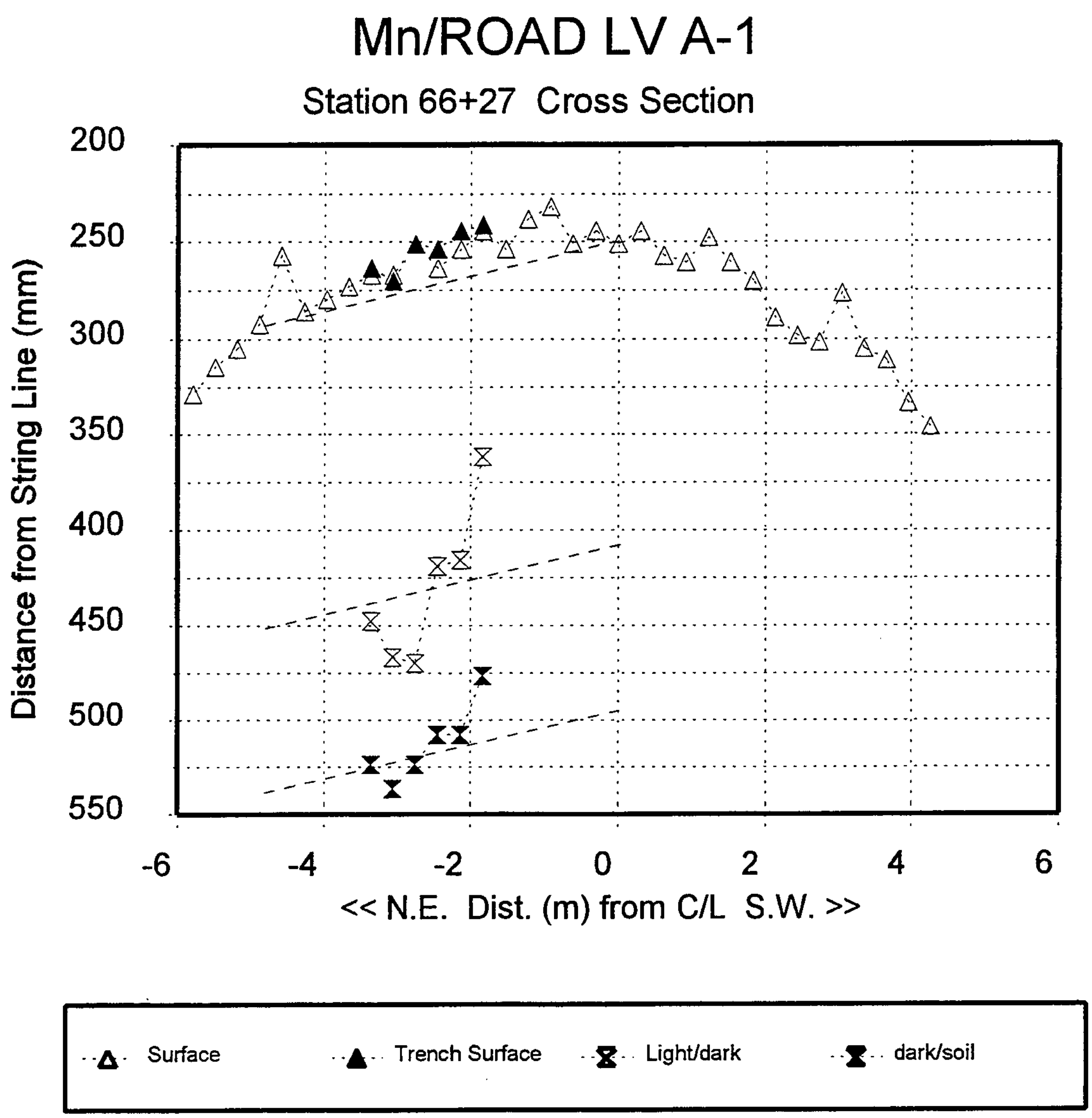


Figure 65. Cross section of trench cut across outside wheel path in severe rutting area.

