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Gravel Surfacing Guidelines for South Dakota

Study SD2009-08

Final Report

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The research team would like to acknowledge the many contributions others have made to the completion of this project. For example, the highway departments in Hand, Custer, and Brookings Counties were willing to build and maintain test cells, and that willingness was a key contributor to carrying out the study. The Technical Panel that served in an oversight capacity throughout this project also contributed, among other ways by providing useful reviews and suggestions on project sites, evaluation, and analysis.

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16. Abstract

South Dakota's low-volume roads (LVR) play an important role in the State's economy, providing essential links not only within rural areas but also between rural and more populated areas. A significant portion of these roads are gravel, constructed with an assortment of different aggregate materials and under a range of governing specifications. Generally speaking, South Dakota's gravel roads have performed well under a variety of traffic and environmental conditions, but ever-increasing traffic loadings, heavy trafficking during weakened support conditions, and decreasing funding levels make it challenging to effectively maintain the surface of these roadways. Furthermore, other issues unique to gravel roads present additional maintenance demands. Thus, local agencies are constantly seeking improved methods to effectively manage and maintain their LVRs.

Improved guidance on the design, construction, and maintenance of gravel road surfacings would help to obtain the best possible performance of these roads. Originally, this project had four objectives, but as the work progressed and new developments took place at the national level, the project became focused on just one objective:

> *Assess the performance and costs of new, unstabilized gravel surfacing test sections constructed with a) commonly used materials and methods that do not meet state specifications; b) materials and methods that comply with state specifications; and c) materials and methods that exceed state specifications*.

To accomplish this objective, experimental test sites were established in three counties representing the eastern, western, and central parts of the state. At each test site, five test sections with different quality gravel materials were designed, laid out, constructed, tested, and monitored for performance. The final report documents all the key aspects of the project including experiment design, materials testing, test section construction, performance monitoring, and analysis of results. It also provides the key findings and conclusions and offers recommendations for future research.

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Acronym	Definition
APTech	Applied Pavement Technology, Inc.
CBR	California Bearing Ratio
COV	Coefficient of Variation
FHWA	Federal Highway Administration
FHWA–FLHD	Federal Highway Administration – Federal Lands Highway Division
LVR	Low Volume Roads
MTTI	Michigan Tech Transportation Institute
NACE	National Association of County Engineers
PASER	Pavement Surface Evaluation Rating
PI	Plasticity Index
SDDOT	South Dakota Department of Transportation
SVAM	Standard Visual Assessment Method
TTAP	Tribal Technical Assistance Program

1. EXECUTIVE SUMMARY

1.1. Introduction

South Dakota's transportation network includes over 83,000 miles of roads, of which about 10 percent are state-controlled and 3 percent are federal routes. The remaining 72,000 miles—most of which are considered to be low-volume roads (LVR), defined as carrying less than 400 vehicles per day—fall under the jurisdiction of counties, townships, and municipalities. These LVRs are secondary roads or local roads that play an important role in the State's economy, providing essential links not only within rural areas but also between rural and more populated areas.

A significant portion of the secondary or local roads in South Dakota are gravel, also commonly referred to as unpaved, unsealed, unbound, or aggregate-surfaced roads. Within the State, these have been constructed with an assortment of different aggregate materials (including pit run, screened, and crushed) and under a range of governing specifications (including state gravel specifications, base course specifications, local specifications, or no specifications at all). Generally speaking, South Dakota's gravel roads have performed well under a variety of traffic and environmental conditions, but ever-increasing traffic loadings, heavy trafficking during weakened support conditions (e.g., springtime planting season), and decreasing funding levels make it increasingly difficult to effectively maintain the surface of these roadways. Furthermore, other issues unique to gravel roads (such as dust control and safety due to loose gravel) present additional maintenance demands. Thus, local agencies are constantly challenged in effectively managing and maintaining their LVRs.

Improved guidance on the design, construction, and maintenance of gravel road surfacings would help to obtain the best possible performance of these roads. This is particularly true in an environment where shrinking budgets compel agencies to maximize their investments. Although there are several good resource documents available on gravel roads, some of these are very general and lack good guidance, others are somewhat dated, and none is specific to South Dakota's unique conditions (semi-arid climate with extreme freeze-thaw cycles, large swings in temperature and moisture levels, and highly variable soils).

Because of its strong interest in improving its practices for the design, construction, maintenance, rehabilitation, and stabilization of gravel-surfaced roads, the SDDOT launched this project in 2009 to investigate many of these practices, study the effect of gravel quality on road performance, and develop new gravel resurfacing guidelines. The focal point of the project was the conduct of a research experiment to evaluate the performance and cost-effectiveness of different quality gravel materials used in South Dakota. Test sites were established in three counties representing the eastern (Brookings County), western (Custer County), and central (Hand County) parts of the state. At each test site, five test sections consisting of standard quality, above standard quality, and substandard gravel materials (with and without compaction during construction) were designed, laid out, constructed, tested, and monitored for performance. The quality of each gravel was defined based on a property of a fine-grained material known as plasticity index (or PI). For road gravels, it is performed on the fine material and provides an indication of how well the gravel will bond together after constructed. The data collected from this field experiment would be used to assess the performance of the different gravel materials and to improve SDDOT's gravel resurfacing guidelines.

During the course of the study, the FHWA released its new *Gravel Road Construction and Maintenance Guide* (FHWA 2015). This document was very well received by SDDOT, as it provides the latest guidance on all of the key practices identified above. Because of the availability of this new *Guide*, the SDDOT elected not to pursue three of this study's four original objectives. Accordingly, the project became focused on one key project objective:

> *Assess the performance and costs of new, unstabilized gravel surfacing test sections constructed with a) commonly used materials and methods that do not meet state specifications; b) materials and methods that comply with state specifications; and c) materials and methods that exceed state specifications.*

The key project findings, conclusions, and recommendations that address this objective are presented below.

1.2. Summary of Key Findings and Conclusions

Because of their direct bearing on the project objective, the key parts of the project are those that addressed the test section construction and monitoring results, the basis for gravel road performance assessment, test site road maintenance, test section performance observations, statistics-based performance comparisons, and key findings and conclusions. The latter two are especially important because they address the questions about test section performance and gravel material performance comparisons. No attention was given to the cost aspects of the gravel materials used, primarily because the performance differences, in general, were not significant enough to justify a performance-cost assessment.

Following is a summary of the key findings and conclusions that resulted from the project's primary research activities.

1.2.1. Test Section Construction and Monitoring Results

SDDOT and the research team members gave considerable attention to designing the field experiment, selecting the experimental sites, laying out and constructing the test sections, and performing the laboratory testing needed to characterize the properties of the materials used in the test sections. Most aspects of the aspects of this activity went very well, especially the identification of the test sites, the testing of the materials, and the construction of the test sections. However, there were some basic problems with the experiment design that, ultimately, had a major impact on the project findings.

- Use of plasticity index to define the quality of the gravel – While it is understood that the use of gravels with a higher PI value (within a certain range) result in better gravel road performance, the use of PI to discriminate between the substandard, standard, and above-standard gravels did not work well for this experiment. Considering the variability of the test for PI and the variability of the materials in the stockpile, it was concluded that the use of the 0-4, 4-7, and 7-12 ranges was not practical.

- Use of more than one location for the test sections at the Custer County test site – The experiment was primarily intended to evaluate the effects of gravel quality on gravel road performance. Unfortunately, by separating the test sections at the Custer County test site between two roads with different traffic levels and different environmental conditions, it became impossible to attribute the performance of each section solely to the gravels used at their respective locations.
- Section layout – Not all of the sections at a given site had uniform geometry that may have affected performance. Some sections had some horizontal curvature issues and some were affected by intersection with other gravel roads. Again, these differences in gravel road performance can impact the assessment of the effect of the type of gravel.

1.2.2. Basis for Gravel Road Performance Assessment

Five different gravel road distress ratings (washboarding, rutting, raveling, potholing, and dusting) and one distress measurement (gravel loss by cast-off) were used as the primary basis for rating the performance of the gravel road test sections in this experiment. The five distress ratings were carried out mostly on a visual basis which resulted in assigning a 0 to 10 rating, while loss of gravel by cast-off was measured by weight of gravel captured on the shoulder. The unique part of this effort was the development of a composite rating formula that uses weighting coefficients on each of the individual distress ratings to produce an overall rating. The weighting coefficients were developed using the results of a survey of 10 experienced county highway supervisors. Overall, the inspection protocols provided a consistent method of rating the gravel roads. However, the study findings lead to two conclusions:

- Based on the apparent rate at which some forms of distress developed during the first few months after construction, the condition surveys should have been performed earlier and more frequently. For purposes of performance monitoring, the condition surveys should have been performed before and after each maintenance activity.
- To put each distress rating into perspective, critical levels should have been defined. These include levels that would trigger some form of maintenance activity (to address safety or ride quality) and levels that are considered unacceptable (i.e., reason for road closure).

1.2.3. Test Site Road Maintenance

Maintenance on each of the test sites was carried out by the local county maintenance crews at each site. It is assumed that the maintenance was performed when one or more distresses at a site reached or approached a trigger level, such as a high level of washboarding or rutting. The maintenance records for each of the three sites indicate the dates at which maintenance was performed. For Hand County and Custer County, the records also provide an estimate of the labor (in man-hours) that was expended. For Brookings County, the records also include information on which test sections were maintained and why the maintenance was performed. For example, test section 1 received maintenance to address washboarding. The main conclusion that can be drawn here is that the maintenance information should have been collected on a consistent basis between test sites and the data should have recorded on a section-by-section basis (as in the case of the Brookings County site).

1.2.4. Test Section Performance Observations

For each test site, a series of graphs were presented that depict the individual distress ratings for each test section over the course of the experiment. The distress ratings represent the average of the distress ratings recorded in the field for each test section and, from a general perspective, provide a valid basis for assessing the performance of any individual section. By examining the results for one type of distress rating at a given site, the graphs also provide a basis for comparing the performance of one section versus another. However, in comparing the performance of test sections using the average distress rating curves, the variability in performance is overlooked. If the range in distress ratings for a given section at a given time was small, then the visual method of comparison might be accurate. On the other hand, if the range of distress ratings is high, then it can lead to incorrect conclusions about the performance of one section versus another. Numerous observations and comments are offered on the performance comparisons between the different gravel materials and the two levels of compaction that assume a low range in distress ratings. Unfortunately, analysis of the field data for this experiment showed that the range of distress ratings for a given site was often high (standard deviation greater than 1). This means that many of the observations that one gravel material performed better (or worse) than another gravel may not be correct and is why a statistical approach to comparing the performance became necessary.

1.2.5. Statistics-Based Performance Observations

Statistical analyses of the test section performance data were performed to address the key questions.

1. The first analysis was to determine if gravel compaction during construction had a statistically significant effect on performance. The results for the data showed that only 23 percent of all the combinations of test site, gravel type, distress rating type, and data collection time resulted in a significant difference. This is a strong indication that compaction did not have a significant impact on performance. For those that did show a significant difference, only a few showed that compaction had a positive effect on performance. Based on these findings, it was reasonable to conclude that compaction does not result in improved gravel road performance—at least not in the time period during over which the condition surveys were performed. It is possible that compaction had a positive effect on performance during the first few months after construction (before the condition surveys began), but there was no data to determine this.
2. Using the standard gravel material for each test site as the basis, the second analysis was performed to determine if the above-standard gravel performed significantly better and if the substandard gravel performed significantly worse. Following is a summary of the conclusions for each test site.
    a. Hand County test site

i. The Bone-Bright (above-standard)-compacted gravel performed the same as the Martinmas (standard)-compacted gravel for all distress ratings. Since the PI of the Bone Bright gravel was 9 and the PI of the Martinmas gravel was 4, the expectation was that the Bone-Bright gravel would perform significantly better than the Martinmas gravel.

ii. The Oakley (substandard)-compacted and uncompacted gravels performed the same as the Martinmas (standard)-compacted and uncompacted gravel materials in terms of the Washboarding, Rutting, Potholing, and Dusting ratings and worse in terms of the Overall and Raveling ratings. These conclusions are based on the assumption that each test section received the same level of maintenance during the experiment. The PI values for both gravels was the same (4), so the expectation was that the performance would be the same.

b. Custer County test site

i. The STAAP+crusher fines (above standard)-compacted gravel material performed the same as the STAAP (standard)-compacted gravel for all distress ratings. This conclusion is based on the assumption that each test section received the same level of maintenance during the experiment. Since the PI of the STAAP+crusher fines gravel material was 3 and the PI for the STAAP gravel was 6, the expectation was that the performance of the STAAP+crusher fines would be worse than the STAAP gravel.

ii. No conclusion can be drawn about the comparison between the Bear Mountain (substandard) gravel materials with respect to the STAAP gravels, because the test sections were constructed on two different road sections.

c. Brookings County test site

i. The Dupraz+clay (above standard)-compacted gravel material performed the same as the Dupraz (standard)-compacted gravel for the Overall, Washboarding, Rutting, Potholing, and Dusting ratings. For the Raveling rating, the performance was significantly higher. These sections received the same level of maintenance during the experiment. The PI values for the Dupraz+clay and Dupraz materials were 7 and 4, respectively. Accordingly, the expectation was that the Dupraz+clay material would perform better than the Dupraz material.

ii. The Bowes (substandard)-compacted gravel performed the same as the Dupraz (standard)-compacted gravel in terms of the Washboarding, Raveling, Rutting, and Dusting ratings. In terms of the Overall rating, the performance was significantly worse, and for Potholing, the performance was significantly better. Since the Bowes-compacted section required two to three times more maintenance than the Dupraz-compacted section, it is valid to conclude that the Bowes-compacted gravel is a lesser quality material. For the Bowes-uncompacted gravel, the performance in terms of Raveling, Rutting, Potholing, and Dusting was the same as the Dupraz-uncompacted gravel. On the other hand, the Overall and Washboarding ratings were significantly worse. These ratings, along with the fact that the Bowes-uncompacted sections also received two to three times the maintenance, support the conclusion that the Bowes-uncompacted gravel is also a poorer quality material than the Dupraz-uncompacted gravel. The PI values for both the Dupraz and Bowes gravel materials was 4, so the expectation was that they would perform the same.

1.2.6. Comparison of Relevant Findings with SD-LTAP Study

For the two areas investigated by SD-LTAP researchers at the Brookings County test site (above standard versus substandard sections), there was clear agreement between the two studies.

- The float test results conducted by SD-LTAP compared favorably with the gravel by cast-off test results performed by SDDOT for this study.
- The comparison of performance in terms of washboarding considering the effects of maintenance were also consistent with the results reported in this study.

1.3. Summary of Observations Regarding this Research

The results of this project showed that there were several project variables that did not have the expected effect on performance. For example, gravel compaction during construction did not result in better road performance compared to the sections that were not compacted. Also, the PI results were inconsistent, and only seemed to indicate that the PI by itself does not determine the quality of a gravel for surfacing.

The following observations and recommendations expand on the research results. These are not listed in any particular order.

- Conduct further research on objective measures of gravel surfacing performance: the researchers identified and applied a number of measures to reflect how gravel roads perform. The selected performance measures did not seem to track well with the project panel’s experience-based ideas of performance. In particular, members of the panel saw significant performance differences at the Brookings site where the research team’s measures showed similar performance. Perhaps further research should consider the impact of some combination of the PI, gravel gradation, CBR, and fractured faces, if not independently, then in some form of a gravel quality index.
- Continue research on appropriate methods of quantifying gravel loss: the researchers hoped to be able to quantify gravel loss. While one lesson learned from the research is that using the DCP to measure gravel thickness is neither particularly effective nor accurate, the alternative – digging test pits – is time-consuming and requires considerable on-site resources. The cast-off method of collecting lost gravel on the shoulder seemed to provide consistent results with the results of the float test conducted by SD-LTAP researchers, but its application was also problematic in some instances.

