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Aggregate Road Surface Rejuvenation

Charles Jahren, Principal Investigator
Department of Civil, Construction, and Environmental Engineering
Construction Management and Technology, Institute for Transportation
Iowa State University

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16. Abstract (Limit: 250 words)

Aggregate surfaced roads become coarser and coarser after a few years of service due to an inherent problem—dust emission. Fines in the surfacing material are kicked up by traffic and blown away by the wind as fugitive dust. One of the alternative rejuvenation methods is to replenish the missing fines to restore the gradation and plasticity of the in situ material. Savings in the material and cost could in return benefit the environment and financial condition of the jurisdiction.

Control and experimental test sections were established in three counties of Minnesota and performance of the sections were assessed using methods including cross-section profile change surveys, gravel loss and loose aggregate measurements, gravel road condition ratings, International Roughness Index estimation, and field observations. Experimental sections in Jackson County did not perform satisfactorily. However, one of the test sections in Beltrami County performed favorably well. A five-year-cycle benefit-cost analysis revealed that a 20 percent cost savings was also achievable in that particular section. Another trial in Olmsted County tested whether modified Class 5 limestone aggregate is appropriate for gravel road surfacing.

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Aggregate Road Surface Rejuvenation

Final Report

Prepared by:

Charles Jahren
Ziliang Zhang
Department of Civil, Construction, and Environmental Engineering
Construction Management and Technology, Institute for Transportation
Iowa State University

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Executive Summary

The current remedy for deteriorating aggregate road surfaces is to haul and place a new surface to cover the problematic surface. However, with aggregate costs and environmental concerns increasing, it would be desirable to reduce the need for new aggregate. This project proposed an alternative solution: analyzing the problematic road surface to determine how the existing material could be rejuvenated by blending the existing road surface with new aggregate that has the proper characteristics to bring the resulting surface to the proper gradation and plasticity.

Several benefits are expected to accrue from adopting an aggregate rejuvenation approach to aggregate road maintenance. Blending new aggregate with existing road surfaces, using only the aggregate needed to rejuvenate the existing surface, will reduce the amount of aggregate required, reduce costs, and increase sustainability. If road performance increases, the maintenance effort will likely decrease as well, allowing maintenance efforts to be diverted to areas of higher need.

Control and experimental test sections were established in three Minnesota counties and performance of the road sections were assessed using methods including cross-section profile change surveys, gravel loss and loose aggregate measurements, gravel road condition ratings, International Roughness Index estimation, and field observations.

Experimental sections in Jackson County did not perform satisfactorily. However, one of the test sections in Beltrami County performed favorably well. A five-year-cycle benefit-cost analysis revealed that a 20 percent cost savings was also achievable in that particular section. Another trial in Olmsted County tested whether modified Class 5 limestone aggregate is appropriate for gravel road surfacing.

1. Introduction

PROBLEM STATEMENT

Aggregate roads across Minnesota have average daily traffic (ADT) ranging from 25 to 700 vehicles per day (vpd) (Johnson and Olson 2009). Traffic on aggregate roads induce fugitive dust as a result of the disturbance of the surface by the wheels of the vehicles. In addition, surface material erosion due to heavy rainfall results in loss of fines in the surface material. Considering other activities that disturb the road surface, such as regular maintenance operations year-round, the fines content in the surface diminishes over the service time. As a result, excessive top size aggregate is left on the road surface as shown in Figure 1.

Figure 1. Excessive Floating Aggregate on Pope County CR 35 July 2013

Numerous problems stem from having excessive loose aggregate on the road surface. The loose aggregate tends to accumulate outside of the wheel paths, forming ridges. The ridge pairs provide water channels that retain water. Water retention is believed to be one of the major causes for distresses and failure of a gravel road. Crust formed on the surface will be softened, leading to rutting and potholes (Skorseth and Selim 2000). In addition, excessive loose aggregate compromises the comfort and quality of the ride, impairing the safety of road users under some severe circumstances.

BACKGROUND

Over time of service, loose aggregate accumulates to an extent that re-graveling is necessary to recover the serviceability of the road. Re-graveling is one of the prevalent practices among counties to treat the problem. Re-graveling, or re-rocking, which is a term that some maintenance crews in county highway departments use, involves re-grading the road and transporting and spreading well-graded new aggregate on the affected roads.

Re-graveling is typically carried out at certain time intervals, depending on a number of factors, such as availability of the material, ADT of the road, types of material accessible, and road condition. The interval varies, although it is common to be within the range of three to five years. However, as the quality aggregate resource is being depleted severely, re-graveling is becoming less environmentally sustainable and financially feasible. County engineers are seeking ways to reutilize the existing aggregate on the surface.

RESEARCH APPROACH

The idea of replenishing fines on a road with loose aggregate on the top could be an alternative that could remedy the situation (Walker 2002). By mixing in fines, the desired gradation and plasticity of surfacing aggregate could be reestablished since proper gradation and plasticity is important in providing an unpaved road that performs well. Although this seems to be a sensible solution, the result of an investigation that could test this method has not been published.

There are incentives to perform an investigation of this type. As the loose aggregate is going to be reutilized, less material is needed to be transported to the site to rejuvenate the gravel road. Therefore, the cost of trucking, which is the major cost for construction and maintenance activities second to that of the material, is reduced. Since the amount of aggregate needed is lessened, cost of the material drops. Economic benefits are manifest if the road surface performance is acceptably preserved. Thus, one of the objectives of this research is to monitor and document the performance difference, if any, between the current practices and the proposed practice at gravel road rejuvenation.

RESEARCH OBJECTIVES

The main objectives of this research were as follows:

- Assess the performance of the proposed road surface rejuvenation method
- Determine the cost effectiveness of adopting the proposed rejuvenation method
- Develop recommendations based on lessons learned through test implementation and observation of the test results

FINAL REPORT CONTENT

The remaining chapters of this report are as follows:

2. Literature Review
3. Research Overview
4. Research Methodology, Field Data Collection, and Test Site Observations
5. Results
6. Economic Analysis
7. Performance Summaries
8. Conclusions and Recommendations

Appendices after the chapters are as follows:

A. Gradation Raw Data
B. Cross-Section Profiles
C. Statistical Analysis Results
D. Unpaved Road Condition Rating System (Beltrami County Example)
E. Condition Rating Graphs
F. Material, Labor, and Equipment Costs
G. Aggregate Sample Origin Map

H. Soil Classifications for 19 Sample Pairs
I. Independent t-Test Results
J. Findings Summary Table

Interim Task Reports were submitted during this project and contain additional material not included in this Final Report.

2. Literature Review

SURFACING MATERIAL PROPERTIES

Gradation

Surfacing material specifications are readily available in many states and regions. Differences can be found in a comparison of jurisdictions. While some states, such as Minnesota and Iowa, specify surfacing gravel top-sized with 3/4 in. or smaller, other states, such as South Dakota, specify strictly that the top size is smaller than 3/4in. That is also true for other sieves within the gradation. For the #200 sieve, Minnesota specifies a range of 3 to 10 percent while Iowa specifies a range of 6 to 16 percent (Iowa DOT 2012, MnDOT 2005). The difference is even larger for specifications abroad. The #200 sieve is specified to range from 10 to 40 percent in Australia and 7 to 30 percent in South Africa (AARB Transport Research and Giummarra 200, CSRA 1989), which are two countries reputed to have good performing gravel roads.

Plasticity

Regarding to plasticity, again jurisdictions provide contrasting specifications according to specification review performed for this project. While many states do recommend the presence of natural silt and clay in the graded aggregate to act as a binder, which helps to consolidate the aggregate after it is put in place, a few states recommend otherwise.

The driving surface aggregate (DSA) guideline developed by the Center for Dirt and Gravel Road Studies in Pennsylvania is one of the exceptions. The guideline stresses that DSA needs to be derived from natural stone formations and that aggregate sources are restricted to that which have been mined or quarried from existing geologic bedrock formations. Rock material must make up as much as 98 percent of fines passing the #200 sieve and no clay or silt soil may be added. Lime kiln and cement kiln dust may be added to the DSA to account for up to 50 percent of fines passing the #200 sieve. Surface aggregate must be delivered at "optimum moisture" and be kept damp until placement is completed (Center for Dirt and Gravel Roads Studies 2014).

SURFACING BLENDING EQUIPMENT AND METHODS

Gradation of existing loose aggregate is likely to be coarser than originally specified since the fines diminish over the service period. To use the existing loose aggregate, adding material with a complementary gradation is advisable. It is desirable to blend the existing coarser loose aggregate uniformly with new finer material that will come close to reestablishing the originally desired gradation. Various methods can be adopted to serve such purposes and used in actual practice.

Motor-Grader

A motor grader with a moldboard blade is the most common equipment used for routine maintenance of unpaved roads. The moldboard is set at the predetermined angle β to avoid material spilling and at the proper pitch, at an angle of α, to enhance the mixing effect, as shown in Figure 2.

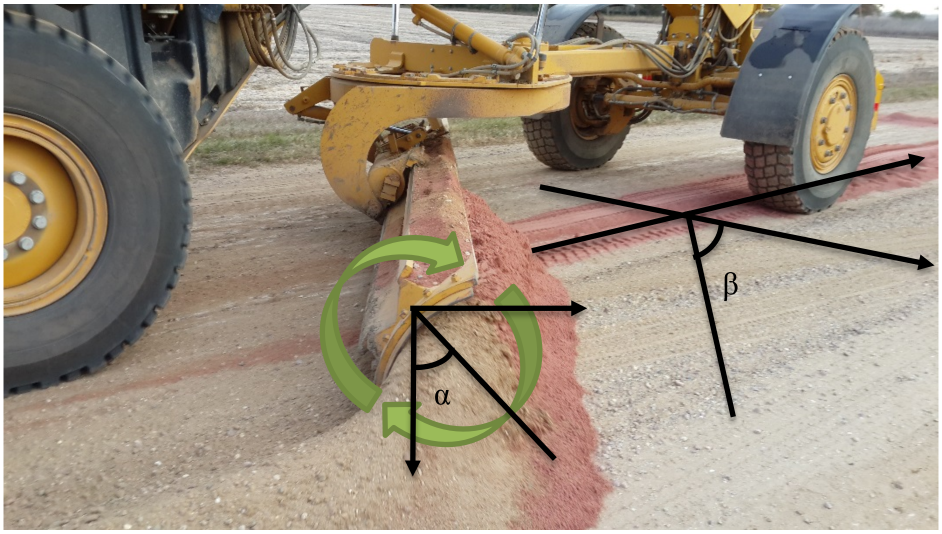


Figure 2. Moldboard Angle and Pitch

Transported material will be spread on the stretch of the road to be maintained. The moldboard is lowered to cut a few inches into the road surface. The motor-grader then advances at a constant speed of 3 to 5 mph. Windrows will be established as the motor-grader operator attempts to move the material from one side of the road to the other. Several passes back and forth are necessary to distribute the material evenly across roads with two lanes.

Motor-Grader with Carbide-Tipped Blades

Instead of using a flat cutting edge in some counties, carbide-tipped grader blades are employed (see Figure 3).

Figure 3. Carbide-Tipped Blades on the Left

The carbide-tipped blade system brings has several benefits (Center for Dirt and Gravel Roads Studies 2005a).

- Durability: A carbide-tipped blade has a service life as much as three times that of the traditional cutting edge.
- Cutting effectiveness: A carbide-tipped blade is more effective for cutting hard surfaces and, therefore, allows deeper cuts.
- Improved productivity: Since a carbide-tipped blade shatters and chisels through rocks rather than pulling them out, higher advancing speed is permissible and the desired cross section can be achieved. Also, aggregate segregation associated with time-consuming raking is eliminated and thus, costly dust emission is reduced.

Full-Depth Reclamation
A full-depth reclaimer is broadly used in asphalt rehabilitation projects. Using a full-depth reclaimer on aggregate road rehabilitation project is rare, although it is not unprecedented. The Virginia Department of Transportation (VDOT) conducted a study on the feasibility of deeply mixing particular soil stabilization materials into unpaved roadbeds, intending to lengthen the

time interval between maintenance (Bushman et al. 2005). Equipment that was employed to blend the additive stabilizer was a full-depth reclaimer (Figure 4).

Figure 4. Full-Depth Reclaimer (Bushman et al. 2005)

Asphalt Zipper

Another variation of a full-depth reclaimer is the Asphalt Zipper, which is an attachment that can be mounted on another machine, such as a track or wheel loader, as shown in Figure 5.

Figure 5. Asphalt Zipper in use for gravel road maintenance in Lafayette County, Mississippi (left) and Palo Pinto County, Texas (right) (Asphalt Zipper Inc. 2013a and 2013b)

The original objective of using this equipment was to make asphalt reclamation affordable since owning a self-contained asphalt reclaimer can be cost prohibitive. The video testimonials showing how this equipment is actually being utilized with great success for aggregate road rejuvenation demonstrate that application of the technology and processes involved look quite promising and worth consideration. The testimonials explain that use of the equipment can save money, which can be used elsewhere, by increasing both maintenance productivity and road performance.

3. Research Overview

The current remedy for deteriorating aggregate road surfaces is to haul and place a new surface to cover the problematic surface. However, with aggregate costs and environmental concerns increasing, it would be desirable to reduce the need for new aggregate. This project proposed an alternative solution: analyzing the problematic road surface to determine how the existing material could be rejuvenated by blending the existing road surface with new aggregate that has the proper characteristics to bring the resulting surface to the proper gradation and plasticity.

Four Minnesota counties participated in this project: Pope, Jackson, Beltrami, and Olmsted. Test sections were constructed in three of the four counties as follows.

In Jackson County, three sections were established on County Road (CR) 76. For the two experimental sections, mixed amounts of crusher dust, which is commonly used for microsurfacing, was mixed with the in situ floating aggregate. Class 5 aggregate was used for the control section.

In Beltrami County, three test sections were established on CR 23. Different amounts were mixed in with the in situ floating aggregate for the two experimental sections. Class 1 aggregate was used for the control section.

In Olmsted County, four sections were established on CR 115. For the two control sections, Class 2 and Class 5 aggregate were used as the surfacing material. For the two experimental sections, a 1:1 mix of Class 2 and Class 5 and a 2:1 mix of Class 5 aggregate and lime were used, respectively.

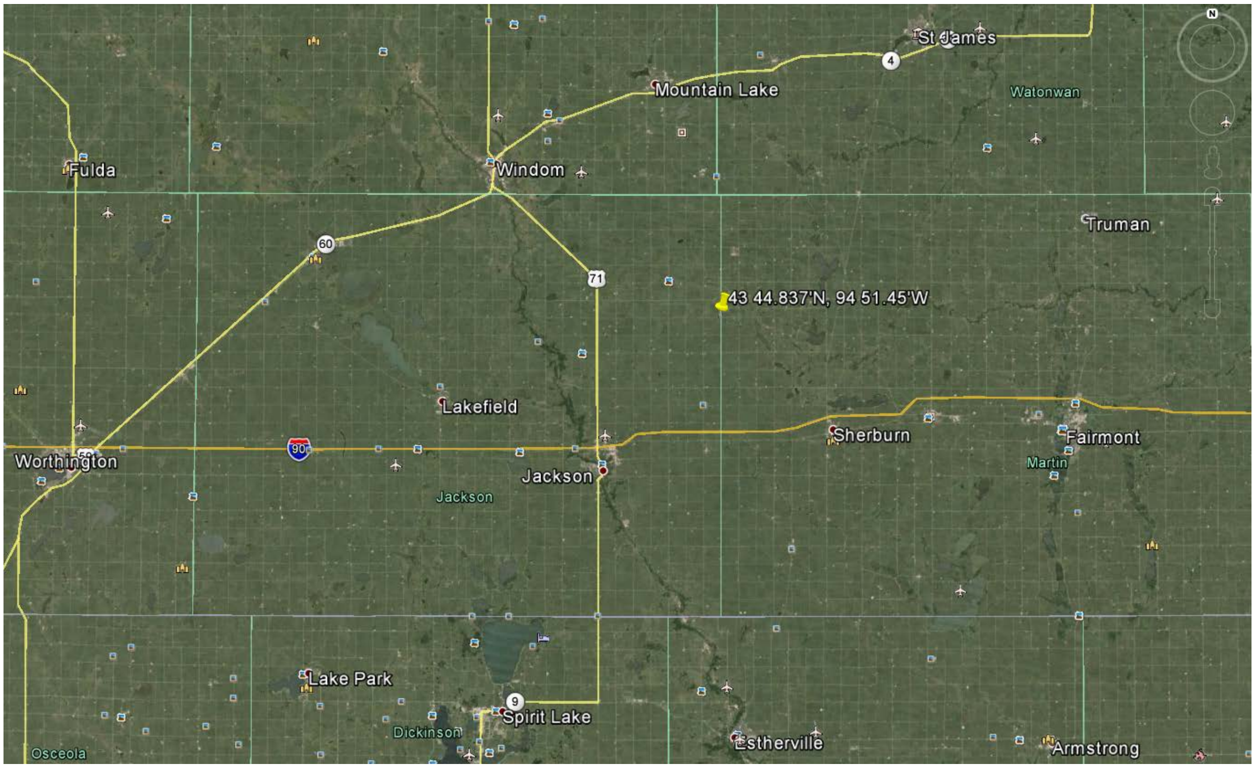
The test section layout for each county follows. The First Test Section was a control test section for each county road and the Fourth Test Section was also a control section for Olmsted County CR 115.

All sites were chosen based on the following criteria:

- Appropriate longitudinal geometry profile
- Moderate average daily traffic
- Moderate amounts of floating aggregate

JACKSON COUNTY CR 76 TEST SECTION LAYOUT

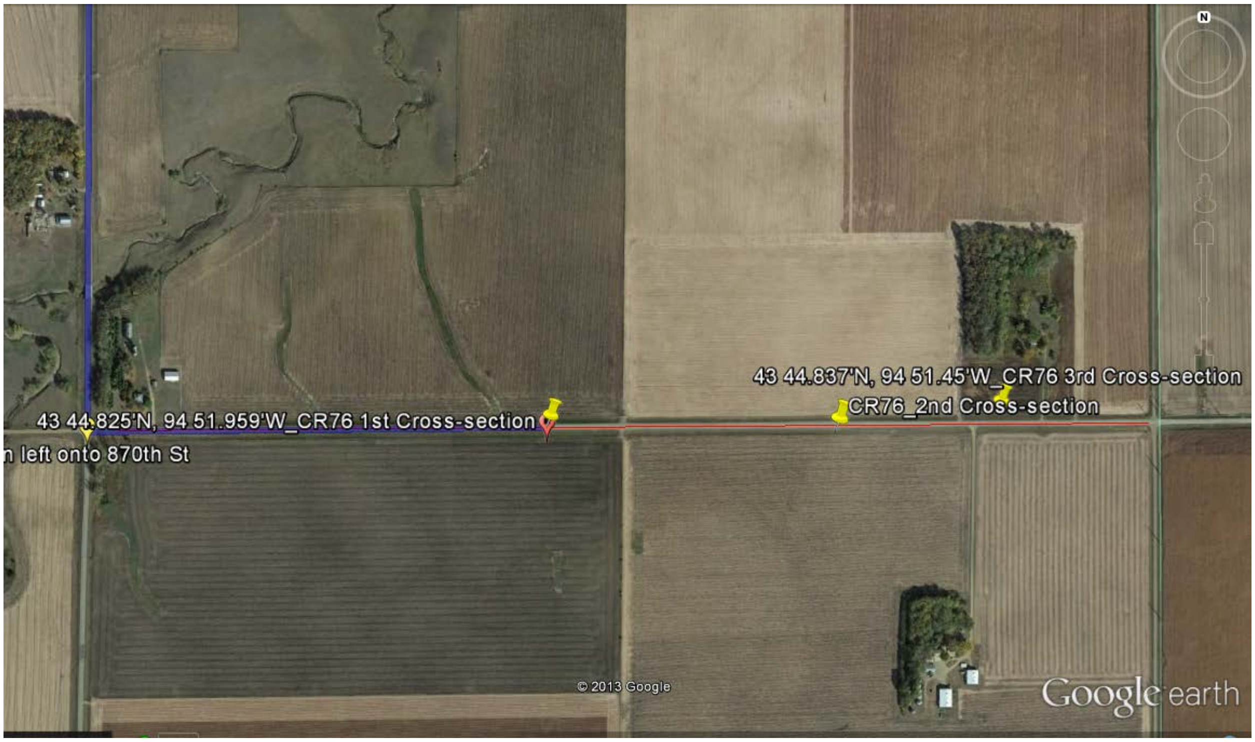
The location of CR 76 in Jackson County is shown in Figure 6.



Map © 2013 Google

Figure 6. Location of CR 76 in Jackson County

Three test sections were established on Jackson County CR 76, one of which served as a control section and the other two as experimental sections. CR 76 has a longitudinal slope from -0.7 percent to 1 percent. Each test section is 500 feet long (see Figure 7).

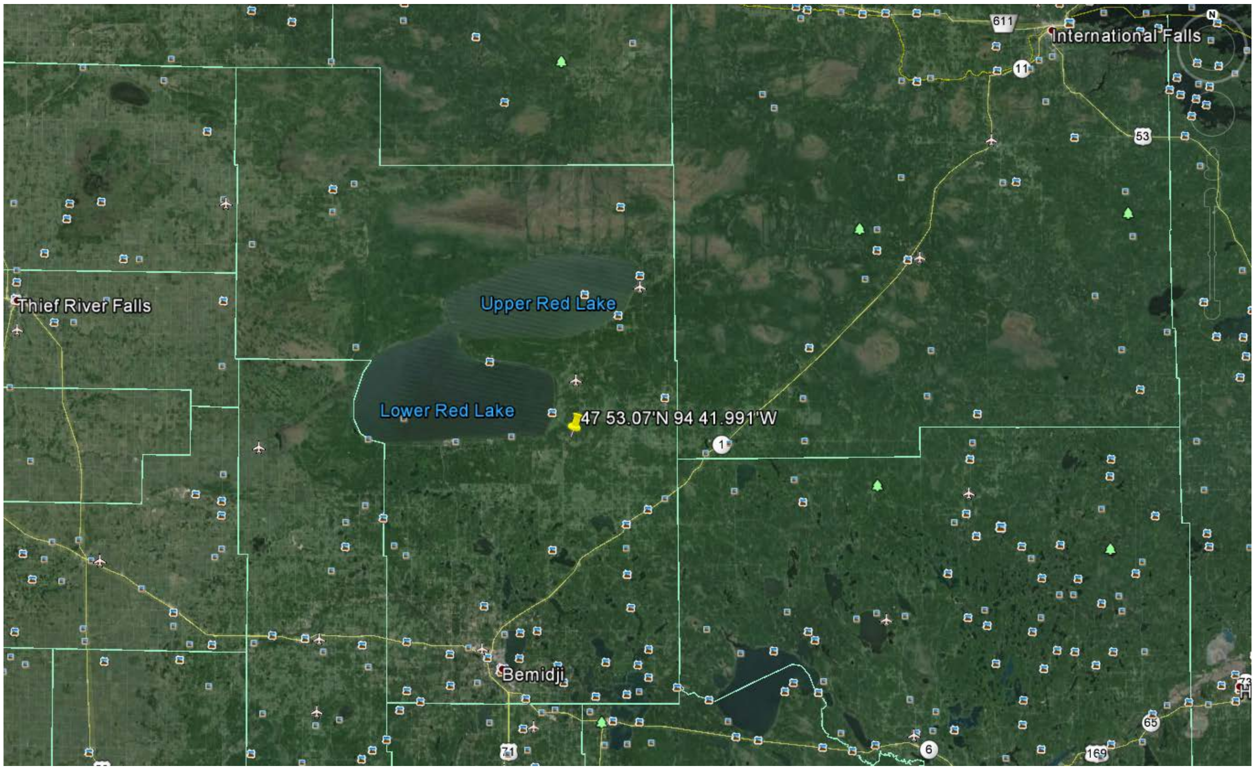


Map © 2013 Google

Figure 7. Plan View of Jackson County CR 76 Cross-Sections

BELTRAMI COUNTY CR 23 TEST SECTION LAYOUT

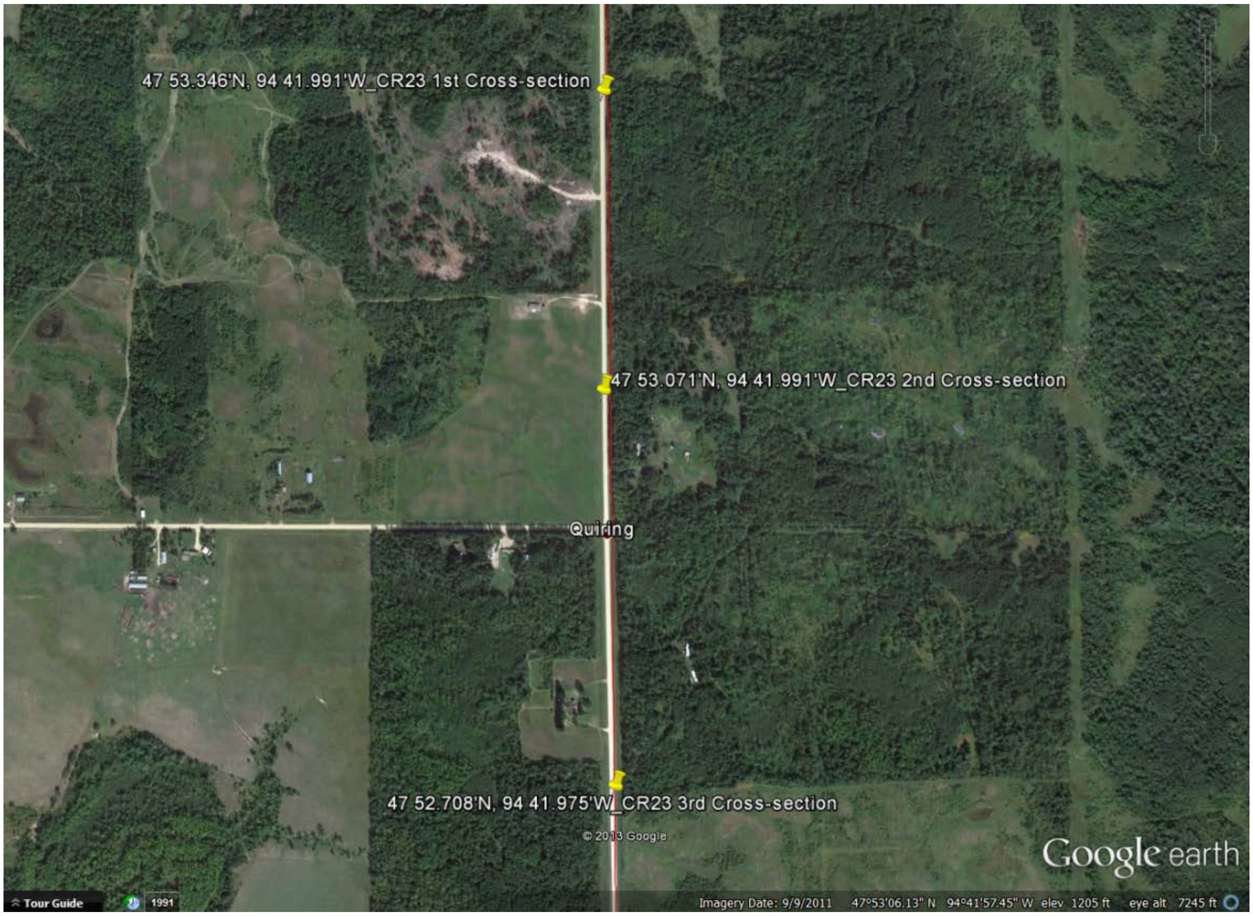
The location of CR 23 is shown in Figure 8.



Map © 2013 Google

Figure 8. Location of CR 23 in Beltrami County

Three test sections were established on Beltrami County CR 23. CR 23 has a longitudinal slope ranging from -0.8 percent to 1.1 percent. Two experimental sections and one control section were established, with 1/3 mile for each section (see Figure 9).

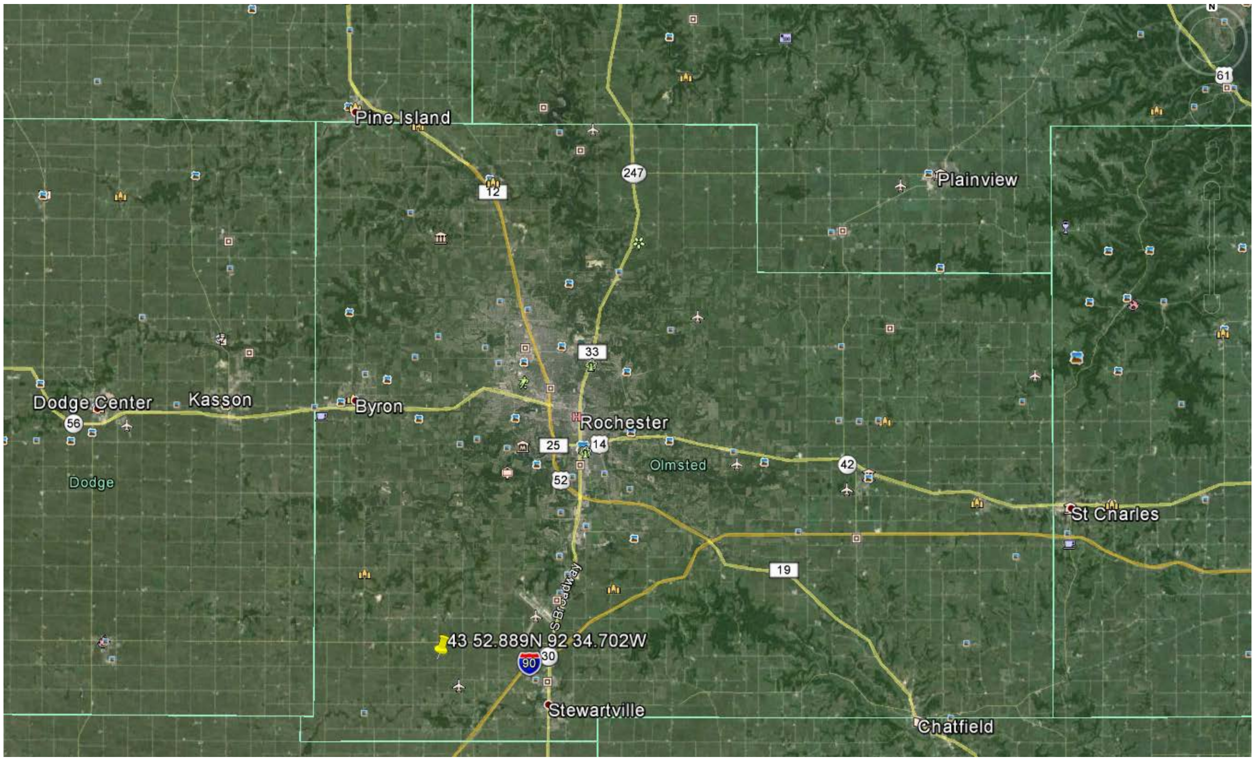


Map © 2013 Google

Figure 9. Plan View of Beltrami County Road 23 Cross-Sections

OLMSTED COUNTY CR 115 TEST SECTION LAYOUT

The location of CR 115 in Olmsted County is shown in Figure 10.



Map © 2013 Google

Figure 10. Location of CR 115 in Olmsted County

Four test sections were established on CR 115. They could not be laid out adjacent to each other due to the geometry of the road and intermittent application of stabilization additive along the road. The four sections were established on the segments of the road where it is flat and no dust palliative is applied. The length of the First to the Fourth test sections is 1,005 feet, 1,148 feet, 1,000 feet, and 1,010 feet, respectively, and Figure 11 shows their locations.

Map © 2013 Google

Figure 11. Plan View of Olmsted County CR 115 Cross-Sections

TRAFFIC VOLUMES FOR THE TEST SECTIONS

The Minnesota DOT (MnDOT) 2012 average daily traffic (ADT) counts are shown for the Jackson County and Beltrami County sites and the 2010 counts are shown for the Olmsted County site in Table 1.

Table 1. Test section traffic volumes.

Test Sections	Year	ADT
Jackson CR 76	2012	35
Beltrami CR 23	2012	80
Olmsted CR 115	2010	95

4. Research Methodology, Field Data Collection, and Test Site Observations

LABORATORY TESTING

In total, 38 samples (including both top and bottom layers) were collected and laboratory tests were run on the samples.

Sieve Analysis

Aggregate samples were used for gradation tests with a washed analysis according to AASHTO T27 (2012).