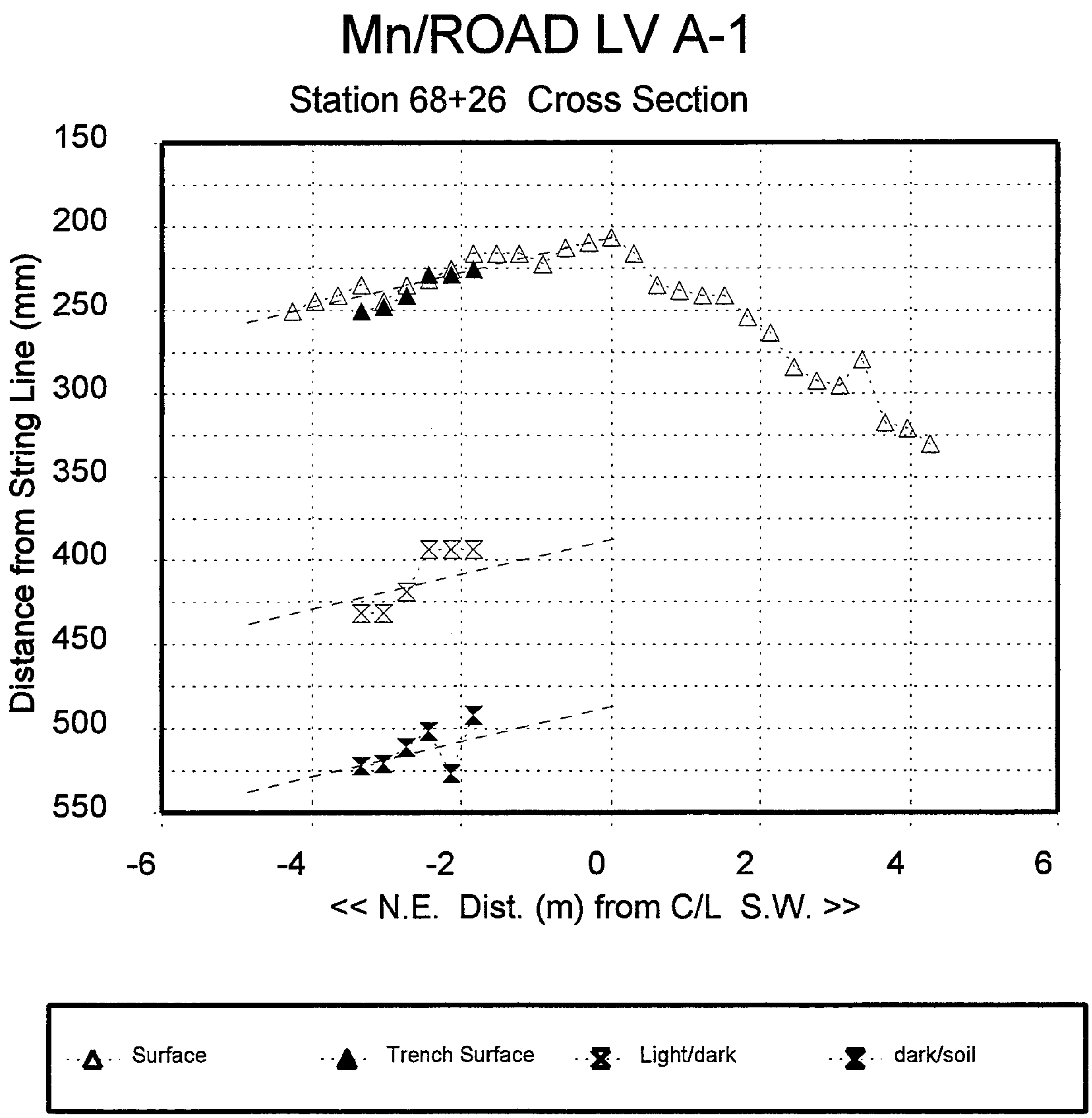


Figure 66. Cross section of trench cut across outside wheel path in low rutting area

CHAPTER 4
SECTION PERFORMANCE

There were three major experimental factors with the aggregate sections in the Low Volume Road (LVR) loop at Mn/ROAD:

- Chip Seal surfacing versus aggregate surfacing;
- Two aggregate gradations within the Mn/DOT Class 1 gradation band, a coarse gradation, and a fine gradation; and
- Loading of the LVR vehicle.