- Greater variability in materials is essential if a follow-up experiment is considered: two characteristics in particular—gradation and PI—should be varied such that sites include materials well below, within, and outside of specified limits. Furthermore, if pre-construction testing on the materials shows that they do not meet the requirements of the experiment, then the materials should either be modified or replaced by materials that do.
- Testing of at least three stockpile samples should be used to characterize material properties prior to construction. This is especially true for calculation of the stockpile PI. Had three PI tests been done on each stockpile, it would have resulted in a much better representation mean and standard deviation of the gravel material.
- Control as much variability as possible in construction. There was a lot of variation in construction practices and this could have had a major impact on the results. For example, in Custer County, the test sections were constructed on two different roads with likely different soil conditions and certainly different traffic conditions. In Hand County and Brookings County, the existing gravel surfacing was removed or re-mixed with the subgrade prior to placement of the test gravel.
- Only perform the maintenance that is needed on test sections and collect complete maintenance data over time in order to determine cost effectiveness. In this study Brookings County performed maintenance only as needed on the cells which were showing problems, whereas Hand County generally graded the entire test section whenever it needed maintenance. Custer County provided limited maintenance records due to personnel turnover, but since the test cells were split over two separate roadway sections (a few miles apart) it is unlikely that they received the same maintenance.

  Other local features may have affected performance in unaccounted ways. These include the presence of driveways (and associated turning traffic), varying vegetation along the road (half the Brookings site was lined with corn fields, and the other half had tall trees on both sides of the roads – the trees provided more shade and blocked wind, so the road held onto more moisture), geometric changes (both Custer roadways were curved and hilly), and intersections (causing variable traffic speed).
- The condition surveys must be performed immediately before (and preferably immediately after) any major maintenance activity and not at arbitrary times between maintenance activities. This will provide for a much better assessment of the performance of gravel materials because it separates the maintenance effect from the gravel quality effect. In addition, the distress condition that is dictating the need for maintenance should be identified.
- Account for, or at least consider, variations in traffic patterns which could have an effect on performance: traffic patterns can have a significant effect on loose surface aggregate/float/raveling. If the traffic remained in established wheel paths, there tends to be very little loose material, regardless of the test section. If there was more traffic wander, or large trucks driving close to the edge and pushing loose material around, there tends to be more loose material.

- Determine if it is possible to control roadway width: what was defined as the roadway width or traveled surface had a large impact on the performance measures. Some roads tend to develop large aggregate particles along the edge, probably from traffic patterns, but since this was outside the traveled wheelpaths it was more or less ignored by the performance measures.

1.4. Recommendations for Future Research

The following are specific recommendations if the study were to be repeated.

- Rather than focusing on a "one size fits all approach," consider developing a method of gravel selection that addresses the particular type of distress observed on an existing gravel road. For example, the best gravel resurfacing solution for a road that is experiencing a washboard problem may be different than a road experiencing a potholing problem.
- Eliminate the compacted versus uncompacted sections and only study the effects of gravel material quality.
- Sample the stockpile materials from the same area of the stockpiles as the actual material used in test sites.
- Determine if there is a test for the plasticity effect of these materials that is more reliable and repeatable than the plasticity index (PI).
- Improve field material sampling: It was difficult to obtain enough material samples without any mixing of underlying gravel or of subgrade material. Because the gravel was so tightly compacted, mechanical methods were used to loosen the material (augers or trenching machine), likely further breaking down the material.
- If possible, blind the researchers as to the characteristics of the test sections. Failure to do so could create a subconscious bias toward gravels known to be "good performers" and against ones known to be "bad."
- Improvements are needed in the objective measurement of performance. At least a part of this improvement should be to confirm those objective measures which align well with how owners make gravel road maintenance decisions and how users view road performance. Part of this involves the determination of critical levels of the key distress ratings (especially washboarding, rutting, and potholing) that are considered unacceptable and triggers for maintenance work. This could be done as part of small field study to investigate what conditions actually trigger maintenance crews to perform maintenance.
- Eliminate as much variability (in cross-section, alignment, driveways, vegetation, etc.) as possible along the test sites.
- Conduct more frequent condition monitoring and ensure that monitoring is performed immediately before (and preferably after) any maintenance activity that significantly affects the gravel road condition.
- Exercise better control over maintenance operations (and winter snow-clearing operations), and better monitor the frequency of maintenance operations and understand why the maintenance was performed.

- Include stabilization as a variable in future studies to determine if this is a cost-effective way to reduce the need for maintenance and control dusting.

2. PROBLEM DESCRIPTION

South Dakota's transportation network includes over 83,000 miles of roads, of which about 10 percent are state-controlled and 3 percent are federal routes (Zimmerman and Wolters 2004). The remaining 72,000 miles—most of which are considered to be low-volume roads (LVR), defined as carrying less than 400 vehicles per day—fall under the jurisdiction of counties, townships, and municipalities. These LVRs are secondary roads or local roads that play an important role in the State's economy, providing essential links not only within rural areas but also between rural and more populated areas.

A significant portion of the secondary or local roads in South Dakota are gravel, also commonly referred to as unpaved, unsealed, unbound, or aggregate-surfaced roads. Within the State, these have been constructed with an assortment of different aggregate materials (including pit run, screened, and crushed) and under a range of governing specifications (including state gravel specifications, base course specifications, local specifications, or no specifications at all). Generally speaking, South Dakota's gravel roads have performed well under a variety of traffic and environmental conditions, but ever-increasing traffic loadings, heavy trafficking during weakened support conditions (e.g., springtime planting season), and decreasing funding levels make it increasingly difficult to effectively maintain the surface of these roadways. Furthermore, other issues unique to gravel roads (such as dust control and safety due to loose gravel) present additional maintenance demands. Thus, local agencies are constantly challenged in effectively managing and maintaining their LVRs.

Improved guidance on the design, construction, and maintenance of gravel road surfacings would help to obtain the best possible performance of these roads. This is particularly true in an environment where shrinking budgets compel agencies to maximize their investments. Although there are several good resource documents available on gravel roads, some of these are very general and lack good guidance, others are somewhat dated, and none is specific to South Dakota's unique conditions (semi-arid climate with extreme freeze-thaw cycles, large swings in temperature and moisture levels, and highly variable soils). Therefore, the SDDOT contracted with Applied Pavement Technology, Inc. (APTech) to carry out this study to help develop improved gravel surfacing guidelines.

3. RESEARCH OBJECTIVES

3.1. Review of Objectives

The original objectives of the study are listed below:

1. Identify and describe current and best practices for the design, construction, maintenance, rehabilitation, and stabilization of gravel surfacing in the Upper Great Plains Region.
2. Assess the performance and costs of new, unstabilized gravel surfacing test sections constructed with a) commonly used materials and methods that do not meet state specifications; b) materials and methods that comply with state specifications; and c) materials and methods that exceed state specifications.
3. Develop guidelines for cost-effective design, construction, stabilization, maintenance, and rehabilitation of gravel surfacing for local agencies in South Dakota.
4. Develop training materials to assist road managers and elected officials with cost-effective gravel surfacing design, construction, maintenance, rehabilitation, and stabilization of gravel-surfaced roads.

During the course of the study, however, the Federal Highway Administration (FHWA) published the *Gravel Roads Construction and Maintenance Guide* (FHWA 2015). This publication, which has been very well received by SDDOT, essentially covers Objectives 1, 3, and 4 of the study. Accordingly, SDDOT instructed the APTech team to omit the discussion of the work associated with these three objectives and to focus only on Objective 2.

To accomplish Objective 2, SDDOT supported construction of a field experiment in which multiple full-scale test sections were built, trafficked, maintained, and routinely surveyed to measure performance. The plan was to construct the experimental sections using standard gravel materials (that met State specifications), above-standard gravel materials (that exceeded State specifications), and substandard gravel materials (that did not meet State specifications) at three roadway site—one located in the eastern part of the State, one in the central part, and one in the western part. With information gathered from the experiment, an assessment could be made of the relative performance of the different gravels and, in turn, the cost effectiveness.

3.2. Overview of Report

In addition to the introductory material, this report includes the following sections:

- Section 4. Task Descriptions – This section identifies each of the study's defined tasks and describes the APTech team's interpretation of the task, and presents the team's original approach to accomplishing it. If there were any significant deviations from the original approach, they are also presented.
- Section 5. Findings and Conclusions – This section provides a discussion of what was learned in the study. It includes the findings of:

  a. The literature review.

b. The survey of South Dakota agencies to characterize local practices for design, construction, and maintenance, rehabilitation, and stabilization of gravel surfacing.
c. The test section construction, materials characterization, and monitoring results.
d. The basis established for assessing gravel road performance, including the selected performance measures.
e. The review of maintenance records.
f. The performance measurements made at each test site after construction (along with associated observations).
g. The statistical analyses made to determine the impact of roller compaction during construction and the performance of the above-standard and substandard gravels relative to the standard gravels for each test site.
h. The relevant comparisons between the results of this study and the findings of the SD LTAP Center on the performance at one of the experimental test sites.

- Section 6. Recommendations – Presents the APTech team's specific recommendations on the application or implementation of the research findings.
- Section 7. Research Benefits – This section summarizes the benefits realized through the completed research and implementation of the research results.

The following appendixes provide more of the detailed information collected and used as part of the study:

- Appendix A – Annotated Bibliography.
- Appendix B – Survey Results
- Appendix C – Telephone Interviews

4. TASK DESCRIPTIONS

This project required a well-constructed research plan in order to satisfy the project objectives. The section provides a description of the contract tasks with some modification to reflect the work that was actually performed.

4.1. Task 1 – Attend Kick-Off Meeting

In this task, the project's Principal Investigator, Dr. Tom Van Dam, P.E. (APTech), and the project's Co-Principal Investigator, Mr. Tim Colling, P.E. (MTTI), participated in a one-day meeting with the project technical panel to discuss the project scope and the overall work plan. This meeting was held in Pierre on March 29, 2010, and meeting notes were submitted separately. During the meeting the Team reviewed the project scope and work plan. Preliminary discussions were held on the location and layout of the test sites.

4.2. Task 2 – Perform Literature Review

This task was led by APTech with assistance provided by MTTI. The research team conducted a detailed literature review to establish the prevailing and best practices regarding gravel surfacing. Particular focus was given to the design, construction, rehabilitation, maintenance, and stabilization of gravel road surfacing, especially having conditions that are similar to those prevalent in the Upper Great Plains region of the United States, which is characterized as being a semi-arid environment with extreme freeze-thaw cycles, radical swings in moisture and temperature, and highly variable soils. The results of this literature review were used to guide the interviews in task 3 and to provide a basis for developing the gravel roads guidelines in task 8.

The literature review began with an internal search of the APTech transportation library and the personal files of all research team members. The next sources accessed were the Transportation Research Information Service (TRIS) database, the Transportation Research Board (TRB) Research in Progress (RIP) database, and other domestic databases, as appropriate. A search on state/national organizations that cater to low-volume roadways (such as FHWA Federal Lands, LTAP, NACE, Center for Dirt and Gravel Roads, and so on) was also conducted. Foreign databases, such as the World Road Association (WRA, formerly PIARC), Transportation Association of Canada [TAC], Transport Research Laboratory [TRL], New Zealand Land Transport, South Africa Land Transport, and the Australian Road Research Board (ARRB), were also reviewed to evaluate the international experience.

Relevant references identified in the literature search were obtained for detailed review and potential use in the study. The materials were compiled according to specific topic areas and then cataloged according to the following technical topic headings:

- Performance of gravel surfacing.
- Design of gravel surfacing.
- Construction of gravel surfacing.
- Maintenance of gravel surfacing.

- Rehabilitation of gravel surfacing.
- Stabilization of gravel surfacing.

The resulting collection of literature and documentation was thoroughly reviewed for potential use in this study. This review focused on the many aspects of gravel surfaces, from the assessment of performance indicators and contributing factors, to the design, construction, maintenance, and rehabilitation of gravel surfacing, concluding with a review of stabilization strategies. Both formal and informal documented practices of selected transportation agencies (local, state, and federal) were carefully reviewed to get a better understanding of the performance, design, construction, maintenance, rehabilitation, and stabilization of gravel surfacing.

Each document deemed pertinent to the study was included in an annotated bibliography and arranged into specific categories described above. The annotated bibliography is included in this report as Appendix A.

4.3. Task 3 – Conduct Interviews

This task was led by MTTI with assistance from APTech. MTTI staff generated and executed an electronic survey using Super Survey™ to identify best practices for the performance, design, construction, maintenance, rehabilitation, and stabilization of gravel surfacing within South Dakota. These survey results were used to identify specific local concerns related to gravel surfacing at South Dakota local agencies and to provide data on practices and problems associated with gravel roads that helped guide the direction of the study, including the potential identification of agencies that have employed unique or innovative practices. The use of an electronic survey also allowed the research team to reach a very large audience of local and tribal agencies.

Working with the SDDOT, the research team e-mailed survey invitations to South Dakota local agencies. MTTI collected contact information from the South Dakota Highway Association of County Highway Superintendents, the South Dakota Local Technical Assistance Program (SD-LTAP), and the South Dakota Municipal League. E-mail addresses for tribal government agencies was collected from the Northern Plains Tribal Technical Assistance Program (TTAP). Staff from SD-LTAP and Northern Plains TTAP were contacted and interviewed for leads on South Dakota local agencies that are employing innovative best practices in gravel road surfacing construction, maintenance, and rehabilitation and those that are using stabilization techniques. Case studies applicable to this project were also sought.

Additionally, the research team identified over a dozen local agency and tribal interview candidates based on survey responses and information from LTAP/TTAP sources. Telephone interviews were conducted with candidates to determine the details of their best practice or innovative practices. A willingness to participate in the construction of the gravel surfacing test sections was also be gauged. Interviews were recorded and summarized in written format. The following are among the topics/issues raised during these interviews:

- The range of gradation specifications in use for gravel surfacings.
- The extent that pit run or other unprocessed material is used for gravel surfaces.

- The types and use of aggregate specifications that “exceed” state DOT specifications.
- The factors that agencies use to select an aggregate specification.
- The perceived shortcomings in existing specifications that have motivated agencies to modify or develop their own aggregate specifications.
- “Typical” gravel road section designs used at the local agency level.
- The extent of the use of compaction equipment for construction of gravel roads.
- The types and frequency of stabilizer use for gravel roads.
- Types of maintenance and rehabilitation activities and their frequencies.
- The types of distresses that trigger maintenance or rehabilitation events on gravel roads.
- Unique areas of concern related to the maintenance and management of gravel roads.

The topics were added or modified as necessary to address the information needs that were identified during the kickoff meeting and the full literature review.

4.4. Task 4 – Prepare Technical Memorandum Documenting Tasks 2 and 3

This task was led by APTech with assistance from MTTI. The research team prepared a memo for the technical panel summarizing the results of the literature review conducted in task 2 as well as the electronic survey and telephone interview results from task 3. This memo summarized prevailing and best practices employed throughout South Dakota, nationally, and internationally, related to gravel surfacing.