Atterberg Limits

Liquid and plastic limits tests were performed on all of the collected samples in accordance with ASTM D 4318-10e1 (2010).

FIELD DATA COLLECTION

Cross-Section Profile Elevation Surveys

Elevation data for a selected number of observation points across cross-sections in the middle of each test section were collected. The objective of the surveys was to reveal the potential loss of aggregate and average elevation changes (Bloser 2007, Sanders et al. 1997) at the representative cross-sections of each test section. A typical cross-section profile is shown in Figure 12.

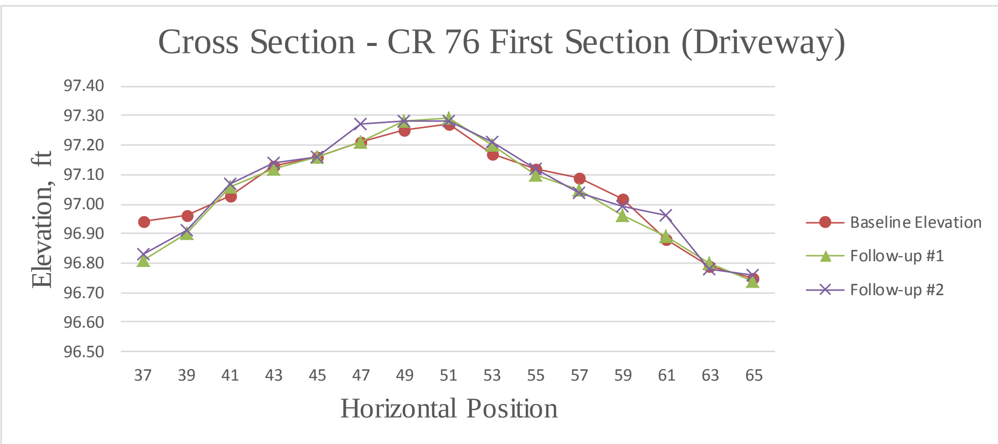


Figure 12. Typical Cross-Section Profile

The multiple regression model presented here represents the cross-section profile upon which statistical analyses were performed. Considering the elevation, y_{ij}, of each surveyed point is dependent on the time, x_i (the reading soon after construction and the readings in the months into the observation period), and the location of the point, x_j (the point in the middle of the road is probably higher than those on both sides), where x_i is a categorical variable and x_j is a numerical variable. The model with only standalone terms, x_i, x_j, and x_j^2, solely explains the situation where the cross section experiences an overall change in elevation. In other words, the elevation of each data point increases or decreases. However, this is not always true. Interaction terms, $x_i x_j$ and $x_i x_j^2$ were introduced to account for situations in which some elevation of data points increase while some others decrease.

$$y_{ij} = \beta_0 + \beta_1 x_i + \beta_2 x_j + \beta_3 x_j^2 + \beta_4 x_i x_j + \beta_5 x_i x_j^2 + \varepsilon_{ij}$$

Where $x_i = \begin{cases} 0, & \text{Baseline} \\ 1, & \text{Follow-up} \end{cases}$, $x_j = x_1 + x_2 + ... + x_n$, n varies from section to section

JMP statistical software was used to output value information including summary of fit and parameter estimates. The summary of fit table provides information on how meaningful the model is to the collected data (that is, how much variation is explained by the regression model). The parameter estimates table provides clues about whether any of the variables contain useless information about y (that is, if the coefficient of the variable is zero or not). The interest here is to find out if the coefficients of the time variable and variables that include time are zero or not. If the coefficients are zero, it means the elevation is not time-related, which means no statistically significant change in cross-section elevation over time.

Unpaved Road Condition Ratings

The rating system used in this research had been used previously in the geographic information system- (GIS-) based asset management program in Wyoming (Huntington and Ksaibati 2005). The rating standard was sent to the research team by Huntington.

Development of the rating standard was influenced by numerous rating systems including the following:

- Unsurfaced road condition index (URCI)
- Utah Local Technical Assistance Program (LTAP) Center's Transportation Asset Management System (TAMS)
- Wisconsin Transportation Information Center's Pavement Surface Evaluation and Rating (PASER) system
- Council for Scientific and Industrial Research (CSIR) of South Africa's Standard Visual Assessment Method for Unsealed Roads
- Australian Unsealed Roads Manual: Guidelines to Good Practice
- Wyoming Technology Transfer (T^2)/LTAP Center's Gravel Roads Management Report

General distresses such as rutting, washboarding, and others are evaluated with these rating standards. Images of categorized distress severity levels were attached in the material provided by Huntington to serve as guidelines for ratings.

This rating standard was selected for its simplicity and the efficiency of use. With time and budgetary constraints, travel frequency was limited for the researchers, so the majority of rating tasks were carried out by county personnel.

A standard rating manual was sent to each person who would carry out the task. The manual was intended to guide the rater to properly rate each distress according to one standard so that results would be comparable regardless of the experience of the rater and other elements that might influence the results.

Dynamic Cone Penetrometer Tests

Dynamic cone penetrometer (DCP) tests were performed on the wheel paths to investigate the shear strength of the supporting road layers. Four cycles of testing were performed at most of the test sections at randomly selected locations. The DCP test measures penetration rate, which may be related to in situ material strength by estimating the in situ California Bearing Ratio (CBR). The ASTM International D 6951/D 6951M-09 standard was followed.

Light Weight Deflectometer Measurements

Light weight deflectometer (LWD) measurements were performed at random locations on the wheel paths in each test section. LWD measurements are generally used for testing the stiffness of the unbound pavement by measuring the deflections. 2011 procedures from ASTM International E 2583-07 were followed.

International Roughness Index Measurement

Roadroid is a smartphone solution that can be used to investigate pavement roughness. One of the competitive advantages is that the equipment is portable and yet powerful. Most smartphone have built-in accelerometer sensors, GPS units and a data logging systems. Albeit a typical smartphone appears to have all the essential elements that Opti-Grade® has, the level of accuracy afforded may not be adequate. A smartphone with Roadroid installed can be used as a roughness measurement method providing up to class 3 or 2 accuracy (Michael W. Sayers et al. 1986). The estimated IRI and Calculated IRI are the two methods for calculating for IRI data. The estimated IRI is based on Peak and Root Mean Square vibrations. The device setup procedure for the estimated IRI is the same regardless of types of vehicle used. The estimated IRI is correlated to Swedish laser measurements on paved roads with a correlation factor up to 0.5, which indicates that there is moderate correlation. Calculated IRI is sensitive to the vehicle types and thus, the type of vehicle is an important input to the setup that is needed in order to produce a correct output. No detailed research has been conducted to study the accuracy of this application as of this writing (Hans Jones and Lars Forslof 2014).

Estimated IRI value thresholds are assigned to four severity levels:

- Estimated IRI less than 2.2; Good
- Estimated IRI between 2.2-3.8; Satisfactory
- Estimated IRI between 3.8-5.4; Unsatisfactory
- Estimated IRI larger than 5.4; Poor

Scrape Tests

The scrape test was a customized test that the research team developed to estimate the amount of floating aggregate on the surface. The test was carried out using a customized hoe (see Figure 13). The steel plate wings were attached on the hoe to prevent material from spilling over the sides.

Figure 13. Customized Hoe

Gentle force was applied while scraping off the loose aggregate on the surface, maintaining a 20-degree angle between the hoe bottom plate and the ground (Figure 14).

Figure 14. Loose Aggregate Collection

A constant dragging speed was desired across the road. Several randomized collections were necessary to estimate the amount of loose aggregate with higher confidence.

PRECONSTRUCTION OBSERVATIONS

Pope County CR 35

The research team visited Pope County in July 2013. CR 35 was considered a typical road section that has a considerable amount of floating aggregate (see Figure 15). The volume of floating aggregate was estimated to be 307.24 tons per mile based on an estimate involving the scrape test.

Figure 15 Floating Aggregate on CR 35 in Pope County

Pope County did not participating in test section construction due to schedule conflicts of their maintenance operation and this research project as well as difficulty in finding suitable fine material that could be used for the rejuvenation process.

Jackson County CR 76

The research team visited the Jackson County CR 76 test site twice, in July and August 2013, before construction. Figure 16 and Figure 23 show the surface conditions at the time of those visits.

Figure 16. Jackson County CR 76 Surface Conditions in July 2013

Figure 17. Jackson County CR 76 Surface Conditions in August 2013

Scattered floating aggregate could be seen along the road but was not considered a serious problem. Floating aggregate tends to accumulate away from the wheel path. Whipped-off coarse aggregate was seen along the shoulder. Floating aggregate tonnage was estimated to be 186 tons per mile according to the estimate based on scrape test results.

The road cross-section did not comply with typical crown slope recommendations which is within the range of 4 to 6 percent (Ken Skorseth and Ali Selim 2000; Center for Dirt & Gravel Roads Studies 2005) . Measurements showed the eastbound cross slope was 2.9 percent and the westbound side was 3.3 percent. The road, from the perspective of the research team, is moderately dusty during the dry season.

Beltrami County CR 23

The research team visited the Beltrami County CR 23 test site in July before construction. The floating aggregate problem was not pronounced, as shown in Figure 18, although there was scattered floating aggregate.

Figure 18. Beltrami County CR 23 Surface Conditions in July 2013

Floating aggregate tonnage was estimated to be 91.3 tons per mile according to estimates based on scrape test results. The road did not comply with typical crown slope recommendations.

Measurements showed that the northbound cross slope was 1.2 percent and the southbound side was 1.9 percent.

Olmsted County CR 115

The research team visited the Olmsted County CR 115 test site in July before construction. A small amount of floating aggregate was present on the road. Wheel paths are clearly seen in Figure 19. The wheel paths are highly compacted and had the appearance of an aged pavement.

Figure 19. Olmsted County CR 115 Surface Conditions in July 2013

Floating aggregate tonnage was estimated to be 71.49 tons per mile by extrapolating from test results. The road has an effective crown slope, which is within the range of 4 to 6 percent (Skorseth and Selim 2000, Center for Dirt and Gravel Roads Studies 2005b). Our measurement shows that the northbound cross slope is 6.7 percent and the southbound side is 6 percent.

CONSTRUCTION OBSERVATIONS

An outline of construction procedures for each county and brief test site construction observations are provided below.

Jackson County CR 76

Construction was completed at the Jackson County test site October 25, 2013 (Figure 20 through Figure 25). The construction for each test section included the following activities:

1. Windrowing existing loose material at the centerline of the road
2. Spreading additional material over the windrowed existing material

3. Blending the existing material and newly added by blading two times with the motor grader

Figure 20. Windrowing Existing Loose Material in the Center of the Road at Jackson County Test Site

Figure 21. Spreading Additional Material at Jackson County Test Site

Figure 22. Blending Newly Added Material with Existing Material at Jackson County Test Site

Figure 23. Jackson County CR 76 East Test Section (7 Tons of Crusher Dust)

Figure 24 Jackson County CR 76 Middle Test Section (12 Tons of Crusher Dust)

Figure 25. Jackson County CR 76 West Control Section (19 Tons of Standard Class 5 Aggregate)

The Jackson County crusher dust was non-binding crushed stone commonly used in the area as aggregate for microsurfacing. The control section (West/First Test Section) used MnDOT-specified Class 5 aggregate. The Class 5 aggregate was imported from Anderson Pit (just across the state line in Iowa), which is operated by Duininck Incorporated with headquarters in Prinsberg, Minnesota. The amount of material added for each test site is shown in Table 2.

Table 2. Amount of aggregate added for Jackson County CR 76.

Jackson County		
Test Section	**Type**	**Amount of material (tons)**
West/First (control)	Class 5 Standard Material	19
Middle/Second	Crusher Dust	12
East/Third	Crusher Dust	7

It was noticeable that the two experimental sections looked different from the control section (the West/First Test Section). The reddish path along the road suggested the concentration of crusher dust. More passes of blading appeared necessary to distribute the crusher dust evenly across the road surface.

Beltrami County CR 23

Construction was completed at the Beltrami County test site November 7, 2013 (Figure 26 through Figure 29). The construction process for each test section included these activities:

1. Stripping the top 1 inch of surfacing aggregate and windrowing on the side
2. Spreading additional material for the test section at the centerline of the road
3. Blending the existing material and newly added material with two passes for each side of the road

Figure 26. Beltrami County CR 23 South Test Section (50 Tons of Crusher Dust)

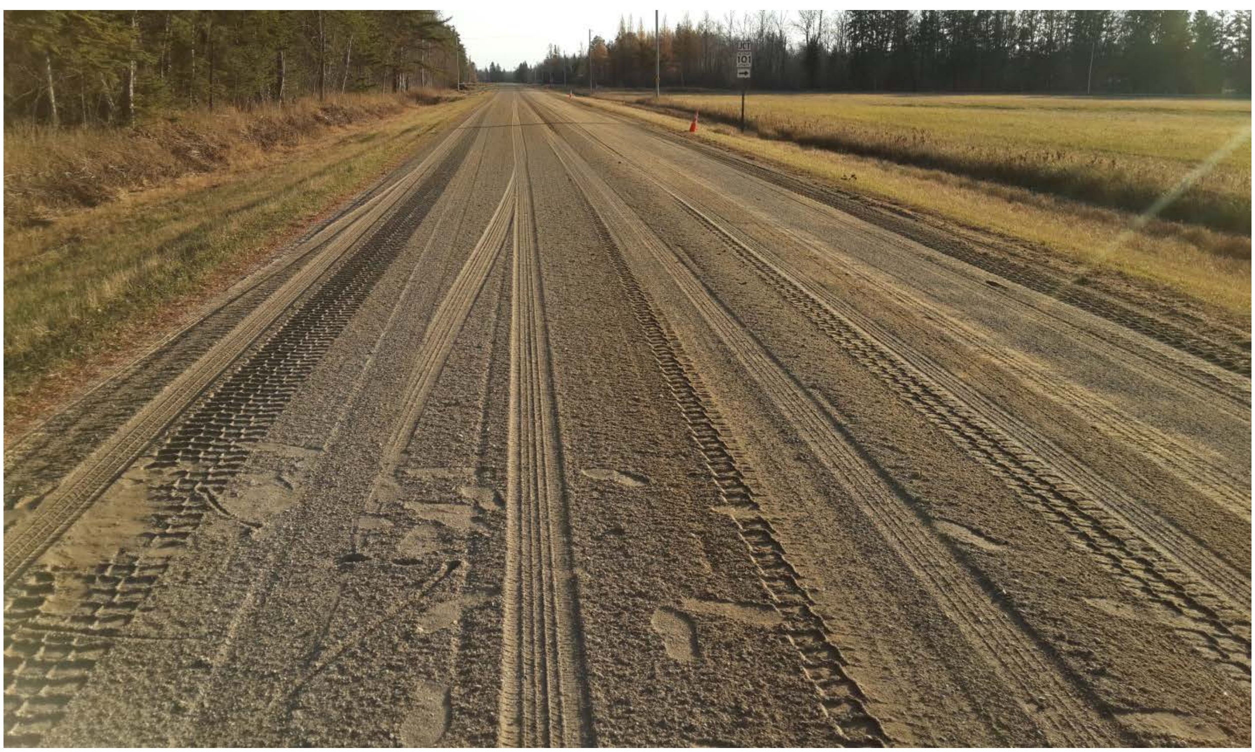


Figure 27. Beltrami County CR 23 Middle Test Section (83 Tons of Crusher Dust)

Figure 28. Beltrami County CR 23 North Control Section (166 Tons of Standard Class 1 Aggregate)

Figure 29. Beltrami County Angularity Comparison between Standard Class 1 (left) and Crusher Dust (right)

The Beltrami County control section (North/First Test Section) used MnDOT-specified Class 1 aggregate, which is used in the area for surfacing. The two experimental sections used crusher dust derived from granite. The crusher dust was evenly distributed across the width of the road on the two experimental sections. Table 3 shows the amount of material used in each section.

Figure 29 shows angularity of surfacing aggregate after construction. The interlock mechanism provided by angular aggregate helps to stabilize the surfacing aggregate. A coarse angularity test was performed as part of this investigation. The proportion of angular aggregate on experimental sections surpassed that on the others by more than 25%.

Table 3. Amount of aggregate added for Beltrami County CR 23.

Beltrami County		
Test Section	**Type**	**Amount of material (tons)**
North/First (control)	Class 1 Standard Material	166
Middle/Second	Crusher Dust	83
South/Third	Crusher Dust	50

The source of crusher dust for the experimental sections was Knife River Corporation, Northern Minnesota Division - Bemidji. Class 1 Standard Material aggregate for the control section originated from Poxleitner Pit. The two experimental sections looked quite different than the control section, as one of the crew pointed out, for their lighter surface color.

Olmsted County CR 115
The research team was not able to observe construction, so construction notes for the Olmsted County test site were solicited from the maintenance supervisor.

The mixing process for the Second Test Section was accomplished in the quarry. A truck was loaded with two buckets of Class 5 and one bucket of lime with the process repeated until the truck was fully loaded. The mixing process for the Third Test Section was implemented on site. Class 5 was spread and leveled before Class 2 was spread on top of the Class 5 material. County personnel reported that the following construction procedure was used:

1. Material was spread and a motor grader blade was used to flattened the material on the road
2. A water truck applied water to pre-wet the material
3. The material was windrowed and spread across the road in about three rounds
4. Water was applied to the road and the material was roller compacted

Standard Class 5 virgin material was used for the First Test Section.Standard Class 5 virgin material mixed with one-third lime was used for the Second Test Section. A 1:1 mix of Standard Class 5 and Standard Class 2 virgin material was used for the Third Test Section. Finally, Standard Class 2 virgin material was used for the Fourth Test Section (the control section). The amounts of material placed are shown in Table 4.

Table 4. Amounts of material added on Olmsted County CR 115.

Olmsted County		
Test Section	**Type**	**Amount of material (tons)**
First South	Class 5	234.94
Second South	2/3 Class 5 and 1/3 Lime	160.75+90.65=251.4
Third North	1/2 Class 5 and 1/2 Class 2	121.5+121.5=243
Fourth North (control)	Class 2	270

MAINTENANCE ACTIVITY TIMETABLES

Maintenance activities were logged and are listed in Tables 5, 6, and 7 for each county that participated.

Table 5. Jackson County maintenance activities timetable.

Jackson County CR 76	
	Date
Maintenance	10/25/2013
First	10/30/2013
Second	11/18/2013
Third	4/16/2014
Fourth	5/21/2014

Table 6. Beltrami County maintenance activities timetable.

Beltrami County CR 23		
	Date	**Remark**
Maintenance	11/7/2013	
First	4/27/2014	South Section alone
Second	5/15/2014	All three sections
Third	6/9/2014	All three sections
Fourth	7/18/2014	South Section and Part of Middle Section

Table 7. Olmsted County maintenance activities timetable.

Olmsted County CR 115	
	Date
Maintenance	9/3/2013-9/4/2013
First	10/4/2013
Second	5/19/2014
Third	7/15/2014

5. Results

SOIL COMPOSITION COMPARISON

Unpaved roads often end up with loose aggregate scattered over the surface due to the loss of fine binding material because it is blown away when traffic stirs it up or because it is washed off with rainwater. The loose aggregate can no longer bear loads from the traffic.

However, on most aggregate roads, the wheel paths are highly compacted, which suggests that given a proper gradation, an unpaved surface can reach high levels of compaction even though compacted by typical traffic alone. Hence, an understanding of the soil composition of the loose aggregate (the top material/aggregate) and that of the compacted bearing layer (the bottom material/aggregate) is of interest.

The research team conducted an extensive investigation regarding the gradation difference between the top and bottom layers of aggregate. In addition to samples collected in Minnesota, samples were collected in Boone and Story Counties in Iowa from roads that were considered to have issues with loose aggregate, although the level of severity varied.

In total, 19 pairs, representing both bottom and top material, were collected from various roads. An independent t-test was performed to detect statistically significant differences in content percentages for each soil classification. A bar chart comparing the top and bottom layers for each soil classification is shown in Figure 30.

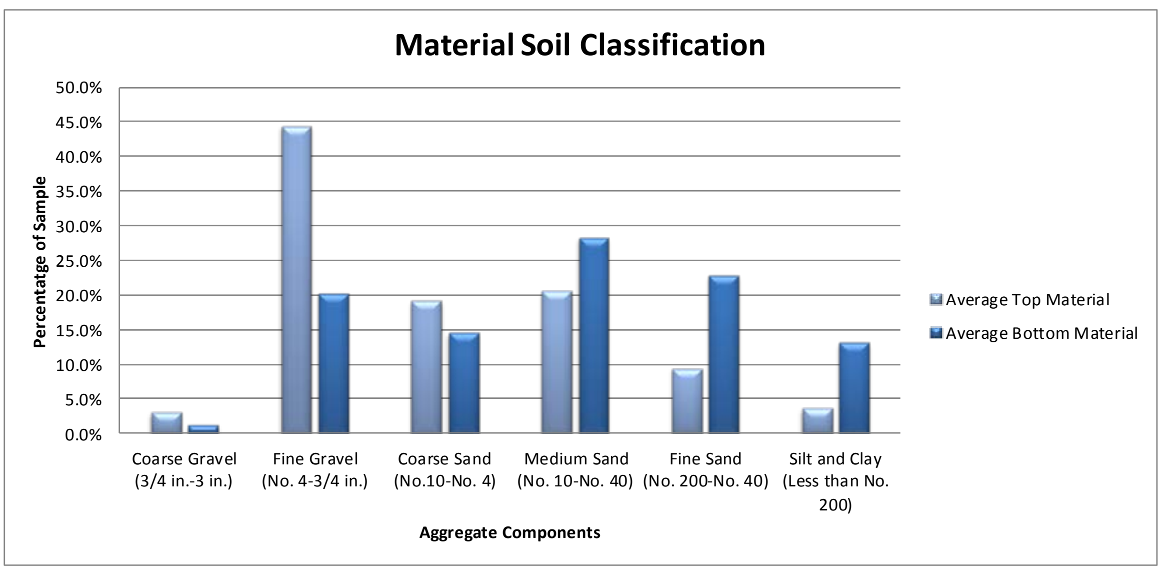


Figure 30. Soil Classification Comparison

The test results suggest that, for all categories except for coarse gravel, a statistically significant difference was detected. The proportion of silt and clay particles, which serve as a binder for unpaved roads, was about 3.6 times higher in the bottom layer compared to the top layer. The bottom layers also had a higher percentage in medium sand and fine sand. Not surprisingly, for the top layers, fine gravel with sizes ranging from No.4 (4.75 mm) to 3/4 inch (19 mm) dominated and made up nearly 45 percent of the compositions. The significantly lower percentages of fine sand and silt and clay likely explains the segregation that is a common occurrence on aggregate roads.

JACKSON COUNTY

Material Properties

The Jackson County particle size distribution (PSD) of material before and after construction are showin in Figure 31.

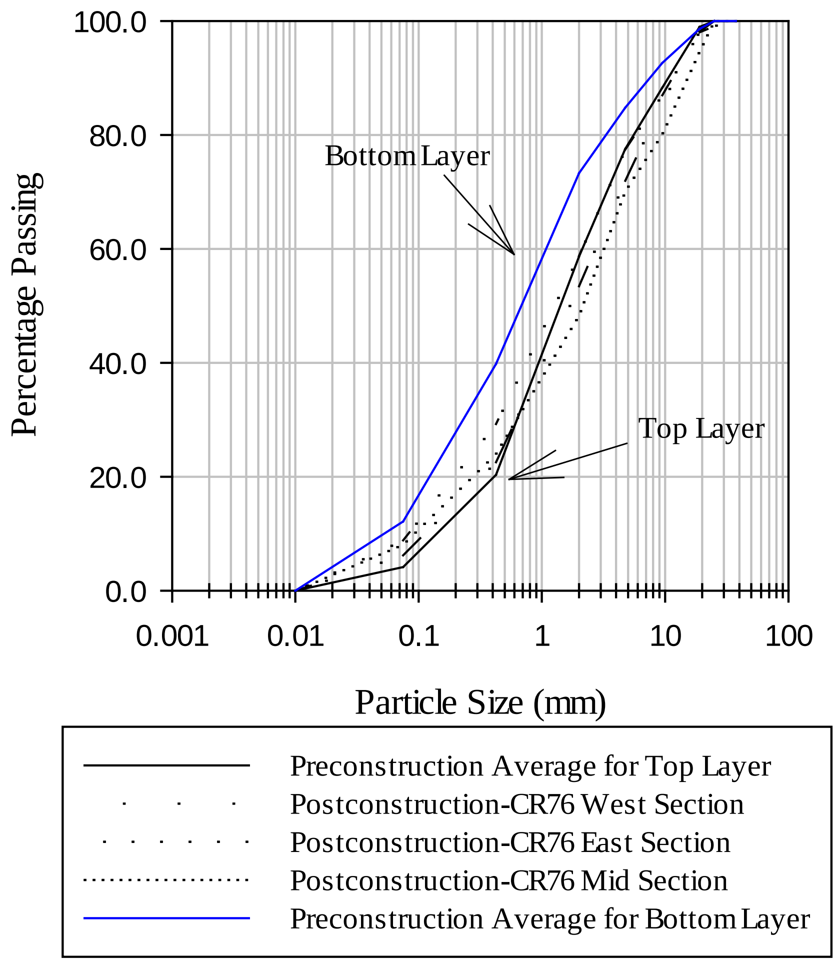


Figure 31. PSD of Material for Jackson County CR 76

The two solid lines represent the preconstruction PSD curve for the top and bottom layers of material, as indicated. The PSD curve for the three test sections post-construction lies between the two solid lines at their left ends, indicating the gradation of the top layer has been modified and become finer. Detailed material properties are summarized in Table 8.

Table 8. Jackson County CR 76 material properties after mixing.

Jackson County CR 76									
Sieve Size	Percentage Passing			Percentage Passing			Percentage Passing		
	East/First		Average	Middle/Second		Average	West/Third		Average
	#1	#2		#1	#2		#1	#2	
1.5 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
1 in.	98.3%	100.0%	99.1%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
3/4 in.	96.1%	100.0%	98.1%	96.0%	93.3%	94.6%	98.2%	98.0%	98.1%
3/8 in.	84.0%	90.1%	87.1%	83.1%	77.3%	80.2%	86.9%	84.2%	85.6%
#4	73.9%	81.2%	77.5%	73.7%	66.7%	70.2%	74.8%	69.0%	71.9%
#8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
#10	55.6%	62.1%	58.9%	51.3%	45.4%	48.3%	56.5%	50.2%	53.3%
#30	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
#40	27.2%	31.4%	29.3%	25.8%	22.3%	24.1%	23.8%	21.2%	22.5%
#100	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
#200	7.9%	9.8%	8.9%	8.8%	7.5%	8.2%	6.5%	5.9%	6.2%
<#200	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Liquid Limit	13.3%			15.3%			14.9%		
Plastic Limit	15.0%			15.5%			15.1%		
Plastic Index	0.00			0.00			0.00		

The proportion of #200 fine particles increased after mixed in the crusher dust. However, the crusher dust had zero plasticity.

DCP and LWD Tests

Figure 32 reveals that the surface and subgrade materials are rather consistent with regard to stability since the penetration rate (PR) does not change, except for in the Middle/Second Test Section. From the plot for the Middle/Second Section, a pronounced downturn is seen at about 120 mm (4.7 in.) from the surface, suggesting heterogeneity of the subgrade material.

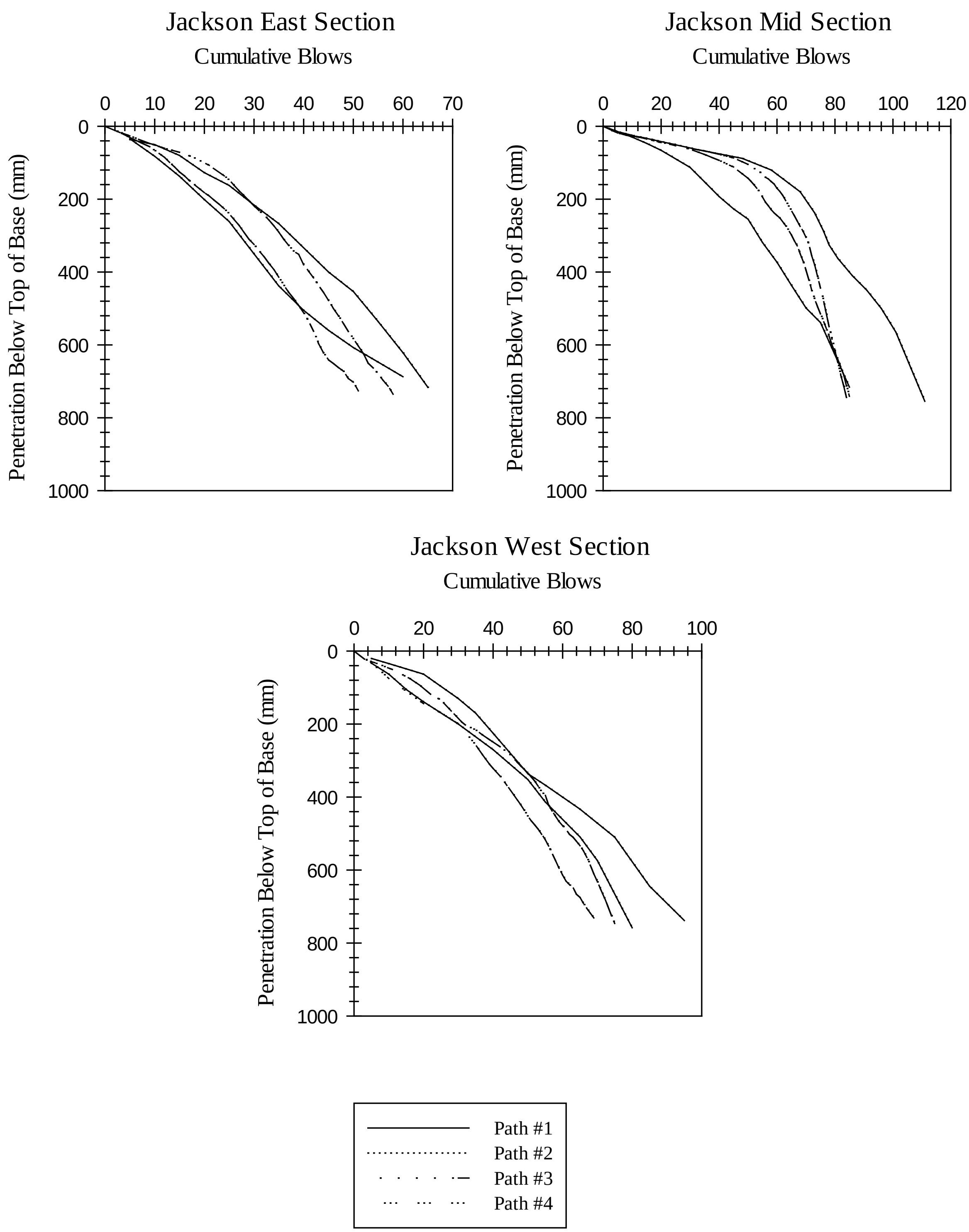


Figure 32. DCP Test showing Cumulative Depth against Cumulative Blows for Jackson County

The California Bearing Ratio (CBR) appears to be comparable between the West/First (control) and East/Third (experimental) Test Sections (Figure 33), indicating that the stiffness of these road sections are similar. However, according to some measurements, the CBR increases to 300 percent within the wearing surface in the Middle/Second Test Section, indicating a greater stiffness in this part of the road section.