The results of about 10 months of traffic on the aggregate Cells provided some definite performance differences between these experimental factors. Performance comparisons can be made on the basis of the observations and measurements that were made over the course of the project; these observations and measurements are primarily rutting and washboarding. The notable differences for the three major experimental factors are as follows:

4.1 CHIP SEAL SURFACING VERSUS AGGREGATE SURFACING

The following performance comparisons can be made:

- The Chip Seal Sections, Cells 32 and 34, were not as susceptible to washboarding as were the aggregate sections.
- Cell 32, the coarse aggregate section with the chip seal surfacing, did not rut as quickly as Cell 33.
- Shoving and slight rutting developed at the west end of the heavy lane of Cell 34 due to braking. This occurred on the first day of heavy loadings when deep rutting occurred near the approach end of Cell 33 when the chip seal was new. The primary mode of deterioration for the rest of the section was low severity rutting.
- In the spring, both sections deteriorated more quickly than the aggregate surfaced sections. The deterioration modes were rutting in Cell 32 and by the overall disintegration of the chip seal in Cell 34. The deterioration occurred in both traffic lanes.

From the time of placement till freeze up in the fall of 1994, both lanes experienced the ten-year equivalent of 5 to 6 HCADT which is higher than a typical residential street and is equivalent to the loadings on a minor county or municipal collector. The performance can be compared to Table 2 of *Minnesota's Design Guide for Low Volume Aggregate Surfaced Roads*[16]. The subgrade is a silty clay loam which has a Soil Factor (SF) range of 100 to 130. At a SF of 100 and 6 HCADT, the design thickness is about 180 mm (7 in.) and at a SF of 130, a design thickness of 230 mm (9 in.). Neither of the sections were able to live up to the design chart; however, the loadings on the LVR do not translate directly to actual Low Volume Road conditions.

4.2 AGGREGATE GRADATION

The following performance comparisons can be made:

- On the basis of rutting, Class 1 Fine provided significantly better performance than Class 1 Coarse. This difference was immediately apparent on the heavy lanes of Cells 33 and 35 whereas the difference between Cells 32 and 34 was not apparent until the following spring.

The aggregate component of the study led to some unexpected results. The initial intent in choosing a coarse and fine gradation was to develop a measure of the influence gradation has on the performance. While it turned out that gradation has a very significant effect, the coarse and fine variations in the sand and gravel size particles did not provide the behavior expected. The coarse aggregate was expected to perform better than the fine, and in fact, it did not perform as well. There is one confounding factor, however, that must be considered before any final conclusions are formed: The subgrade support on Cells 32 and 33 where the coarse aggregate was placed was not as good as in Cells 34 and 35. Considering the load softening behavior of the subgrade soils as shown in Figures 14 to 17, the subgrade support in Cells 32 and 33 would be lower if the Class 1 Coarse aggregate did not distribute the loads as well as the Class 1 Fine.

The actual performance differences between the coarse and fine aggregates indicate the coarse aggregate may not have been able to provide as much structural support as the fine aggregate, and the coarse aggregate tended to be more susceptible to washboarding.

Laboratory tests of the aggregate materials performed at the University of Illinois[14], however, revealed a significant difference between the two aggregates. The Class 1C provided very little shear resistance, and could not survive the conditioning cycles of the repeated load triaxial test used to determine the resilient modulus. The ranking of the results of the laboratory testing are consistent with the performance ranking of the aggregates in the study.

4.3 LEGAL VERSUS HEAVY LOAD

- The loading repetitions on the LVR were distributed between the legal-loaded lane and the heavy-loaded lane to approximate the four-to-one ratio of the truck factors. Specific performance conclusions with regard to the loading are:

Cell 32 The performance of the two lanes were similar, both developing some rutting in the summer and fall and both failing in rutting during the quick thaw that occurred the week of March 20, 1995. The approximate 102 to four-to-one ratio of the number of truck passes indicated that the accumulated ESALfor the legal and heavy lanes were similar.