Based on these prevailing and best practices, the team produced a comprehensive plan for the construction and monitoring of three gravel surfacing test sections to be performed under task 6. At the time, it is envisioned that one test section would be located in the Rapid City Region, one in the Pierre Region, with the third in either the Mitchell Region or Aberdeen Region. The SDDOT regions are shown in figure 1. This distribution was intended to capture the geographical and climatic diversity present in South Dakota from east to west. To the degree possible, similar site conditions (topography, soil support, road geometry, and so on) were sought in each of the three test sections to facilitate comparisons of surfacing performance. Although this was a challenge, it was considered critical that the site conditions within each test section be held constant so that meaningful performance comparisons could be made between the various gravel surfacings.

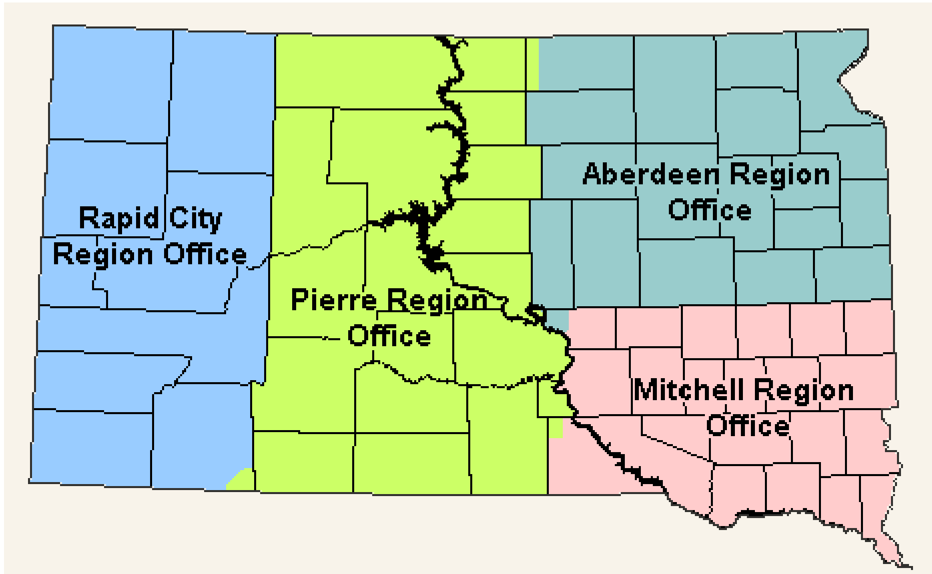

Figure 1. Map of South Dakota identifying the four SDDOT regions.

4.4.1. Test Section Layout

Each test site was planned to have an overall length of at least 1,650 ft, containing five 250-ft test sections, separated by 100-ft transition zones. Two test sections were planned to be constructed with materials meeting State specifications (and both compacted and uncompacted), two sections with materials not meeting State specifications (most likely pit run gravel, with compacted and uncompacted sections), and one compacted section with materials exceeding State specifications. The planned layout for a given test site is shown in figure 2.

The exact design of each test section depended upon the results of tasks 2 and 3 and on the specific nature of the sites approved by SDDOT's Office of Research. At the beginning of the project, one of the major concerns was the fact that the materials not meeting State specifications were the use of pit run, unprocessed local gravel and so this material (compacted and uncompacted) would likely be used for two of the test sections at each test site. Materials exceeding State specifications often have a higher plasticity index to facilitate binding of the surface and these were incorporated into one test section. It was noted in the original RFP that some agencies have exceeded State specifications through the use of chemical stabilizers in high-traffic areas. Although chemical stabilizers were not initially considered in this study, they could have been incorporated into one or more of the test sections, if necessary. This decision was made during task 5 when the research team met with the SDDOT's project technical panel.

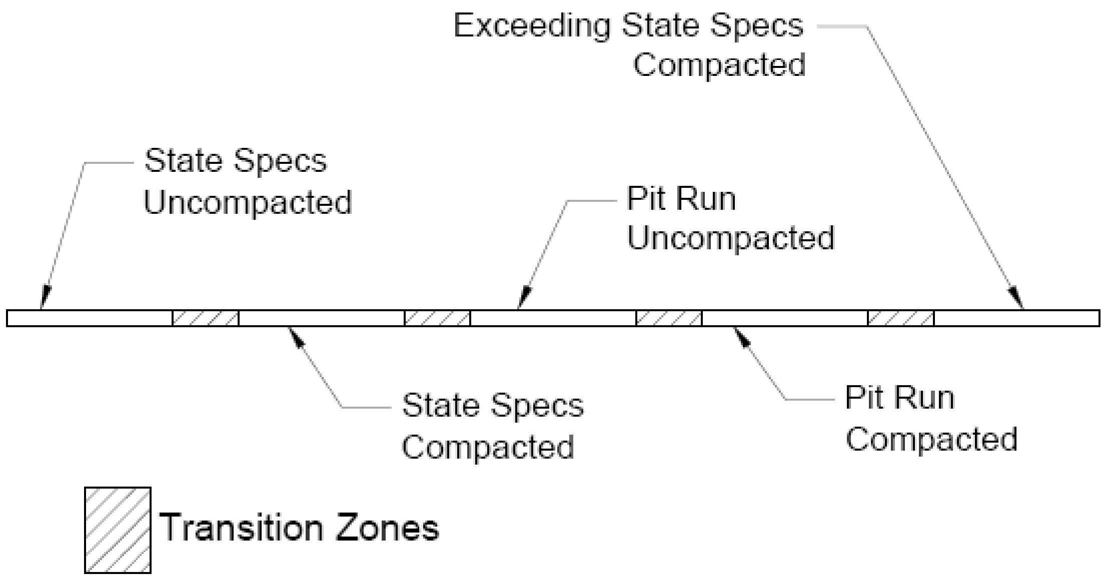

Figure 2. Proposed test site layout showing five 250-ft long test cells with 100-ft transition zones between them.

4.4.2. Test Section Monitoring

As discussed under task 6, each test section was visited during construction and subsequently underwent three inspection cycles. During the construction visit, detailed information on the gravel surfacing construction process was documented, including the extensive use of digital photographs and video. In addition, some gravel sources were visited, gravel properties documented, and the overall construction sequence described in detail. The prevailing climatic conditions were also recorded. Local site conditions were documented to ensure uniformity and to note any underlying conditions that might contribute to the performance of the gravel surfacing. Prior to leaving the site, the gravel surface thickness was to be measured using the approach discussed in the next section. For each test site, a project portfolio was written documenting the entire construction process, and all available construction records were scanned and included as part of the portfolio. The research team relied on the construction records to obtain pertinent gravel surfacing material testing data, including aggregate gradation, soundness, fractured faces, and plasticity index values.

Each inspection was planned to include visual assessment and physical testing of the gravel surface to assess the performance of the surface and the amount of gravel loss. Visual assessment of the surface condition was to be made by applying the objective rating method used by FWHA-Federal Lands Highway Division. This method evaluates the surface condition of the road based on dust, washboarding (corrugation), raveling (otherwise known as “wash” or “loose surface aggregate”), rutting, and potholing. With the exception of dust, the distresses are measured in representative areas of the roadway, and are assigned a severity from 0-10 based on their severity. Each 250-ft test cell was to be divided into five 50-ft long sample units for distress assessment. A single subjective assessment of dust was assessed, using a 0-10 scale, from the middle of each test section.

4.4.3. Aggregate Loss Assessment

There are a number of ways in which aggregate loss has been assessed over the years, but all have some limitations. The most common method has been to use rod and level surveys to measure changes in surface elevation, but this method does not assess gravel loss specifically, but instead overall changes in elevation of the road surface, which can be due to a number of factors (many not related to aggregate loss). The use of test pits has also been common, but this has the drawback of being time intensive, disruptive to the pavement structure, and limited in how representative they may be of an entire project. Applying nondestructive assessment, such as ground penetrating radar, was of interest, but the cost of the technology the lack of documentation in its use for this application ruled it out.

The research team's original plan included a combination of different methods to assess gravel loss with the hope of narrowing the different approaches down to a single one once the efficacy was demonstrated. One approach involved the use of a dynamic cone penetrometer (DCP), in which the change in resistance to penetration would be used to identify the boundary between the gravel surfacing and the underlying subgrade. Unfortunately, this method was not accurate and was replaced by a technique referred to as the *gravel loss by cast off* method. This method involved SDDOT constructing catch basins on the shoulder of the road to catch gravel as it was cast from the road during trafficking. SDDOT personnel regularly traveled to each site, weighed the gravel collected, and used it to estimate the gravel loss over the entire test section over time.

Weather data were analyzed to determine the effects of temperature, humidity, and precipitation on the condition of the test sections. These data were obtained from the nearest weather station.

The test sections were constructed on active roadways, and thus maintenance by grading—by the locally responsible agency—was necessary. The research team planned to coordinate with the local agency in the hope of conducting scheduled inspections prior to maintenance grading. Unfortunately, because of the frequency of maintenance and the differences in timing between the different sites, this was found to be impractical. Thus, the inspections were scheduled at three specific times for each test site.

4.4.4. Material Testing

During each inspection period, over 300 lb of gravel material was collected from each test section to perform the following tests:

- AASHTO T 19: Unit Weight and Voids in Aggregate.
- AASHTO T 27: Sieve Analysis of Fine and Coarse Aggregates.
- AASTTO T 84: Specific Gravity and Absorption of Fine Aggregate.
- AASHTO T 85: Specific Gravity and Absorption of Coarse Aggregate.
- AASHTO T 89: Determining the Liquid Limit of Soil.
- AASHTO T 90: Determining the Plastic Limit and Plasticity Index of Soil.
- AASHTO T 96/ASTM C131: Resistance to Degradation of Small-Sized Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.

- AASHTO T 104: Soundness of Aggregate by Use of Sodium Sulfate of Magnesium Sulfate (Done on coarse and fine aggregate, so two tests will be needed per section).
- AASHTO T 193: The California Bearing Ratio (CBR).
- AASHTO T 335: Determining the Percentage of Fractured Particles in Coarse Aggregate.

All testing was performed by the SDDOT and done in accordance with SDDOT testing protocols, which may vary slightly from the AASHTO standards cited. The test matrix reflects the need to establish the suitability of an aggregate source for use as a gravel road surface. Thus, extensive testing was conducted on the aggregate stockpiles and less on the surface immediately after construction and during the subsequent inspections. A summary of the test matrix is presented in table 1.

Table 1: Summary of testing requirements.

Test Method	Stockpile	After Construction	Two Intermediate Inspections	Final Inspections
AASHTO T 19	X	X		X
AASHTO T 27	X	X	X	X
AASHTO T 84	X			
AASHTO T 85	X			
AASHTO T 89	X	X	X	X
AASHTO T 90	X	X	X	X
AASHTO T 96	X			
AASHTO T 104	X			
AASHTO T 193	X			X
AASHTO T 335	X	X		X

4.4.4.1. Testing of Preconstruction Stockpile

Three materials were used at each test site, so a total of nine gravel sources were tested. All of the test methods listed above were used to link material properties of the stockpile to observed surfacing performance over the duration of the study. Previous research has indicated that aggregate wear (AASHTO T 96), gradation (AASHTO T 27), plasticity (AASHTO T 89 and T 90), fractured faces (AASHTO T 335), and soaked CBR (AASHTO T 193) are important factors contributing to performance. Soundness testing (AASHTO T 104) was used as a surrogate for wear. Assessment of aggregate unit weight (AASHTO T 19) and specific gravity/absorption (AASHTO T 84 and T 85) were used to provide information on mass-volume relationships as well as to establish links with other relevant properties.

4.4.4.2. Immediately After Construction

All five test sections were sampled at each test site resulting in a total of 15 material samples. The testing conducted was pared down, including unit weight (AASHTO T 19), gradation (AASHTO T 89 and T 90) to assess intermediate changes in the aggregate surface that occurred as a result of being in service.

4.4.4.3. Two Intermediate Inspections

At each test site, all five test sections were sampled, resulting in a total of 15 material samples. The testing conducted included only gradation (AASHTO T 27) and plasticity (AASHTO T 89 and T 90) to assess intermediate changes in the aggregate surface that occurred as a result of being in service.

4.4.4.4. Final Inspection

At each test site, all five test sections were sampled, resulting in a total of 15 material samples. The testing program was identical to that done immediately after construction, including unit weight (AASHTO T 19), gradation (AASHTO T 27), plasticity (AASHTO T 89 and T 90), and fractured faces (AASHTO T 335). This allowed comparisons to be made between the aggregate surface as placed and its properties at the end of the project, assessing changes in the material that occurred throughout the design life.

4.5. Task 5 – Attend Technical Panel Review Meeting

After submission of the technical memorandum prepared under task 4, the project PI, Dr. Tom Van Dam, P.E. and the project Co-PI, Mr. Tim Colling, P.E. met with the project's technical panel on February 3, 2011. The purpose of the meeting was to review the technical memorandum, with the main focus on the proposed gravel road test section construction and evaluation plan. All questions or concerns from the panel regarding the construction, condition assessment, or gravel loss characterization were discussed and resolved at this time, resulting in the development of a revised test plan that governed the task 6 work activities.

4.6. Task 6 – Monitor Test Sections

This task was conducted by APTech. As described under Task 4, this task required oversight and monitoring of the construction of each test section. An APTech engineer was on location at each test site to document the entire construction process. The project Principal Investigator, Dr. Tom Van Dam, participated in the first site visit in order to finalize the test site layout and approach to data gathering.

Gravel road inspections were conducted in June and October of 2011, May 2012, and October and June of 2013. Inspections were conducted by a team of two APTech staff. Dr. Van Dam was part of the team on the first inspection to finalize the inspection procedures.

4.7. Task 7 – Analyze Cost and Performance Data

This task was conducted by APTech. The original plan for this task was for the research team to compare the performance and life cycle costs of the test sections within each gravel surfacing test site using the collected data, including initial surfacing construction costs, surface condition over time, gravel loss over time, weather, traffic, frequency and cost of maintenance over the duration of the study. The original plan also included projecting the need for re-graveling, estimating the surfacing life, and comparing the test sections within different test sites to determine if sufficient similarities between the test sites exist.

This plan was revised during the course of the project when the actual performance of the test sections did not match up with the expected performance. For example, the first round of section-to-section comparisons based on comparison of the average condition ratings indicated that the above-standard gravel at the Hand County test site performed worse than the standard gravel. Accordingly, the emphasis of the research on this task switched to 1) applying a more rigorous statistical analysis to make performance comparisons, 2) drawing conclusions about the relative quality of the different gravel materials, 3) identifying the weaknesses in the field experiment, and 4) developing recommendations for a future experiment as well as the use of the gravel materials used in the experiment.

4.8. Task 8 – Develop Gravel Surfacing Guidelines

The original plan for this task was to develop comprehensive guidelines for the design, construction, maintenance, rehabilitation, and stabilization of gravel surfaces in South Dakota. The guidelines were to be developed based on findings from the previous project activities including the literature review, interviews of state and local officials, and analysis of the gravel surfacing test sections. The scope of these guidelines was restricted specifically to the gravel surfacing, although other contributing factors were to be addressed. The original outline for the guidelines is shown in table 2.

After FHWA published the *Gravel Roads Construction and Maintenance Guide* (FHWA 2015), SDDOT determined that its content addressed almost all the requirements set forth for the gravel surfacing guidelines under this research project. Accordingly, SDDOT instructed the APTech team to omit the discussion of any work on this task and to focus on the discussion of work related to Objective 2 of the project.