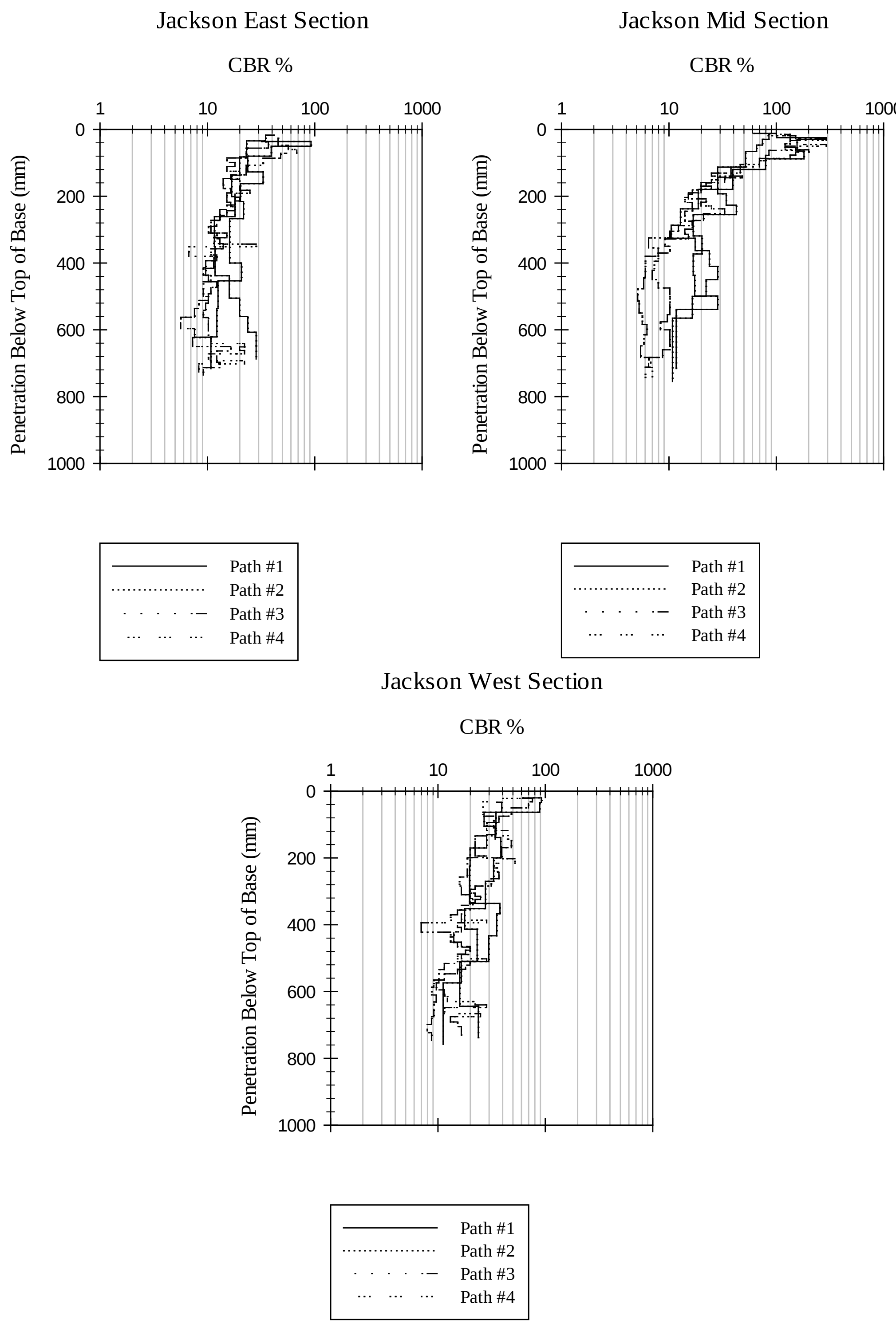


Figure 33. DCP Test Cumulative Depth against CBR Percentage for Jackson County

The LWD tests show a consistency in elastic modulus (E-modulus) readings for the three sections, as shown in Figure 34. The East/Third Test Section had the highest E-modulus value of 45.2 megapascals (Mpa), indicating that this road section has the greatest amount of structural stiffness.

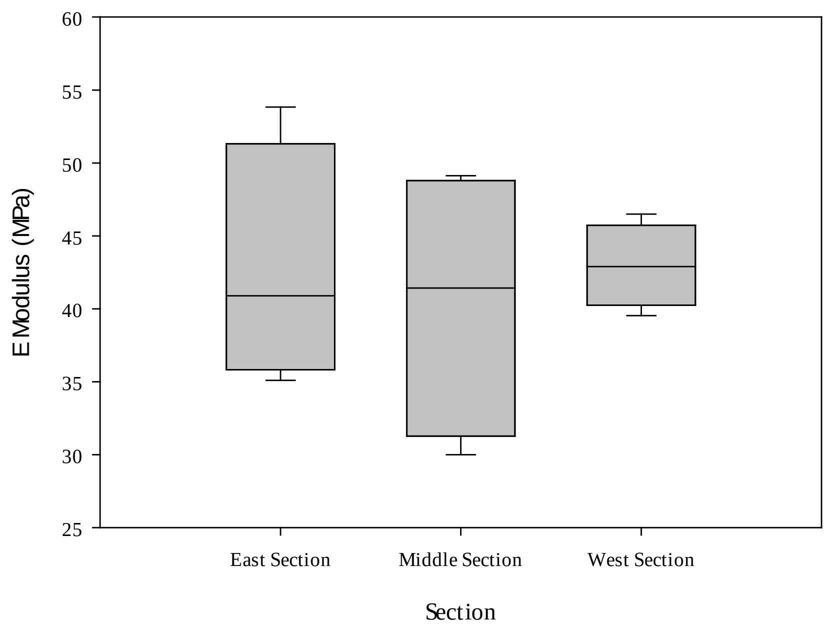


Figure 34. Jackson County LWD Readings

Cross-Section Elevation Profile Surveys

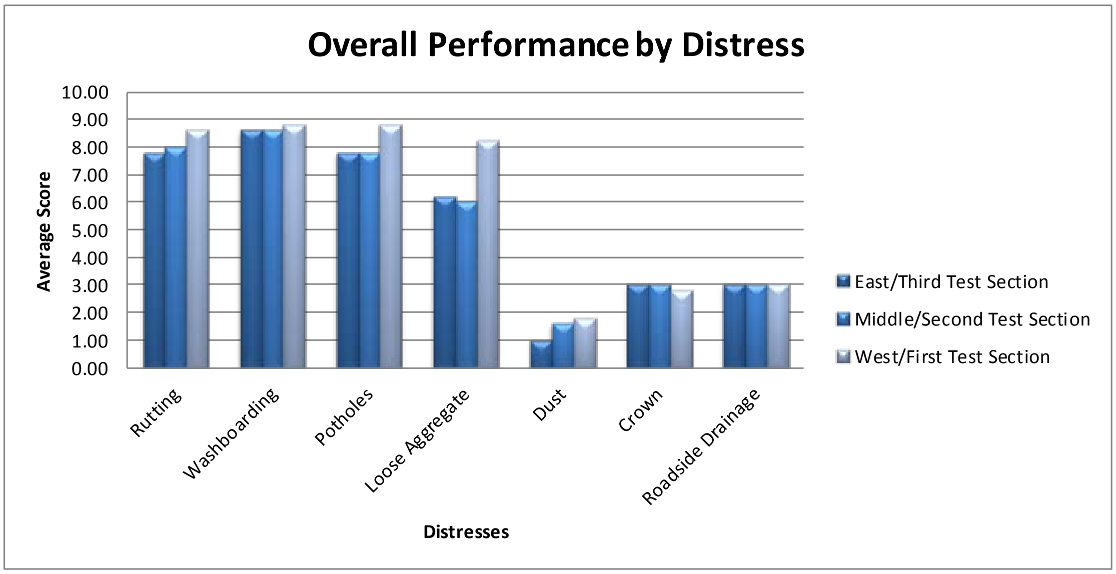
After nine months of service, the road surface cross-section profile for each section did not show a substantial change from that of the baseline, which represents each cross-section after construction. The average cross-section elevation change was -0.37 ft for the East/Third Section, -0.20 ft for the Middle/Second Section, and 0.09 ft for the West/First Section, which was the control section.

By calculating the aggregate areas encompassed by the baseline and average profiles, potential gravel loss was estimated. The loss of gravel amounted to 9.8 cubic yards per mile for the West/First Section, which was the control section, 75.2 cubic yards per mile for the Middle/Second Section, and 120.1 cubic yards per mile for the East/Third Section.

Comparative analysis of multiple regression curves showed that, in terms related to time, the West/First Section (which was the control section) and Middle/Second Section (which was an experimental section) had coefficients of zero, meaning that no statistically significant difference was detected in the elevation over the observation period for either section. The result for the East/Third Section, however, suggested that the elevation did change over the observation period. The paired t-test for the East/Third Test Section suggested that the statistically significant difference was found in the elevation of the area 8 feet away from the center of the road.

Unpaved Road Condition Ratings

County personnel monitored the road conditions after the completion of construction and provided ratings of road performance. A rating chart with scoring criteria was used by the raters to assist in documenting the condition of the road on the day of the visit. Additional remarks were made to descriptively record the observation. Figure 35 shows that rutting, washboarding (corrugation), and potholes were rated as Good or Very Good, indicating a relatively low level of such distresses.

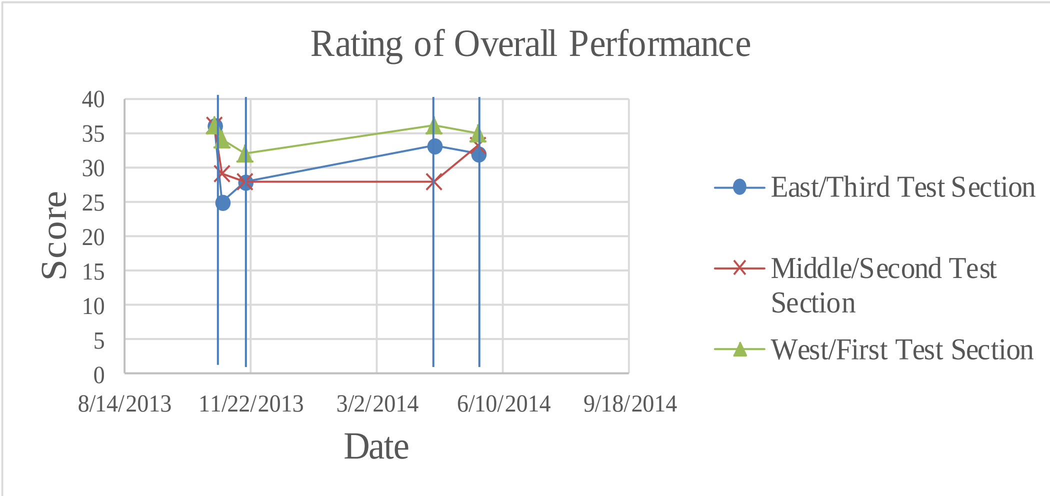


The scale for Dust, Crown, and Roadside Drainage was 3.0, while the scale for Rutting, Washboarding, Potholes, and Loose Aggregate was 10.0. More detailed Condition Rating line graphs, by distress type, for all test sections in each county are included in Appendix E.

Figure 35. Jackson County Pavement Condition Ratings by Distress Type

For the above three distresses, the conditions were comparable since they lie within the same severity level. For the distress of loose aggregate, however, the West/First Section outperformed the other two sections. The West/First Section fell in the Good category in terms of condition of loose aggregate. The other two sections were rated as Fair. In addition, for dust emission, the East/Third Section was rated as Medium, lower than the control (West/First) and other experimental (Middle/Second) sections. This could be significant given that dust loss is the major source of material loss.

The overall performance ratings also indicated that, throughout the observation period, the control (West/First) section outperformed the other two sections, as shown in Figure 35. The darker solid vertical lines indicate dates of maintenance activities.



The darker solid vertical lines indicate dates of maintenance activities.

Figure 36. Jackson County Overall Performance Ratings by Date

Necessary maintenance activities were carried out during the observation period. Ratings were obtained before the maintenance activities. Figure 37 shows that the two experimental sections (the Middle/Second and East/Third Test Sections) suffered from loose aggregate soon after construction and that the problem remained since then.

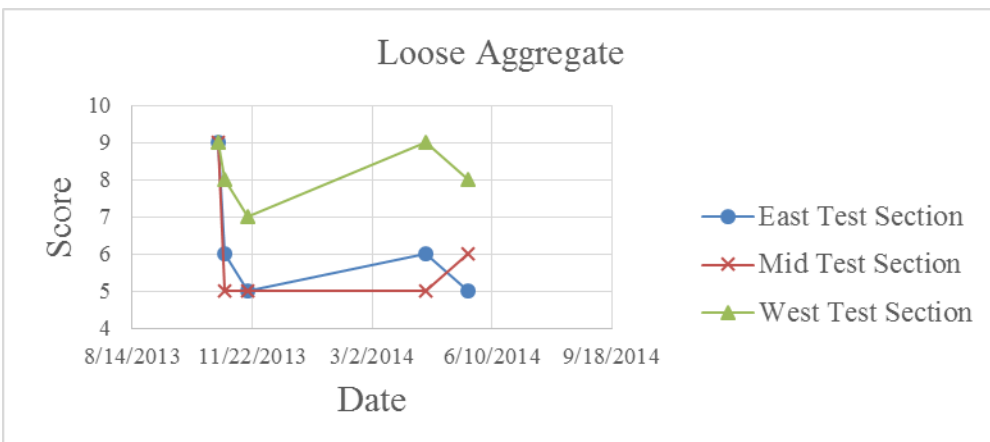


Figure 37. Jackson County Loose Aggregate Ratings by Date

Segregation that resulted generated a large amount of loose aggregate, which compromised the performance of the experimental sections.

Remarks from the county employee who served as the observer reflected his concern that the surfacing material was not binding. In April 2014, which was soon after maintenance activities resumed, county personnel could not see any trace of the crusher dust that remained in the East/Third Section.

Field Observations
The first follow-up trip to Jackson County by the researchers was in May 2014, approximately seven months after construction. The crusher dust mixture, which was noticeable originally with its red color, was nearly invisible. That was particularly true for the East/Third Test Section, which had the least amount of crusher dust mixed in. Figure 38 shows a contrasting image of the road surface seven months after construction.

Figure 38. Jackson County CR 76 Seven Months after Construction

Both experimental sections appeared to have failed to provide the desired performance.

Scrape test results seven months after construction indicated an estimated 96.99 tons per mile of loose aggregate on the surface of the Middle/Second Section (which had 12 tons of crusher dust added) and 96.53 tons per mile of loose aggregate on the surface of the East/Third Section (which had 7 tons of crusher dust added). These loose aggregate estimates were 40 percent higher than that on the surface of the West/First (control) Section (which had 19 tons of Class 5 aggregate added). A trace of crusher dust was visible in the Middle/Second Section.

The second follow-up visit to Jackson County was in June 2014. No additional follow-up visits were made to the site since the crusher dust mixture under these conditions did not appear to be providing the desired results.

BELTRAMI COUNTY

Material Properties
The addition of crusher dust on Beltrami County CR 23 successfully boosted the fine content of the in situ loose aggregate on the surface (see Figure 39). The North/First (control) Section had the highest fine content among the three sections.

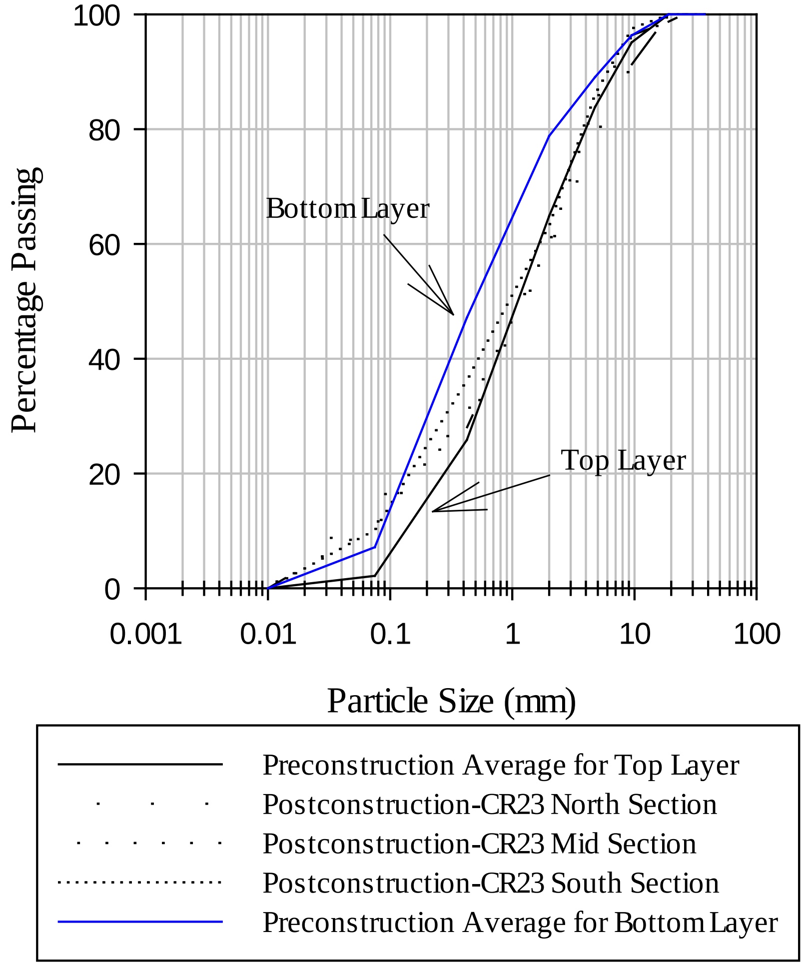


Figure 39. PSD of Material for Beltrami County CR 23

The two solid lines represent the preconstruction PSD curve for the top and bottom layers of material, as indicated. Detailed material properties are summarized in Table 9.

Table 9. Beltrami County CR 23 material properties after mixed.

Beltrami County CR 23									
Sieve Size	Percentage Passing			Percentage Passing			Percentage Passing		
	North/First		Average	Middle/Second		Average	South/Third		Average
	#1	#2		#1	#2		#1	#2	
1.5 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
1 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
3/4 in.	98.4%	100.0%	99.2%	100.0%	99.1%	99.6%	100.0%	100.0%	100.0%
3/8 in.	96.5%	91.5%	94.0%	97.9%	96.3%	97.1%	97.2%	97.9%	97.6%
#4	84.9%	78.2%	81.5%	87.1%	84.9%	86.0%	85.4%	87.1%	86.2%
#8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
#10	59.9%	59.0%	59.4%	64.9%	60.4%	62.7%	61.9%	64.9%	63.4%
#30	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
#40	30.6%	28.3%	29.5%	37.6%	30.8%	34.2%	35.2%	37.6%	36.4%
#100	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
#200	10.9%	15.4%	13.1%	10.5%	11.2%	10.8%	10.0%	10.5%	10.2%
<#200	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Liquid Limit	17.0%			17.0%			17.0%		
Plastic Limit	13.6%			14.3%			15.6%		
Plastic Index	4.00			3.00			2.00		

Unlike the resulting material in Jackson County, the resulting material in Beltrami County contains clayey soil, which possesses some binding capacity. Although the plasticity index does seem to be at the lower end of the typical range recommended in the literature which is 4-12 (Ken Skorseth and Ali Selim 2000), the material used in Beltrami County apparently had sufficient plasticity to provide a better, smoother surface in comparison to that of Jackson County.

DCP and LWD Tests

From the penetration-cumulative blows plotted in Figure 40, it is apparent that the various layers of road surface and subgrade material are consistent with regard to stability because the penetration per blow is relatively constant.

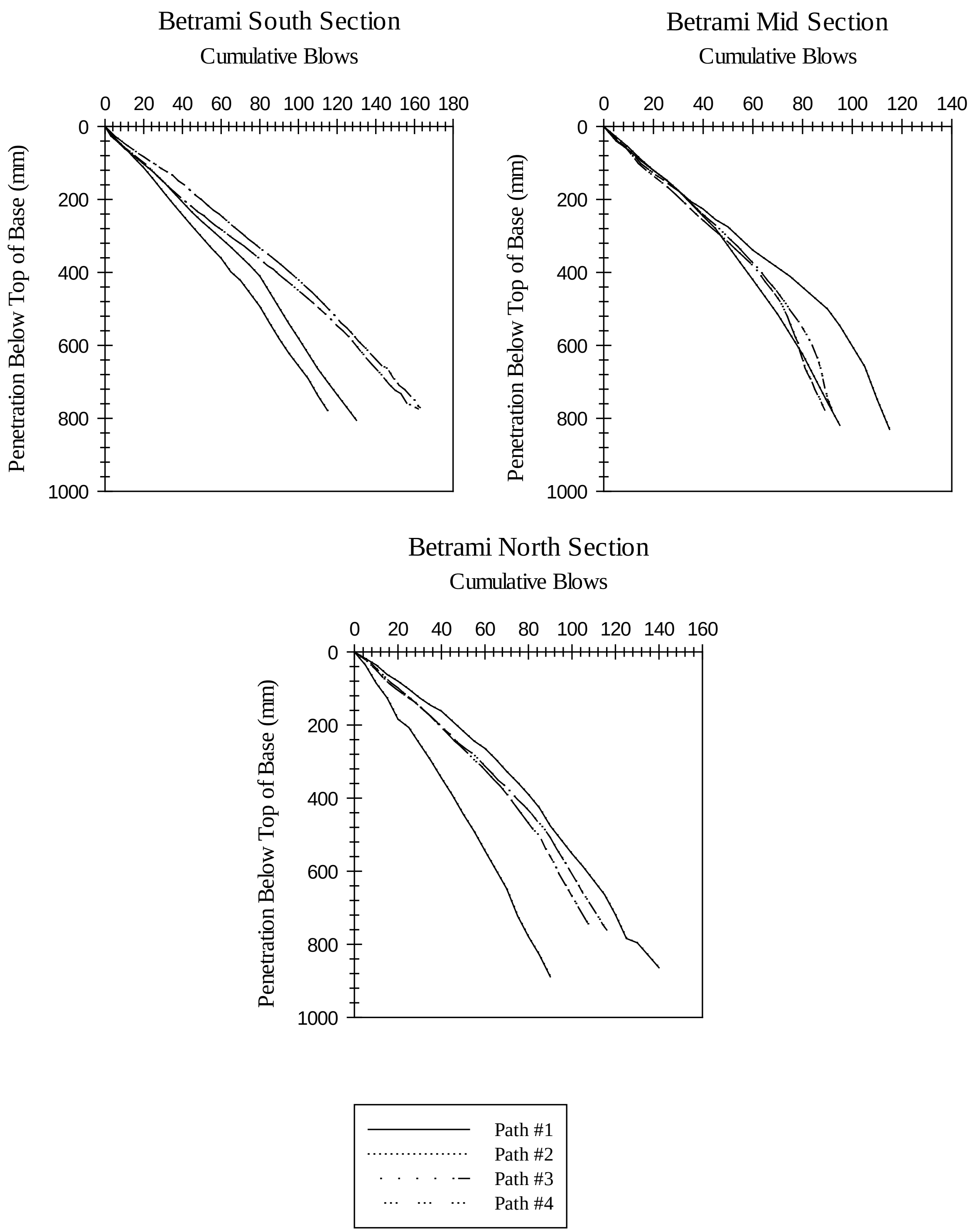


Figure 40. DCP Test showing Cumulative Depth against Cumulative Blows for Beltrami County

Figure 41 shows CBR values for the each section along the depth of the pavement. The CBR value for the top 200 mm (7.87 in.) has an average value of 46.18 for the North/First Section, 40.26 for the Middle/Second Section, and 50.26 for the South/Third Section.

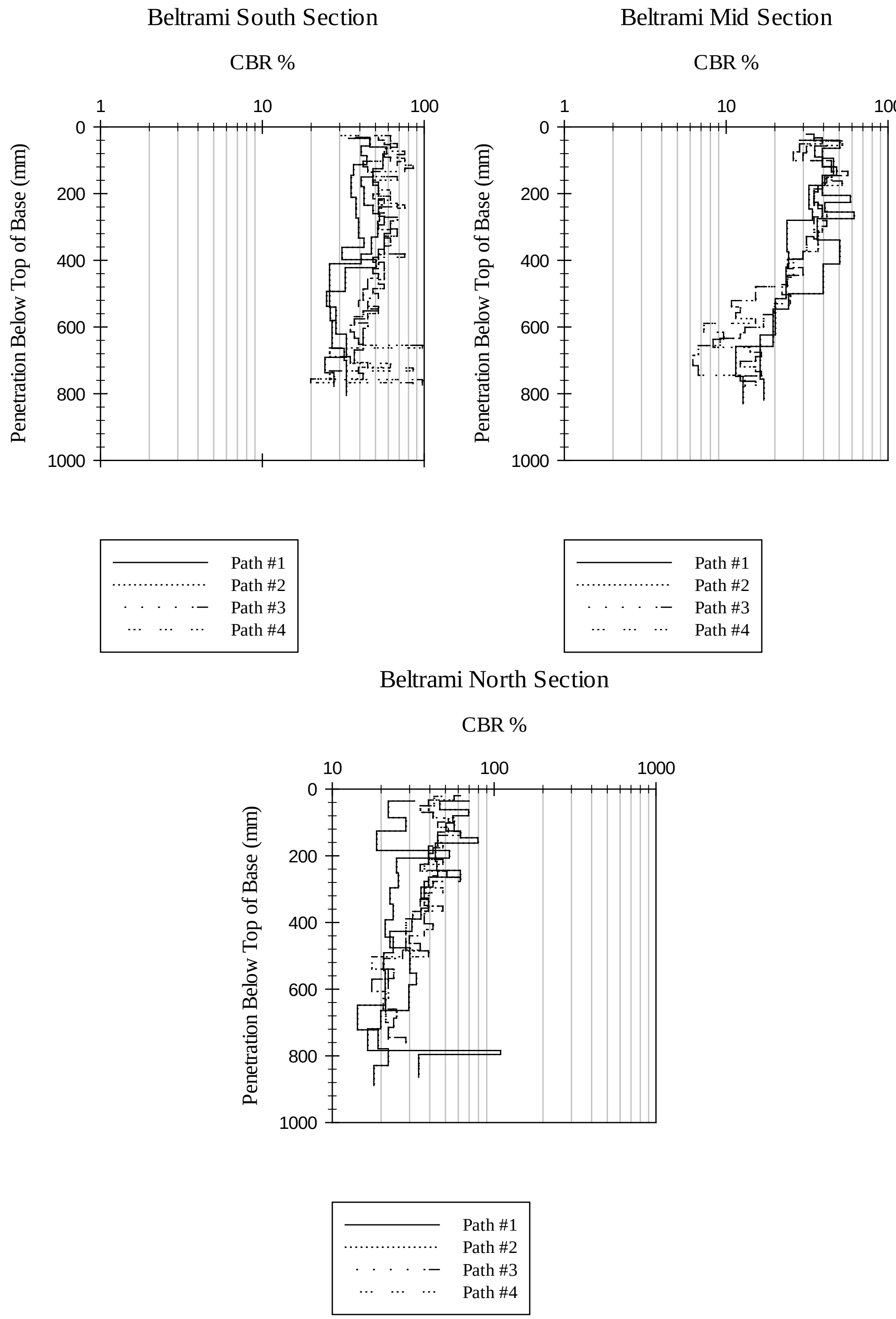


Figure 41. DCP Test showing Cumulative Depth against CBR Percent for Beltrami County

LWD data show comparable stiffness across test sections, as Figure 42 shows that data in the range between the 25th and 75th percentile overlap.

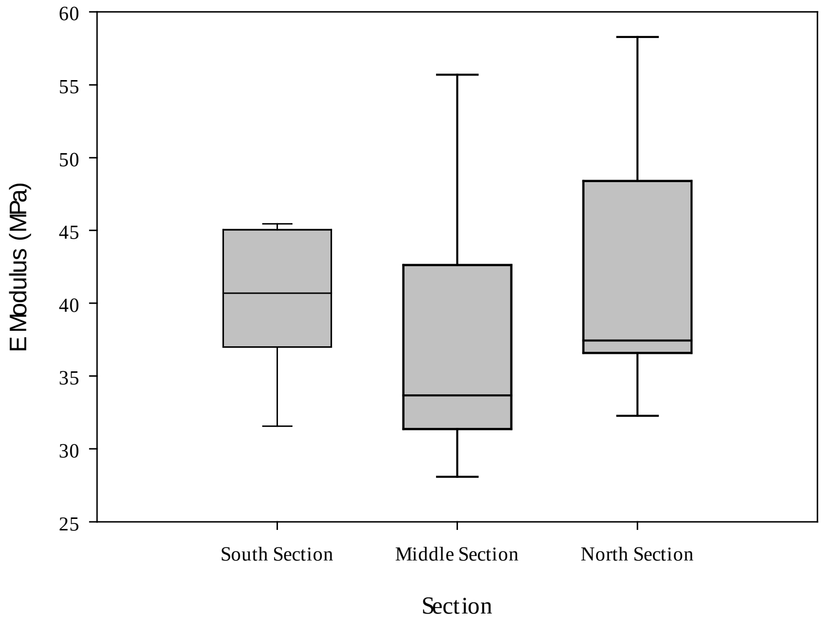


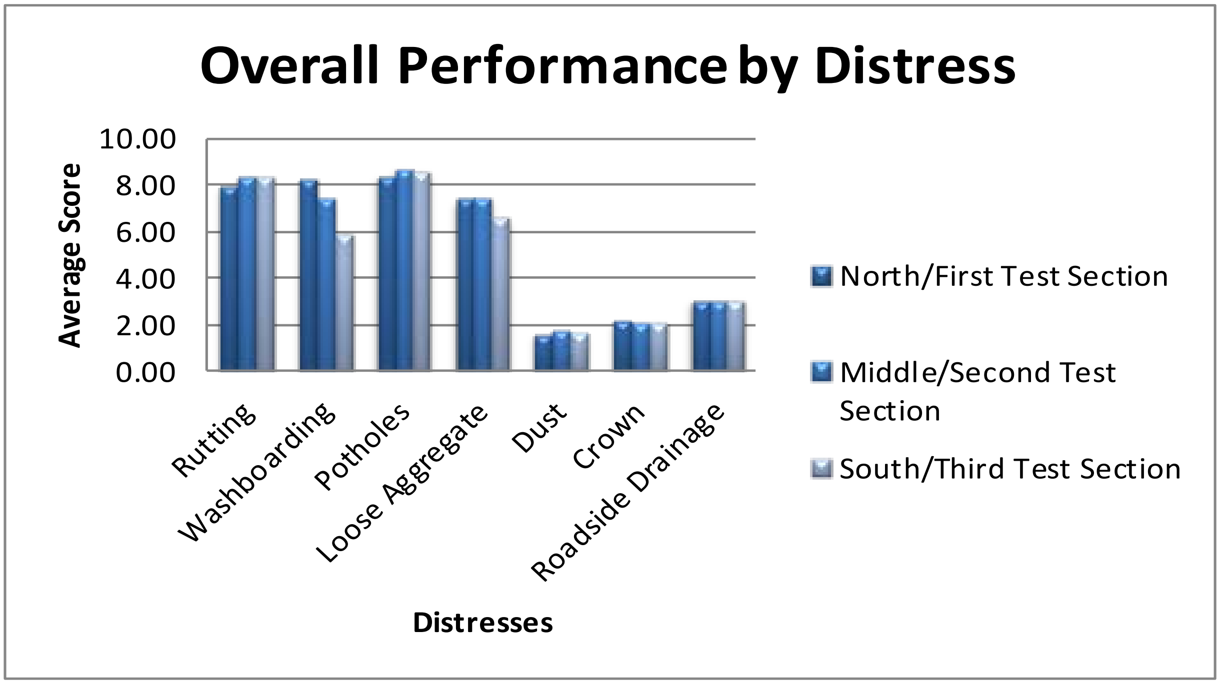
Figure 42. Beltrami County LWD Readings (Test Date: 6/22/2014)

Cross-Section Elevation Profile Surveys
During the eight months of service, the average elevation change was nearly unnoticeable. The North/First (control) Section had -0.05 ft of elevation change, the Middle/Second Section had -0.06 ft of change, and the South/Third Section had -0.09 ft of change. Compared to the three test sections in Jackson County, the road surfaces in Beltrami County performed better maintained, most likely because the surfacing material that resulted from the mixing process had a relatively higher plasticity than that in Jackson County.

The estimated amount of gravel loss for the North/First (control) Section was 20.2 cubic yards per mile, the Middle/Second Section was 24.7 cubic yards per mile, and the South/Third Section was 35.2 cubic yards per mile according to calculations based on cross-section data.

Regression analysis was performed and the results indicated that that no statistically significant difference was found in any one of the three test sections for Beltrami County.