Cell 33 On the first day of traffic on the heavy-load lane, severe localized rutting occurred in less than 40 passes of the truck. The rutted areas were repaired by blading, but would rut again. It was not until 100- to 150-mm (4- to 6-in.) Class 6 aggregate blister patches were placed over the soft spots that the section could support heavy load passes. The section simply was not strong enough to handle the heavy load. The legal load side would develop rutting but the dominant mode of deterioration that needed attention was washboarding. The development of washboarding related much more to the number of truck passes rather than the weight of the truck.

Cell 34 Cell 34 provided similar performance between lanes, except for shoving on the northwest end of the heavy lane that developed soon after loadings started because of the truck braked for the ruts in Cell 33. Aside from the shoving, both lanes deteriorated in similar fashion, finally failing in rutting and chip seal deterioration during the spring thaw.

One notable factor in the deterioration of Cell 34, is that the chip seal prevented the use of blading to correct the rutting and deterioration that eventually developed. The chip seal, however, kept the surface in reasonably good riding condition during the summer, fall, and winter of

1994 without the need for any maintenance. This Cell also carried the ten-year equivalent traffic of a minor collector for a county or municipality.

Cell 35 Cell 35 was the best structural performer of the four cells, showing only low to medium severity of rutting, even through the spring thaw. The measured subgrade strength on this section was stronger than that of the other cells which confounds drawing the conclusion that the Class 1F provided much better structural performance. Both lanes of this Cell carried the ten-year equivalent of 8 to 10 HCADT, the equivalent to a county or municipal collector. At the end of the study, this cell had equaled the design capacity according to Table 2 for a SF of 130 and is expected to provide the design capacity of a SF of 100; however, it will take about four years to generate the equivalent HCADT.

This section provided similar structural performance for both lanes. The legal load lane, as described for Cell 33, also developed washboarding much quicker than the heavy-loaded lane.

The washboarding on Cell 35 developed at a slower rate than on Cell 33. The Class 1F aggregate gradation may be the reason for the better resistance to washboarding; however, the section strength may also have influenced the rate of washboarding. It is not possible to clearly state, on the basis of performance, that the Class 1F aggregate is better than the Class 1C because Cell 35 had a stronger subgrade.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUDING DISCUSSION

5.1.1 Monitoring of Gravel Roads for Research Purposes

Mn/ROAD is a structural experiment; the intended results of the Mn/ROAD aggregate study were to evaluate the structural performance of two aggregate gradations, with two surface types, under two levels of loadings. The structural aspects of the experiment are the ability to carry load, and the stability of aggregate. (The aggregate stability may not have been an original consideration of the experiment, but instead, its ability to sustain axle loadings was likely to be foremost in mind when the experimental sections were designed.)

There are several established processes of rating gravel roads, including the Cold Regions Research and Engineering Laboratory (CRREL) method which was extended into the PAVER Pavement Condition Index (PCI) concept. Another method called PASER was developed by the University of Wisconsin. Neither of these rating procedures were very well suited to the monitoring of the aggregate sections at Mn/ROAD, because of the severity limits defined in the system and because the rating system is intended to rate items that do not vary at Mn/ROAD such as ditch section, width, and drainage. The severity levels for rutting, washboarding, and float did not provide the resolution necessary for the performance monitoring at Mn/ROAD.