4.9. Task 9 – Prepare Technical Memorandum Documenting Tasks 6 through 8

APTech submitted the results of the initial performance analysis of the gravel surfacing test sections along with some preliminary gravel road surfacing guidelines as part of a draft final report in March 2015. The report also included the findings of other key project activities, including the literature review, the survey of local agencies, and the laboratory testing of the gravel materials. Feedback from the SDDOT review panel provided the basis for conducting the more rigorous statistical analyses on the test section performance data and the submission of a separate memo (dated June 24, 2016) that documented the results.

Table 2. Original outline for gravel road surfacing guidelines.

Chapter	Content
1. Introduction	• Introduction • Background • Overview of manual
2. Structural Design and Performance of Gravel Roads	• Soil bearing capacity • Road classification and traffic levels • Gravel surfacing structural design • Performance expectations • Structural effects of gravel loss
3. Important Material Properties of Gravel Surfacing	• Gradation • Gravel sources • Aggregate angularity and texture • Plasticity • Wearing resistance
4. Performance Factors Affecting Gravel Surfacing	• Aggregate loss • Distresses • Environmental factors • Traffic • Safety
5. Construction of Gravel Surfaces	• Compaction • Stabilization • Equipment • Cross-section • Testing and monitoring
6. Maintenance and Rehabilitation of Gravel Surfaces	• Maintenance strategies • Routine regrading and regraveling • Rehabilitation • Timing • Dust control and stabilization
7. Economics of Gravel Surfacing	• Life-cycle cost analysis inputs • Efficient use of resources • Reducing gravel consumption
8. Conclusions	• Summary • Sources for additional information • Recommendations

4.10. Task 10 – Develop Training Materials

The original plan for this task was for the project team to develop training materials to accompany the guidelines after receiving approval from the SDDOT technical panel. No work was ever done on this task because work on the gravel surfacing guidelines was not completed. As with Task 8, SDDOT instructed the project team to omit the discussion of any work on this task and to focus on the discussion of work related to Objective 2 of the project.

4.10.1. Training Resources for Technical Staff

This involved the preparation of a PowerPoint presentation for a 3- to 4-hour workshop that is targeted at road superintendents and other technical staff. The planned training schedule for this presentation is shown in table 3.

Table 3. Proposed training schedule for technical staff.

Session	Duration	Content
1. Introduction and Business Rules	15 min	• Introduction • Training objectives
2. Structural Design and Performance of Gravel Roads	30 min	• Soil bearing capacity • Gravel surfacing structural design
3. Important Material and Construction Properties of Gravel Surfacing	45 min	• Gradation • Aggregate angularity and texture • Plasticity • Wear • Compaction • Stabilization
4. Performance Factors Affecting Gravel Surfacing	30 min	• Aggregate loss • Distresses • Environmental factors • Traffic
5. Research Results	45 min	• Results of this research study
6. Maintenance of Gravel Surfaces	30 min	• Maintenance strategies • Regrading/regraveling • Timing • Dust control/stabilization
7. Economics of Gravel Surfacing	30 min	• Life-cycle cost analysis inputs
8. Summary and Wrap-Up	15 min	

The completed presentation would consist of slides and very minimal notes. The finalized PowerPoint presentation would be narrated and converted into a Macromedia Flash or other suitable format for use as a streamed media file. Since all of the presentation slides would be narrated, an instructor's manual would not be necessary for this material.

4.10.2. Training Resources for Elected Officials / Non-Technical Staff

The original plan for this PowerPoint presentation was to consolidate and modify the 4-hour workshop into a 30 to 40-minute presentation for elected officials and other non-technical staff. The general topics planned for this presentation are shown in table 4.

Table 4. Proposed outlined for training resources for elected officials/non-technical staff.

Chapter	Duration	Content
1. Types of Pavement Deterioration and Relationships to Materials and Construction	15 min	• Aggregate loss • Distresses • Environmental factors • Traffic
2. Research Results	5 min	• Summary of research results
3. Specific Design and Construction Issues of Greatest Importance	5 min	• Quality of aggregate • Stabilization
4. Economics of Gravel Surfacing	5 min	• Life-cycle cost analysis inputs
5. Summary	5 min	

The completed presentation would consist only of slides and very minimal notes. As before, the limited resources available in this study preclude the development of a detailed instructor's guide. Accordingly, the final PowerPoint presentation would be narrated and converted into a Macromedia Flash or other suitable format for use as a streamed media file.

4.10.3. Fact Sheet for Elected Officials:

The last component of the original plan was to create a one-page (front and back) publication that would be suitable for print or for electronic distribution (as a pdf file). The document would detail the results of the study in non-technical language.

4.11. Prepare Final Report and Executive Summary

This task was led by APTech. The research team prepared a final report that included an executive summary, a detailed description of all the findings, conclusions, and recommendations. This final report addresses all the questions and comments raised by SDDOT on the draft final report and a memo documenting the additional statistical analyses to evaluate test section performance. The letter identifying the questions and raising the concerns was from R.D. Longbons (SDDPT Research Engineer) dated January 6, 2017.

Table 5. Proposed outline for final report.

Chapter	Content
1. Introduction	• Introduction • Background • Overview of report
2. Background on Gravel Roads	• Design • Construction • Maintenance • Management
3. Survey Approach and Results	• Description of the survey • Survey results
4. Test Section Construction and Monitoring	• Test section selection • Specific layout and materials used for each test section • Documentation of constructions of each test site • Results from the three inspections • Analysis of results
5. Economic Analysis	• Economic data • Life-cycle analysis
6. Introduction to Guidelines	• Description of guidelines • Implementation
7. Summary and Conclusions	• Summary of results • Recommendations
Gravel Surfacing Guidelines *(Stand-Alone Document)*	See table 2 for content

4.12. Make Executive Presentation

At the conclusion of the project, the plan was for the Principal Investigator, Dr. Tom Van Dam, to make an executive presentation to the SDDOT Research Review Board summarizing the research approach and methodology, the project's findings, and a summary of the final products. This presentation and associated meeting did not take place.

5. FINDINGS AND CONCLUSIONS

This section documents the findings of all the key research activities carried out under this study. These activities include:

- Literature review.
- Survey approach and results.
- Test section construction and monitoring results.
- Basis for gravel road performance assessment.
- Test site road maintenance.
- Test section performance observations.
- Statistics-based performance observations.
- Comparison of relevant findings with SD-LTAP study.

Where appropriate, conclusions are provided that help address the study's primary objective.

5.1. Literature Review

As part of the research project, APTech and its research partner, the Michigan Tech Transportation Institute (MTTI), conducted a literature search on the following topics related to gravel surfacing:

- Aggregate loss mechanisms.
- Aggregate loss measurement methods.
- Gravel surface distress rating systems.
- Gravel road stabilization.
- Materials used for gravel surfacings.
- Maintenance of gravel roads.
- Environmental effects on gravel roads.

Aggregate loss is a major concern for gravel roads. It can be categorized into three groups: dusting, casting, and incorporation. Some research has been conducted into the mechanisms and prevention of aggregate loss, and the subject is explored more thoroughly in this research project. Aggregate loss has been traditionally measured by periodically recording differences in vertical elevation of the road surface over time. However, due to significant sources of error, including effects of frost heave and consolidation, this method is not ideal. Another traditional method is digging pits and visually recording the gravel depth. While digging pits is destructive and time-consuming, it is also the most direct means to assess gravel loss.

There are numerous surface distress rating systems available for gravel roads, but most are not detailed or objective enough for use in this project. The best rating system available for a small-scale detailed research project such as this was developed by the Federal Highway Administration – Federal Lands Highway Division (FHWA–FLHD) (Woll et al. 2008), and measures the quantity of washboarding, potholing, raveling, and rutting; it also provides a qualitative assessment of dust problems.

In South Dakota, as well as in many other parts of the country, decreasing aggregate sources have led to an increased variety in the types of gravels used in gravel road construction. Although counties are not required to use state specifications for their material, many still follow them, feeling that it improves their roads' performance. Others use pit run gravels and other materials that do not meet the state gravel specification. Still others are using materials or construction methods that exceed state specifications, such as better compaction, higher plasticity, or the use of stabilizers. The results of a literature review conducted on this topic are presented and an annotated bibliography is found in Appendix A.

5.1.1. Aggregate Loss Mechanisms

Studies have shown that aggregate loss can account for as much as 60 percent of the total maintenance costs on gravel road systems (Henning, Giummarra, and Roux 2008). The loss of aggregate results in structural weakening of the pavement section, which reduces its load-carrying capacity and can also lead to the development of surface rutting and potholing.

Several factors have been identified as contributing to aggregate loss. Early work by Visser and Hudson (1981) identified aggregate weathering, traffic, and maintenance as three primary mechanisms leading to aggregate loss, with aggregate material properties, road alignment and road width as factors influencing those three mechanisms. Later work conducted by Paterson (1987) identified aggregate material properties (plasticity index [PI]), precipitation, and geometry of the road as predictive factors for modeling aggregate loss. More recent studies have identified key aggregate material properties (plasticity factor, which is related to PI and aggregate gradation [percent passing the 0.075 mm sieve]), precipitation, and traffic volume as prime factors in predictive models for aggregate loss (Giummarra, Hoque, and Roper 2007). A Canadian study identified traffic speed, aggregate gradation, tire inflation pressure, aggregate layer thickness, and subgrade material as key factors in aggregate loss (Berthelot and Carpentier 2003).

Central to many of these studies is the identification of three mechanisms that lead to aggregate loss: loss by dusting, loss by casting, and loss by incorporation. Dusting is considered by many as a significant source of material loss. Dusting primarily occurs when the fine material in the aggregate gradation becomes airborne when disturbed. Fine material originally present in the gravel surface is an obvious target for loss by dusting; however, larger material can become susceptible to this loss mechanism as it is abraded and broken down by traffic, thereby generating fine material.

Aggregate loss by "casting" has also been identified as a factor. Casting is the displacement of coarse aggregates that is caused by trafficking movements or by maintenance practices such as grading and snow plowing. Casting has the potential to result in significant aggregate loss due to its ability to displace larger-sized aggregate, especially in locations where snow plowing may take place on an unfrozen road surface.

The third aggregate loss mechanism is the incorporation of aggregate into underlying pavement layers under traffic. While surface aggregate incorporation into the underlying subgrade layer is not, strictly speaking, removed or "lost" from the pavement structure, many road managers consider this aggregate as effectively lost because it is no longer present in a dense-graded aggregate matrix that lends significantly to the structure of the pavement.

5.1.2. Aggregate Loss Measurement Methods

Although the importance of aggregate loss is acknowledged, most studies have employed rudimentary methods for measurement of aggregate loss. Of the research projects reviewed in the literature search, the majority employed comparative surface elevation surveys as a means of determining aggregate loss. While the surface elevation survey is a relatively quick and easy measurement method, most of the studies were conducted in temperate climates where elevation change due to frost heave was not a consideration. Furthermore, an elevation survey cannot differentiate whether elevation loss is due to aggregate loss through dusting or casting, aggregate incorporation into the underlying layer, or whether densification of the underlying subgrade layer has occurred.

Another method used to track aggregate loss is the excavation of small pits through the gravel surface layer into the subgrade. Excavation allows the existing profile and thickness to be visually identified and directly measured. While it can be fairly accurate, this method presents a drawback for long-term studies in that repeated excavations to obtain thickness measurements will result in significant disturbance of the gravel layer, which can be difficult to repair and can produce distresses such as potholes. Even if extreme care is exercised in replacing material in the excavation, a change in the gradation and density of materials with respect to the surrounding aggregate will likely occur when the loose coarse aggregates are remixed and replaced into the layer profile. Furthermore, in most cases only a limited number of excavations can be conducted on a given section of road because of time and budgetary constraints, meaning that the variability of the aggregate loss over the pavement project may not be adequately captured.

5.1.3. Gravel Surface Distress Rating Systems

In addition to directly assessing aggregate loss, it is also desirable to record the initiation and progression of distresses that occur on the gravel surface. The primary distresses used in the monitoring and management of gravel road systems are as follows:

- Washboarding (surface corrugations).
- Potholing.
- Rutting.
- Dusting (airborne dust).
- Raveling (also called wash or loose aggregate).
- Loss of cross section.

A number of different distress rating systems have been developed for gravel roads, both nationally and internationally. These rating systems either provide indirect measures of distress (by developing a numerical indicator of condition) or summarize specific distress types and quantities. Rating systems that indirectly account for distress parameters or systems that combine distress parameters into a single numerical index are not generally satisfactory for research projects where the characteristics of the individual distress parameters are of primary interest. The Pavement Surface Evaluation Rating (PASER) rating system is an example of this type of a distress rating system (Walker 1989). While PASER accounts for a wide array of distresses, including those indicated above, the presence and relative extent of the distress observed is used to categorize roads into one of five rating categories. Generally speaking, different roads classified as having the same PASER category (rating) will have similar recommended maintenance requirements; however, there may be significant differences in the type and extent of distresses that could be present. For example, a gravel road rated as a “3” using PASER may or may not exhibit rutting, yet the recommended maintenance requirements for that road will be similar regardless of whether it was rutted or not. Thus, while the PASER rating system is effective for use as a management tool where a general condition measurement is required to establish recommended maintenance requirements, it is not appropriate for use in a research project where the specifics of the individual distress parameters are needed.

A frequently cited surface distress rating system for gravel road systems was developed by CSIR Transportek, Pretoria, South Africa under contract with the South African Committee of Land Transport Officials (Jones and Paige-Green 2000; Jones, Paige-Green, and Sadzik 2003). The Standard Visual Assessment Method (SVAM) for unsealed roads evaluates a number of operational and physical characteristics, such as washboarding, potholing, rutting, dusting, and loose material. This rating system utilizes a 5-point scale for each distress based on a range of measurements for individual distresses. The range of measurements for each distress is not very specific, allowing identification strictly by visual means without the need for direct measurement. For example a rutting rating of “3” would have a rut depth between 0.8 in and 1.6 in.

The “coarseness” of the interval of measurements for the SVAM makes it ideal for quickly and cost effectively rating many miles of road where high precision is not necessary. However, this “coarseness” of measurement is a disadvantage for a research study where high precision of measurement is required.

The FHWA–FLHD has used both subjective and objective distress measurement systems for the analysis of gravel road distresses (Surdahl, Woll, and Marquez 2005; Woll et al. 2008). Both approaches included an evaluation of washboarding, potholing, rutting, dusting, and raveling (which is the same as loose aggregate).

The subjective rating system used by FHWA–FLHD allows a rating to be assigned from 1 to 10 based on the rater’s perception of the severity of the parameter. Although this system facilitates rapid condition assessment because a physical measurement of the distress is not required, it is more subjective than systems such as PASER and SVAM due to the complete lack of guiding parameters other than the rater’s judgment. This rating system would not be suitable for a research project where precise measurement is required.

The objective rating system used by FHWA–FLHD, which is loosely based on the SVAM rating system, also rates each distress on a 10-point scale. The FHWA–FLHD rating method subdivides the original five rating states provided in SVAM into ten more finely segregated divisions. Ratings on the 10-point scale are assigned based on physical measurements for washboarding, potholing, rutting, and raveling. Physical measurements for each distress are aggregated into ranges of distress measurements. For example, a rutting rating of 5 has ruts between 0.8 in and 1.0 in deep. A scale is provided for measurement of dusting, although it is somewhat subjective in nature as it is related to descriptors such as “little loss of visibility,” “significant loss of visibility,” and so on.