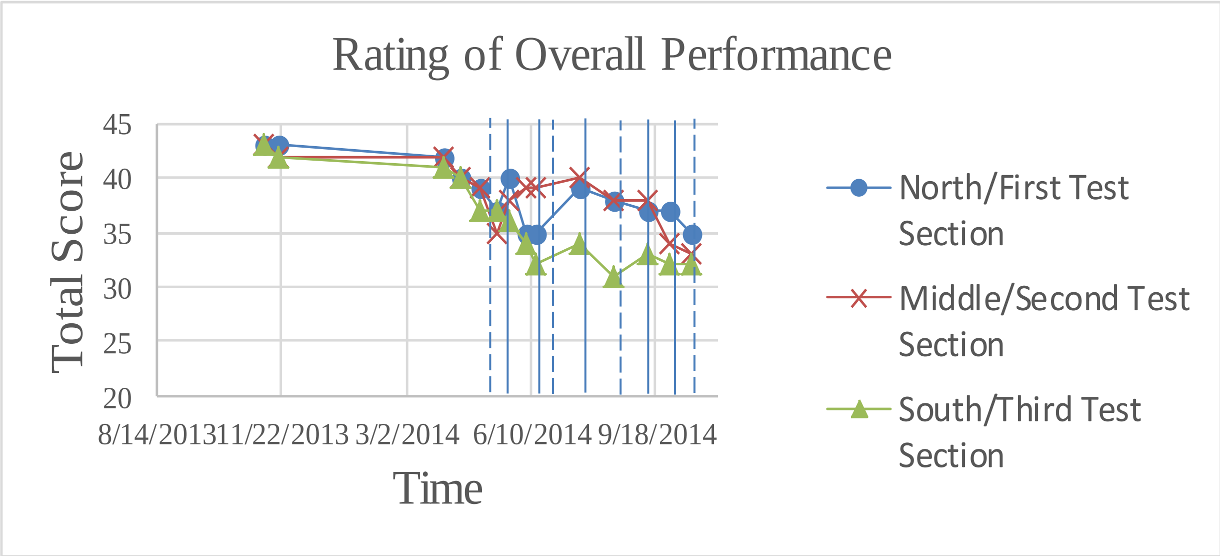
Unpaved Road Condition Ratings
The South/Third Test Section was rated Fair for the distress of washboarding, which reflects the lasting distress that was observed in this section (see Figure 43). A Fair level of washboarding suggests that 10 to 25 percent of the roadway appears to suffer from corrugations that are generally 1 to 2 inches deep and vehicle control could be compromised.



The scale for Dust, Crown, and Roadside Drainage was 3.0, while the scale for Rutting, Washboarding, Potholes, and Loose Aggregate was 10.0. More detailed Condition Rating line graphs, by distress type, for all test sections in each county are included in Appendix E.

Figure 43. Beltrami County Pavement Condition Ratings by Distress Type

Considering that the scores assigned to the distresses of dust, crown, and roadside drainage were very close, if not exactly the same, between test sections, the overall performance according to the rating would be highly dependent on the other distress ratings. Figure 44 shows that the Middle/Second Test Section performed generally as well as the North/First (control) Section, including during the dryer part of the summer starting in June. In most cases, the Middle/Second Section performed better than the South/Third Section.



The darker solid vertical lines indicate dates of maintenance activities carried out for all sections.
The dashed vertical lines indicate dates of maintenance activities carried out on certain sections.

Figure 44. Beltrami County Overall Performance Ratings by Date

The South/Third Section remained at the lowest score level for the majority of the observation period, even though it received more frequent maintenance. The South/Third Section started to deteriorate noticeably beginning in late May 2014 as it was entering into a dryer summer season. The deterioration is most pronounced in terms of washboarding, as shown in Figure 45.

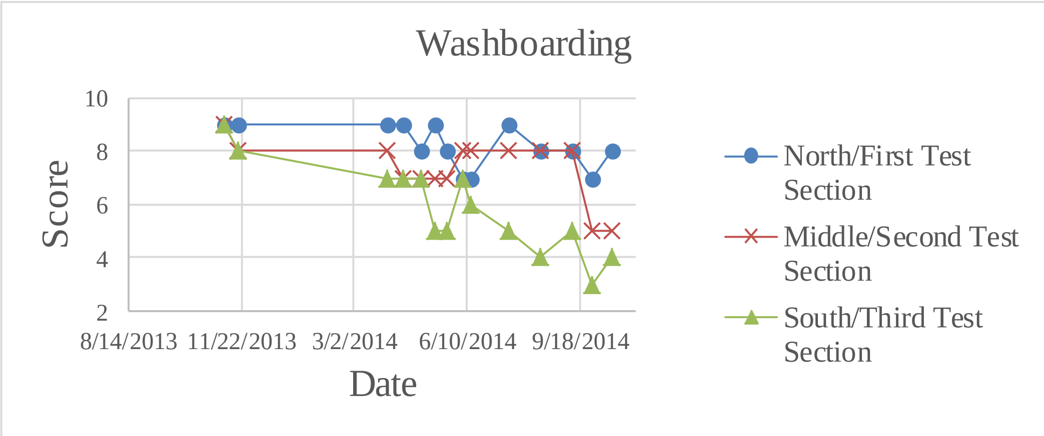


Figure 45. Beltrami County Washboarding Ratings by Date

Loose aggregate issues started to occur in May as well, and were the worst for the South/Third Section, as shown in Figure 46.

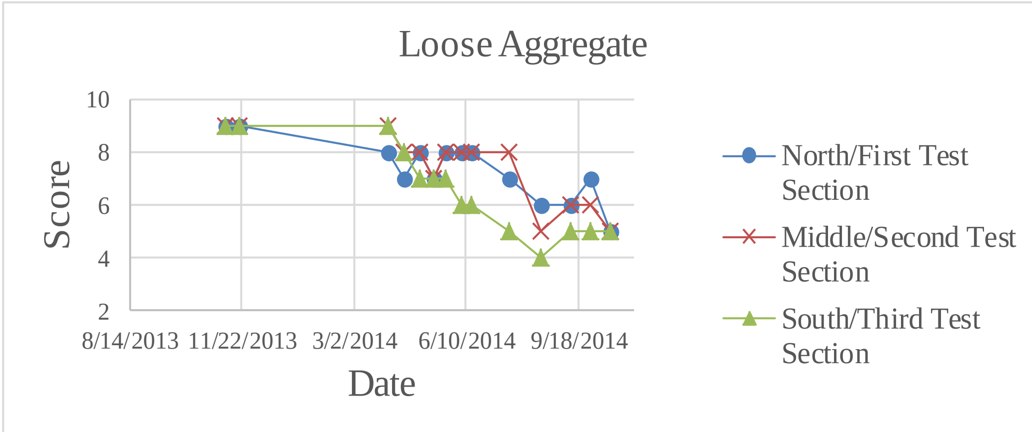
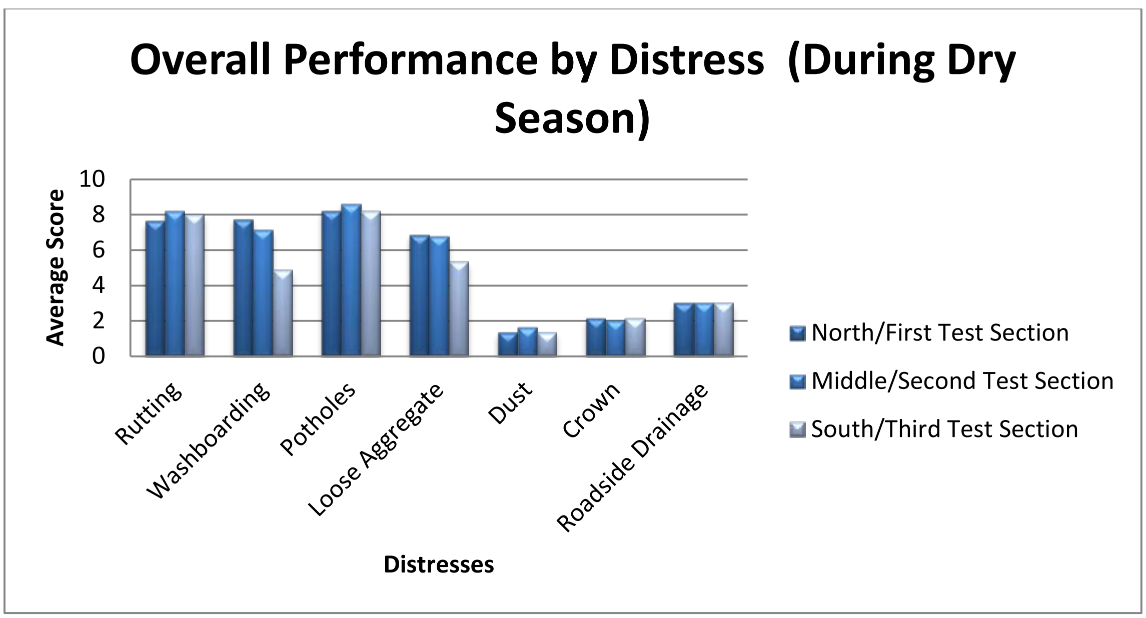


Figure 46. Beltrami County Loose Aggregate Ratings by Date

It is of interest to reveal how all the sections were performing during the dry season, after late May in this case. Figure 47 shows that the ratings for washboarding and loose aggregate for the South/Third Section dropped substantially versus those shown in Figure 43, while the ratings for both the North/First (control) Section and Middle/Second Section exhibit a noticeably less substantial drop.



The scale for Dust, Crown, and Roadside Drainage was 3.0, while the scale for Rutting, Washboarding, Potholes, and Loose Aggregate was 10.0. More detailed Condition Rating line graphs, by distress type, for all test sections in each county are included in Appendix E.

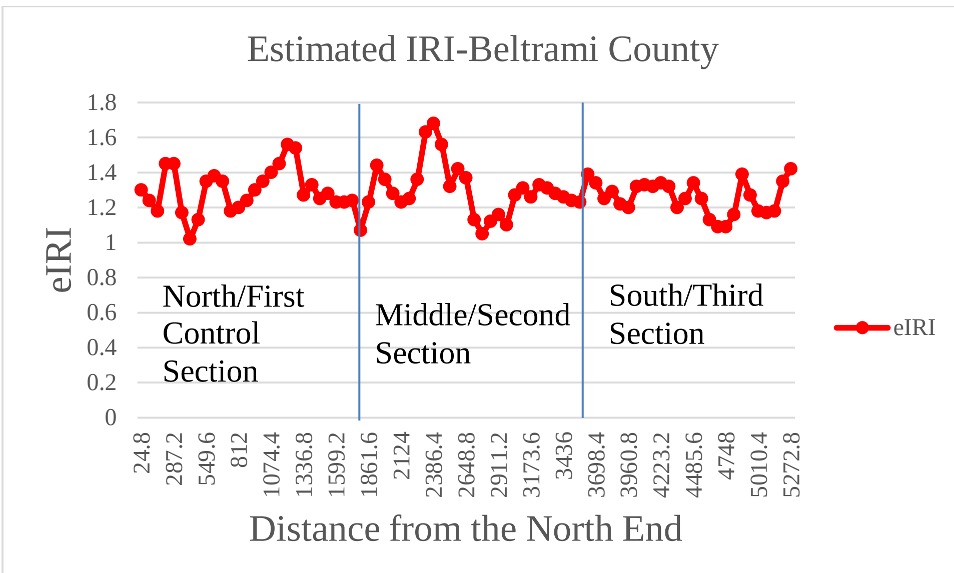
Figure 47. Beltrami County Overall Ratings by Distress Type during Dry Season

Remarks made by the maintenance supervisor who was in charge of this rating activity reflected that he was generally satisfied with the outcome from the two experimental sections. Although he admitted there had been some improvement by mixing in crusher dust for the South/Third

Section, the corrugation formed reduced its serviceability in a more noticeable way. He thought the traffic volume might differ for the South/Third Section because the intersection with CR 110 is between the South and Middle Test Sections. This is discussed further later.

The Middle/Second Section generally met expectations; that is, it was presumed that the higher volume of crusher dust perhaps was beneficial. The performance was comparable to the North/First (control) Section, although the person performing the rating personally favored the performance of the North/First Section.

Estimated International Roughness Index
Roadroid generated estimated IRI (eIRI) as shown in Figure 48.



Solid vertical lines indicate boundaries of test sections.

Figure 48. Beltrami County CR 23 Estimated IRI Values

From the graph, although it appears that some segments of the North/First (control) Section and the Middle/Second (experimental) Section were rougher than the rest of the road. However, the three test sections generally provide a good ride quality, as the estimated IRI is lower than 2.2.

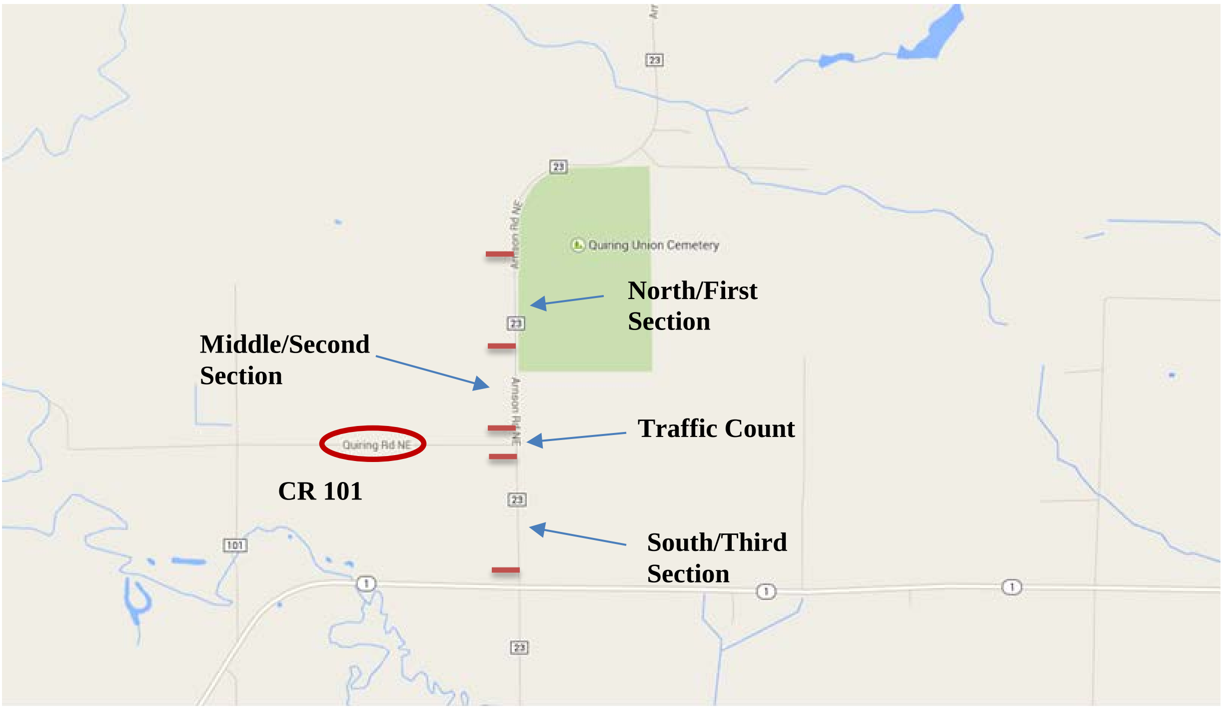
Field Observations
The first follow-up visit to the Beltrami County test sections was May 23, 2014, approximately six months after construction. The North/First (control) Section (which had 166 tons of Class 1 Standard Material added) and Middle/Second Test Section (which had 83 tons of crusher dust added) were holding up in a satisfactory manner, as shown in Figure 49.

Figure 49. Beltrami County CR 23 North/First (Control) Section (left) and Middle/Second Test Section (right)

The more lightly colored areas indicate that the area is more highly compacted. The larger the lighter area was, the lower the amount of loose aggregate that remained on the surface. It turned out that in the South/Third Test Section, the loose aggregate was estimated to be 59 tons, 24 percent higher than that on the surface of the North/First (control) Section. Corrugation appeared throughout the South/Third Test Section as shown in Figure 50.

Figure 50. Typical Corrugation in the Beltrami County South/Third Test Section

The depth of corrugation was approximately 1/2 inch; meanwhile, corrugations did not form on the two other test sections. To further investigate if differences in traffic volume contributed to the difference in performance, a four-hour traffic count (from 6 a.m. to 10 a.m Wednesday, July 2, 2014) was performed by Beltrami County Highway Department personnel. Figure 51 indicates the location of the traffic count in relation to the three test sections.



Map © 2013 Google

Figure 51. Beltrami County CR 23 Traffic Count and Test Section Locations

The four-hour traffic count revealed that the South/Third Section had 17 vehicles while the Middle/Second Section and North/Second Section each had 18 vehicles.

The fair performance of the South/Third Section was then attributed to the lower amount of crusher dust (50 tons) that was mixed in as binder compared to the Middle/Second Section (83 tons), where slight corrugation was seen near the intersection. No corrugation was seen in the North/First (control) Section.

OLMSTED COUNTY

Objective of the Olmsted County Test Sections

Limestone is a major source of surfacing aggregate for the unpaved roads in the area. Class 2 specified gradation has been adopted for the aggregate used for this purpose. From past experience, the Class 2 specification aggregate used for the wearing surface gradually became finer over the time of service. The use of Class 5 specification aggregate, on the contrary, led to too many "marbles," as floating loose aggregate particles were described informally by county personnel.

Olmsted County proposed to construct trial test sections using a 1:1 mix of Class 5 and Class 2 aggregate, a 1:2 mix of lime and Class 5 aggregate, and solely Class 5. The lime is the term used to describe the fines that result from the limestone crushing process.

The four test sections on CR 115 were not laid out continuously, but in pairs, with the First and Second Sections located at the south end of CR 115 and the Third and Fourth Sections located at the north end of CR 115.

Material Properties
PSD plots for Olmsted County CR 115 South and North are shown in Figure 52 and Figure 53, respectively.

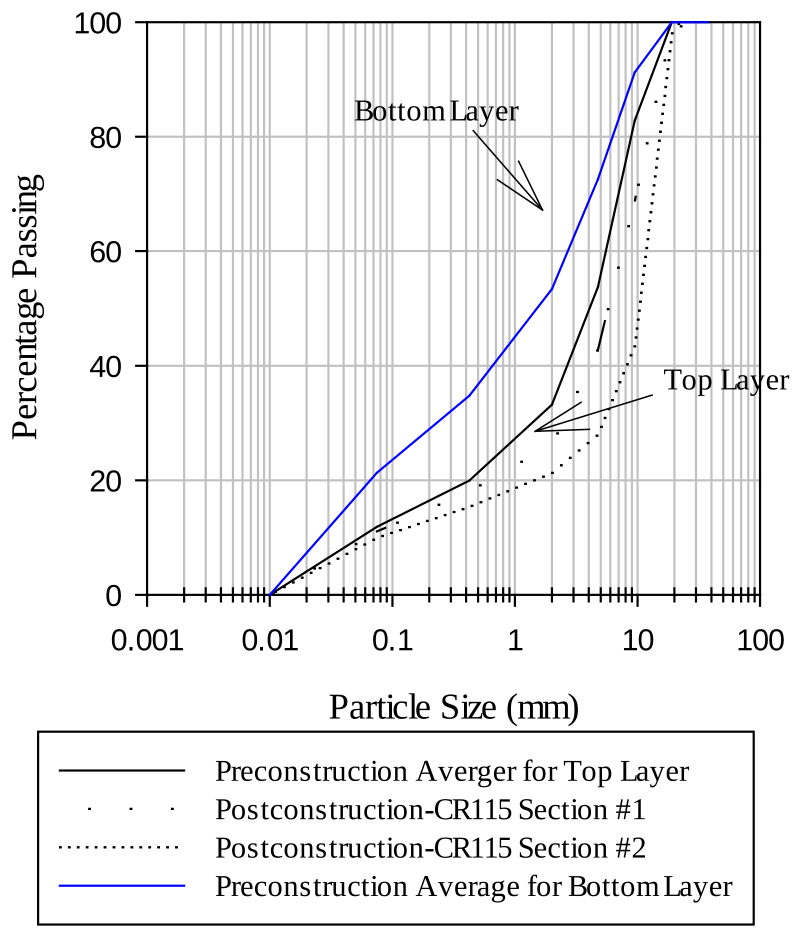


Figure 52. PSD of Material for Olmsted County CR 115 South

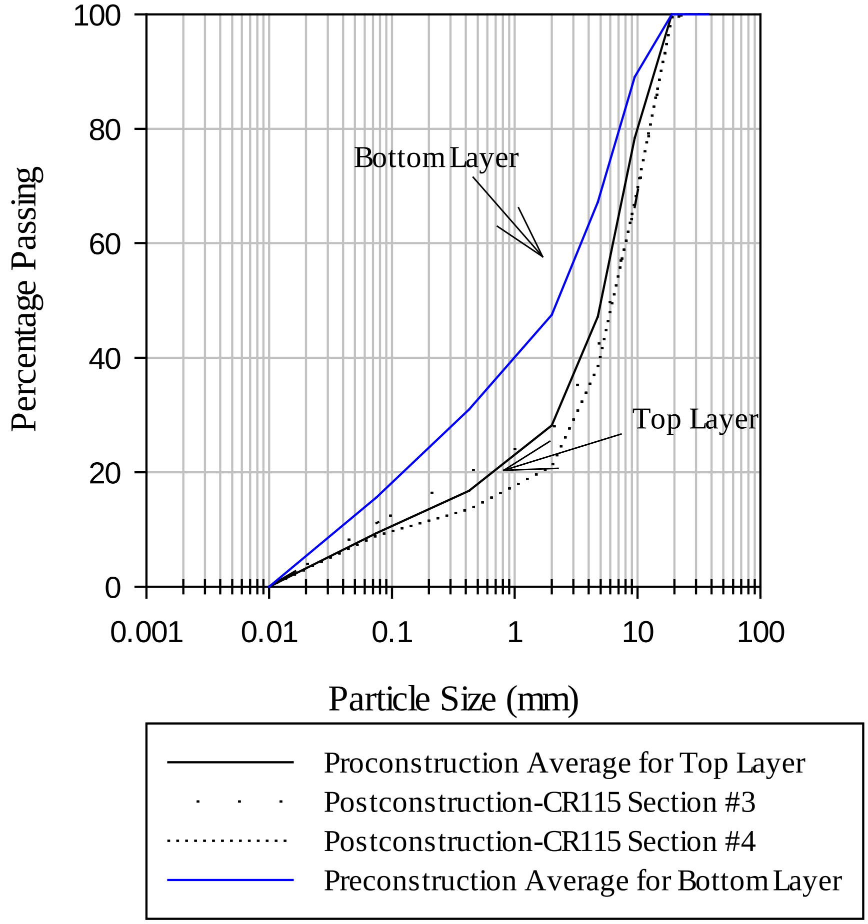


Figure 53. PSD of Material for Olmsted County CR 115 North

The two solid lines represent the preconstruction PSD curve for the top and bottom layers of material, as indicated. It is interesting to note that the resulting gradation of the newly placed material was coarser than that of the top material. All material was determined to be non-plastic as shown in Table 10.

Table 10. Olmsted County CR 115 material properties after mixed.

Olmsted County CR 115												
Sieve Size	Percentage Passing			Percentage Passing			Percentage Passing			Percentage Passing		
	First South		Average	Second South		Average	Third North		Average	Fourth North		Average
	#1	#2		#1	#2		#1	#2		#1	#2	
1.5 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
1 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
3/4 in.	99.6%	99.2%	99.4%	97.3%	98.7%	98.0%	99.3%	99.1%	99.2%	99.7%	99.3%	99.5%
3/8 in.	62.9%	74.2%	68.5%	46.8%	40.4%	43.6%	66.1%	66.6%	66.3%	60.9%	71.2%	66.1%
#4	37.9%	47.4%	42.7%	30.6%	25.5%	28.0%	41.1%	42.2%	41.7%	34.3%	41.0%	37.7%
#8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
#10	24.2%	28.1%	26.2%	23.0%	19.6%	21.3%	27.0%	27.5%	27.3%	19.1%	22.2%	20.6%
#30	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
#40	17.0%	18.9%	17.9%	15.5%	15.1%	15.3%	19.8%	20.2%	20.0%	11.7%	14.7%	13.2%
#100	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
#200	10.7%	11.3%	11.0%	9.0%	10.8%	9.9%	10.9%	11.2%	11.1%	8.5%	9.2%	8.8%
<#200	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Liquid Limit	15.4%			17.1%			15.6%			14.1%		
Plastic Limit	16.4%			16.7%			16.2%			15.1%		
Plastic Index	0.00			0.00			0.00			0.00		

DCP and LWD Tests

Figure 54 shows a clear indication of the location of the interface between the crushed rock layer and the subgrade layer. The crushed rock of the test sections had various depths ranging from 200 mm (7.9 in.) to 300 mm (11.8 in.).

Figure 57 shows comparable CBR values that are close to or higher than 200 percent within the gravel layer.

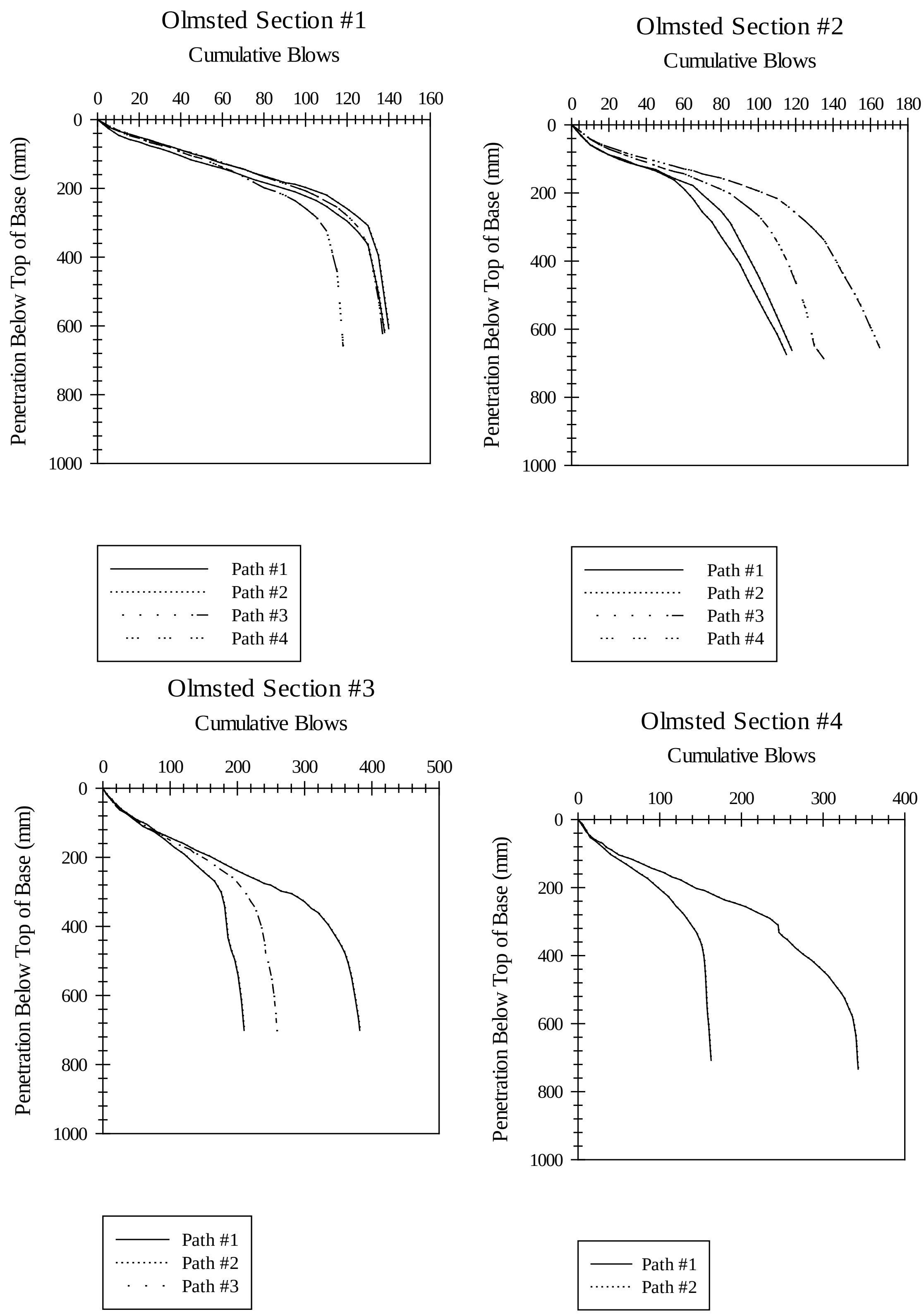


Figure 54. Cumulative Depth against Cumulative Blows for Olmsted County (Test Date: 6/20/2014)

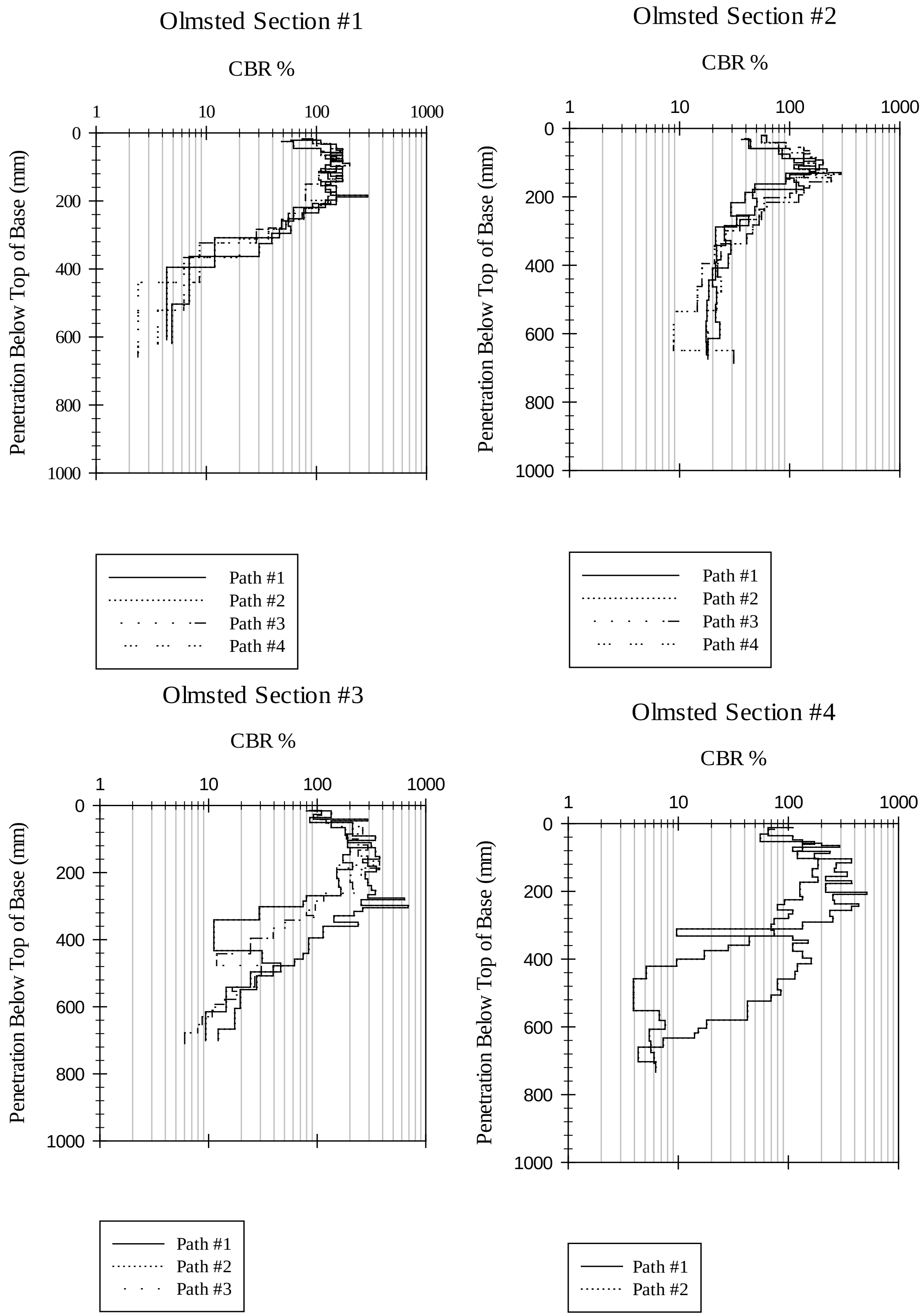


Figure 55. DCP Test showing Cumulative Depth against CBR Percent for Olmsted County

Figure 56 shows comparable LWD readings. In other words, no noticeable difference was found in the stiffness of the road surfacing materials for the four test sections.