For the Mn/ROAD aggregate surfaced sections, the attributes that were most relevant to the performance were rutting and washboarding. Perhaps the most relevant measure of performance of these sections was driveability. When the truck could no longer maintain a 50 to 60 kph (30 to 35 mph) speed because of localized ruts or washboarding, the sections were bladed. The ability to maintain speed ended up being the dominant measure of functionality of the sections. There were only two distress mechanisms that limited the speed of the truck; severe localized rutting that created bumps, and washboarding in the low- to medium-severity category. Rutting would normally not affect speed, but in the case of Cell 33, the ruts were very localized, creating a severe bump. Many would call the ruts soft spots rather than ruts because they were less than 10 m (11 yd) in length. Washboarding became a controlling factor whenever the washboard profile amplitude was sufficient to cause the steel weights on the truck flatbed to start shifting. It seemed that combined effect of the rear suspension of the trailer, the washboarding (spacing and amplitude), and speed of the vehicle, would cause the bed of the trailer to oscillate up and down with sufficient force to lift the one-half ton weights to decouple from the bed. The corrugations were about 0.6 m (2 ft) apart. Since the spacing of the tandem axle is 1.22 m (4 ft), both axles of the tandem would move up and down at the same time. When the washboarding amplitude got in the range of 12 to 18 mm (0.50 to 0.75 in.), the weights would start shifting. At 50 kph (30 mph), or 13.4 m/sec (44 ft/sec), the axles would experience one up and down oscillation every 0.6 m (2 ft), or 22 times per second. The amplitude of vertical up and down acceleration (vibration) of the trailer bed was approaching or exceeding one gravity, lifting the weights off the truck bed and allowing them to shift. The vertical amplitude of oscillation is a major problem when it comes to cargo shifting or cargo damage. Twenty-two Hertz tends to be in the resonant frequency range of the tires. Adjusting tire pressure, therefore, may have influenced the wavelength of the corrugations.

It was interesting to note that when the corrugation was of sufficient severity to cause the truck to change speeds, the ride in an automobile (Ford Taurus in this case) was satisfactory. The roughness was not sufficient to cause the driver to slow down for comfort sake, nor for handling concerns. This indicates there is a strong vehicle sensitivity to certain roughness frequencies.

5.1.2 Performance of the Aggregate

Two aggregates gradations were selected for the Mn/ROAD aggregate sections (Cells 32 to 35 or LVR-A-1 to LVR-A-4). Both gradations were within the Mn/DOT Class 1 gradation band; one, Class 1 Coarse, was on the coarse side of the gradation and the other, Class 1 Fine, was on the fine side. (The Class 1 gradation band was essentially split in two, with a minor overlap between the two gradations.) The initial expectation was that the Class 1C would perform better than the Class 1F because the coarse fraction of the aggregate would increase the shear strength and internal angle of friction. (This expectation may still be valid for many aggregates.) For the Class 1C and Class 1F, however, that did not turn out to be the case. The Class 1F performed significantly better than the Class 1C, both in the field, and in laboratory test results. Unfortunately, the materials were from two different sources, rather than different gradation blends from a single source. That brings up questions about the nature of the aggregate shape factors or other factors that may be responsible for the difference in the aggregates. On the basis of the tests and performance, we cannot conclude that the gradation alone can explain the difference, but we can conclude that the gradation alone is not a good predictor of performance. The primary conclusion of the Mn/ROAD performance is that some means of evaluating a wearing coarse aggregate is needed. At this time, it is expected that the evaluation should relate to the cohesion and the shear strength, and that it needs to be simple to do. It became obvious from Mn/ROAD, that gradation is not a reliable predictor of shear strength, as initially anticipated.

The poor shear strength of the Class 1C was first measured at the University of Illinois. The aggregate was found to be sensitive, poor, or both in several ways. It was also found to be sensitive to moisture in the standard moisture density test, to have a very low shear strength in a laboratory Dynamic Cone Penetrometer (DCP) test, low quick shear results, and low resilient modulus results. The simplest of the tests performed at the University of Illinois is the laboratory DCP test which is deserving of further investigation as a quick test method to evaluate the suitability of aggregate material for use as a wear surface.

5.1.3 Binder in the Aggregate

During the course of the experiment, members of the project advisory panel and others including the author, observed that the aggregates had little or no plastic (clay) binder. If clay binder alone controlled the performance, the Class 1F would not have been an apparent success because it had little or no clay content either. The interest in the clay content was so great that the rehabilitation of the aggregate sections was centered around the binder concept. An argument could be made that a good aggregate wear could be designed by specifying a VMA and blending in sufficient quantity of clay to bind the aggregate, but not too much to cause it to become slippery due to excess clay at the surface. An ideal aggregate wear, then, would have low permeability, good stability, low dust production, and good frictional characteristics. It may be possible to make such a mix from the Class 6 granite used at Mn/ROAD bound with a clay soil.