This subdivision of distress measurements into more finely divided ranges makes visual estimation of distress measurements impossible and necessitates physical measurement of the distresses. The objective FHWA–FLHD methodology provides basic guidance for field measurement of each of the distresses it tracks. The objective FHWA–FLHD method (or modification thereof) would thus provide a suitable distress measurement technique for research studies on gravel roads.

5.1.4. Gravel Road Stabilization

Stabilization is the process of blending in additives to alter the mechanical properties, and hence the performance, of a gravel road. Traditionally, stabilizers are thought to improve the performance of gravel roads through reduction of dust, surface distresses, improved mechanical properties of the stabilized material over time, and reduction in need for grading and regraveling. Indeed, there is a significant amount of reported research on the performance of stabilizers for dust prevention, minimization of aggregate loss, and reduction of maintenance. It has been reported that the performance of most stabilizers varies greatly depending on the type of surfacing material.

There are a number of different types of stabilizers that can be used for gravel road stabilization. The U.S. Forest Service, which maintains approximately 360,000 miles of unpaved roads, divides stabilizers and dust palliatives into seven categories: water, water absorbing, organic petroleum, organic non-petroleum, electrochemical (including ionic stabilizers), synthetic polymer, and clay additives (Surdahl, Woll, and Marquez 2005). The *2000 South Dakota Gravel Roads Maintenance and Design Manual* mentions chlorides (water absorbing), resins (organic non-petroleum), clay additives, asphalts (organic petroleum), and soybean oil (organic non-petroleum) (Skorseth and Selim 2000).

In a Canadian study, the effect of ionic stabilization on the amount of gravel loss was characterized, but only by visual assessment on one road (Berthelot and Carpenter 2003). The stabilized sections had reduced dust, although the surface became slippery when wet. The authors of the study believe that this issue could be resolved with better design and application procedures.

In the past 10 years, the FHWA–FLHD undertook studies of stabilizers at national wildlife refuges in Arizona and Wyoming (Surdahl, Woll, and Marquez 2005; Woll et al. 2008). Both of these studies looked at the same set of six different stabilizers: lignosulfonate (organic non-petroleum), magnesium chloride (water-absorbing) plus lignosulfonate (Mag-Lig), Caliber DC 2000 (vegetable corn oil [organic non-petroleum] plus magnesium chloride), Soil Sement® (synthetic polymer emulsion), Permazyme (electrochemical enzyme), and Terrazyme® (electrochemical enzyme), as well as magnesium chloride alone as a control.

Two notable differences between the two areas were climate and aggregate material type. The Arizona project was located in Buenos Aires National Wildlife Refuge in the south central region of the State, with mild temperatures and little precipitation, whereas the Wyoming project was located in Seedskadee National Wildlife Refuge, which is subjected to a prolonged freezing period. For the Arizona project, in which all the treatments were successful, the aggregate surfacing material used was a native pit run gravel; the Wyoming project, which was subjected to a harsh winter and a rapid spring thaw that significantly damaged one project, used a specified gravel surfacing course.

In both projects, the sections were judged visually and qualitatively based on dusting, washboarding, raveling, and potholing. The Wyoming project also had qualitative measurements of surface conditions. Additionally, material tests for moisture-density, gradation, liquid limit, plastic limit, R-value, CBR, and silt loading were performed. The best performing stabilizers were the Caliber DC 2000 followed by Mag-Lig at the Arizona site, and lignosulfonate followed by Mag-Lig at the Wyoming site. It should be noted that both aggregate surfacing materials were nonplastic or very close to nonplastic, and the electrochemical enzymes are intended to work with plastic clay particles for full effectiveness. Additionally, in the Arizona project, all the test sections were in acceptable condition at the end of the 2-year study period without requiring any regrading during the study.

A study by Tingle et al. (2007) discussed seven types of nontraditional stabilizers, characterizing their possible stabilization mechanisms, appropriate materials for use, and overall effects on strength, volume stability, and waterproofing. The researchers determined that ionic and enzyme stabilizers are best suited for fine-grained soils. Salts (magnesium chloride and calcium chloride) were suggested for both fine- and coarse-grained soils, and were determined to work both by attracting water to keep the soil moist and through a certain amount of cation exchange with clays in the soil. Tree resins and lignosulfonates were determined to act by physically bonding soil particles. They are very similar except that tree resins are closer to their natural state, and lignosulfonates are highly processed. Finally, petroleum resins and polymers were suggested for physical bonding of granular soils, but these materials may result in a weak upper layer susceptible to crumbling and cannot be reworked with a grader (Skorseth and Selim 2000).

Geosynthetic materials, particularly geotextiles and geogrids, have been successfully used to improve the performance of unpaved roads, particularly those constructed on poor subgrade materials. Over the years, a number of changes have been made to these materials and new empirical design methods have been developed for their use and application. An overview of the new methods and a cost-benefit comparison for the use of various geosynthetics on certain soil types has been prepared by the Army Corps of Engineers (Tingle and Jersey 2007). They demonstrate that cost savings can be obtained by using geosynthetics due to a concomitant reduction in required gravel surface thickness. In addition, the use of geosynthetics may lead to a decrease in overall maintenance costs due to an increased ability to resist rutting and other structural distresses.

5.1.5. Materials Used for Gravel Surfacing

Gravel sources vary based on availability and cost, among other factors. Typical gravel sources are glacial deposits, river gravels, or even quarries. Good gravel for an unpaved road is a mix of stone, sand, and plastic fines. Ideally, the larger particles have a high percentage of fractured faces from crushing, which are present in quarried aggregate or gravels that are crushed to meet a gradation specification. The stone particles provide the strength necessary to resist traffic loads, while the sand particles fill the gaps between the stones and create a dense, stable matrix. The plastic fines bind the mixture together and provide a water-resistant surface. Occasionally, material for gravel roads is taken from stockpiles produced for other uses, particularly those for roadway base material or fill for building sites. These are generally designed to drain quickly and contain minimal plastic fines, and will thus form a very loose surface if used for a gravel road. Additionally, materials graded for roadway bases have larger stones that will make maintenance with a grader difficult (Skorseth and Selim 2000).

South Dakota's gravel surfacing gradation is shown in table 6. In addition to these gradation requirements, the material retained on the Number 4 sieve should have 30 percent or more particles with one or more fractured faces. Furthermore, the PI of gravel surfacing material should be between 4 and 12, and the maximum allowable loss during the L.A. abrasion test is 40 percent.

While South Dakota's counties are not bound by the State's gravel surfacing specifications, due to gravel supply concerns, rising costs, and tightening budgets, some agencies would like to use a range of aggregate materials beyond those that meet the State's gravel surfacing specifications. Currently some South Dakota Districts use modified versions of the statewide specification, some use an aggregate that may meet the statewide specification for base layer aggregate, and still others may use straight pit run or natural gravel. These materials have a lower initial cost, but may have higher maintenance costs in the form of more frequent grading and re-graveling requirements.

Alternatively, some Districts are using materials that exceed the State gravel surfacing specification in an attempt to decrease gravel loss and the need for re-graveling. Included here are the use of materials with a higher PI and therefore a greater cohesion. In addition, some Districts mix in natural clays to raise the plasticity of the gravel. And, as mentioned earlier, some local agencies use more crushed stone with a higher percentage of fractured faces. Finally, other Districts use chemical stabilizers or dust palliatives such as chlorides and others previously mentioned. These materials have a higher initial cost, but may result in improved performance and decreased maintenance costs. The decision process for quality of gravel material may be compared to the decision of whether or not to pave a gravel road and must consider the tradeoff between initial costs and maintenance costs over time (Zimmerman and Wolters 2004).

Table 6: South Dakota's gravel surfacing gradation

Sieve Size	Percent Passing
¾-inch	100
½-inch	--
No. 4	50 to 78
No. 8	37 to 67
No. 40	13 to 35
No. 200	4 to 15

5.1.6. Maintenance of Gravel Roads

Traditional gravel road maintenance consists of removing ruts, potholes, and washboards with a grader, as well as occasionally reshaping the whole road to restore crown. A study by the Wyoming Department of Transportation classifies construction and maintenance activities into eleven categories for the purpose of future cost estimation (Huntington and Ksaibati 2009):

- Snow plowing.
- Grading.
- Cleaning ditches.
- Mowing and spraying.
- Spot maintenance.
- Reshaping ditches.
- Applying dust suppressant.
- Regraveling.
- Spot repairs.
- Rehabilitation.
- Reconstruction.

The cost of the first four activities vary only with length of roadway treated, while the costs of the remaining items increase with both length of roadway treated and with increasing roadway classification.

A common maintenance activity used for all gravel roads, including those in South Dakota, is regrading. A grader is used to rework the surface of the road, removing surface distresses. If necessary, new gravel is applied in problem areas in a process referred to as regraveling. If available, a roller is used to compact the gravel. New maintenance developments that were described in the previous version of the gravel maintenance handbook include improvements to technology: more durable grader blades, grader-mounted rollers, windrow pulverizers, and rock rakes (Skorseth and Selim 2000).

One new maintenance technique that may decrease the need for new gravel was evaluated in a Canadian study (Berthelot and Carpenter 2003). A rock rake was used to collect gravel from the side of the road. This method was successful in recovering rock that could then be used for resurfacing; however, the process was quite time- and labor-intensive.

5.1.7. Environmental Effects on Gravel Roads

The semi-arid environment of South Dakota poses additional challenges in gravel road maintenance. Extreme freeze-thaw cycles cause rapid changes in support as frost advances and retreats in and out of the subgrade. Moisture present in the subgrade combined with extended periods of very cold weather contribute to the formation of ice lenses, which can result in frost heave and rapid weakening and collapse upon thawing. Furthermore, large changes in moisture levels mean that roads may experience dusting in dry times and mud from pumping subgrades or rutting from weakened subgrades in wet times. Additionally, many of the gravel roads have poorly drained subgrades, which weaken in wet weather. The presence of expansive clays is also of concern, as considerable volume changes may result due to changes in subgrade moisture.

A study of gravel roads in Wyoming found that the effects of precipitation were much more significant than seasonal changes (Huntington and Ksaibati 2007). The study also noted that deterioration rates in the winter and spring were relatively easy to predict based on past performance. However, isolated and unpredictable rain events, particularly in the fall, caused rapid deterioration of the roads that was difficult to predict.

5.1.8. Literature Review Summary

Aggregate loss is recognized as a major problem in the performance of gravel roads and one that has been extensively researched. It is broadly categorized into three groups: dusting, casting, and incorporation. Aggregate loss has traditionally been measured by periodically recording differences in vertical elevation of the road surface over time. However, due to the potential for significant error in this method of measurement, largely because of the effects of frost heave and subgrade consolidation, this method has limited applicability. Another method of measuring aggregate loss is digging pits and visually observing the gravel depth, but that method is destructive and time-consuming.

There are numerous surface distress rating systems available, but most are not detailed or objective enough for use in a research project. The best rating system available for a small-scale detailed research project is the objective rating system developed by the FHWA-FLHD, which measures quantities of washboarding, potholing, raveling, and rutting, and includes a qualitative assessment of dust problems.

A number of researchers have evaluated the performance of stabilizers for dust prevention, minimization of gravel loss, and reduction of maintenance. Chlorides are widely used, although organic non-petroleum products such as lignosulfonate have been used successfully as well. The performance of most stabilizers varies depending on the type of surfacing material.

In South Dakota and many other areas, diminishing aggregate sources have led to an increased variety of gravel sources used for gravel roads. In using these different sources, some areas are still following State specifications while others are using pit run gravels and other materials that do not meet the State gravel specification. Still others are using materials or construction methods that exceed State specifications, such as better compaction, higher plasticity, or the use of stabilizers.

In the literature review, very little new information was found on gravel road maintenance or rehabilitation, or the effects of South Dakota’s climate on gravel roads.

5.2. Survey Approach and Results

As part of this project, an electronic survey was conducted to identify South Dakota best practices for the performance, design, construction, maintenance, rehabilitation, and stabilization of gravel surfacing. The survey results identified specific local concerns related to gravel surfacing by South Dakota local agencies, providing important data on practices and problems associated with gravel roads that can help guide the direction of the study. This work was led by MTTI with assistance from APTech.

5.2.1. Gravel Roads Survey Question Development

The gravel roads survey was developed to collect data in four general areas: material specifications, material testing, construction, and maintenance relating to local and tribal agency owned gravel surfaced roads. A copy of the survey is presented in Appendix B.

5.2.2. Survey List Generation

The distribution list for the survey was developed using numerous information sources to determine a contact name, mailing address, and where possible an e-mail address for the prime contact at each agency. The contact list included at least one contact for each of the 66 counties, the 13 cities with populations over 5,000, and the nine tribal governments in South Dakota.

The contact list for South Dakota county governments was generated from a list of county road superintendents supplied by the South Dakota DOT. This list contained contact names and mail addresses, but did not contain e-mail addresses. E-mail addresses were cross referenced and added to the contact list from the National Association of County Engineers (NACE) records. The completed list contained contacts and mailing addresses for all 66 counties, and e-mail addresses for 32 counties.

The contact list for South Dakota city governments was generated by searching for contact information for the city engineer from city web sites. Phone calls were made in cases where the city engineer was not listed. Cities contacted include Aberdeen, Brandon, Brookings, Huron, Madison, Mitchell, Pierre, Rapid City, Spearfish, Sturgis, Vermillion, Yankton, and Watertown.

The contact list for tribal governments was provided by the Northern Plains Tribal Technical Assistance Program (TTAP). Contact names and e-mail addresses were provided for each of the nine tribal governments with land inside of South Dakota.

The full list of individual who were asked to complete the survey is provided in Appendix B.

5.2.3. Distribution of the Surveys

Local and tribal agency contacts with e-mail addresses were sent an e-mail request to complete the survey with a link to the survey website. Contacts without an e-mail address were mailed a request letter and the survey, and could respond by fax, mail, or through the online survey.

Initial distribution of the survey via e-mail and hard mailings was on August 24, 2010. E-mail reminders were sent to individuals who had not completed the survey on September 7, 2010 and on September 17, 2010. The survey was closed on September 22, 2010.

5.2.4. Survey Responses

Nineteen agencies completed the survey by the closing date, consisting of 16 counties and 3 cities. One additional county responded that they do not have any gravel roads, bringing the total number of responses to 20. This represents an overall response rate of approximately 26 percent for counties and 23 percent for cities, which are both around the normal rate for unsolicited surveys of this nature. Responses for each of the survey questions, summary tables, and maps of responses by location are provided in Appendix B.

The majority of respondents primarily use aggregate surfacing that meets the SDDOT gravel surfacing specification, with 10 of the 19 agencies indicating that they use the SDDOT-specified material exclusively, and another 6 respondents indicating that they use the State specification at least 90 percent of the time. The next common material type was unprocessed or coarse screened "bank run," with seven of the 19 agencies reporting using it between 2 and 50 percent of the time. One agency reported using a small amount of asphalt millings (1 percent), and another reported that 75 percent of the materials they use are asphalt millings and concrete grindings. These results are summarized in table 7 below. Only six agencies reported using a modified version of the SDDOT gravel surfacing specification, five of which involve using a modified range of allowable PI.

Table 7: Types of materials used by counties, reported as percent by weight of material used.

Materials Used	Responses
100% state spec	9 counties 1 city
≥ 90% state spec ≤ 10% bank run	5 counties
≥ 90% state spec ≤ 10% asphalt millings or concrete grindings	1 county
75% state specs 25% bank run	1 county
≤ 50% state specs	2 cities

Most of the agencies (12 of 19) reported "most of the time" or "all of the time" when asked how often they test the material to determine whether it meets specifications. Only three reported "rarely" or "never," suggesting that most agencies understand that testing to ensure materials meet the specifications is important. The most commonly conducted tests are gradation and plasticity, although about half the agencies that conduct tests also check percent fractured faces. None of the respondents test for wear.