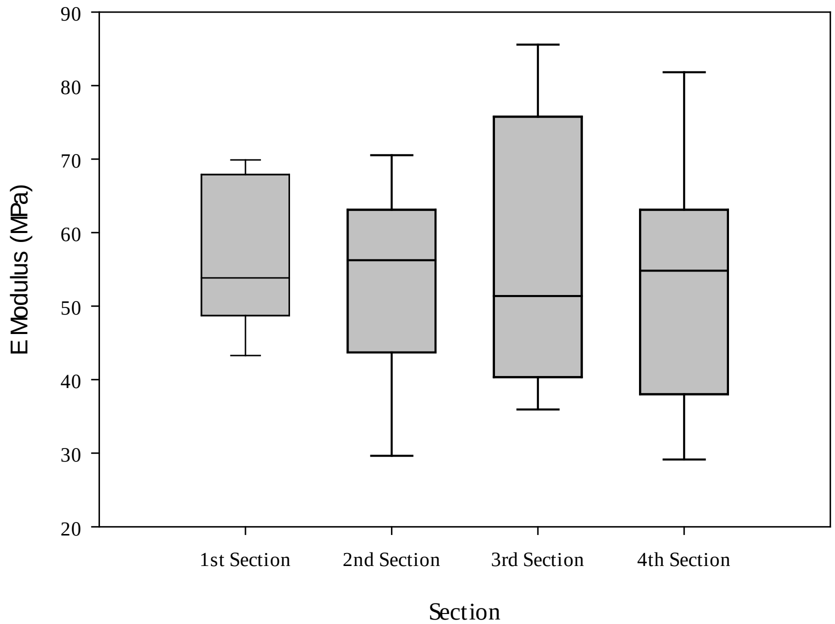


Figure 56. Olmsted County LWD Readings

Cross-Section Elevation Profile Surveys

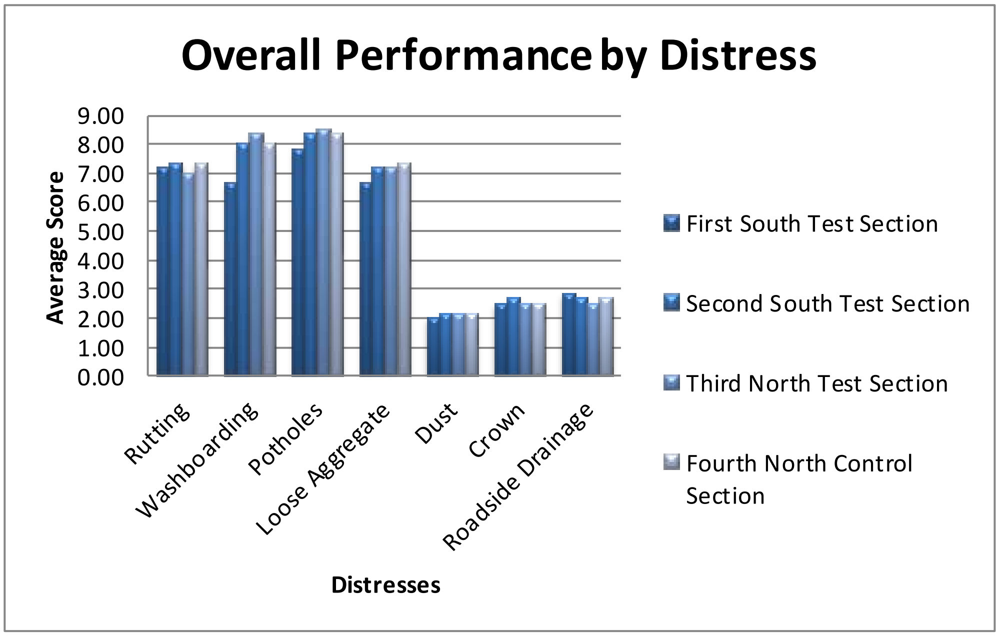
After 12 months of service, the road surface was still well maintained with good crown to shed water. There was some rutting, but not a substantial amount. Since the aggregate used to build the road was non-plastic, gravel loss could be substantial due to the fact that fugitive dust emission would be expected to be generally high with no dust control actions taken. The two control sections, the First South Section and Fourth North Section, had average elevation decreases of 0.19 ft and 0.28 ft, respectively. The Second South and Third North (experimental) Sections experienced elevation decreases of 0.24 ft and 0.1 ft, respectively.

The gravel loss for the First South (experimental) Section was estimated to be up to 86 cubic yards per mile, the Second South (experimental) Section was estimated to be 104.2 cubic yards per mile, the Third North (experimental) Section was estimated to be 65.8 cubic yards per mile, and the Fourth North (control) Section was estimated to be 93.8 cubic yards per mile.

Regression analysis revealed that the Fourth North (control) Section experienced a statistically significant elevation change during the observation period. Further paired t-test results suggested that the southbound lane of the test section experienced a larger elevation loss.

Unpaved Road Condition Ratings

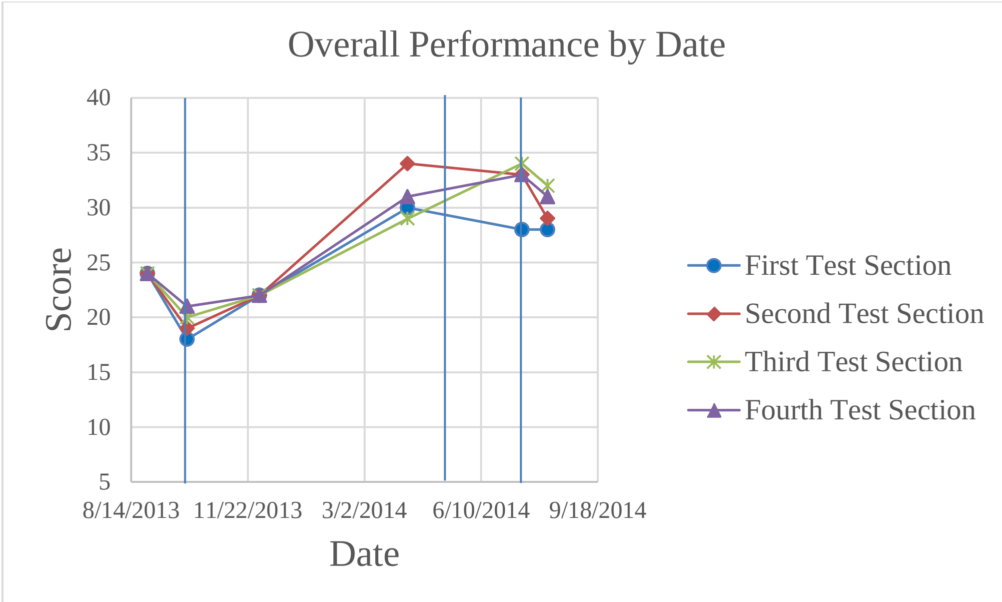
All four test sections were considered to be performing reasonably well, except that the First South (experimental) Section received a rating of Fair with respect to loose aggregate, while the other sections were rated Good. In addition, the First South Section had more severe corrugation compared to the other sections, probably due to its proximity to an intersection. Figure 57 shows the rating results by distress.



The scale for Dust, Crown, and Roadside Drainage was 3.0, while the scale for Rutting, Washboarding, Potholes, and Loose Aggregate was 10.0. More detailed Condition Rating line graphs, by distress type, for all test sections in each county are included in Appendix E.

Figure 57. Olmsted County Pavement Condition Ratings by Distress Type

Considering that nearly identical scores were given to dust, crown, and roadside drainage distresses for all four sections, differences in the overall rating must be due to differences in the other distress ratings. Figure 58 shows the rating outcomes by date.



The darker solid vertical lines indicate dates of maintenance activities.

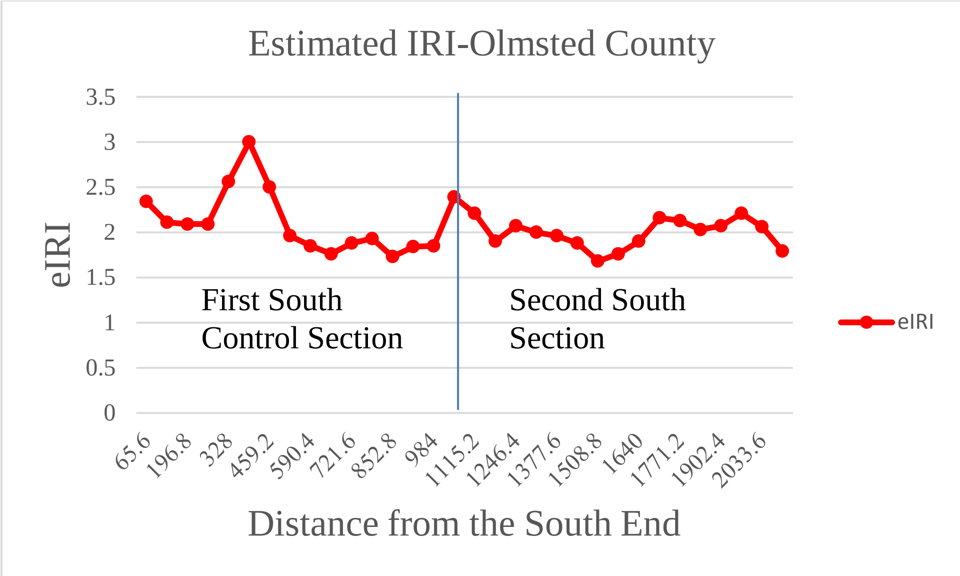
Figure 58. Olmsted County Overall Performance Ratings by Date

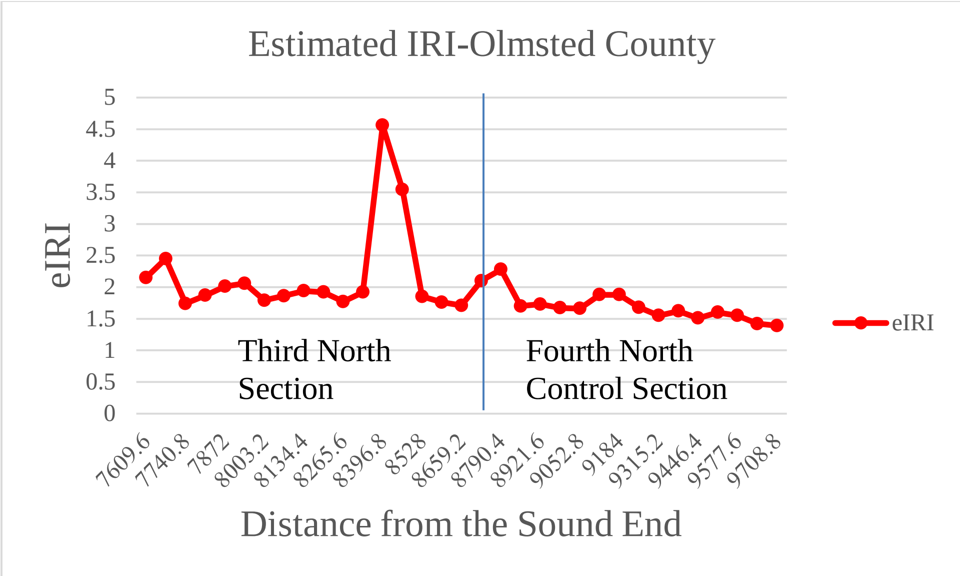
The sudden jump resulted from the addition of the distress of washboarding. Washboarding was not expected to be problematic, since the test sections were located some distance away from intersections. During the dry season, there was not a significant difference in performance among the four sections.

Remarks made by the maintenance supervisor were positive. He expressed that the sections were holding up very well. The only major problem that he reported during several email exchanges was that there was a noticeably higher amount of loose aggregate on the surface of the First South (experimental) Section.

Estimated International Roughness Index

There were spikes in the roughness measurements for the First South (experimental) Section and the Third North (experimental) Section for a short time (see Figure 59). Otherwise, all four sections had stable estimated IRI values. Generally, the surfaces provided a good riding surface, as the average estimated IRI value for each section was lower than 2.2.





Solid vertical lines indicate boundaries of test sections.

Figure 59. Olmsted County CR 115 Estimated IRI Values

Field Observations

The first follow-up visit was approximately eight months after construction was completed. Overall, all four sections were holding up satisfactorily. There had been two grading maintenance actions implemented from May through August. The desired crown for effective water shedding was maintained throughout the period. Clear wheel paths were exposed for all except the First North (experimental) Section, as seen in Figure 60, providing a firm and smooth driving surface.

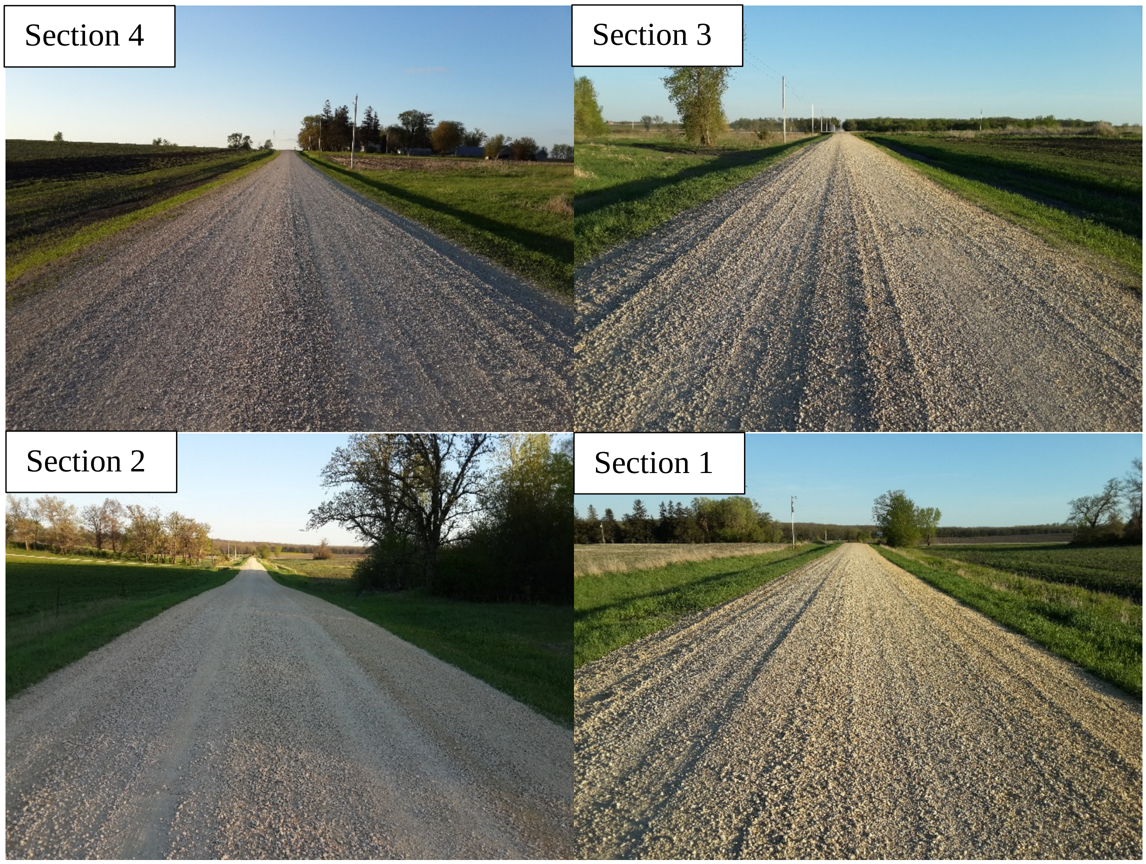


Figure 60. Olmsted County CR 115 Test Section Surfaces

There was relatively little loose aggregate on the surface of all except the First North (experimental) Section, where the amount of loose aggregate was compromising the ride quality, as shown in Figure 61.

Figure 61. Extensive Floating Aggregate on the Surface of the Olmsted County CR 115 First South (Experimental) Section

The visual observation was in line with the results of the scrape tests, which revealed that the amount of loose aggregate was higher for the First South (experimental) Section compared to other three test sections by 15 percent.

CHAPTER SUMMARY

This chapter discussed the material composition differences between the top and the bottom layers of the test sections and the performance assessments conducted in the three counties that participated in test section construction.

The investigation regarding the difference between the top and bottom layers of road surfacing material revealed that the top layer is lacking in the proportion of particles with the No. 4 (4.75 mm) size and smaller. The shortfall becomes larger as the particle size becomes smaller. The bottom material is 3.6 times the proportion of No. 200 fines in comparison to the top material.

The test sections demonstrated that by mixing crusher dust, it is possible to rejuvenate the aggregate surface if the following is given consideration.

- The resulting mixture apparently needs to have some binding capacity if the existing aggregate is non-plastic. The lack of improvement seen with test sections in Jackson County appears to be mainly attributable to the non-plasticity of the resulting mixtures. These results suggest that if the crusher dust and the original aggregates are non-plastic, adding crusher dust without any other additives to help stabilize the surface is not an effective approach to rejuvenate the aggregate surface.

- The amount of fine material added appears to be important. An inadequate amount of added fine material also appears to have led to the ineffective rejuvenation efforts that Jackson County experienced. Given current knowledge, empirical judgment seems to be necessary to estimate the required amount of fine material to add. Calculations conducted by the research team based on analysis of the gradation of the top and the bottom material did not produce the desired results in Jackson County.

  Based on the advice of the Beltrami County maintenance supervisor, the amount of added aggregate was increased from the amount that the researchers recommended (based on their calculations). By having a greater amount of fine material (crusher dust, in this case), the mixing process was more successful in Beltrami County than in Jackson County, which used a significantly smaller amount of fine material.

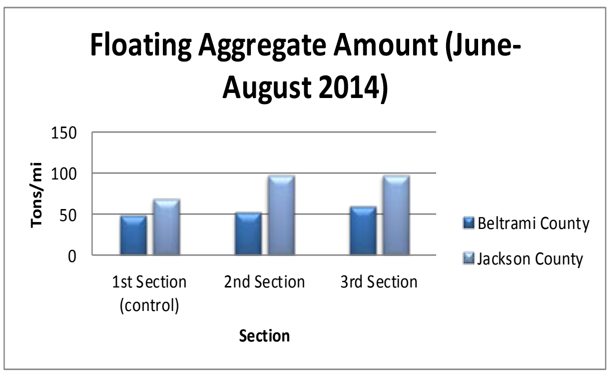
In Jackson County, the experimental sections did not perform as expected. Results there indicated that the control section performed better than the experimental sections.

In Beltrami County, the South/Third Section did not perform as well as the Middle/Second Section, where performance was comparable to the North/First (control) Section. The Middle/Second Section might have had the best performance. In addition, the reduction in the upfront cost is considered as a positive performance attribute. Cost-benefit analysis that was performed is covered and in the next chapter.

In Olmsted County, all four test sections provided excellent performance according to the rating system adopted by this investigation during the period of observation. Collected data show a comparable performance among the four sections. Nevertheless, the Fourth North (control) Section experienced some cross-section deterioration. The volume of loose aggregate on the surface of the First South (experimental) Section was of concern since the excessive loose aggregate could compromise driving safety.

In terms of road roughness, all sections in Beltrami County and Olmsted County that were assessed with Roadroid were in the Good category, suggesting at least adequate ride quality.

The amounts of floating aggregate and gravel loss after construction estimated for each test section are presented in Figure 62 through Figure 64.



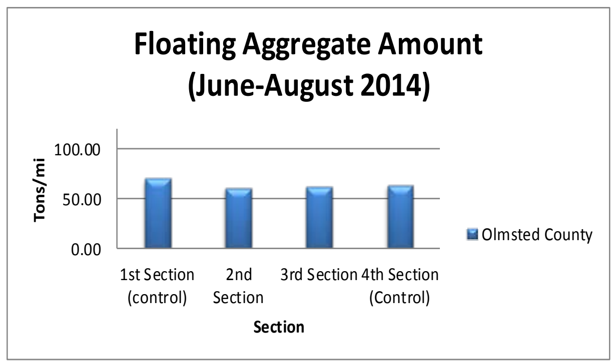
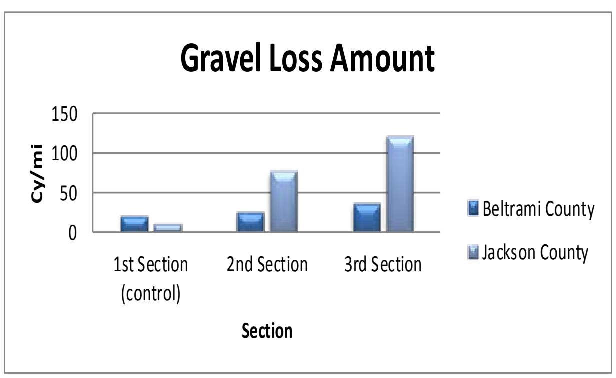


Figure 62. Postconstruction Floating Aggregate Results



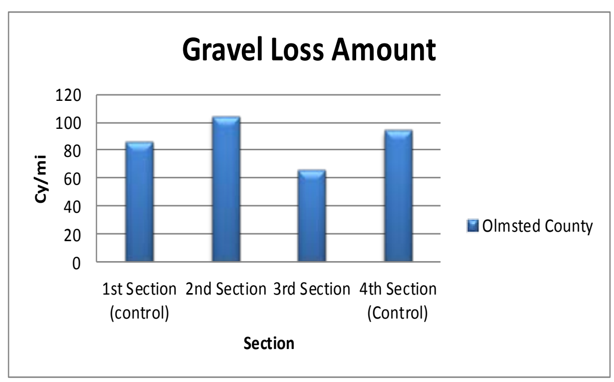


Figure 63. Postconstruction Aggregate Loss Results

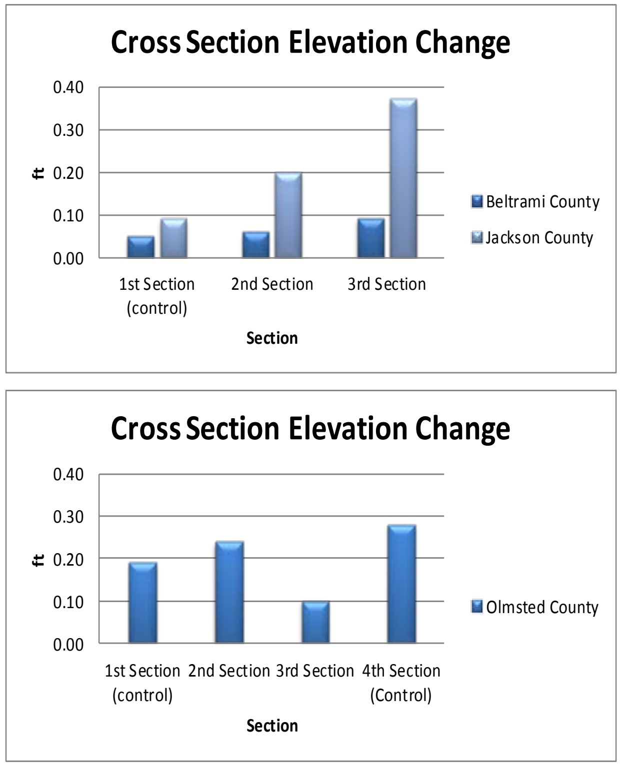


Figure 64. Postconstruction Cross-Section Elevation Decrease Results

6. Economic Analysis

To meet one of the objectives of this research, economic analyses were conducted. The research team collected cost data from highway departments of the participating counties. The objective of the economic analysis was to determine whether or not the concept of aggregate rejuvenation is economically feasible on the premise that serviceability is not compromised.

COST COMPARISON ANALYSIS

Cost comparisons were performed for the upfront costs, to assess the cost effectiveness of adopting the aggregate rejuvenating concept. The cost comparisons focused primarily on three major cost components in constructing unpaved roads: labor, equipment, and material.

Hours of equipment operation and labor were approximately estimated by developing a construction process design, estimating the number of hours to execute the design, multiplying the hourly costs by the number of hours, and summing each cost element to provide a total. The calculated cost estimates were in dollars per mile.

Motor-graders were assumed to work 50 percent longer than trucks to account for their relatively low traveling speed to mobilize from the work shop to the construction site and the extra amount of time involved in grading the last spread of material.

When a multiyear benefit-cost analysis was conducted as part of this investigation, the time value of money was considered. In general, funds spent or obtained in the future are considered to have less value than funds spent or obtained in the present. A discount rate is often selected for economic analysis calculations to facilitate a comparison between future values and present values. An economic analysis calculation using a discount rate is somewhat similar to a financial analysis calculation using an interest rate. A higher discount rate like a higher interest rate indicates a stronger preference for having money in the present compared to having money in the future.

COST COMPARISON RESULTS

Table 11 through Table 13 show the construction costs for each test section and the estimated savings for each experimental section by county.

Table 11. Jackson County CR 76 construction costs and estimated savings.

Test Section	Total Cost	Savings
West/First (control)/200.64 ton/mi	$4,025.56	n/a
Middle/Second/126.72 ton/mi	$3,364.62	16%
East/Third/73.92 ton/mi	$2,108.76	48%

Table 12. Beltrami County CR 23 construction costs and estimated savings.

Test Section	Total Cost	Savings

Test Section	Total Cost	Savings
North/First (control)/166 ton/mi	$8,513.93	n/a
Middle/Second/83 ton/mi	$5,417.52	36%
South/Third/50 ton/mi	$3,325.95	61%

Table 13. Olmsted County CR 115 construction costs.

Test Section	Total Cost	Savings
First South	$23,236.60	5%
Second South	$22,528.43	8%
Third North	$25,050.04	-3%
Fourth North (control)	$24,446.69	n/a

BENEFIT-COST ANALYSIS

Considerable economic savings were realized in the Third Test Section of both Jackson County and Beltrami County, with nearly 50 percent cost savings for Jackson County and more than 60 percent for Beltrami County in the upfront construction. The Second Test Section for both counties provided cost-savings upfront as well. For Beltrami County, the savings was up to 36 percent and performance was acceptably well over the period of observation, according to data analysis and site feedback.

Even though both the Second Section and the Third Section in Jackson County and Beltrami County demonstrated cost savings upfront, maintenance costs could balance out savings. Benefit-cost analysis was performed for Beltrami County. The result showed that in a five-year cycle, the Middle/Second Section saved $2,400, which is a cost saving of 19 percent

Beltrami County CR 23 Analysis Details

The Beltrami County Highway Department actively maintains aggregate roads in the jurisdiction seven months of the year, usually from late April through early November. By the end of September 2014, they had conducted eight maintenance activities on the South/Third Section and five maintenance activities on the Middle/Second Section and the North/First Section. The research team projected, based on the maintenance frequency observed, that there would probably be 10 maintenance activities implemented on the South/Third Section, eight on the Middle/Second Section, and seven on the North/First Section in 2014.

Cost and maintenance information was solicited. Maintenance cost per mile each year for the South/Third Section came to $1,500, $1,050 for the Middle/Second Section, and $900 for the North/First (control) Section.

In Beltrami County, roads are typically re-graveled every five years. For comparison purposes, the researchers assumed that the cost for maintenance would be constant throughout the five-year life cycle (Table 14).

Table 14. Beltrami County CR 23 benefit-cost analysis.

	Test Section		
	North (Control)	South	Middle
Construction cost	$8,513.93	$3,325.95	$5,417.52
Maintenance cost			
First year	900	1,500	1,050
Second year	900	1,500	1,050
Third year	900	1,500	1,050
Fourth year	900	1,500	1,050
Fifth year	900	1,500	1,050
Net present value	$12,680.83	$10,270.79	$10,278.91
Savings		19%	19%

Taking the discount rate of 4 percent recommended by the Beltrami County Highway Department into account, the final result suggests that, in a five-year cycle, a mile of rejuvenated aggregate road adopting the method used on the Middle/Second Section saves $2,400, which is a cost savings of 19 percent, while the road performance is acceptably well. In this case for Beltrami County, the cost savings increase as the re-gravel cycle is shortened.

7. Performance Summaries

JACKSON COUNTY CR 76

The disappointing performance of the test sections in Jackson County can likely be attributed to the lack of binding capacity of both the crusher dust and the in situ material. Segregation occurred soon after the arrival of dry weather. The two experimental sections returned to their initial conditions. A considerable amount of loose aggregate appeared within half a year.

The East/Third Section experienced a statistically significant amount of gravel loss according to a statistical analysis of cross-section elevation results and likely resulted in road surface deterioration. However, other issues cannot be ignored, such as having an inadequate amount of crusher dust to mix in with the in situ material, which apparently led to uneven blending of the crusher dust and the in situ material.

Cost savings in construction were realized compared to the standard method of re-graveling the road, but, given the disappointing performance, the opportunity for cost savings is unlikely to be considered worthwhile.

However, there is a cost savings up to 48% in one of the experimental sections. This cost savings could be invested in adding binding silt and clay as well as dust emission palliative. The addition possibly would increase the cost. Nevertheless, benefit from improved performance should not be ignored. Maintenance supervisor Edmond Geving in an informal discussion once mentioned that if the natural binder content in crushed gravel is too low, silt and clay from natural soils in their pits would be added to raise #200 sieve percentage up to 10%.

BELTRAMI COUNTY CR 23

At the end of the observation period, the two experimental test sections in Beltrami County were performing better than those in Jackson County, apparently because the resulting aggregate on the surface after blending possessed more binding capacity. Although the two experimental sections on Beltrami County CR 23 were not as compacted as the control section, which was surfaced with MnDOT Class 1 aggregate, they did hold up and provided a driving surface that met expectations during the observation period.

Between the two experimental test sections, the Middle/Second Section appeared to outperform the South/Third Section in all respects. As the maintenance supervisor reflected in notes and the collected data suggest, the Middle/Second Section performed well compared to the North/First Section, which was the control section. The biggest concern over the South/Third Section was the corrugation formed throughout the section.

A benefit-cost analysis revealed that the Middle/Second Section generates cost savings up to 19 percent. From the performance point of view, the Middle/Second Section provided an acceptable surface for road users while the South/Third Section failed to do so.

OLMSTED COUNTY CR 115

The four sections on CR 115 in Olmsted County provided excellent road surfaces for road users. Remarks from the maintenance supervisor and the data collected suggested comparable performance among all four sections. However, due to the non-binding characteristic of limestone used in Olmsted County, road surfacing material loss appeared to be higher.

The two test sections that were constructed with Class 2 and Class 5 aggregate experienced cross-sectional changes and excessive loose aggregate, respectively. The experimental Second Section generated the highest amounts of loose aggregate. The experimental Third Section was favorable as the trial results indicate.

8. Conclusions and Recommendations

The conclusions and recommendations are based on the observations of the test sections that were constructed in Beltrami, Jackson and Olmsted Counties, in addition to other research activities that led up to the construction and observation of these test sections.

The results of the Beltrami County test section observations suggest that the unpaved road rejuvenation method of adding fine material with some plasticity has the potential to improve gravel road performance and reduce costs. The results from the Jackson County test sections suggest that such improvement may not occur unless a proper mixture of fine material with some binding ability is provided. With regard to the road rejuvenating method of adding fine material to roads that have excessive floating material, the planning process for test section construction indicated that identifying an economical source suitable fine material for mixing and binding the floating material was a challenge in each case of test section construction. The Olmstead County test sections served to provide a comparison of various crushed limestone road surfacing materials rather than to demonstrate rejuvenating a road surface by adding fine material. An Olmstead county test section with one half Class 5 material and one half Class 2 material provided marginally better performance in comparison to the others.

Based on experience with the Beltrami County test sections, adding materials that increase plasticity a reasonable amount is desirable for fine aggregate such as granite that have high relative mineral hardness and have a limited ability to bind. A mixture of crusher dust that includes clay and possibly some silt apparently increases the binding capacity of the road surface providing a better outcome for road users.

Ensuring the even distribution of the added fine material is important. For example, crusher dust stockpiles in a humid environment tend to form crusts that can break into chunks that are hard to distribute evenly on the road surface. Stockpile blending may be necessary to break up the crust and disperse the moisture before the materials is loaded onto trucks for transport to the job sites.

Finding locally accessible road surfacing materials is an important aspect of ensuring the economic feasibility of an unpaved road surfacing program. The advantages in cost savings can be realized by the reduction of trucking hours and/or material costs. Trucking cost makes up a large proportion of the total construction costs for crushed rock or gravel road resurfacing. Shortening transportation distances is often more effective in reducing costs compared to efforts to purchase less expensive material at a gravel pit or quarry.

Finally, it is advisable to perform an economic feasibility study before adopting a road surface rejuvenation method. Depending on the location of the source of material, the cost can vary considerably, even within the same jurisdiction.

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Appendix A. Gradation Raw Data

The numbered (#1 and #2) columns of data in the following four tables are for replicate top material and bottom material samples for each road section.