Discussions with the County Engineers quickly brings the lofty goal of an ideal aggregate wear back down to the ground. Low volume aggregate surfaced roads must utilize local materials to the extent possible; an asphalt bound poor aggregate may perform better than a clay bound good aggregate, and may be less costly. This brings the emphasis back to finding an easy means of evaluating the performance potential of an aggregate material by some means other than gradation. Rather than build a number of sections at Mn/ROAD, it may be more cost effective to evaluate a variety of aggregates currently in use around the state, both from a materials shear strength standpoint and from a performance under traffic standpoint.

It must be pointed out that the poor performance of the Class 1C was not clearly identified to be due to the aggregate itself. The 46,535 kg (102,500 lb) load side of Cell 33 developed localized failures after only a limited number of passes of the truck (less than 40). Cell 33 showed higher deflections than Cell 35 which had Class 1F, and the shape of the deflection basin indicated some of the strength loss was due to the subgrade. The localized failures could be due to soft pockets in the subgrade, rather than a poorly performing aggregate. One DCP test in the rutted area had a PI of over 240 mm (9 in.)/blow which is due to **very soft** soils. Undisturbed samples taken from the subgrade, however, were not able to identify the nature of the low subgrade strength that the DCP had measured. An undisturbed sample was not taken at exactly the location the DCP test was taken and the very soft soil condition was probably very localized.

Although no permeability information was available for the Class 1C and Class 1F, it was anticipated that the Class 1C took on water much more readily than the Class 1F. This could not be confirmed by any of the moisture content measurements made. The subgrade was a silty clay loam of low permeability. If the Class 1C could take on more moisture than the Class 1F, and it was moisture sensitive as found at the University of Illinois, plus any moisture that collected at the bottom of the aggregate may have resulted in a very thin, but soft, soil layer at the aggregate/subgrade interface. The measured deflection basins can be duplicated with elastic layer theory using the following section:

150 mm (6 in.) 103 MPa (15,000 psi) aggregate;
150 mm (6 in.) 35 MPa (5,000 psi) aggregate (bottom half of the aggregate wet);
2.5 mm (0.10 in.) 0.69 MPa (100 psi) soil (thin saturated soil layer);
5.8 m (0.22 in.) 68.9 MPa (10,000 psi) soil; and
hardbottom, infinite half-space.

There are a number of minor variations of the above section that can be used to approximate the measured deflection basins in Cell 33. It can be anticipated, however, that any section that would generate such basins would have very little bearing capacity.

The actual mode of failure in the severe rutting areas seemed to be a lateral displacement of the aggregate, rather than a development of a significant rut in the subgrade. Measurements of the cross slope of the interface between the aggregate and soil showed only little evidence of rutting at the top of the subgrade. The following scenario is offered as a possible explanation of the pass-by-pass mode of failure. A high moisture content at the very top of the subgrade, and in the lower part of the aggregate reduced the shear strength of the aggregate, and reduced the lateral confining pressure available to the aggregate. (Aggregate strength is highly dependent on lateral confining pressures if it has low shear strength.) Several passes started to move the aggregate forward, disturbing any remaining confining force, and caused the aggregate to shear and dilate (lose density). Visual observations of the surface of the aggregate in the vicinity of the soft areas showed a small but definite forward movement of the surface with each axle pass. The trench sections that were dug to evaluate the rutting showed that the aggregate adjacent to the rut had actually lifted 50 to 75 mm (2 to 3 in.) above a straight line between the surface at the centerline to the surface just past the lane edge. The elevations at both the centerline and the lane edge did not appear to be affected during the failure. The longitudinal profile through the rutted areas in either wheel path showed an initial dip followed by a bump, indicating that aggregate material was being pushed forward.