Regarding construction, nine agencies use compaction on the majority of their gravel road projects and 11 use windrowing, watering, or both during placement. Four agencies reported using some type of stabilizer, while another eight reported a little use of stabilizers and seven reported no use of stabilizers.

The major factor determining when maintenance grading was required was listed as "scheduled cycles" by nine agencies, "surface defects" by six agencies, "average daily traffic" by one agency, and a combination of factors by two agencies. Of the agencies reporting, seven reported that maintenance grading is used 11 or more times per year, four reported that it is used 7 to 10 times per year, and four reported using it 3 to 6 times per year. All the agencies that responded that they conduct maintenance grading 11 or more times per year were located in the eastern half of the state.

With regards to re-graveling, the most frequent response given for conducting it was "lack of adequate material for grading operations" followed by "exposed subsurface material."

The survey results did not reveal that there is much innovation going on with gravel surfacings. While 10 respondents indicated that they employed innovative practices, most of the practices cited were not necessarily "innovative," but really represented common best practices.

A large majority of the respondents (17 of the 19) felt it was more cost effective to use more expensive processed materials that meet specifications rather than less expensive, unprocessed materials that do not meet specifications.

Overall, the survey results indicated that the respondents recognized the cost effectiveness of using high-quality materials, tested their materials to ensure they met specifications, and thought that the use of higher plasticity materials would be advantageous. The survey also suggested that maintenance grading is a frequent occurrence, being routinely scheduled to occur roughly on a monthly basis.

5.2.5. Follow-Up Interviews

Follow-up telephone interviews were conducted by MTTI. Interviews were recorded using a digital audio recorder with the interviewee's consent. Interviews were conducted with agencies that had indicated that they had innovative material, maintenance, or construction practices on the gravel surfacing guidelines survey. Another pool of interview candidates was developed from an interview with Ken Skorseth from the South Dakota LTAP center. Mr. Skorseth identified several local agencies that use innovative practices at their agency. Nine interviews were conducted in total, including one with Mr. Skorseth; four of the interviews were with survey respondents. Interview summaries are included in Appendix C.

The interviews focused on determining innovative practices that may not have been captured in the survey. Among the innovative technologies mentioned were the "walk and roll" packer, shown in figure 3, and a lightweight towed blading device, referred to as a "groomer," which could be towed by a tractor or heavy-duty pick-up truck. In both cases, the equipment was not considered to be as effective as heavier, separate equipment, but was believed to be more cost effective as only a single piece of equipment is employed to complete the task.

Figure 3: Walk and roller packer attached to a grader
(image from http://www.walknrollpackers.com/)

Some agencies discussed blending aggregate sources on grade to achieve the desired plasticity and others used salt-based stabilizing agents (either calcium chloride or magnesium chloride) or even proprietary natural materials composed primarily of soybean oil. A couple of agencies discussed the use of recycled materials, including both asphalt millings and crushed concrete.

5.3. Test Section Construction and Monitoring Results

5.3.1. Introduction

The key part of this study was the construction and monitoring of gravel surfacing test sections. Counties representing the geographical diversity of South Dakota were asked to construct these test sections to test the effects of different materials on performance and maintenance. In addition to the counties' responsibility to construct the sections and provide certain information about the locations, the SDDOT was responsible for materials collection and testing, and APTech, with support from SDDOT, was responsible for documenting site conditions and carrying out periodic performance evaluations.

5.3.2. Test Site Overview

Sites in three regions—eastern, central, and western South Dakota—were sought to represent the different climatic regions of the state. For site selection, a minimum traffic level of 100 ADT was targeted. The three counties that volunteered to provide the test sections are Hand, Custer, and Brookings.

5.3.2.1. Materials

State specifications for gravel surfacing material include requirements of gradation, plasticity index (PI), and material processing (SDDOT 2004). Three different aggregate materials were planned for each test section. One material was to represent standard State specifications, one was to exceed the State specifications, and one was to not meet State specifications. The criterion for discriminating between the material categories was based on the PI of the material passing the #40 sieve for each gravel material. That was because most of the available gravel materials met the State requirements for crushing and gradation and would not provide a good means for categorizing each gravel material.

Since the State specification requires a PI for the material passing the #40 sieve to be in the range of 4 to 12, the definitions for each material quality category were established as follows:

- Substandard material – PI less than 4.
- Standard material – PI between 4 and 7.
- Above-standard material – PI between 7 and 12.

Unfortunately, the PI values for each gravel material do not provide for a clear classification into one of the three PI ranges. This is reflected in table 8, which summarizes the PI test results for each of the nine gravel materials. As can be seen, five of the nine PI results are on one of the two thresholds, while a sixth PI result (the 3 in Custer County) reclassifies an above-standard material into a substandard material. It should further be noted that each PI result shown is based on a test of a single sample from each stockpile. Because there can be significant test variability in the PI results for any given sample, there is some added uncertainty to the categorization of each material. Despite the flaws in categorizing the gravel materials, it is still possible to evaluate and compare their performance as if they were not categorized. However, if the quality of the gravel material is defined in large part by its PI within the ranges shown above, then these values could help explain any unexpected findings in the performance of the gravel materials.

Table 8: PI summary for all tested gravel materials.

Site (Geographic Region)	Aggregate Material		Plasticity Index (PI)
	Quality Level	Source/Description	
Hand County (Central)	Above-standard	Bone Bright	9
	Standard	Martinmas	4
	Substandard	Oakley	4
Custer County (Western)	Above-standard	STAAP + crusher fines	3
	Standard	STAAP	6
	Substandard	Bear Mountain	Non Plastic
Brookings County (Eastern)	Above-standard	Dupraz + clay	7
	Standard	Dupraz	4
	Substandard	Bowes	4

Gradation analyses were performed on stockpile materials (or windrow samples for road-mixed materials), after construction, and at each of three later performance inspections. Testing during the three performance periods was conducted to evaluate gradation changes over time that may have been caused by the loss of fines from dusting, the loss of material from cast-off, or the breakdown of the aggregate due to trafficking. Other tests performed on the gravel materials include unit weight, sulfate soundness, resistance to wear, fractured faces, and California bearing ratios (CBRs). The testing plan is summarized in table 9 below matches that set forth in the original research plan (see task 4 under Section 4). The test results are presented later in this report.

Table 9: Testing plan summary.

Test	Specification	Pre-Construction (Stockpile)	Post Construction	Two Intermediate Inspections	Final Inspection
Unit weight	AASHTO T 19	X	X		X
Gradation	AASHTO T 27	X	X	X	X
Specific gravity and absorption (fine aggregate)	AASHTO T 84	X			
Specific gravity (coarse aggregate)	AASHTO T 85	X			
Plasticity (liquid limit)	AASHTO T 89	X	X	X	X
Plasticity (plastic limit)	AASHTO T 90	X	X	X	X
Resistance to wear	AASHTO T 96	X			
Soundness	AASHTO T 104	X			
CBR	AASHTO T 193	X			X
Fractured faces	AASHTO T 335	X	X		X

5.3.2.2. Experiment Layout

To evaluate its effect on performance, compaction was added to the experiment as another level. The standard and substandard materials were constructed with and without initial compaction, while the above-standard material was only constructed with compaction. This resulted in five test sections for each site.

Each site was planned to be 1 mile long, with the experimental test section being about 1,000 feet long. Transition zones were established between each test section to help avoid the situation where the poor performance of one section affects that of an adjacent section. Appendix D provides additional construction information and plan view maps showing the layout of the test sections at each site.

5.3.2.3. Sampling and Testing Schedule

After construction, gravel material samples were obtained and tested by SDDOT at construction and at three selected times after construction for each of the three sites. Each of these times intentionally coincided with the performance inspections conducted at each site. The intended schedule was to collect and test samples from each site, immediately after construction, after the first winter, during the following fall, and then after the second winter. Due to construction timing of the Custer site, two fall inspections and one spring inspection were conducted. Table 10 presents the sampling/testing/ inspection schedule for each site. E1 (Event 1) refers to the period during or immediately after construction, while E2, E3, and E4 refer to one of the three performance monitoring events after construction; the material testing performed on stockpile samples before construction is referred to as E0.

Table 10: Sampling/testing/inspection schedule for each site.

Site (County)	2010			2011												2012												2013					
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
Hand	E1								E2				E3							E4													
Custer									E1				E2							E3					E4								
Brookings													E1							E2					E3								E4

5.3.3. Characteristics and Material Properties for the Three Test Sites

5.3.3.1. Hand County Test Site

The Hand County test site is located in the central region. The test site was located on an approximate 1-mile stretch of 198th St. just west of 369th Ave., east of the town of Miller. The five experimental sections were constructed in October 2010. A layout of the site is presented in Appendix D.

5.3.3.1.1. Traffic

Traffic levels on this road were measured by the SDDOT from October 19 through November 17, 2010. The counter was located approximately 1 mile west of the test section, although there were no turnoffs other than private driveways and farm field access between the counter and the site. Data collected included vehicle class, date and hour of passage, and direction of travel. The trucks hauling material from the Oakley and Martinmas pits had to cross the traffic counter on the way to the site, and as gravel placement and compaction proceeded October 20 through November 11 (estimated), the data were examined to determine what effect the construction traffic had on the traffic counts. Traffic was measured during fall harvest season and the site is located between farm fields.

Traffic levels were essentially the same throughout the week for cars, with an average of 21 cars per day Monday through Friday, and 23 cars per day Saturday and Sunday. For all other vehicle classes, almost entirely trucks, the Monday through Friday average was 64 vehicles per day, whereas the weekend average was only 48 vehicles per day.

5.3.3.1.2. Material Selection

Materials from three different gravel sources were used at the Hand County test site. The above-standard material was from the Bone Bright pit, the standard material was from the Martinmas pit, and the substandard material was from the Oakley pit. Due to construction timing, testing on the PI was not performed on the Oakley material before construction, but it was believed to be non-plastic based on past performance. However, a subsequent test showed that it had a PI of 4.

5.3.3.1.3. Layout

From east to west, the test sections at the Hand County site were:

- Bone Bright-compacted.
- Oakley-compacted.
- Oakley-uncompacted.
- Martinmas-uncompacted.
- Martinmas-compacted.

The first four test sections were 900-feet long with 100-feet transition zones between them. The last section, Martinmas (compacted), was only 600-feet long due to space constrictions. A 500-foot buffer zone was established at the east end to prevent a test section from being too close to a stop sign where vehicle braking could lead to washboarding. Additional construction information and a plan view map showing the layout of the Hand County test sections is presented in Appendix D.

5.3.3.1.4. Material Testing

Gradation

Stockpile (pre-construction) gravel gradations for the Hand County test site are summarized in table 11 and graphically illustrated in figure 4. Each gradation shown is based on a test performed by SDDOT from a single stockpile sample.

Table 11: Hand County gravel gradation points.

Sieve Size	State Specs	Bone Bright	Martinmas	Oakley
3/4 in	100	98.3	97.8	97.3
1/2 in	-	86.5	89.2	87.7
#4	50-78	64.5	70.4	68.9
#8	37-67	53.0	59.4	54.9
#40	13-35	17.9	26.6	15.7
#80	-	10.7	15.7	9.2
#200	4-15	8.0	10.9	7.0

Note: Shaded areas indicate out-of-specification gradation points.

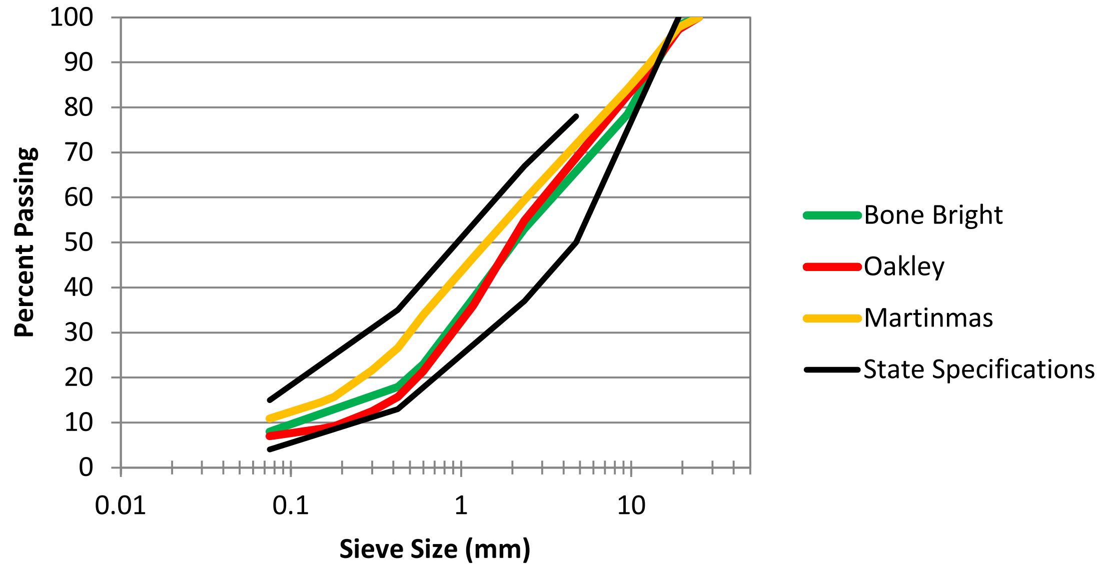

Figure 4: Hand County gravel gradation curves.

None of the three gravel materials met the requirement for 100 percent passing the ¾-inch sieve. However, all three gravel materials did meet all of the other required gradation requirements. The Bone Bright and Oakley gradation curves are very similar.

In addition to the pre-construction testing, gradation testing was performed by SDDOT on samples obtained during each of the four subsequent sampling/testing/inspection periods (see E1, E2, E3, and E4 in table 10). Tables 12 through 16 provide the gradation test results for each of the periods. As before, each gradation curve is the result of a test on a single gravel sample. Because of the interest in evaluating the change in gradation over time, the average change in gradation per month for each sieve was determined and included in each of the tables.