Beltrami County CR 23

Sieve Size	Top Material Percentage Passing CR 23			Bottom Material Percentage Passing CR 23		
	#1	#2	Average	#1	#2	Average
1.5 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
1 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
3/4 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
3/8 in.	95.1%	95.2%	95.1%	95.8%	96.8%	96.3%
#4	84.7%	83.2%	83.9%	89.1%	89.1%	89.1%
#8	N/A	N/A	N/A	N/A	N/A	N/A
#10	67.8%	62.3%	65.0%	78.2%	79.4%	78.8%
#30	N/A	N/A	N/A	N/A	N/A	N/A
#40	28.1%	23.9%	26.0%	46.5%	47.9%	47.2%
#100	N/A	N/A	N/A	N/A	N/A	N/A
#200	2.3%	2.1%	2.2%	7.3%	7.1%	7.2%
<#200	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Jackson County CR 76

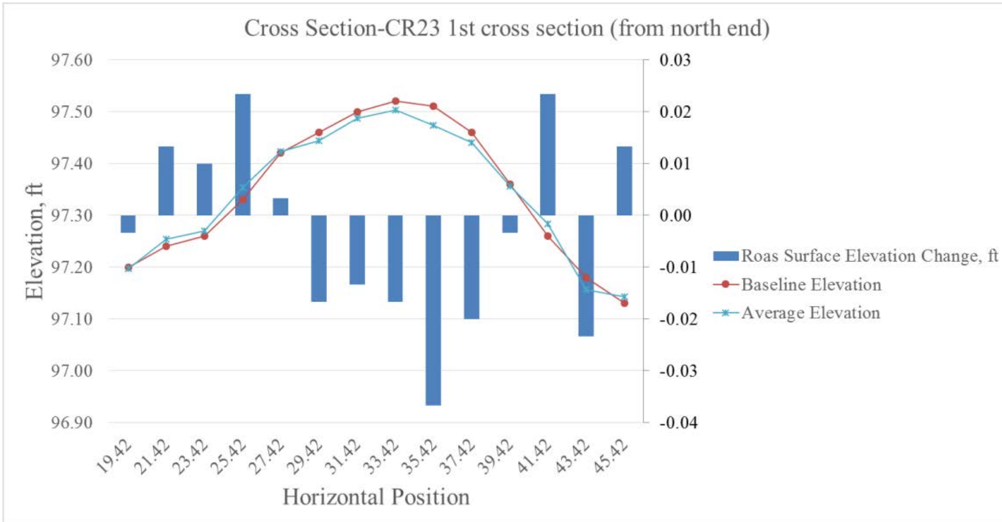
Sieve Size	Top Material Percentage Passing CR 76			Bottom Material Percentage Passing CR 76		
	#1	#2	Average	#1	#2	Average
1.5 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
1 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
3/4 in.	99.3%	98.6%	99.0%	98.9%	98.4%	98.6%
3/8 in.	89.9%	86.7%	88.3%	94.0%	91.4%	92.7%
#4	79.0%	76.1%	77.6%	87.0%	82.7%	84.9%
#8	N/A	N/A	N/A	N/A	N/A	N/A
#10	59.0%	58.4%	58.7%	75.6%	71.1%	73.4%
#30	N/A	N/A	N/A	N/A	N/A	N/A
#40	20.6%	20.1%	20.4%	41.2%	38.5%	39.9%
#100	N/A	N/A	N/A	N/A	N/A	N/A
#200	4.2%	4.2%	4.2%	12.7%	11.7%	12.2%
<#200	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Olmsted County CR 115

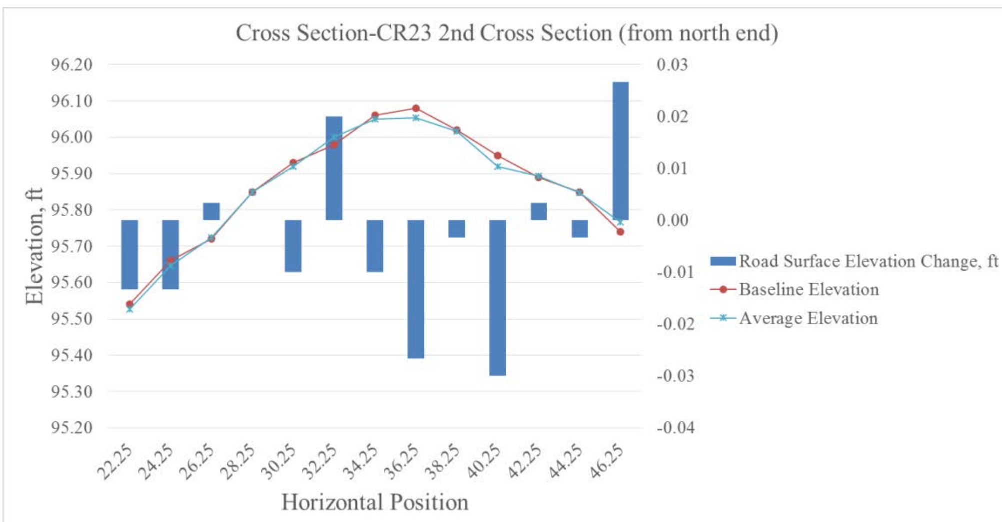
Sieve Size	Top Material Percentage Passing			Bottom Material Percentage Passing		
	North CR 115		Average	North CR 115		Average
	#1	#2		#1	#2	
1.5 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
1 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
3/4 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
3/8 in.	75.4%	81.3%	78.4%	89.0%	89.2%	89.1%
#4	39.9%	54.3%	47.1%	66.5%	67.9%	67.2%
#8	N/A	N/A	N/A	N/A	N/A	N/A
#10	20.9%	35.3%	28.1%	46.6%	48.5%	47.5%
#30	N/A	N/A	N/A	N/A	N/A	N/A
#40	11.7%	21.8%	16.8%	28.8%	33.1%	30.9%
#100	N/A	N/A	N/A	N/A	N/A	N/A
#200	6.6%	12.2%	9.4%	10.9%	19.8%	15.4%
<#200	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Sieve Size	Top Material Percentage Passing			Bottom Material Percentage Passing		
	South CR 115		Average	South CR 115		Average
	#1	#2		#1	#2	
1.5 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
1 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
3/4 in.	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
3/8 in.	81.2%	84.2%	82.7%	91.2%	91.3%	91.2%
#4	55.8%	51.9%	53.8%	73.3%	71.6%	72.4%
#8	N/A	N/A	N/A	N/A	N/A	N/A
#10	36.1%	30.5%	33.3%	54.2%	52.4%	53.3%
#30	N/A	N/A	N/A	N/A	N/A	N/A
#40	22.1%	18.0%	20.0%	35.1%	34.3%	34.7%
#100	N/A	N/A	N/A	N/A	N/A	N/A
#200	13.4%	10.6%	12.0%	21.5%	21.1%	21.3%
<#200	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

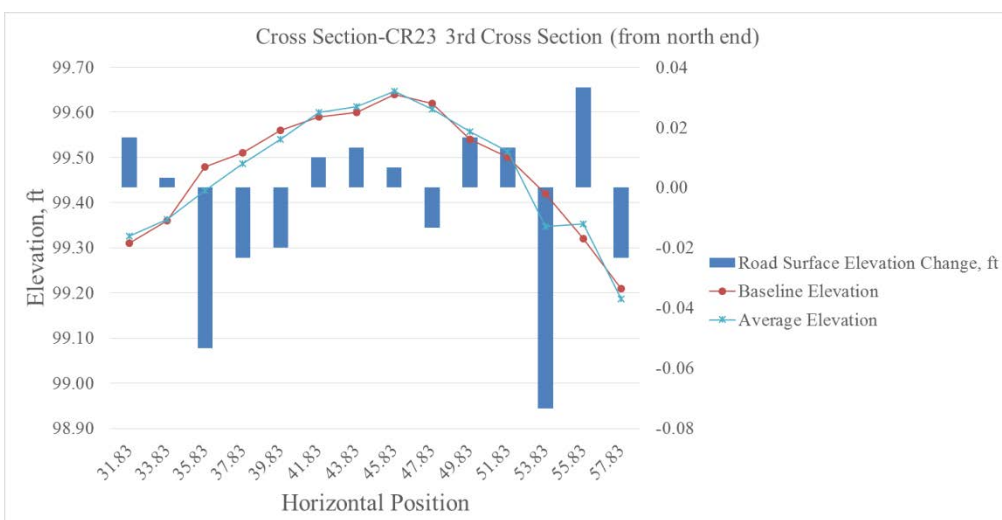
Appendix B. Cross-Section Profiles



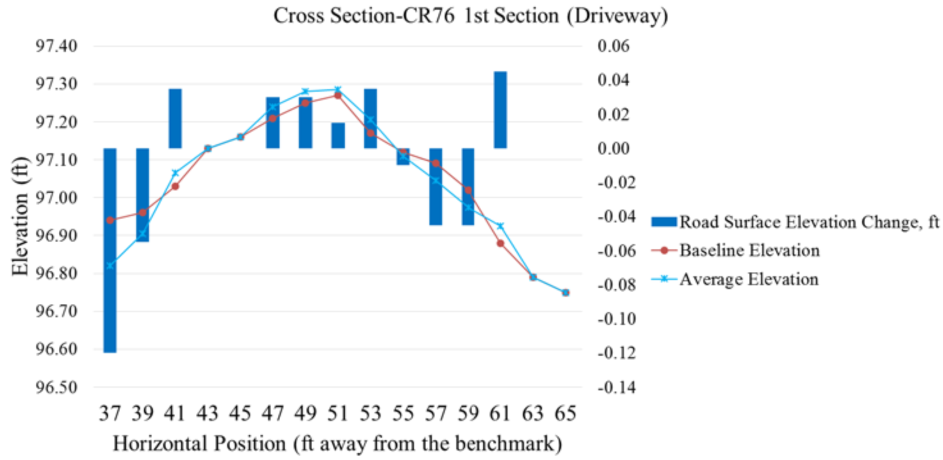
Cross Section-CR23 1st cross section (from north end)
Elevation, ft
Horizontal Position
Roas Surface Elevation Change, ft
Baseline Elevation
Average Elevation

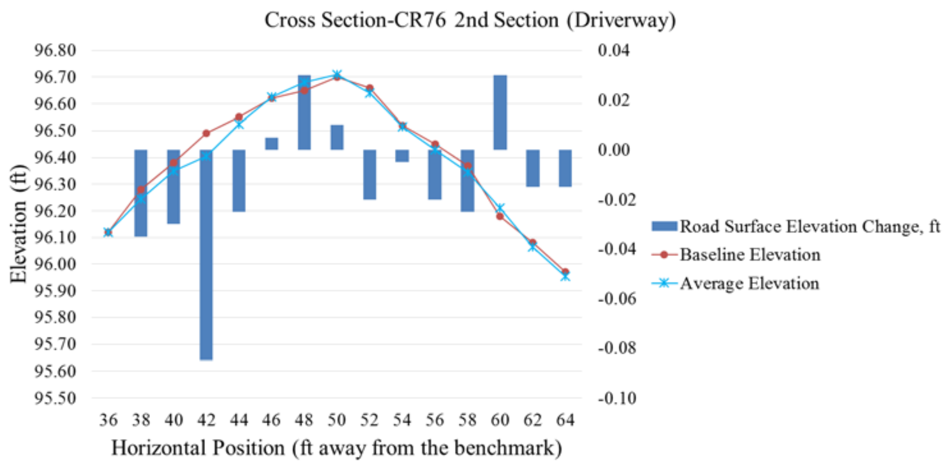


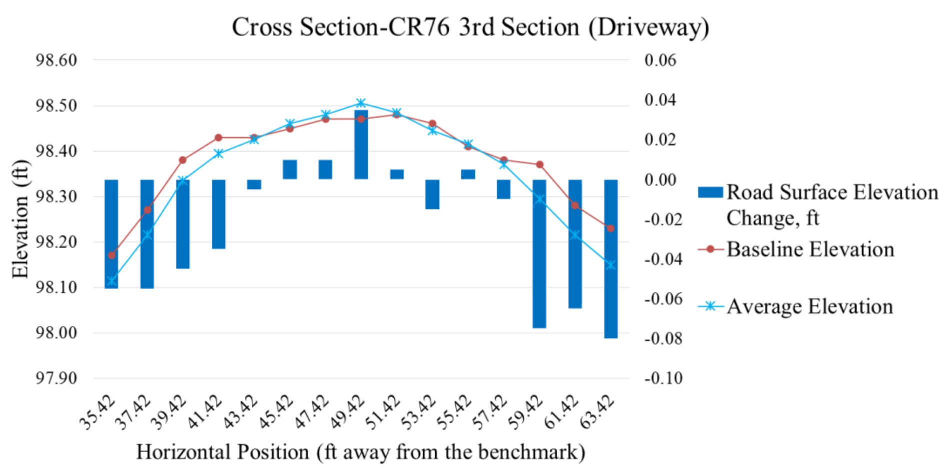
Cross Section-CR23 2nd Cross Section (from north end)
Elevation, ft
Horizontal Position
Road Surface Elevation Change, ft
Baseline Elevation
Average Elevation

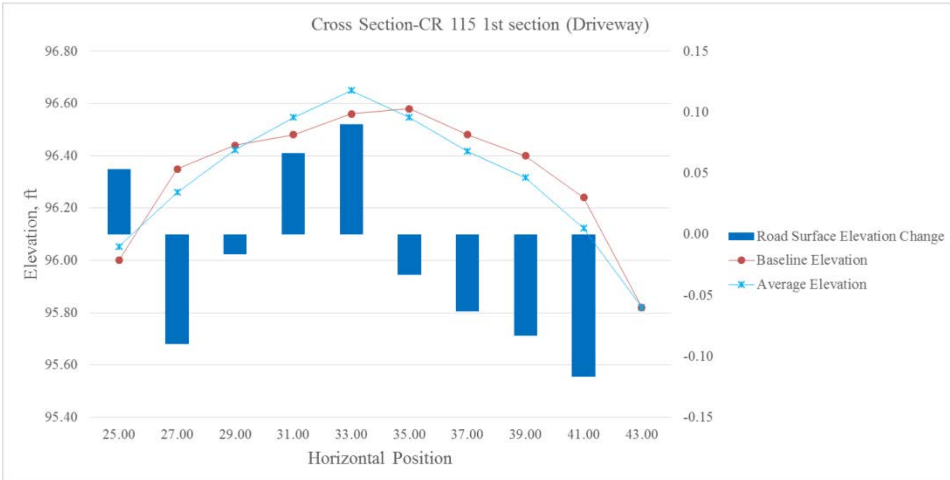


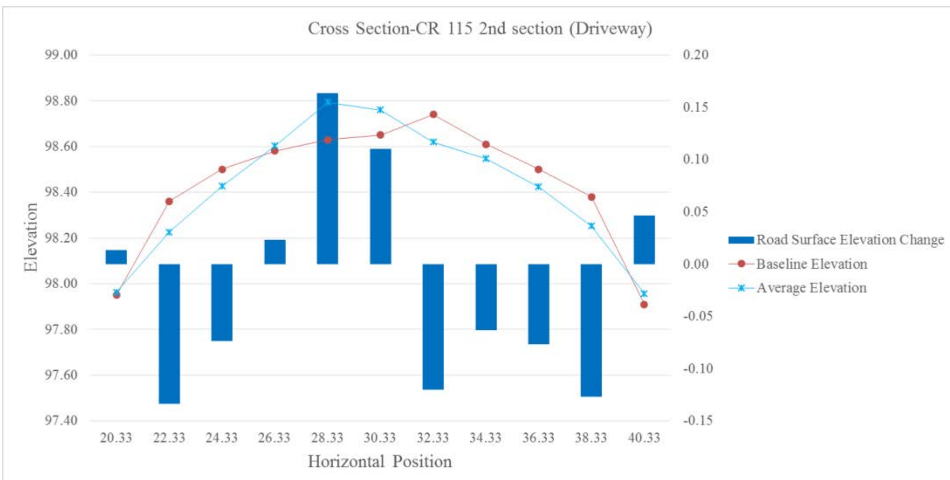
Cross Section-CR23 3rd Cross Section (from north end)
Elevation, ft
Horizontal Position
Road Surface Elevation Change, ft
Baseline Elevation
Average Elevation

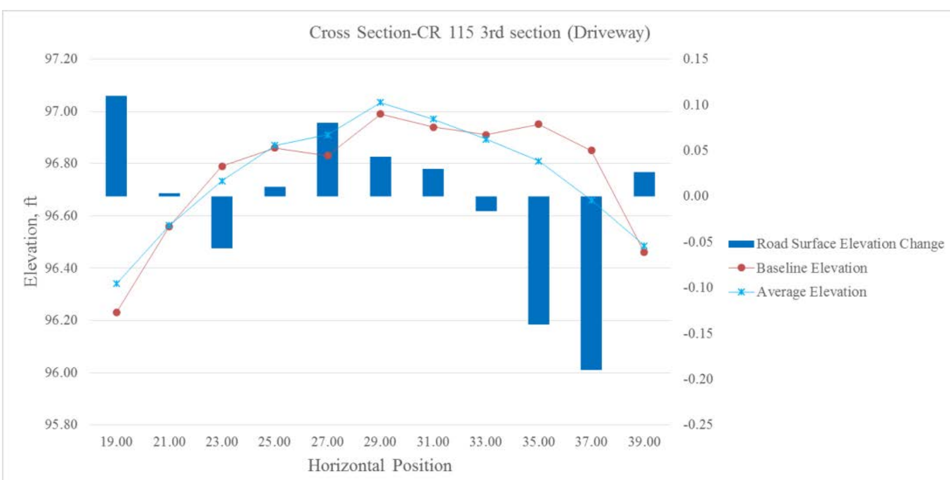

Cross Section-CR76 1st Section (Driveway)
Elevation (ft)
97.40
97.30
97.20
97.10
97.00
96.90
96.80
96.70
96.60
96.50
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
37 39 41 43 45 47 49 51 53 55 57 59 61 63 65
Horizontal Position (ft away from the benchmark)
Road Surface Elevation Change, ft
Baseline Elevation
Average Elevation

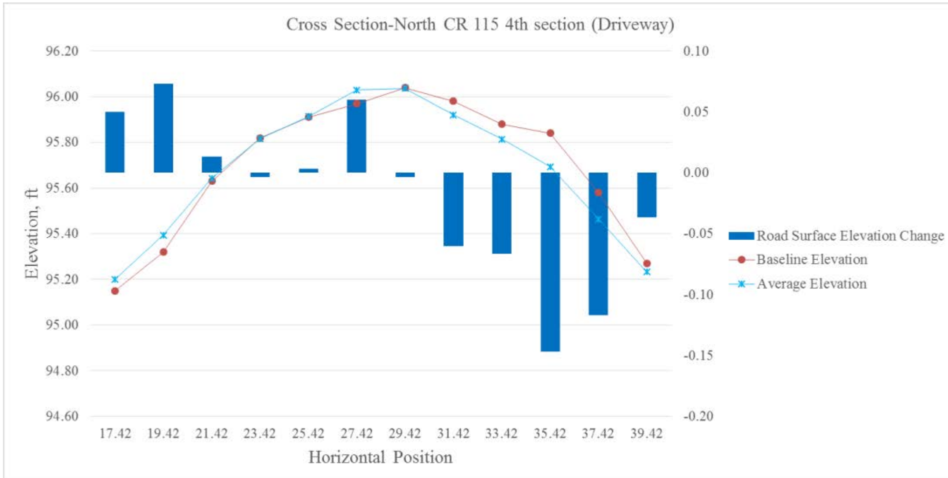

Cross Section-CR76 2nd Section (Driverway)
Elevation (ft)
96.80
96.70
96.60
96.50
96.40
96.30
96.20
96.10
96.00
95.90
95.80
95.70
95.60
95.50
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
36 38 40 42 44 46 48 50 52 54 56 58 60 62 64
Horizontal Position (ft away from the benchmark)
Road Surface Elevation Change, ft
Baseline Elevation
Average Elevation


Cross Section-CR76 3rd Section (Driveway)
Elevation (ft)
98.60
98.50
98.40
98.30
98.20
98.10
98.00
97.90
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
35.42 37.42 39.42 41.42 43.42 45.42 47.42 49.42 51.42 53.42 55.42 57.42 59.42 61.42 63.42
Horizontal Position (ft away from the benchmark)
Road Surface Elevation Change, ft
Baseline Elevation
Average Elevation


Cross Section-CR 115 1st section (Driveway)
Elevation, ft
96.80
96.60
96.40
96.20
96.00
95.80
95.60
95.40
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
25.00
27.00
29.00
31.00
33.00
35.00
37.00
39.00
41.00
43.00
Horizontal Position
Road Surface Elevation Change
Baseline Elevation
Average Elevation


Cross Section-CR 115 2nd section (Driveway)
Elevation
99.00
98.80
98.60
98.40
98.20
98.00
97.80
97.60
97.40
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
20.33
22.33
24.33
26.33
28.33
30.33
32.33
34.33
36.33
38.33
40.33
Horizontal Position
Road Surface Elevation Change
Baseline Elevation
Average Elevation


Cross Section-CR 115 3rd section (Driveway)
Elevation, ft
97.20
97.00
96.80
96.60
96.40
96.20
96.00
95.80
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
19.00
21.00
23.00
25.00
27.00
29.00
31.00
33.00
35.00
37.00
39.00
Horizontal Position
Road Surface Elevation Change
Baseline Elevation
Average Elevation



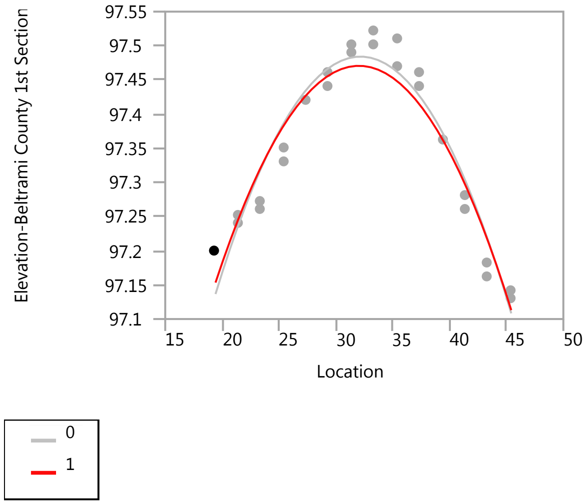
Cross Section-North CR 115 4th section (Driveway)
96.20
96.00
95.80
95.60
95.40
95.20
95.00
94.80
94.60
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
Elevation, ft
17.42 19.42 21.42 23.42 25.42 27.42 29.42 31.42 33.42 35.42 37.42 39.42
Horizontal Position
Road Surface Elevation Change
Baseline Elevation
Average Elevation

Appendix C. Statistical Analysis Results

COMPARISON OF MULTIPLE CURVES

Response Elevation-Beltrami County First Section (Control)

Regression Plot



Summary of Fit

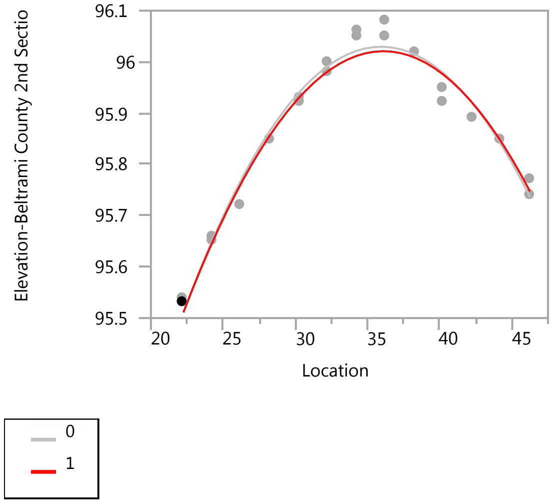
RSquare	**0.924477**
RSquare Adj	0.907313
Root Mean Square Error	0.038642
Mean of Response	97.34286
Observations (or Sum Wgts)	28

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	97.519333	0.044348	2199.0	**<.0001***
Time[1-0]	-0.013661	0.022003	-0.62	0.5411
Location	-0.001088	0.001281	-0.85	0.4049
(Location-32.42)*(Location-32.42)	-0.002139	0.000179	-11.95	**<.0001***
(Location-32.42)*(Location-32.42)*Time[1-0]	0.0001442	0.000253	0.57	0.5747
(Location-32.42)*Time[1-0]	-0.000462	0.001812	-0.25	0.8013

Response Elevation-Beltrami County Second Section

Regression Plot



Summary of Fit

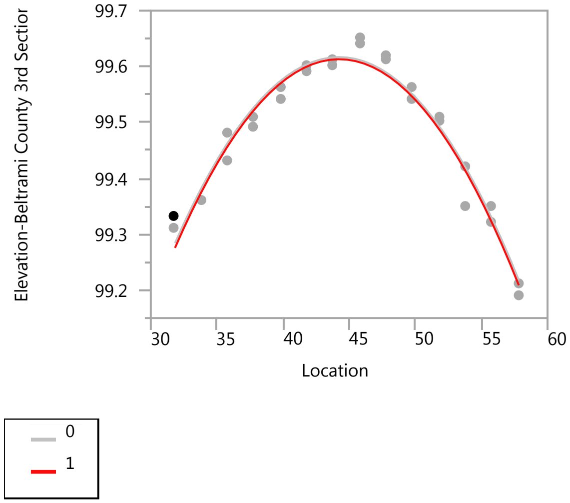
RSquare	**0.9689**
RSquare Adj	0.961125
Root Mean Square Error	0.031166
Mean of Response	95.865
Observations (or Sum Wgts)	26

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	95.70082	0.041653	2297.6	**<.0001***
Time[1-0]	-0.00979	0.018429	-0.53	0.6011
Location	0.0093681	0.001155	8.11	**<.0001***
(Location-34.25)*(Location-34.25)	-0.002763	0.000174	-15.87	**<.0001***
(Location-34.25)*(Location-34.25)*Time[1-0]	0.0001061	0.000246	0.43	0.6711
(Location-34.25)*Time[1-0]	0.000467	0.001634	0.29	0.7779

Response Elevation-Beltrami County Third Section

Regression Plot



Summary of Fit

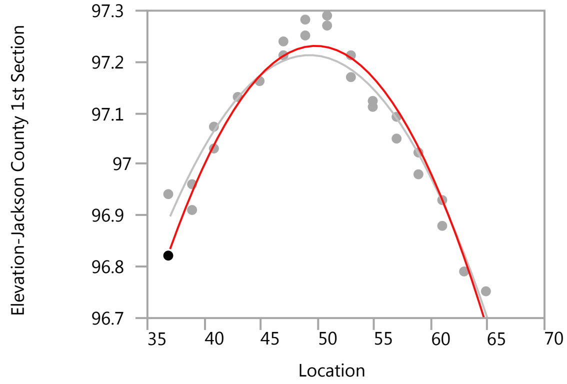
RSquare	**0.960138**
RSquare Adj	0.951079
Root Mean Square Error	0.029256
Mean of Response	99.47286
Observations (or Sum Wgts)	28

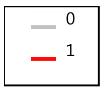
Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	99.73052	0.045044	2214.1	**<.0001***
Time[1-0]	-0.003817	0.016658	-0.23	0.8209
Location	-0.002549	0.00097	-2.63	**0.0153***
(Location-44.83)*(Location-44.83)	-0.002162	0.000136	-15.95	**<.0001***
(Location-44.83)*(Location-44.83)*Time[1-0]	-2.919e-5	0.000192	-0.15	0.8803
(Location-44.83)*Time[1-0]	-0.000022	0.001372	-0.02	0.9874

Response Elevation-Jackson County First Section (Control)

Regression Plot





Summary of Fit

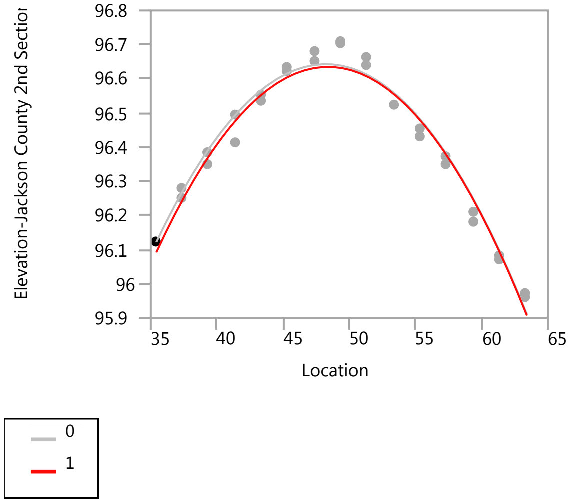
RSquare	**0.948536**
RSquare Adj	0.937814
Root Mean Square Error	0.04156
Mean of Response	97.04967
Observations (or Sum Wgts)	30

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	97.572291	0.065363	1492.8	**<.0001***
Time[1-0]	0.0208597	0.022849	0.91	0.3704
Location	-0.007161	0.001242	-5.77	**<.0001***
(Location-51)*(Location-51)	-0.002086	0.000162	-12.90	**<.0001***
(Location-51)*(Location-51)*Time[1-0]	-0.000324	0.000229	-1.42	0.1695
(Location-51)*Time[1-0]	0.0015	0.001756	0.85	0.4015

Response Elevation-Jackson County Second Section

Regression Plot



Summary of Fit

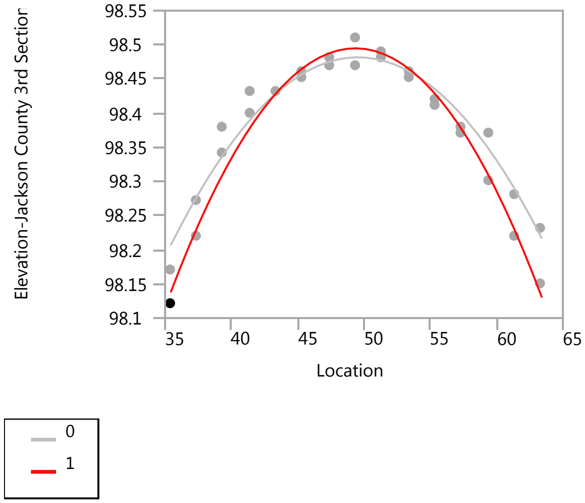
RSquare	**0.972057**
RSquare Adj	0.966236
Root Mean Square Error	0.041889
Mean of Response	96.396
Observations (or Sum Wgts)	30

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	97.010732	0.063966	1516.6	**<.0001***
Time[1-0]	-0.006805	0.02303	-0.30	0.7702
Location	-0.007536	0.001252	-6.02	**<.0001***
(Location-49.42)*(Location-49.42)	-0.003174	0.000163	-19.47	**<.0001***
(Location-49.42)*Time[1-0]	0.0009286	0.00177	0.52	0.6047
(Location-49.42)*(Location-49.42)*Time[1-0]	-5.171e-5	0.000231	-0.22	0.8244

Response Elevation-Jackson County Third Section

Regression Plot



Summary of Fit

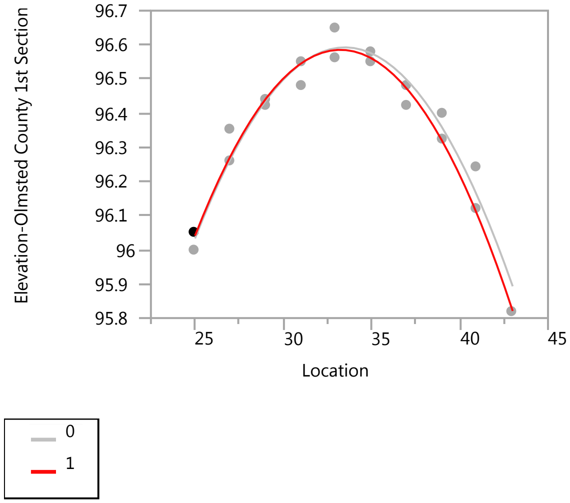
RSquare	**0.974812**
RSquare Adj	0.969564
Root Mean Square Error	0.019504
Mean of Response	98.368
Observations (or Sum Wgts)	30

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	98.464033	0.029784	3306.0	**<.0001***
Time[1-0]	0.0132217	0.010723	1.23	0.2295
Location	0.0003571	0.000583	0.61	0.5458
(Location-49.42)*(Location-49.42)	-0.00138	0.000076	-18.17	**<.0001***
(Location-49.42)*(Location-49.42)*Time[1-0]	-0.000463	0.000107	-4.31	**0.0002***
(Location-49.42)*Time[1-0]	-0.000625	0.000824	-0.76	0.4557

Response Elevation-Olmsted County First Section (South Control)