5.1.4 Section Design

During the course of the project, the advisory panel pointed out that the cross section of the aggregate section was not what would be used for the construction of an aggregate surfaced road. The primary difference is the cross slope of the subgrade, and the surface. Mn/ROAD was built to a cross slope of 1.5 percent, whereas aggregate roads are typically built with a cross slope of 4 to 6 percent. The steeper cross slope is intended to help the surface shed water better, and for the water that collects at the soil aggregate interface to more quickly drain away. If there is any loss of crown in the subgrade, the Mn/ROAD section would actually end up holding water and reducing performance. It was recommended that the next rehabilitation of the sections include regrading the subgrade to a 6 percent cross slope.

5.2 SUMMARY OF CONCLUSIONS

1. Aggregate gradations alone are not reliable predictors of performance.

   On the basis of rutting, the equivalent truck loadings (legal and overloaded) were approximately equal, indicating the ratio of the truck factors as calculated by the AASHTO method holds and that the accumulation of ESALs on the legal and overloaded lanes were similar.

2. The most dominant deterioration modes for the sections were rutting or washboarding. Washboarding was much more dependent on the number of truck passes rather than the truck loadings.

3. Forensic studies showed that most of the rutting occurred in the aggregate, not in the subgrade.

4. Dynamic Cone Penetrometer, resilient modulus, and shear tests conducted in the laboratory at the University of Illinois predicted the Class 1C aggregate would not perform as well as the Class 1F, which was confirmed by the field performance.

5.3 RECOMMENDATIONS

1. A simple test, such as a laboratory DCP test, should be evaluated for inclusion in the specifications for aggregate wearing materials.

2. Future research should include the use of different aggregates in Cells 32 through 34, and on existing aggregate surfaces roads, to broaden the experience regarding the structural performance of aggregate wearing materials and to provide a basis for the development of tests to be included as part of the specifications for aggregate surfacing materials.

ANNOTATED BIBLIOGRAPHY

Design Criteria for Aggregate-Surfaced Roads and Airfields, Technical Report GL-89-5 by Chou, Yu. T. WES, PO Box 631, Vicksburg, MS 39181-0631. Available from NTIS, 5285 Port Royal Road, Springfield, VA 22161.

A good reference on Aggregate-surfaced Roads. p. 19 gives gradations for aggregate materials; Gives thickness requirements for low CBR surface materials for low repetitions, more suited to C-130's etc.; gives a CBR vs. coverage chart. Discusses and shows examples of applications of various thickness design relationships that can or have been used for aggregate thickness design. Mostly based on CBR of underlying soils, CBR of the aggregate, and repetitions. Discusses gradation requirements for aggregate to provide good shear strength, calling for enough fines (-#40 sieve) to increase the friction component and not too much to reduce permeability.

Validation of the Mechanistic Approach to Nondestructive Pavement Evaluation for Aggregate Surfaced Roads, by Lynne H. Irwin, Isao Ishibashi, and Wei-shih Yang. Department of Agricultural Engineering and School of Civil and Environmental Engineering, Cornell University, Ithaca, New York. April 1985.

Second report. See also *Resilient Behavior of Base and Subgrade Materials,* Geotechnical Engineering Report No. 84-4 and Cornell Local Roads Program Report 84-2, August 1984. Noted the Boussinesq equations were presented in 1885 (point load and a semi-infinite elastic body). Uniform load condition equations by Love in 1923. Westergaard in 1926. Burmister in 1943 and 1945 solved the elastic two layered system using classical theory of elasticity. Both CHEVRON and BISAR are based on Schiffman's (1962) solutions for stresses, and displacements at any point in the layered system. (See Schiffman, R.L., *General Analysis of Stresses and Displacements in Layered Elastic Systems,* Int. Conf. of the Design of Asphalt Pavements, proceedings, 1962 pp 365-375.) Regression of rut depth is:

$$RD = 0.1741 \frac{P_k^{0.4707} t_P^{0.5695} N^{0.2476}}{LOG(t)^{2.002} C_1^{0.9335} C_2^{0.2848}}$$

Where:

RD = Rut Depth, in.