Table 12: Bone Bright-compacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	98.3	98.0	98.3	98.7	97.8	0.01
1/2 in	86.5	86.7	86.8	85.8	88.8	0.08
#4	64.5	63.9	65.6	64.0	68.9	0.18
#8	53.0	51.6	53.6	52.6	57.4	0.21
#40	17.9	19.2	19.1	21.8	25.3	0.33
#80	10.7	11.8	11.9	14.2	16.6	0.27
#200	8.0	9.1	9.2	11.0	12.7	0.21

Table 13: Martinmas-compacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	97.8	97.3	97.3	97.2	97.6	0.00
1/2 in	89.2	88.2	87.9	86.3	89.4	-0.01
#4	70.4	66.9	68.6	66.9	66.8	-0.11
#8	59.4	55.5	56.1	54.1	53.8	-0.20
#40	26.6	25.5	24.7	23.8	24.4	-0.11
#80	15.7	16.5	15.9	14.6	16.6	0.00
#200	10.9	11.7	11.1	10.5	12.3	0.03

Table 14: Martinmas-uncompacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	97.8	95.6	97.4	97.8	97.0	0.03
1/2 in	89.2	83.3	87.2	87.5	87.4	0.06
#4	70.4	63.2	66.1	69.1	69.1	0.12
#8	59.4	51.7	53.8	56.9	57.9	0.10
#40	26.6	24.4	25.4	27.8	30.0	0.21
#80	15.7	15.9	16.6	18.9	20.2	0.23
#200	10.9	10.2	11.0	13.1	13.7	0.17

Table 15: Oakley-compacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	97.3	94.3	96.4	95.4	96.0	0.00
1/2 in	87.7	84.1	86.3	88.6	88.1	0.13
#4	68.9	66.3	69.1	70.9	70.9	0.18
#8	54.9	54.6	57.8	58.6	57.5	0.18
#40	15.7	15.6	18.8	18.1	21.4	0.28
#80	9.2	9.0	11.0	10.8	13.4	0.20
#200	7.0	6.3	8.1	8.0	9.9	0.15

Table 16: Oakley-uncompacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	97.3	93.9	97.2	95.7	96.4	0.03
1/2 in	87.7	79.1	86.3	85.9	88.6	0.24
#4	68.9	49.5	66.9	66.3	72.9	0.64
#8	54.9	39.3	53.7	52.9	58.5	0.54
#40	15.7	10.4	15.7	17.0	22.4	0.44
#80	9.2	6.1	10.3	10.9	14.4	0.32
#200	7.0	4.6	8.2	8.3	10.6	0.23

The following observations can be made about the results of the gravel material gradation testing over time. It should be noted that attention is only given to the sieves that show a change.

- The Bone Bright-compacted gravel (table 12) shows a *small* increase over time in the percent passing the finer fractions. The #4 and smaller sieves show clear increases, with the #40 and #80 sieves showing the greatest increase.
- The Martinmas-compacted gravel (table 13) shows *no* increase over time in the percent passing on any of the sieves. The #4, #8, and #40 sieves show a *very slight* decrease in the percent passing over time.
- The Martinmas-uncompacted gravel (table 14) shows a *slight* increase over time in the percent passing the finer fractions (#4 and smaller) over time. The largest increases are on the #40, #80, and #200 sieves.
- The Oakley-compacted gravel (table 15) shows a *slight* increase over time in the percent passing the finer fractions over time. The increase is reflected in the #4 and smaller sieves, with the #40 sieve showing the greatest increase.
- The Oakley-uncompacted gravel (table 16) shows a *moderate* increase over time in the percent passing all sieves, except for the ¾-inch. The increase is about 2 to 3 times greater than the corresponding Oakley-compacted gravel for the ½-inch, #4, and #8 sieves, and about 1.5 times greater for the #40, #80, and #200 sieves.

The two primary purposes for the gradation testing were 1) to confirm that the gravel material met the gradation requirements established for the experiment and 2) to provide a basis for evaluating the change in gravel gradation over the course of the experiment. For purposes of the study, it is assumed that any increases in percent passing are attributable to the effects of vehicle trafficking and maintenance operations.

- With the exception of a small percent retained on the ¾-inch sieve for all three gravels, all three were in conformance with SDDOT specifications.
- The Bone Bright-compacted, Oakley-compacted, and Oakley-uncompacted gradation results over time reflect a small, but significant increase in the percent passing the #4 and smaller sieve sizes. This is an indication that the Bone Bright and Oakley gravels are slowly breaking down under traffic. The Martinmas-compacted gravel shows no change in gradation while the Martinmas-uncompacted gravel shows a very small amount of aggregate breakdown.

Plasticity Index

The Hand County test site PI results over time are summarized in table 17. Each PI value shown is the result of an SDDOT test on a single sample of gravel material. The last column of this table shows the average rate of change in PI on a per month basis.

Table 17: Hand County PI results over time.

Material – Method	PI by Event Number					Average Change in PI per Month
	E0	E1	E2	E3	E4	
Bone Bright-compacted	9	10	10	14	12	0.17
Martinmas-compacted	4	6	4	6	7	0.10
Martinmas-uncompacted		4	4	5	6	0.10
Oakley-compacted	4	4	5	7	10	0.29
Oakley-uncompacted		7	8	9	7	0.12

Despite the inherent variability in PI testing, the results indicate a slight increase in the PI over time for all the gravel materials, both compacted and uncompacted. The increase in PI for the Oakley-compacted gravel is the greatest and most likely to indicate a meaningful change in PI over time.

The two primary purposes for conducting PI testing were 1) to confirm that the gravel materials met the requirements established for the experiment design and 2) to evaluate any change in material plasticity over time that might have impacted performance.

- Based on the PI criteria for discriminating between the quality of the gravel materials used in each test section, all five test sections technically satisfy their initial groupings. However, the fact that both the Oakley and Martinmas gravels have a PI that is on the threshold between two quality levels does increase the likelihood that two gravel materials may exhibit the same performance.
- All five gravels show some increase in PI over the period of the experiment; however, only the Oakley-compacted gravel reflects a meaningful increase. By the end of the experiment, the Bone Bright and Oakley gravels maintained their respective above-standard and standard classifications, while the Martinmas gravel moved from a substandard to standard classification.

CBR

CBR values for the Hand County test site are summarized in table 18. Each CBR shown is the average of three tests performed by SDDOT on separate samples of gravel material. The coefficient of variation (COV) is the standard deviation of CBR divided by the mean CBR, expressed as a percent.

Table 18: Hand County CBRs, measured at 0.1-inch penetration.

Material – Method	Stockpile (E0)				Final Inspection (E4)				Ratio of Final CBR to Stockpile CBR	
	Soaked		Unsoaked		Soaked		Unsoaked			
	Avg	COV	Avg	COV	Avg	COV	Avg	COV	Soaked	Unsoaked
Bone Bright-compacted	5.7	17%	19.3	27%	10.7	35%	3.3	69%	1.88	0.17
Martinmas-compacted	8.0	18%	7.3	46%	3.0	33%	1.7	35%	0.38	0.23
Martinmas-uncompacted					13.0	71%	4.3	53%	1.63	0.59
Oakley-compacted	11.7	4%	3.0	46%	44.3	9%	20.3	65%	3.79	6.77
Oakley-uncompacted					18.0	71%	7.7	20%	1.54	2.57

The following observations can be made about the CBR results.

- The variability of the CBR results from the stockpile is low (COV of 4 to 18%) for the soaked samples and clearly higher (COV of 27 to 46%) for the unsoaked samples.
- The variability of the CBR results from the final inspection is high (COV of 9 to 71%) for the soaked samples and also high (COV of 20 to 69%) for the unsoaked samples.
- Overall, the variability of the CBR results is much higher for the final inspection tests as compared to the stockpile tests.
- For the Bone Bright gravel overall, the CBR (soaked) is well below the expected range for a gravel material.
- For the Bone Bright-compacted gravel, the CBR results show an increase in strength from stockpile to final inspection tests for the soaked samples, but a large decrease in strength for the unsoaked samples.
- For the Martinmas gravel overall, the CBR (soaked) is well below the expected range for a gravel material.
- For the Martinmas-compacted gravel, there is a definite reduction in CBR from stockpile to final inspection tests for both the soaked and unsoaked samples.
- For the Martinmas-uncompacted gravel, there is a definite increase in CBR from stockpile to final inspection tests for the soaked samples and a significant decrease for the unsoaked samples.
- Although the initial CBRs (soaked) were low for all three gravels, the results from the final inspection tests indicate a significant increase in strength. Of the five test sections, only the Martinmas-compacted gravel showed a loss in CBR (soaked) from stockpile to final inspection tests.
- For the Oakley gravel overall, the CBR (soaked) is below the expected range for a gravel material.
- For the Oakley-compacted gravel, the increase in CBR from stockpile to final inspection tests is very high for the soaked samples and even higher for the unsoaked samples.
- For the Oakley-uncompacted gravel, the increase in CBR from stockpile to final inspection tests is high for the soaked samples and very high for the unsoaked samples.

There was no minimum CBR requirement for the gravels, so the primary purpose of the CBR testing was to monitor the strength of gravel to determine if it was correlated with section performance. For purposes of this analysis, the focus was on CBR test results determined under soaked conditions using 0.1 inch of piston penetration.

The initial CBR values (6, 12, and 8) indicate that all three gravels have a relatively low strength. By the end of the experiment, four of the five gravels showed a significant increase in strength while the last one (Martinmas-compacted) showed a significant decrease in strength. Since the gravels that showed an increase in strength corresponded directly to the gravels that exhibited breakdown over time, it is reasonable to conclude that the increase in strength is related to the breakdown of the gravel into a more load-resistant gradation.

Fractured Faces

The percent fractured faces was measured on the stockpile material, after construction, and at the end of the monitoring period. The results are provided in table 19. Each result shown is based on SDDOT's test of a single sample of gravel material.

Table 19: Hand County fractured faces testing results over time.

<table>
<tr><th>Material – Method</th><th>Stockpile (E0)</th><th>1st Inspection (E1)</th><th>Final Inspection (E4)</th></tr>
<tr><td>Bone Bright-compacted</td><td>51% 1-face
32% 2-face</td><td>59% 1-face
41% 2-face</td><td>43% 1-face
32% 2-face</td></tr>
<tr><td>Martinmas-compacted</td><td rowspan="2">68% 1-face
47% 2-face</td><td>60% 1-face
41% 2-face</td><td>33% 1-face
31% 2-face</td></tr>
<tr><td>Martinmas-uncompacted</td><td>72% 1-face
38% 2-face</td><td>50% 1-face
44% 2-face</td></tr>
<tr><td>Oakley-compacted</td><td rowspan="2">58% 1-face
40% 2-face</td><td>66% 1-face
34% 2-face</td><td>38% 1-face
32% 2-face</td></tr>
<tr><td>Oakley-uncompacted</td><td>73% 1-face
32% 2-face</td><td>44% 1-face
41% 2-face</td></tr>
</table>

Testing for fractured faces on the gravel materials serves two purposes. One is to confirm that the SDDOT specification (i.e., minimum 30% of the aggregate retained on the #4 sieve with one or more fractured faces) is met by each of the gravels. The other is to evaluate the change in fractured faces over time.

- The percent fractured faces (1 face) for the Bone Bright, Oakley, and Martinmas gravels was 51%, 58%, and 68%, respectively. So the 30% minimum requirement is satisfied.
- By the end of the experiment, the percent fractured faces (for one face) decreased considerably for all five test sections. However, all still passed the SDDOT minimum requirement.
- The reduction in fractured faces could be explained by traffic wear over time; however, it contradicts the significant increase in strength (CBR) in four of the test sections.

Unit Weight

The unit weight of all gravel materials was measured by SDDOT before construction (E0, stockpile samples), after construction (E1), and during the final inspection (E4). The results are presented in table 20. Each unit weight shown is based on a test performed on a single gravel sample.

Table 20: Hand County unit weights over time.

Material – Method	Unit Weight (lb/ft^3)			Ratio of Unit Weights	
	E0	E1	E4	E1/E0	E4/E0
Bone Bright-compacted	97	95	132	0.98	1.36
Martinmas-compacted	93	102	136	1.10	1.46
Martinmas-uncompacted		108	137	1.16	1.47
Oakley-compacted	93	102	134	1.11	1.46
Oakley-uncompacted		102	128	1.11	1.39

The following key observations that can be made about the unit weight results.

- The unit weights after construction (E1) for all the gravel materials are relatively low (95 to 108 lb/ft^3).
- For the Bone Bright-compacted gravel, the unit weight after construction (E1) is slightly lower than the stockpile (E0) unit weight. Because of the compactive effort, the expectation is that it should be higher.
- For the Martinmas-compacted gravel, the unit weight after construction (E1) is higher than the stockpile (E0) unit weight, although not as high as expected.
- For the Martinmas-uncompacted gravel, the unit weight after construction (E1) is higher than the stockpile (E0) unit weight, and within the expected range.
- There is a large increase in unit weight by the end of the experiment (E4) for all of the gravel materials as compared to the unit weight after construction (E1).
- For the Oakley-compacted gravel, the unit weight after construction (E1) is higher than the stockpile (E0) unit weight, although not as high as expected.
- For the Oakley-uncompacted gravel, the unit weight after construction (E1) is the same as the Oakley-compacted gravel, despite the fact that it was not compacted.

South Dakota's standard specifications do not have a requirement on the unit weight (or density) of the gravel material, so it is not a critical property for gravel road construction. As shown above, the unit weights measured for the Hand County gravels after construction are relatively low. However, over time and traffic, the unit weights for all gravels increased considerably by the end of the experiment.

Absorption and Specific Gravity

Table 21 provides the absorption and specific gravity results from tests performed by SDDOT on stockpile samples of the three gravel materials used at the Hand County test site. Each result shown is based on a single test of each gravel.

Table 21: Hand County absorption and specific gravity results.

Material	Absorption		Specific Gravity	
	Fine Agg.	Coarse Agg.	Fine Agg.	Coarse Agg.
Bone Bright	4.3	2.9	2.273	2.553
Martinmas	3.3	3.3	2.486	2.541
Oakley	3.7	3.2	2.452	2.537

There are no gravel specification requirements for absorption or specific gravity. The absorption values in table 21 indicate the presence of some voids in the aggregate, while the specific gravities are relatively low. These properties probably have little effect on the gravel performance.

Soundness and Resistance to Wear

Sulfate soundness and resistance to wear (L.A. abrasion) tests were performed by SDDOT on the stockpile samples for all three Hand County gravel materials. These results are summarized in table 22. Each result shown is based on a single test for each gravel.

Table 22: Hand County soundness and resistance to wear.

Material	Soundness		Resistance to Wear
	Fine Agg.	Coarse Agg.	
Bone Bright	12	9	21
Martinmas	8	10	25
Oakley	9	11	23

Soundness and resistance to wear are significant aggregate tests because they give an indication of the rate at which an aggregate will degrade under exposure to freezing/thawing and traffic, respectively. Following is a comparison of the test results for the Hand County gravel materials.

- Soundness – The South Dakota standard specifications requirement for sodium sulfate soundness is 15% maximum for the both the fine and coarse aggregate material. The soundness test results shown in table 22 show values in the range of 8 to 12, so all three gravels met this requirement.

- Resistance to wear – The specification requirement for L.A. Abrasion is a maximum of 40. The values for the three aggregates are in the range of 21 to 25, so all three gravels satisfy the resistance requirement too.

5.3.3.2. Custer County Test Site

The western region is represented by Custer County. The test site consists of five test sections split between two roads northwest of the City of Custer. Three of the test sections are located on Medicine Mountain Rd. (Route 297) and the remaining two are on Saginaw Rd. (Route 285).

5.3.3.2.1. Traffic

Traffic data for the Custer County test site were collected by SDDOT from April 28 to May 11, 2011. The traffic levels were 92 and 63 vehicles per day for Medicine Mountain Rd. (STAAP test sections) and Saginaw Rd. (Bear Mountain test sections), respectively. There is no information on the split between trucks and automobiles.

5.3.3.2.2. Material Selection

The gravel materials for the Custer County test site came from two primary sources. The standard and above-standard gravel materials were obtained from the STAAP pit. The difference between the two is that the above-standard gravel material was produced by adding limestone crusher fines. The substandard material was obtained from the Bear Mountain pit (a U.S. Forest Service source).

5.3.3.2.3. Layout

The Custer County test sections are defined as follows:

- STAAP plus crusher fines-compacted.
- STAAP-compacted.
- STAAP-uncompacted.
- Bear Mountain-compacted.
- Bear Mountain-uncompacted.