Regression Plot



Summary of Fit

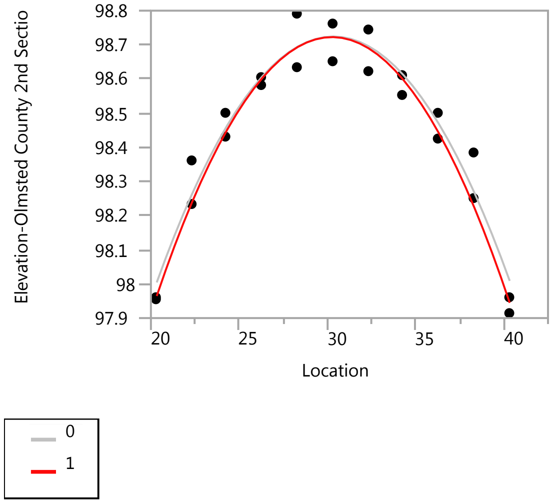
RSquare	**0.969061**
RSquare Adj	0.958011
Root Mean Square Error	0.050577
Mean of Response	96.3255
Observations (or Sum Wgts)	20

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	96.855413	0.097705	991.30	**<.0001***
Time[1-0]	-0.009938	0.034221	-0.29	0.7758
Location	-0.007788	0.002784	-2.80	**0.0143***
(Location-34)*(Location-34)	-0.007746	0.00055	-14.08	**<.0001***
(Location-34)*(Location-34)*Time[1-0]	-0.000275	0.000778	-0.35	0.7294
(Location-34)*Time[1-0]	-0.004455	0.003937	-1.13	0.2769

Response Elevation-Olmsted County Second Section

Regression Plot



Summary of Fit

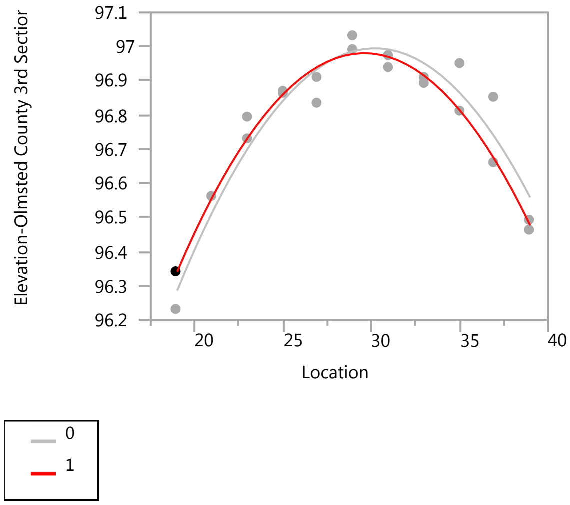
RSquare	**0.956368**
RSquare Adj	0.942733
Root Mean Square Error	0.065833
Mean of Response	98.42636
Observations (or Sum Wgts)	22

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	98.717442	0.099801	989.14	**<.0001***
Time[1-0]	-0.001655	0.042406	-0.04	0.9694
Location	0.0002273	0.003138	0.07	0.9432
(Location-30.33)*(Location-30.33)	-0.007177	0.000562	-12.77	**<.0001***
(Location-30.33)*(Location-30.33)*Time[1-0]	-0.000504	0.000795	-0.63	0.5348
(Location-30.33)*Time[1-0]	-0.001227	0.004438	-0.28	0.7857

Response Elevation-Olmsted County Third Section

Regression Plot



Summary of Fit

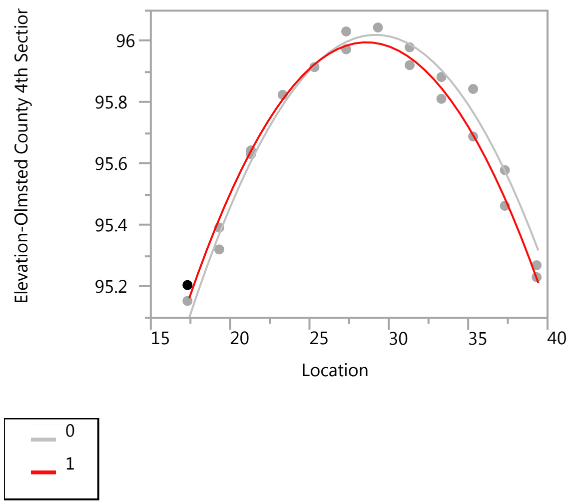
RSquare	**0.939231**
RSquare Adj	0.92024
Root Mean Square Error	0.063136
Mean of Response	96.75591
Observations (or Sum Wgts)	22

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	96.591329	0.091903	1051.0	**<.0001***
Time[1-0]	-0.008019	0.040669	-0.20	0.8462
Location	0.0136364	0.00301	4.53	**0.0003***
(Location-29)*(Location-29)	-0.005647	0.000539	-10.48	**<.0001***
(Location-29)*(Location-29)*Time[1-0]	-4.953e-5	0.000762	-0.06	0.9490
(Location-29)*Time[1-0]	-0.006864	0.004257	-1.61	0.1264

Response Elevation-Olmsted County Fourth Section (North Control)

Regression Plot



Summary of Fit

RSquare	**0.98567**
RSquare Adj	0.981689
Root Mean Square Error	0.039876
Mean of Response	95.68875
Observations (or Sum Wgts)	24

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	95.733886	0.050467	1896.9	**<.0001***
Time[1-0]	-0.020804	0.024564	-0.85	0.4082
Location	0.0099825	0.001667	5.99	**<.0001***
(Location-28.42)*(Location-28.42)	-0.00668	0.000273	-24.48	**<.0001***
(Location-28.42)*(Location-28.42)*Time[1-0]	-6.244e-7	0.000386	-0.00	0.9987
(Location-28.42)*Time[1-0]	-0.00771	0.002358	-3.27	**0.0043***

PAIRED T-TEST RESULT

t-Test: Paired Two Sample for Means-Jackson County Third Section Crown

	Variable 1	*Variable 2*
Mean	98.448125	98.44375
Variance	0.001928125	0.001198214
Observations	8	8
Pearson Correlation	0.94985466	
Hypothesized Mean Difference	0	
df	7	
t Stat	0.800700628	
P(T<=t) one-tail	0.224811316	
t Critical one-tail	1.894578605	
P(T<=t) two-tail	**0.449622633**	
t Critical two-tail	2.364624252	

t-Test: Paired Two Sample for Means-Jackson County Third Section 8 ft from Center

	Variable 1	*Variable 2*
Mean	98.24571429	98.30428571
Variance	0.010136905	0.008528571
Observations	7	7
Pearson Correlation	0.989969309	
Hypothesized Mean Difference	0	
df	6	
t Stat	-9.68624054	
P(T<=t) one-tail	3.47231E-05	
t Critical one-tail	1.943180281	
P(T<=t) two-tail	**6.94463E-05**	
t Critical two-tail	2.446911851	

t-Test: Paired Two Sample for Means-Olmsted County Fourth Section Northbound

	Variable 1	*Variable 2*
Mean	95.71904762	95.69142857
Variance	0.10434709	0.116380952
Observations	7	7
Pearson Correlation	0.996688199	
Hypothesized Mean Difference	0	
df	6	
t Stat	2.246330341	
P(T<=t) one-tail	0.032886064	
t Critical one-tail	1.943180281	
P(T<=t) two-tail	0.065772127	
t Critical two-tail	2.446911851	

t-Test: Paired Two Sample for Means-Olmsted County Fourth Section Southbound

	Variable 1	*Variable 2*
Mean	95.62466667	95.71
Variance	0.076675556	0.0823
Observations	5	5
Pearson Correlation	0.987877152	
Hypothesized Mean Difference	0	
df	4	
t Stat	-4.23966589	
P(T<=t) one-tail	0.006633547	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	**0.013267094**	
t Critical two-tail	2.776445105	

Appendix D. Unpaved Road Condition Rating System (Beltrami County Example)

Score	9	8	7	6	5	4	3	2	1
	Very Good	Good		Fair		Poor		Very Poor	Failed
Rutting Rating Descriptions	No or negligible ruts	Ruts <1" deep; ruts over <5% roadway		Ruts 1" to 3" deep; ruts over 5% to 15% of road way		Ruts 3" to 6" deep; Rut over 10% to 40% of roadway; Drivers tend to drive between the ruts not through them		Ruts 6" to 12" deep	Ruts over 12" deep
Washboarding Rating Descriptions	No or negligible corrugations	Corrugations generally <1" deep; less than 10% of roadway with significant corrugations; little loss of vehicle control		Corrugations generally 1"-2" deep;10%-25% of roadway with significant corrugations; some area safety is significantly compromised as vehicle lost control		Corrugations generally 2"-3" deep; over 25% of roadway with significant corrugations; Major safety issue as drivers are tempted to driver faster, skimming over the top of the corrugations		Similar to "Poor" but deeper and more extensive corrugations	Similar to "Very Poor" but deeper and more extensive corrugations
Potholes Rating Descriptions	No or negligible potholes	Some small potholes; most <1" deep and <1' in diameter		Up to 3" deep though most <2"; <2" diameter		Many potholes; up to 4" deep and 3' in diameter		Up to 8" deep and >4' in diameter	Impassable
Loose Aggregate Rating Descriptions	No or negligible loose aggregate; Negligible risk of chipped windshields	Loose aggregate in berms <1" deep; Loose aggregate usu. <3/4" thick		Loose aggregate in berms <2" deep; Loose aggregate usu. <1.5" thick		Loose aggregate in berms 2"- 4" deep;		Loose aggregate in berms >4" deep	Sand dunes

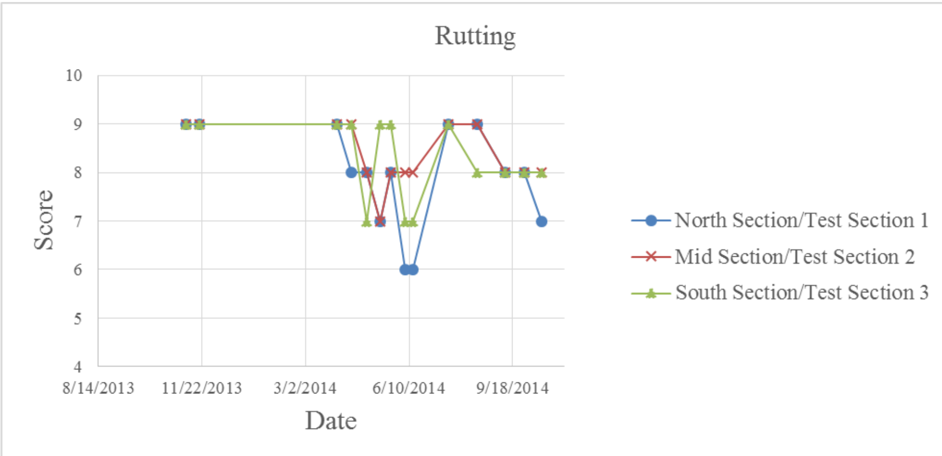
Score	3	2	1	0	U
	None	Low	Medium	High	Not Rated
Dust Rating Descriptions	No visible dust	Minor dust emissions; No visibility obstruction	Significant dust emissions; Dust loss is major concern from a material loss standpoint	Heavy dust emission; Dust loss is major concern from a material loss standpoint but this loss is overshadowed by safety concerns	Due to the moisture in the top road surface material, dust was not assessed

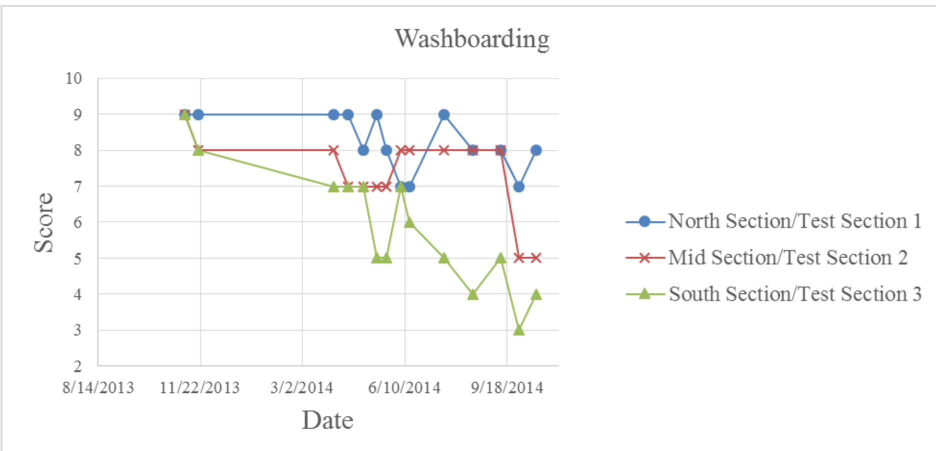
Score	3	2	1
	Good	Fair	Poor
Crown Rating Descriptions	Cross slope >3%; Good rooftop shape	Cross slope 1% to 3%	Cross slope <1%

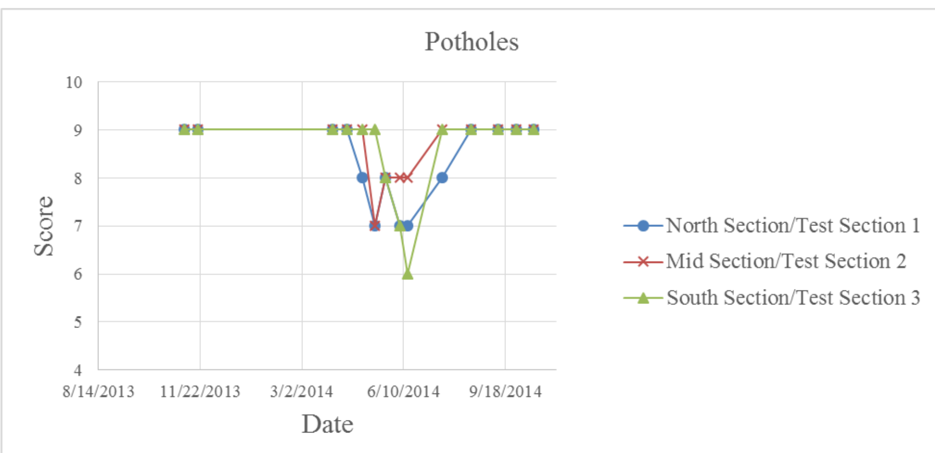
Score	3	2	1
	Good	Fair	Poor
Roadside Drainage Rating Descriptions	Roadway above surrounding terrain; Good foreslopes; Ditches and culverts quickly carry water away	Roadway near the grade of surrounding terrain; Good foreslopes; Marginal foreslopes, ditches, and culverts; Secondary ditches; Occasional transverse erosion	Roadway at or below the grade of the surrounding terrain; Few or no ditches: Runoff stays on roadway; Transverse and longitudinal erosion

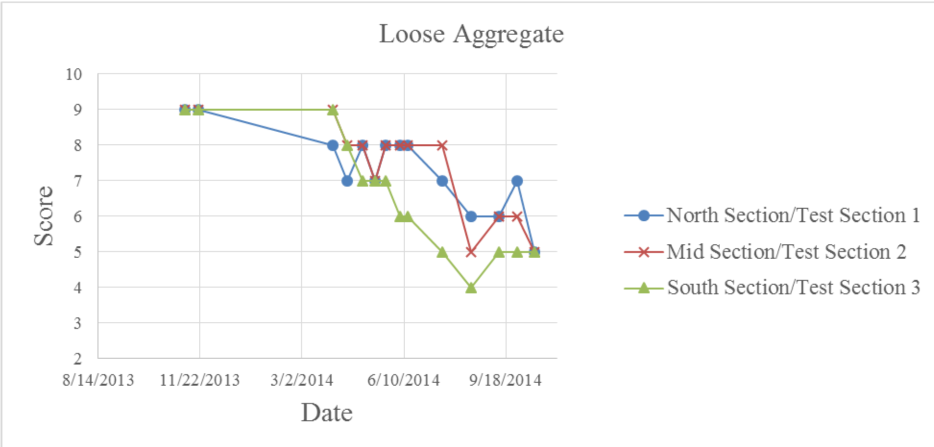
Appendix E. Condition Rating Graphs

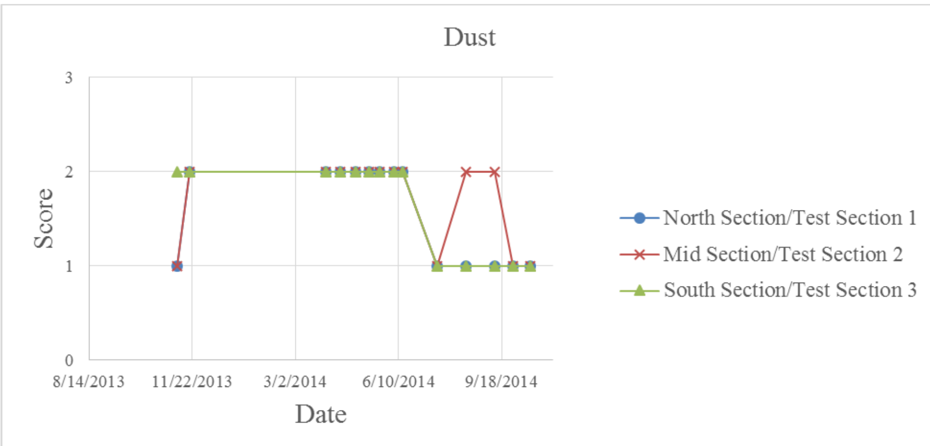
BELTRAMI COUNTY CR 23 TEST SECTION COMPARISONS

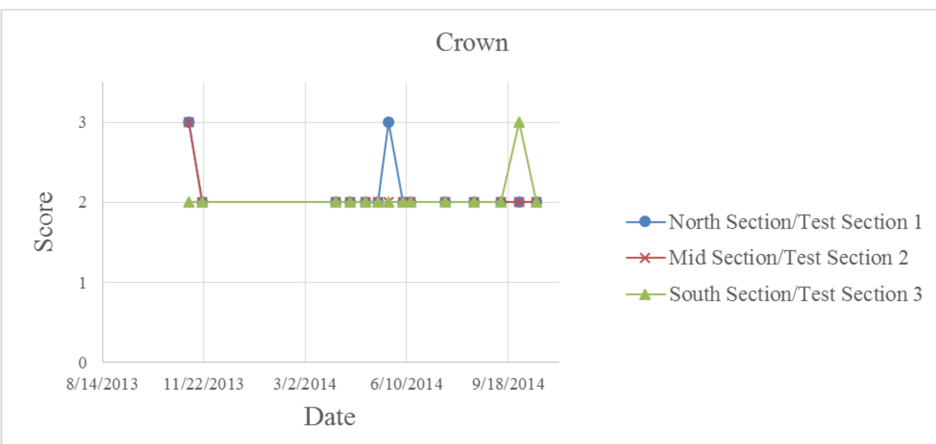




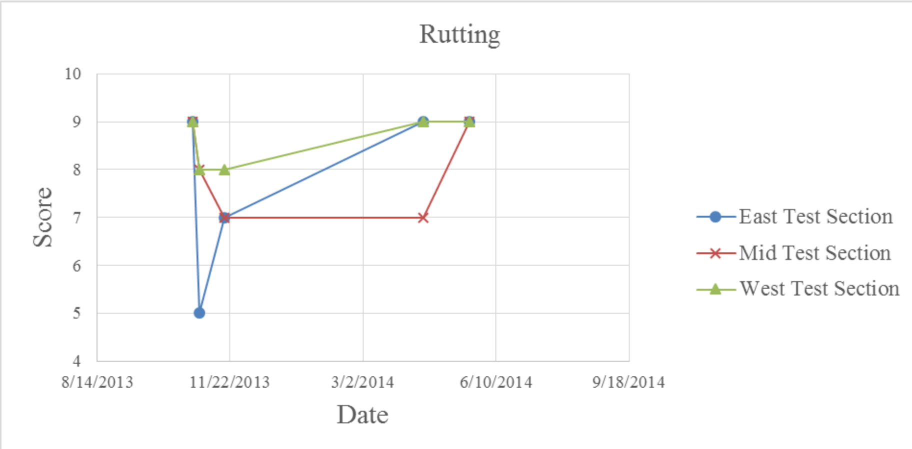


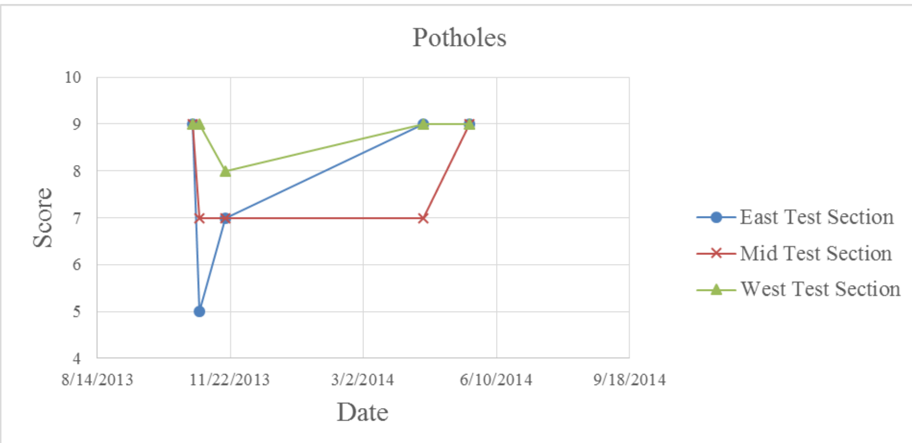

Loose Aggregate
Score
Date
10
9
8
7
6
5
4
3
2
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
North Section/Test Section 1
Mid Section/Test Section 2
South Section/Test Section 3

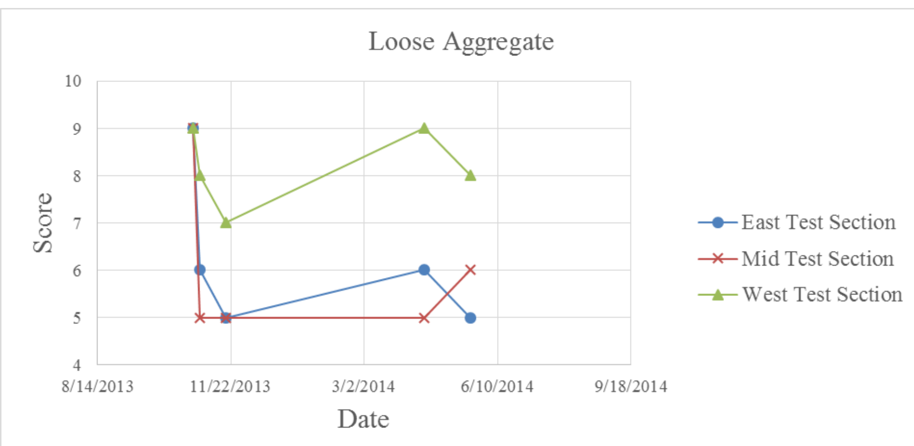

Dust
Score
Date
3
2
1
0
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
North Section/Test Section 1
Mid Section/Test Section 2
South Section/Test Section 3

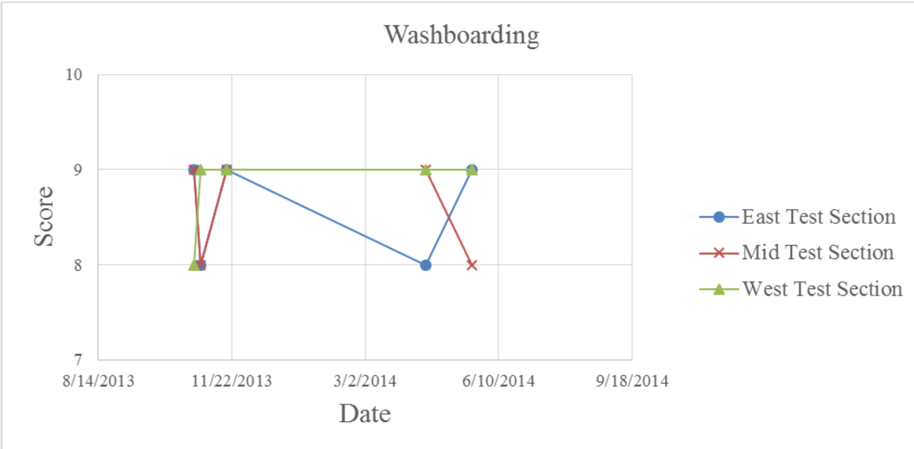

Crown
Score
Date
3
2
1
0
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
North Section/Test Section 1
Mid Section/Test Section 2
South Section/Test Section 3

JACKSON COUNTY CR 76 TEST SECTION COMPARISONS

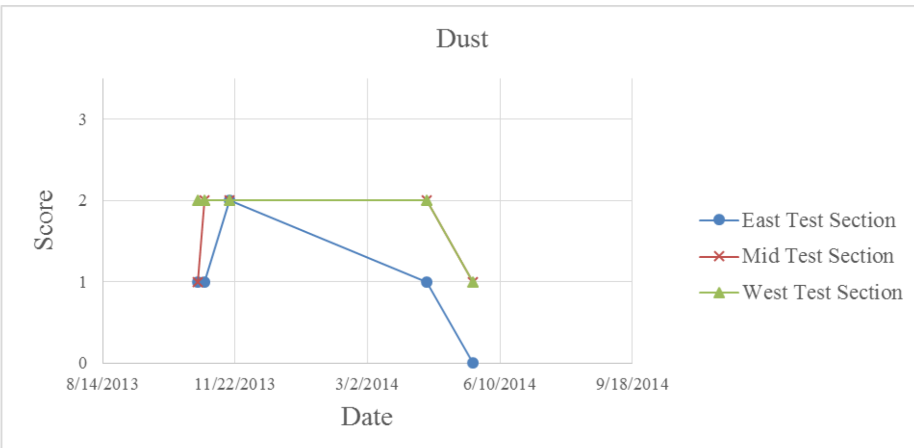




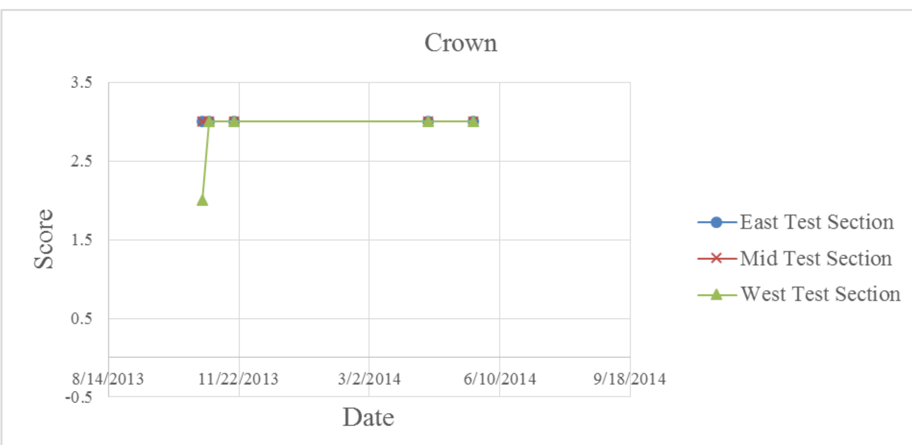




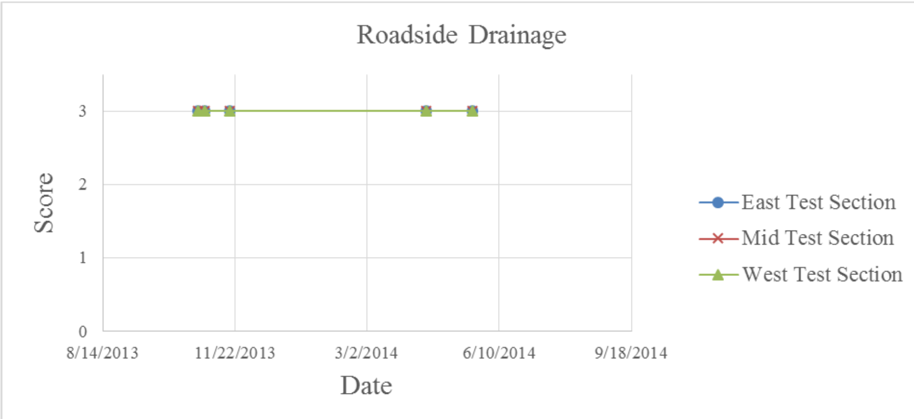
Washboarding
10
9
8
7
Score
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
Date
East Test Section
Mid Test Section
West Test Section



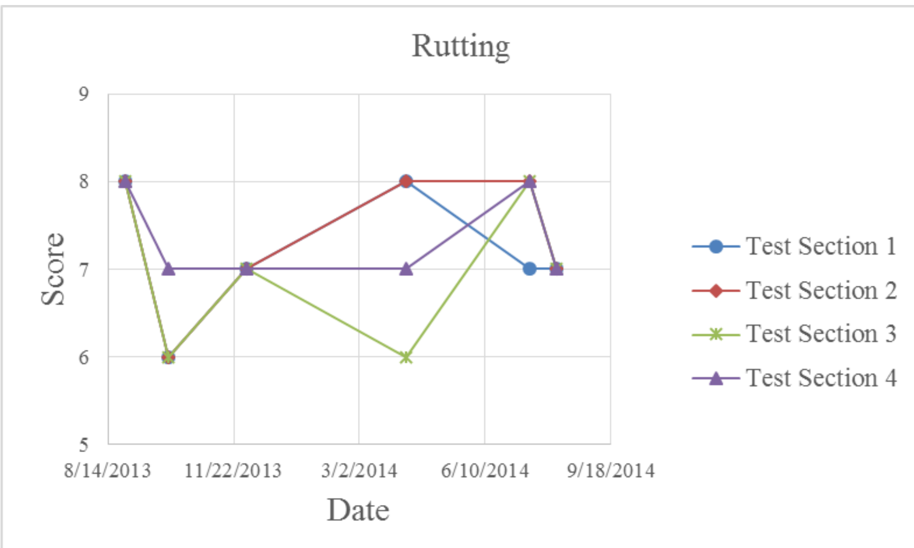
Dust
3
2
1
0
Score
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
Date
East Test Section
Mid Test Section
West Test Section

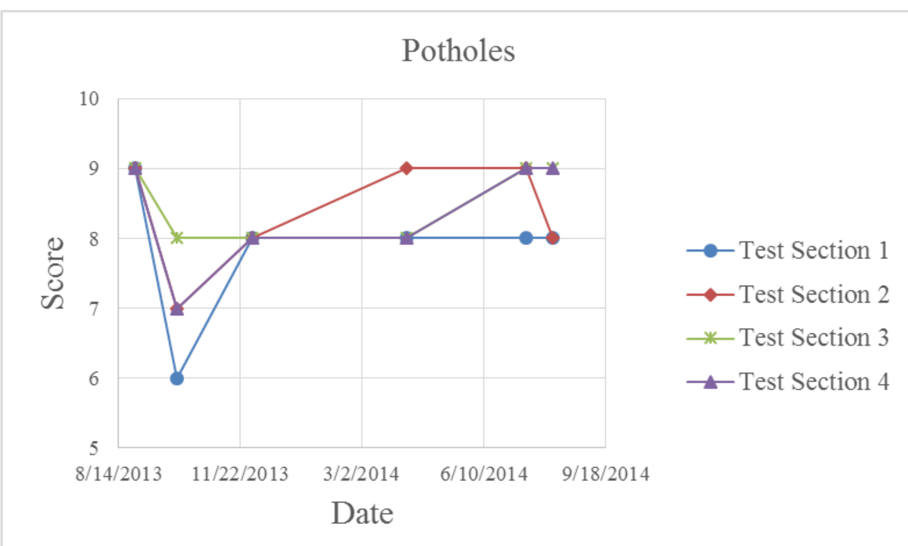


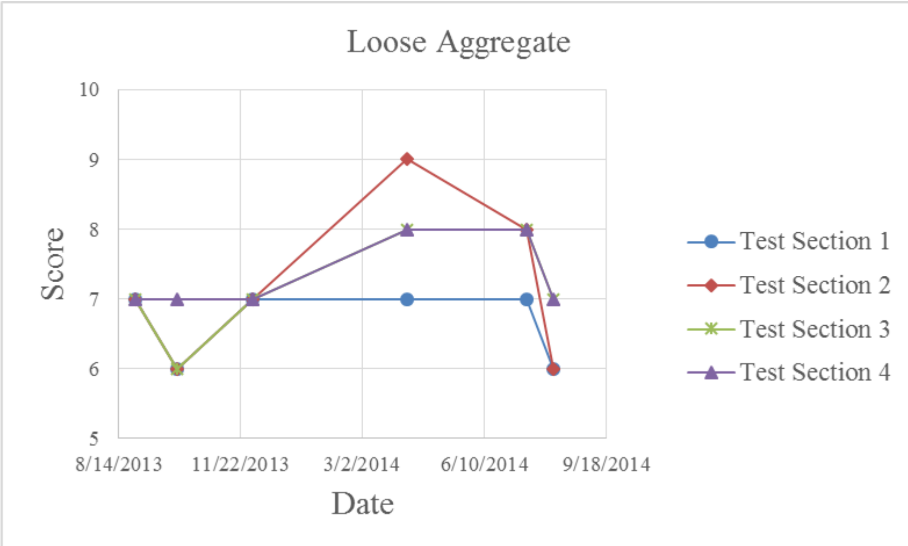
Crown
3.5
2.5
1.5
0.5
-0.5
Score
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
Date
East Test Section
Mid Test Section
West Test Section