C_1 = Aggregate CBR

C_2 = Subgrade CBR

P_k = equivalent single-wheel load, kips

t_p = tire pressure, psi

t = thickness of aggregate

This report is an evaluation of the mechanistic characteristics of gravel roads based on FWD, and Bison Soil Strain Gages. Both FWD and truck loadings were evaluated with the gages. (They used dummy setup, sensors that could not experience a strain, in the same vicinity as the actual gages to measure the influence the truck and FWD had on the strain readings and subtracted the dummy signal from the live gages.)

The latter part of their analysis showed a definite change in rutting rate based on the time of year. It showed 127,000 ESALs to produce a rut in July conditions and 7 in April; 2,861 in September (getting wetter), etc.

REFERENCES

1. Lukanen, E.O. and Skok, Dr. Eugene L., *A Synthesis Study of Surfacing Designs and Construction Technology for Low-Volume Roads,* FHWA/MN/LRRB-82/07, Minnesota Local Road Research Board, St. Paul, Minnesota, April 1982.

2. David E. Newcomb, Richard Wolters, Steve Lund, *Minnesota Cold Regions Pavement Test Facility*, Proceedings, Symposium on State of the Art Pavement Response Monitoring Systems for Roads and Airfields, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, March 1989.

3. David E. Newcomb, Nelrae Succio, Steve Lund, *Minnesota Road Research Project*, Proceedings, 38th Annual Geotechnical Conference, University of Minnesota, Minneapolis, Minnesota, March 1990.

4. *Standard Specifications for Construction,* 1995 Edition, Minnesota Department of Transportation, St. Paul, Minnesota.

5. Lukanen, Erland O., and Skok, Dr. Eugene L., *A Synthesis Study of Surfacing Designs and Construction Technology for Low-Volume Roads,* Investigation 655, Minnesota Department of Transportation, April 1982.

6. Mn/ROAD Home Page. http://mnroad.dot.state.mn.us/general.html#history.

7. Eaton, Robert A. and Beaucham, Ronald E., *Unsurfaced Road Maintenance Management,* Special Report 92-26, U.S. Army Corps of Engineers Cold Regions Research & Engineering Laboratory, December 1992.

8. Walker, Donald, and Entine, Lynn, *Gravel-PASER Manual, Pavement Surface Evaluation and Rating,* Transportation Information Center, University of Wisconsin - Madison, May 1989.

9. Eaton, R.A., Gerard, S., and Cate, D. W., *Rating Unsurfaced Roads, A field manual for measuring maintenance problems,* Special Report 87-15, U.S. Army Corps of Engineers Cold Regions Research & Engineering Laboratory, August 1987, Revised September 1988.

10. Shahin, M.Y., Kohn, S.D., *Pavement Maintenance Management for Roads and Parking Lots,* CERL-TR-M-294, U.S.Army Construction Engineering Research Laboratory, Champaign, Illinois, October 1981.

11. *Standard Test Method for the Collection and Measurement of Dustfall (Settleable Particulate Matter), D 1739-89*, Annual Book of ASTM Standards, Vol. 11.03, AMERICAN SOCIETY FOR TESTING AND MATERIALS, West Conshohocken, Pennsylvania.

12. Taylor, Deborah Jean, Irwin, Lynne H., and Aneshansley, Daniel J., *A Device to Measure Road Dustiness on Aggregate-Surfaced Roads,* EM 7170-8, United States Department of Agriculture, Forest Service, Washington, D.C., June 1987.

13. Thompson, Marshall R., Letter to George Cochran, Mn/DOT Physical Research Engineer, November 7, 1994.

14. Burnham, Tom, and Johnson, David, *In Situ Foundation Characterization Using the Dynamic Cone Penetrometer,* MN/RD-93/05, Minnesota Department of Transportation, St. Paul, Minnesota, May 1993.

15. Model 1050 Clegg Impact Soil Tester Operators Manual, Lafayette Instrument Company, Lafayette, Indiana.

16. Beaudry, Terrance M., *Minnesota's Design Guide for Low Volume Aggregate Surfaced Roads,* MN/RD 92-11, Minnesota Department of Transportation, St. Paul, Minnesota, July 1992.