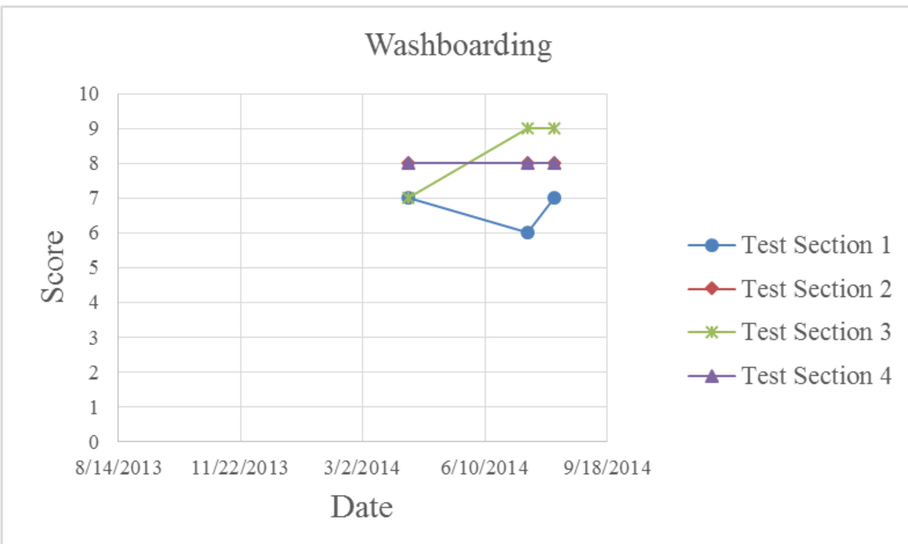


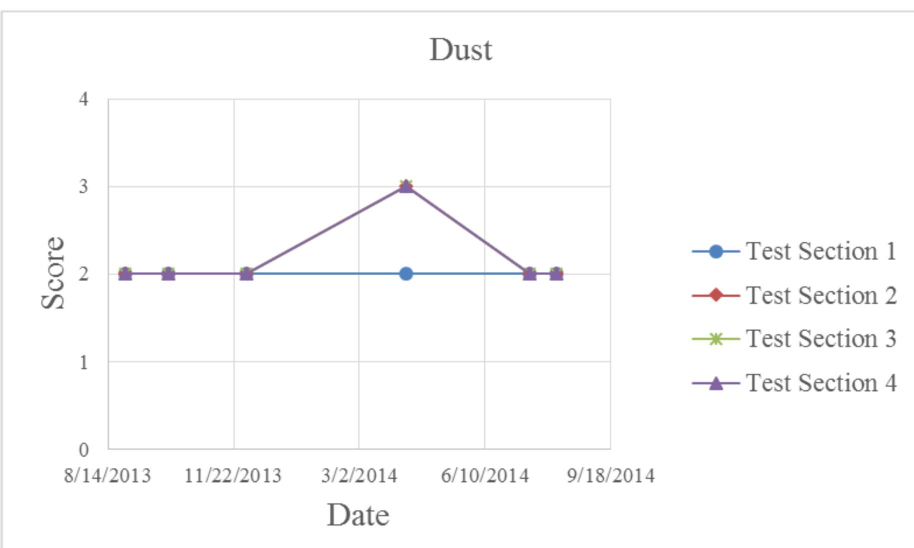
OLMSTED COUNTY CR 115 TEST SECTION COMPARISONS

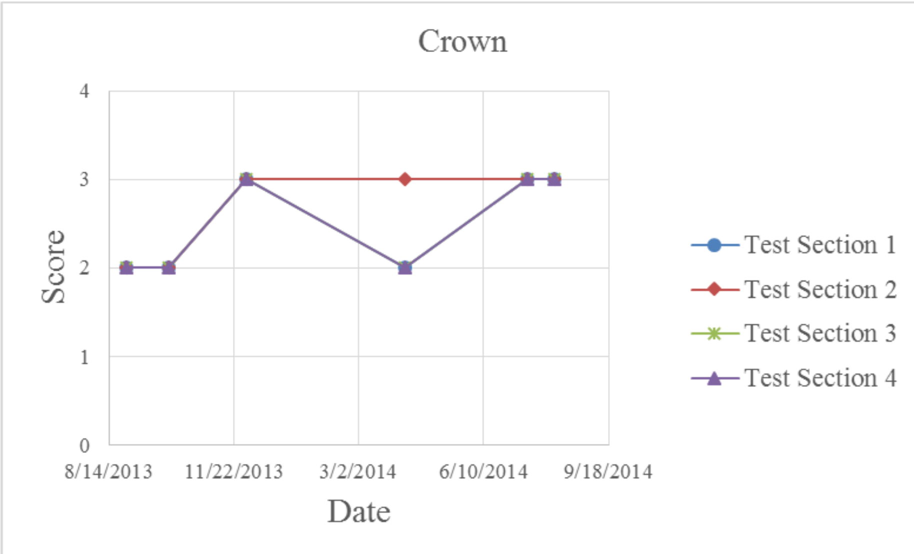




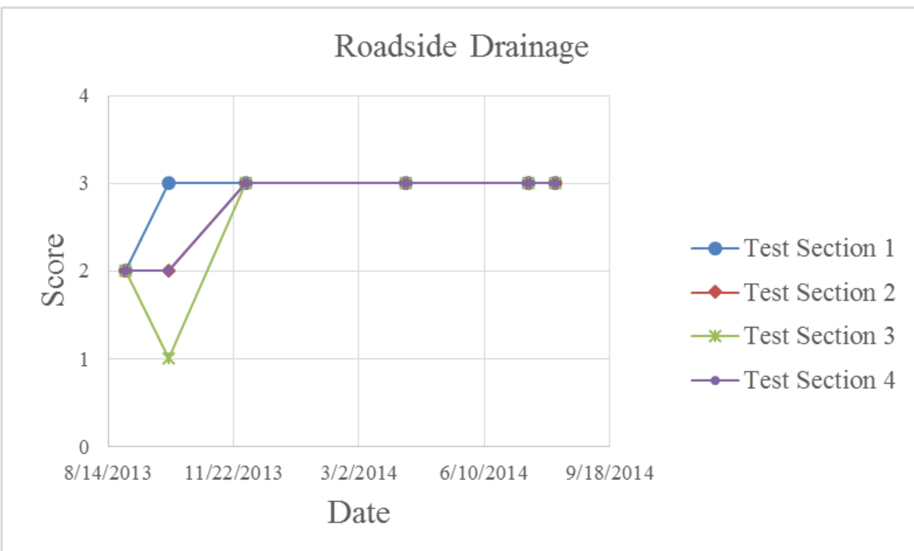

Loose Aggregate
10
9
8
7
6
5
Score
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
Date
Test Section 1
Test Section 2
Test Section 3
Test Section 4


Washboarding
10
9
8
7
6
5
4
3
2
1
0
Score
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
Date
Test Section 1
Test Section 2
Test Section 3
Test Section 4


Dust
4
3
2
1
0
Score
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
Date
Test Section 1
Test Section 2
Test Section 3
Test Section 4



Crown
Score
4
3
2
1
0
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
Date
Test Section 1
Test Section 2
Test Section 3
Test Section 4



Roadside Drainage
Score
4
3
2
1
0
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
Date
Test Section 1
Test Section 2
Test Section 3
Test Section 4

Appendix F. Material, Labor, and Equipment Costs

BELTRAMI COUNTY CR 23

Material Cost

North/First Section (Control)		
Amount of Material	498.00	ton per mile
Cost of Material	$ 6,225.00	per mile

Middle/Second Section		
Amount of Material	249.00	ton per mile
Cost of Material	$ 2,988.00	per mile

South/Third Section		
Amount of Material	150.00	ton per mile
Cost of Material	$ 1,800.00	per mile

Labor and Equipment Cost

	Test Section		
	North/First (Control)	Middle/Second	South/Third
Motor Grader +Operator	$ 421.79	$ 562.38	$ 281.19
Truck+Operator	$ 1,867.14	$ 1,867.14	$ 1,244.76
Water Truck +Operator	$ -	$ -	$ -
Rubber-Tired Roller+Operator	$ -	$ -	$ -

JACKSON COUNTY CR 76

Material Cost

West/First Section (Control)		
Amount of Material	200.64	ton per mile
Cost of Material	$ 1,103.52	per mile

Middle/Second Section		
Amount of Material	126.72	ton per mile
Cost of Material	$ 982.08	per mile

East/Third Section		
Amount of Material	73.92	ton per mile
Cost of Material	$ 572.88	per mile

Labor and Equipment Cost

	Test Section		
	West/First (Control)	**Middle/Second**	**East/Third**
Motor Grader+ Operator	$ 382.04	$ 477.54	$ 447.54
Truck+Operator	$ 2,540.00	$ 1,905.00	$ 1,058.33
Water Truck +Operator	$ -	$ -	$ -
Rubber-Tired Roller+Operator	$ -	$ -	$ -

OLMSTED COUNTY CR 115

Material Cost

First South Section (Control)		
Amount of Material	1234.31	ton per mile
Cost of Material	$ 8,430.35	per mile

Second South Section		
Amount of Material	1156.26	ton per mile
Cost of Material	$ 7,722.18	per mile

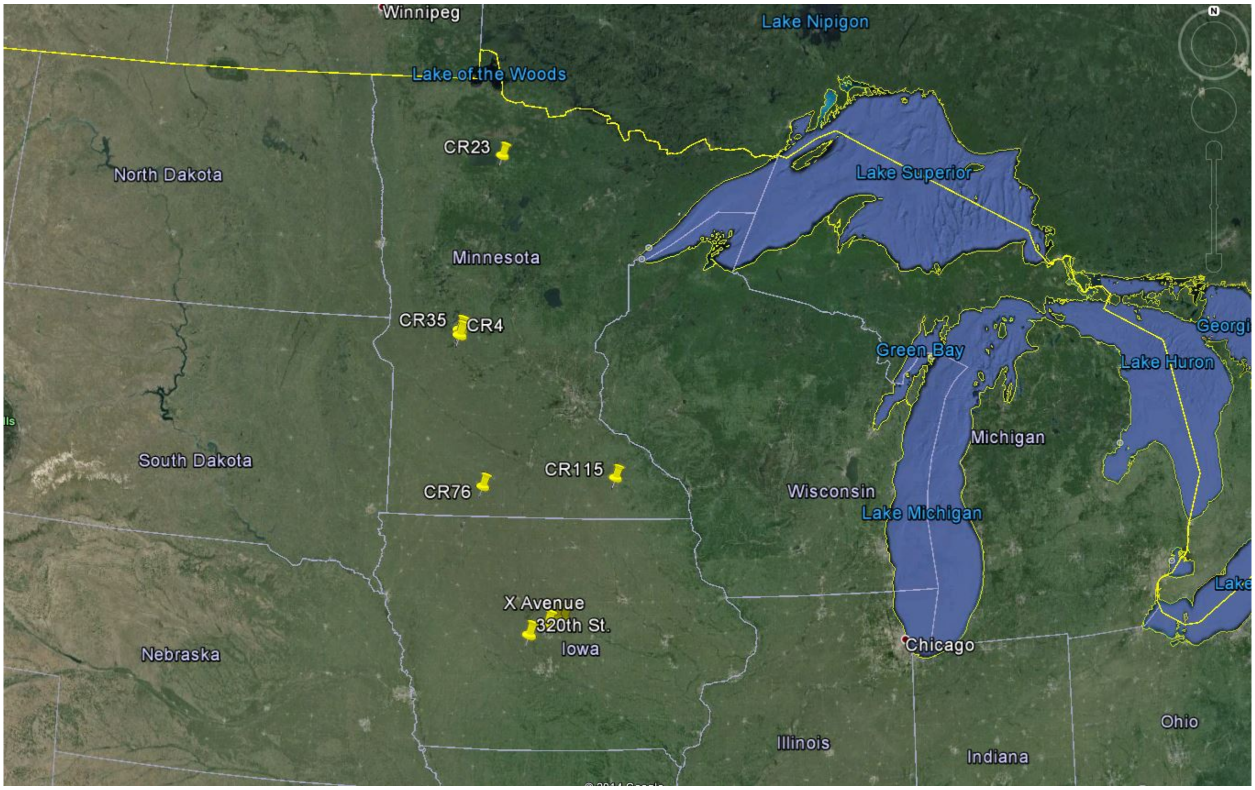
Third North Section		
Amount of Material	1283.04	ton per mile
Cost of Material	$ 8,763.16	per mile

Fourth North Section (Control)		
Amount of Material	1411.49	ton per mile
Cost of Material	$ 9,640.44	per mile

Labor and Equipment Cost

	Test Section			
	First South (Control)	**Second South**	**Third North**	**Fourth North (Control)**
Motor Grader +Operator	$ 1,181.25	$ 945.00	$ 1,299.38	$ 1,417.50
Truck+Operator	$ 11,000.00	$ 8,800.00	$ 12,100.00	$ 13,200.00
Water Truck +Operator	$ 1,375.00	$ 1,100.00	$ 1,512.50	$ 1,650.00
Rubber-Tired Roller +Operator	$ 1,250.00	$ 1,000.00	$ 1,375.00	$ 1,500.00

Appendix G. Aggregate Sample Origin Map



Map © 2013 Google

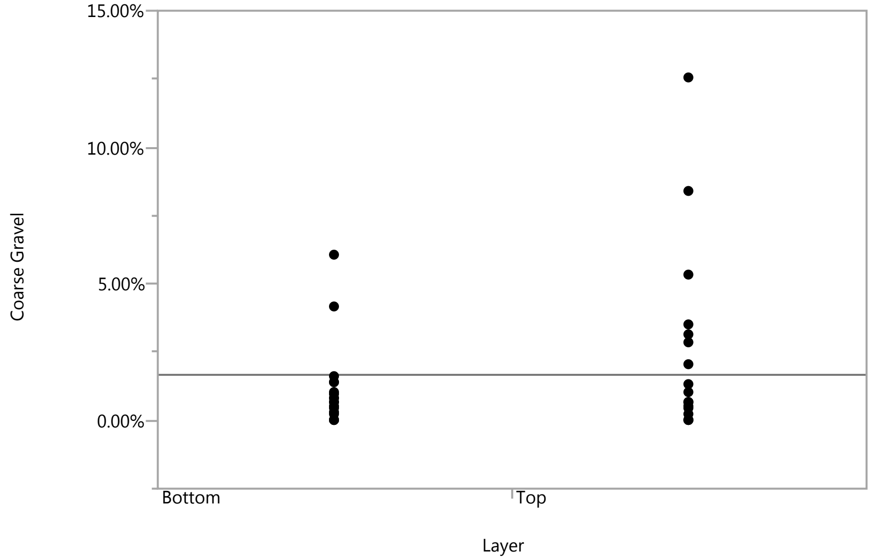
Appendix H. Soil Classifications for 19 Sample Pairs

Samples		Unified Soil Classification System (USCS) Classification	
		Top Material	**Bottom Material**
IA	Story County 160th, collected 11/14/13, top 1 in., bottom 2 in.	Well-graded Gravel with Sand	Silty Sand with Gravel
	Boone County X Ave., collected 11/14/13, top 1 in., bottom 2 in.	Well-graded Sand with Gravel	Well-graded Sand with Silt and Gravel
	Boone County 150th, collected 11/14/13, top 1 in., bottom 1.5 in.	Poorly graded Sand with Silt and Gravel	Well-graded Sand with Silt
	Boone County 320th, collected 11/14/13, top 1 in., bottom 2 in.	Well-graded Gravel with Sand	Poorly graded Sand with Silt and Gravel
MN	Beltrami CR 23, collected 8/22/13, top 1 in., bottom 2 in.	Well-graded Sand with Gravel	Poorly graded Sand with Silt
	Olmsted North CR 115, collected 8/20/2013, top 1.5 in., bottom 2 in.	Poorly graded Gravel with Silt and Sand	Silty Sand with Gravel
	Olmsted South CR 115, collected 8/20/2013, top 1.5 in., bottom 2in.	Poorly graded Gravel with Silt and Sand	Silty Sand with Gravel
	Jackson CR 76, collected 10/24/13, top 1 in., bottom 2 in.	Well-graded Sand with Gravel	Silty Sand with Gravel
	Pope CR 35 #1, collected 8/23/13, top 1.5 in., bottom 2 in.	Poorly graded Sand with Silt and Gravel*	Poorly graded Sand with Silt and Gravel*
	Pope CR 35 #2, collected 8/23/13, top 1.5 in., bottom 2 in.	Poorly graded Sand with Gravel	Poorly graded Sand with Silt and Gravel
	Pope CR 35 #3, collected 8/23/13, top 1.5 in., bottom 2 in.	Poorly graded Sand with Gravel	Well-graded Sand with Silt
	Pope CR 4, collected 7/21/13, top 1 in., bottom 2 in.	Well-graded Gravel with Sand	Silty Sand with Gravel
Post Construction			
MN	Beltrami CR 23 North/First Control Section, collected 8/8/2014, top 1 in., bottom 2 in.	Well-graded Sand with Gravel	Silty Sand with Gravel
	Beltrami CR 23 Middle/Second Test Section, collect 8/8/2014, top 1 in., bottom 2 in.	Poorly graded Gravel	Silty Sand
	Beltrami CR 23 South/Third Test Section, collect 8/8/2014, top 1 in., bottom 2 in.	Well-graded Sand with Gravel	Poorly graded Sand with Silt
	Olmsted CR 115 First South Control Section, collected 8/8/2014, top 1 in., bottom 2 in.	Poorly graded Gravel	Silty Sand with Gravel
	Olmsted CR 115 Second South Test Section, collected 8/8/2014, top 1 in., bottom 2 in.	Poorly graded Sand with Gravel	Clayey Gravel with Sand
	Olmsted CR 115 Third North Test Section, collected 8/8/2014, top 1 in., bottom 2 in.	Poorly graded Gravel with Sand	Clayey Gravel with Sand
	Olmsted CR 115 Fourth North Control Section, collected 8/8/2014, top 1 in., bottom 2 in.	Poorly graded Gravel	Silty Sand with Gravel

* Pope County CR 35 #1 was the only road section that had top material and bottom material with the same soil classification

Appendix I. Independent t-Test Results

Oneway Analysis of Coarse Gravel by Layer

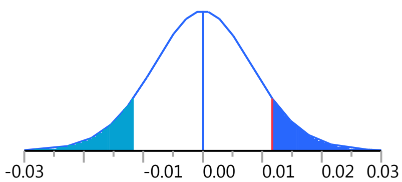


t-Test

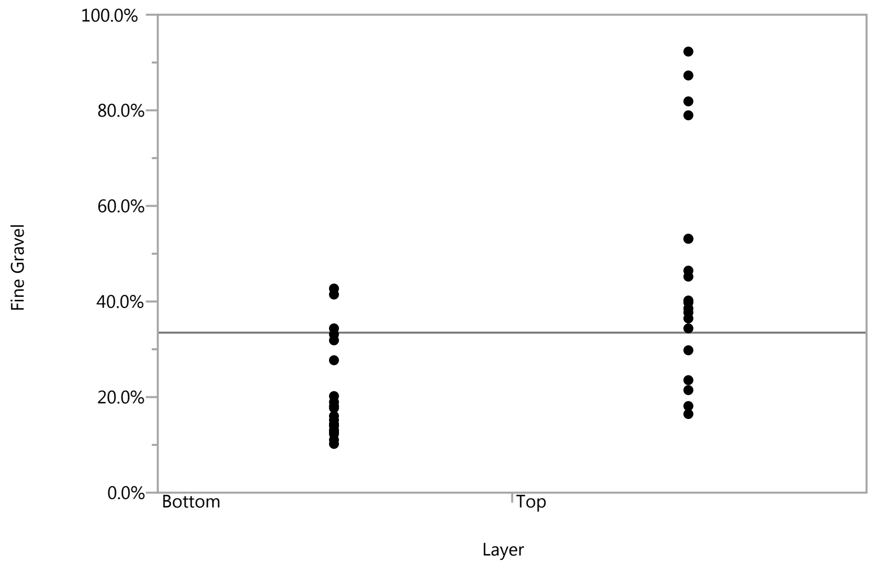
Top-Bottom

Assuming unequal variances

Difference	0.01168	t Ratio	1.401478
Std Err Dif	0.00834	DF	25.25028
Upper CL Dif	0.02885	Prob > |t|	**0.1732**
Lower CL Dif	-0.00548	Prob > t	0.0866
Confidence	0.95	Prob < t	0.9134



Oneway Analysis of Fine Gravel by Layer

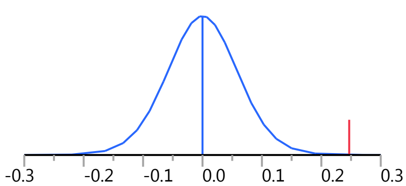


t-Test

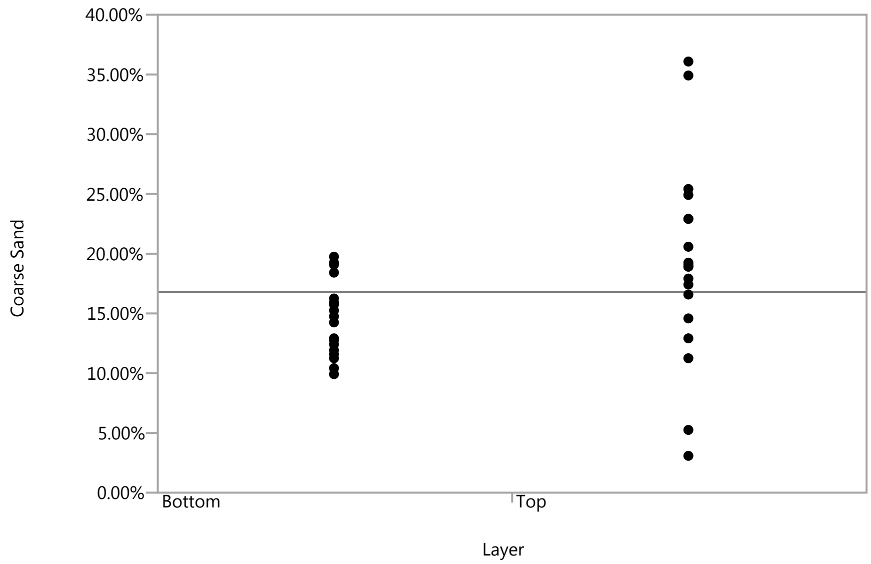
Top-Bottom

Assuming unequal variances

Difference	0.246895	t Ratio	4.216605
Std Err Dif	0.058553	DF	24.93888
Upper CL Dif	0.367502	Prob > |t|	**0.0003***
Lower CL Dif	0.126288	Prob > t	0.0001*
Confidence	0.95	Prob < t	0.9999



Oneway Analysis of Coarse Sand by Layer

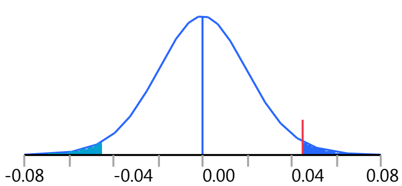


t-Test

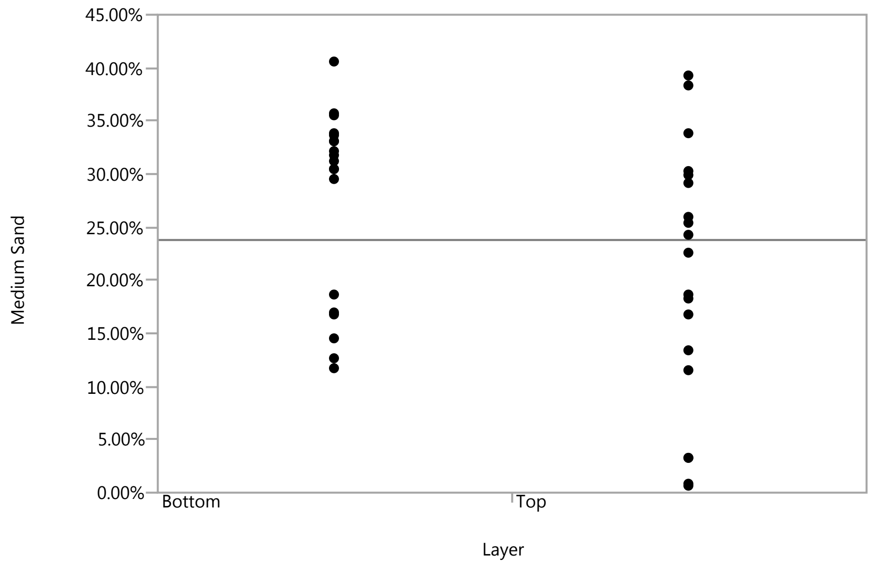
Top-Bottom

Assuming unequal variances

Difference	0.044947	t Ratio	2.227186
Std Err Dif	0.020181	DF	22.91796
Upper CL Dif	0.086704	Prob > |t|	**0.0360***
Lower CL Dif	0.003191	Prob > t	0.0180*
Confidence	0.95	Prob < t	0.9820



Oneway Analysis of Medium Sand by Layer

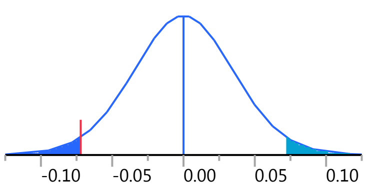


t-Test

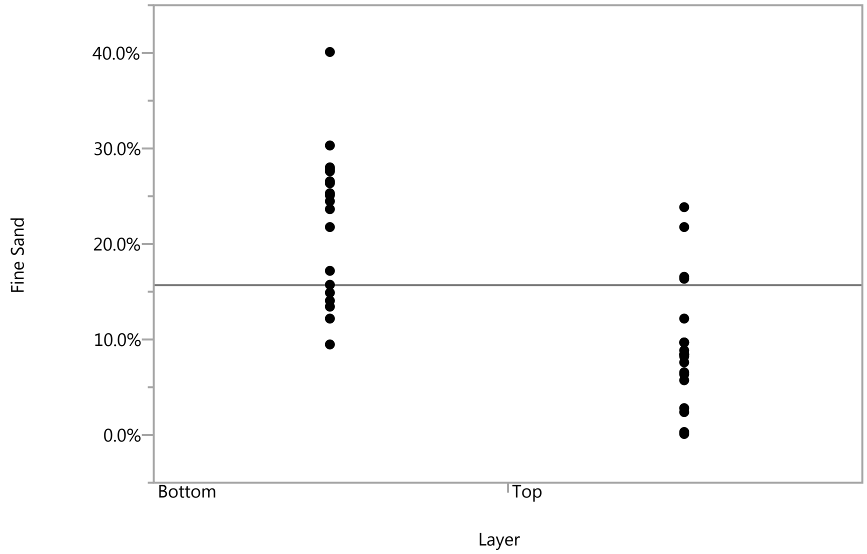
Top-Bottom

Assuming unequal variances

Difference	-0.07211	t Ratio	-2.06681
Std Err Dif	0.03489	DF	33.03872
Upper CL Dif	-0.00113	Prob > |t|	**0.0467***
Lower CL Dif	-0.14308	Prob > t	0.9767
Confidence	0.95	Prob < t	0.0233*



Oneway Analysis of Fine Sand by Layer

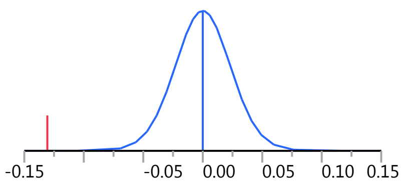


t-Test

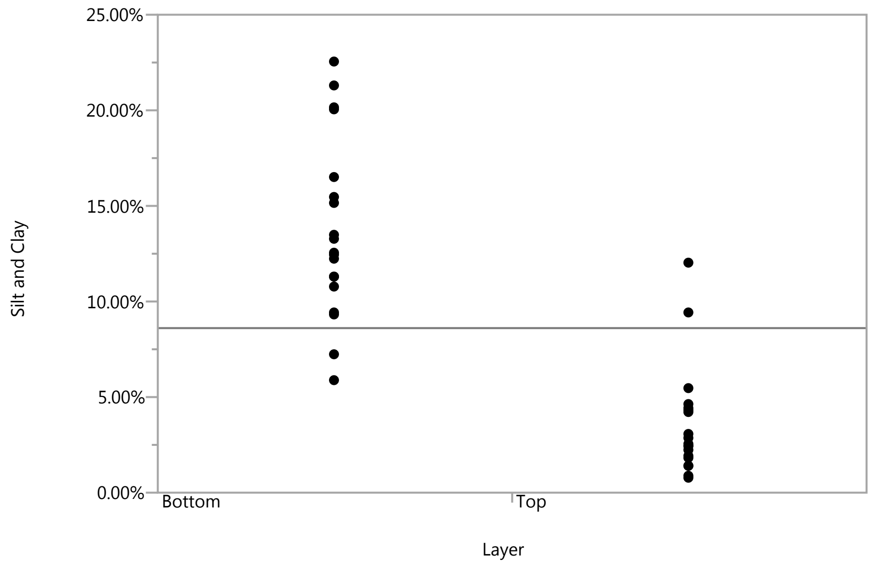
Top-Bottom

Assuming unequal variances

Difference	-0.13063	t Ratio	-5.6338
Std Err Dif	0.02319	DF	35.01097
Upper CL Dif	-0.08356	Prob > |t|	**<.0001***
Lower CL Dif	-0.17770	Prob > t	1.0000
Confidence	0.95	Prob < t	<.0001*



Oneway Analysis of Silt and Clay by Layer

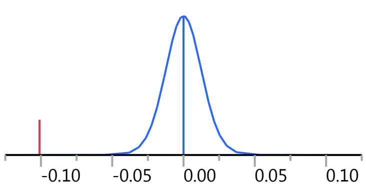


t-Test

Top-Bottom

Assuming unequal variances

Difference	-0.10100	t Ratio	-7.98802
Std Err Dif	0.01264	DF	29.82673
Upper CL Dif	-0.07517	Prob > |t|	**<.0001***
Lower CL Dif	-0.12683	Prob > t	1.0000
Confidence	0.95	Prob < t	<.0001*



Appendix J. Findings Summary Table

County	Test Section	Significant cross-section deterioration	Distress				Roughness (<2.2=good)	Gravel loss (yd^3/mi)	Elevation change (ft)	Loose aggregate (ton/mi)	Benefit-cost analysis (five-year cycle)
			Rutting	Wash-boarding	Pot-holes	Loose aggregate					
Jackson	West/First (control)	No	Good	Good	Good	Good	NA	9.80	-0.09	67.98	N/A
	Middle/Second (experimental)	No	Good	Good	Good	Fair	NA	75.20	-0.20	96.99	
	East/Third (experimental)	Yes	Good	Good	Good	Fair	NA	120.10	-0.37	96.53	
Beltrami	North/First (control)	No	Good	Good	Good	Good	1.30	20.20	-0.05	47.59	$12,680.83
	Middle/Second (experimental)	No	Good	Good	Good	Good	1.30	24.70	-0.06	51.70	$10,278.91
	South/Third (experimental)	No	Good	Fair	Good	Fair	1.26	35.20	-0.09	59.38	$10,270.29
Olmsted	First South (control)	No	Good	Fair	Good	Fair	2.12	86.00	-0.19	69.72	N/A
	Second South (experimental)	No	Good	Good	Good	Good	1.99	104.20	-0.24	60.59	
	Third North (experimental)	No	Good	Good	Good	Good	2.17	65.80	-0.10	61.50	
	Fourth North (control)	Yes	Good	Good	Good	Good	1.70	93.80	-0.28	63.11	

Notes:
For Jackson County, neither of the experimental sections met expectations.
For Beltrami County, of the two experimental sections, the Middle/Second Test Section performed the best.
For Olmsted County, of the two experimental sections, the Third North Test Section performed the best.