The STAAP plus crusher fines section and the other two STAAP test sections were located on Medicine Mountain Rd. The STAAP plus crusher fines section was located at the south end of the test section and was 890 feet long. The STAAP-compacted section was located on the north end and was 670 feet long. The STAAP-uncompacted section was just south of the compacted section, and was 405 feet long. A transition zone of 20 feet was established between the STAAP-compacted and STAAP-uncompacted sections, and a transition zone of 67 feet was established between the STAAP-uncompacted and STAAP plus crusher fines sections. Additional construction information and a plan view map showing the layout of the site is presented in Appendix D.

The two Bear Mountain test sections are located on Saginaw Rd., just north of a stop sign. Each section is 530 feet long and there is a 20-ft transition zone between the two. No buffer zone was left between the uncompacted section and the stop sign; however, performance measurements were not taken near the stop sign to avoid gathering data influenced by braking action.

Figures 5 and 6 provide aerial views of the Custer County site. As can be seen, there is some slight horizontal curvature along each section of roadway, primarily in the STAAP-uncompacted and Bear Mountain-compacted test sections.

Figure 5: Layout of two STAAP and STAAP plus crusher fines sections (Google Earth images).

Figure 6: Layout of two Bear Mountain test sections (Google Earth images).

5.3.3.2.4. Material Testing

Gradation

Initial gradations for Custer County are summarized in table 23 and illustrated in figure 7. The STAAP and Bear Mountain data reflect samples taken from the gravel stockpiles, while the STAAP plus crusher fines data came from samples taken from the windrow after mixing the material on the road surface.

Table 23: Custer County gravel gradation points.

Sieve Size	State Specs	STAAP + crusher fines	STAAP	Bear Mountain
3/4 in	100	100.0	100.0	97.6
1/2 in	-	89.7	94.3	79.9
#4	50-78	56.1	61.3	50.9
#8	37-67	40.3	45.3	37.4
#40	13-35	21.4	25.5	22.1
#80	-	16.9	20.1	18.6
#200	4-15	12.5	13.3	13.7

Note: Shaded areas indicate out of specification gradation points.

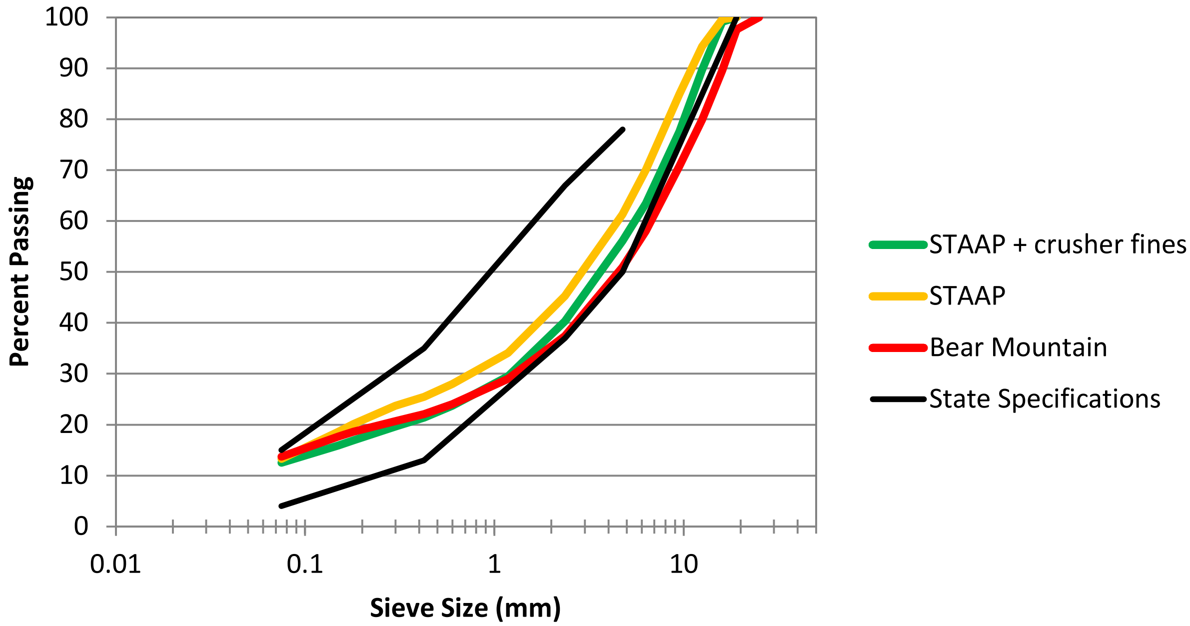

Figure 7: Custer County gravel gradation curves.

Both the STAAP and STAAP plus crusher fines materials met all the gradation requirements. However, the Bear Mountain material did not meet the requirement for 100 percent passing the ¾-inch (19-mm) sieve. Also, it is almost too coarse on the #4 (4.75-mm) and #8 (2.36-mm) sieves. Overall, the shapes of all three gradation curves are very similar.

In addition to the pre-construction testing, SDDOT performed gravel gradation testing on samples from all four subsequent inspection periods (E1, E2, E3, and E4). The key gradation points over time are presented for each test section in tables 24 through 28. Like the pre-construction testing, each gradation curve is the result of a test on a single gravel sample. Because of the interest in evaluating the change in gradation over time, the average change in gradation per month for each sieve was determined and included in each of the tables.

Table 24: STAAP plus crusher fines-compacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	100.0	99.9	99.9	98.3	99.6	-0.05
1/2 in	89.7	89.4	89.4	87.9	92.7	0.11
#4	56.1	55.1	55.1	52.9	61.3	0.21
#8	40.3	39.4	39.4	40.5	45.7	0.29
#40	21.4	20.6	20.6	21.3	24.2	0.16
#80	16.9	16.2	16.2	16.2	18.4	0.08
#200	12.5	11.8	11.8	11.6	13.1	0.03

Table 25: STAAP-compacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	100.0	99.8	99.8	98.7	100.0	-0.02
1/2 in	94.3	89.2	89.2	87.9	91.1	-0.11
#4	61.3	50.8	50.8	53.4	51.0	-0.27
#8	45.3	37.6	37.6	42.2	39.8	-0.04
#40	25.5	21.0	21.0	25.8	24.6	0.13
#80	20.1	16.0	16.0	19.7	18.2	0.06
#200	13.3	11.2	11.2	13.6	11.8	0.02

Table 26: STAAP-uncompacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	100.0	98.8	99.9	100.0	99.8	0.03
1/2 in	94.3	83.8	93.0	92.8	94.1	0.26
#4	61.3		59.9	58.3	62.1	0.01
#8	45.3	45.6	45.6	44.4	47.1	0.05
#40	25.5	26.9	26.9	25.2	27.0	0.01
#80	20.1	20.8	20.8	19.8	20.1	-0.03
#200	13.3	14.3	14.3	14.2	13.2	-0.02

Table 27: Bear Mountain-compacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	97.6	97.6	97.6	97.5	95.9	-0.08
1/2 in	79.9	77.8	77.8	83.5	77.9	0.07
#4	50.9	47.7	47.7	52.4	46.0	-0.07
#8	37.4	36.3	36.3	41.3	33.9	-0.03
#40	22.1	23.1	23.1	25.6	20.4	-0.04
#80	18.6	19.8	19.8	21.6	17.3	-0.04
#200	13.7	15.2	15.2	16.4	13.2	-0.02

Table 28: Bear Mountain-uncompacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	97.6	96.6	96.6	95.5	96.5	-0.06
1/2 in	79.9	75.2	75.2	75.8	79.7	0.07
#4	50.9	45.2	45.2	46.3	49.8	0.05
#8	37.4	34.5	34.5	34.8	37.4	0.05
#40	22.1	20.7	20.7	21.1	22.2	0.03
#80	18.6	17.7	17.7	18.0	18.9	0.03
#200	13.7	13.4	13.4	13.8	14.7	0.06

The following observations are made about the results of the gravel material gradation testing over time, focusing solely on the sieves that show a change.

- The STAAP plus crusher fines-compacted gravel (table 24) shows a *small* increase over time in the percent passing on three sieves: the #4, #8, and #40.
- The STAAP-compacted gravel (table 25) shows a *small* decrease over time in the percent passing on one sieve, the #4.
- The STAAP-uncompacted gravel (table 26) shows a *small* increase over time in the percent passing on one sieve, the ½-inch.
- The Bear Mountain-compacted gravel (table 27) shows *no* change over time in the percent passing on any of the sieves.
- The Bear Mountain-uncompacted gravel (table 28) also shows *no* change over time in the percent passing on any of the sieves.

The two primary purposes for gradation testing are to confirm that the gravel material met the gradation requirements established for the experiment and to provide a basis for evaluating the change in gravel gradation over time. For purposes of the study, it is assumed that any increases in percent passing are attributable to the effects of vehicle trafficking and maintenance operations.

- With the exception of a small percent of particles retained on the ¾-inch sieve for the Bear Mountain gravel, all three gravels were in conformance with SDDOT specifications.
- The gradation results over time for the STAAP plus crusher fines gravel reflect a small but significant increase in the percent passing the #4, #8, and #40 sieves. This is an indication that this gravel is slowly breaking down under traffic.
- The STAAP-compacted gravel shows a small decrease in the percent passing the #4 sieve while the STAAP-uncompacted gravel shows a small increase over time in the ½-inch sieve.
- Both the Bear Mountain-compacted and Bear Mountain-uncompacted gravels show no change in gradation.

Plasticity Index

The PI test results over time are summarized in table 29. Each PI value shown is the result of a test performed by SDDOT on a single sample of gravel material.

Table 29: Custer County PI results over time.

Material – Method	PI by Event Number				
	E0	E1	E2	E3	E4
STAAP+crusher fines-compacted	3	0	0	0	0
STAAP-compacted	6	0	0	0	0
STAAP-uncompacted		0	0	0	0
Bear Mountain-compacted	0	0	0	0	0
Bear Mountain-uncompacted		0	0	0	0

Although the STAAP and STAAP plus crusher fines materials had some measurable plasticity at the beginning of the test period, all other inspection period measurements were reported as non-plastic. The Bear Mountain material was consistently non-plastic throughout.

PI testing was conducted to confirm that the gravel materials met the requirements established for the experiment design and to evaluate a change in material plasticity over time that might have impacted performance.

- Based on the PI criteria for discriminating between the quality of the gravels used in each test section, only the STAAP (compacted and uncompacted) and Bear Mountain (compacted and uncompacted) gravels satisfied their initial groupings based on the initial stockpile tests. The STAAP plus crusher fines-compacted gravel did not satisfy its initial grouping. In fact, the PI of 3 puts it into the substandard category rather than the above-standard category.
- After construction, the PI test results indicated that all of the gravels became non-plastic, which would put them all in the substandard grouping.

CBR

CBR values for the Custer County gravel materials are summarized in table 30. Each CBR value shown represents the average of three tests performed on separate samples of gravel material.

Table 30: Custer County CBR results, measured at 0.1-inch penetration.

Material – Method	Stockpile (E0)				Final Inspection (E4)				Ratio of Final CBR to Stockpile CBR	
	Soaked		Unsoaked		Soaked		Unsoaked			
	Avg	COV	Avg	COV	Avg	COV	Avg	COV	Soaked	Unsoaked
STAAP+crusher fines-compacted	46.7	3%	21.7	31%	55.0	15%	10.3	80%	1.18	0.47
STAAP-compacted	45.3	16%	17.7	7%	4.0	20%	1.3	35%	0.09	0.07
STAAP-uncompacted					39.0	32%	5.0	16%	0.86	0.28
Bear Mountain-compacted	46.0	17%	39.7	12%	42.3	25%	12.3	10%	0.92	0.31
Bear Mountain-uncompacted					31.7	21%	35.7	28%	0.69	0.90

The following observations can be made about the CBR results.

- The variability of the CBR results from the stockpile is low (COV of 3 to 17%) for the soaked samples and somewhat higher (COV of 7 to 31%) for the unsoaked samples.
- The variability of the CBR results from the final inspection is moderate (COV of 15 to 32%) for the soaked samples and generally higher (COV of 10 to 80%) for the unsoaked samples.
- Overall, the variability of the CBR results is much higher for the final inspection tests compared to the stockpile tests.
- The CBR values (soaked) for all three gravels are identical and well within the expected range for a gravel material.
- For the STAAP plus crusher fines-compacted gravel, the CBR results from stockpile to final inspection tests reflect a slight increase in strength for the soaked samples and a definite decrease for the unsoaked samples.
- For the STAAP-compacted gravel, the CBR results from stockpile to final inspection tests indicate relatively large drops in strength for both the soaked samples and unsoaked samples.
- For the STAAP-uncompacted gravel, the CBR results from stockpile to final inspection tests indicate a slight drop in strength for the soaked samples and a relatively high drop in strength for the unsoaked samples.
- For the Bear Mountain-compacted gravel, the CBR results from stockpile to final inspection tests indicate essentially no change in strength for the soaked samples and a relatively high drop in strength for the unsoaked samples.
- For the Bear Mountain-uncompacted gravel, the CBR results from stockpile to final inspection tests indicate a sizeable drop in strength for the soaked samples and essentially no change in strength for the unsoaked samples.
- Overall, the CBR results indicate a general loss in gravel strength from stockpile to final inspection tests for both soaked and unsoaked samples.

Since there was no minimum CBR requirement for the gravels, the primary purpose for the CBR testing was to monitor the strength of gravel to determine if it was correlated with section performance. For purposes of this analysis, the focus was on CBR test results determined under soaked conditions using 0.1 inch of piston penetration.

The initial CBR values indicate that all three gravels have reasonable strength. By the end of the experiment, one of the gravels (STAAP-compacted) showed a large decrease in strength, one (STAAP plus crusher fines-compacted) showed a slight increase in strength while the remaining three (STAAP-compacted, the Bear Mountain-compacted, and the Bear Mountain-uncompacted) showed a small decrease in strength.

Fractured Faces

The percent fractured faces was measured by SDDOT on the stockpile material and on material samples at the end of the monitoring period. The test results showed 100 percent fractured faces for all samples from both periods. Measurements were also supposed to be made on samples from the post-construction (E1) inspection. Unfortunately, the tests were not completed or the results were lost. Since all of the stockpile tests and the final inspection tests showed 100 percent fractured faces, it is assumed that the missing test results would show 100 percent fractured faces as well.

The testing for fractured faces on the gravel materials was done to confirm that the SDDOT specification (i.e., minimum 30% of the aggregate retained on the #4 sieve with one or more fractured faces) were met by each of the gravels and to evaluate the change in percent fractured faces over time.

The percent fractured faces (one face) for all three gravels was 100%, respectively. Thus, the 30% minimum requirement is satisfied. By the end of the experiment, the percent fractured faces (for one face) for all five test sections did not change.

Unit Weight

The unit weight of all gravel materials was measured by SDDOT before construction (E0), after construction (E1), and during the final inspection (E4). The results are presented in table 31. Each unit weight shown is based on a test performed on a single gravel sample.

Table 31: Custer County unit weight over time.

<table>
<tr><th rowspan="2">Material – Method</th><th colspan="3">Unit Weight (lb/ft³)</th><th colspan="2">Ratio of Unit Weights</th></tr>
<tr><th>E0</th><th>E1</th><th>E4</th><th>E1/E0</th><th>E4/E0</th></tr>
<tr><td>STAAP+crusher fines-compacted</td><td>100</td><td>104</td><td>103</td><td>1.04</td><td>1.03</td></tr>
<tr><td>STAAP-compacted</td><td rowspan="2">90</td><td>108</td><td>102</td><td>1.20</td><td>1.13</td></tr>
<tr><td>STAAP-uncompacted</td><td>98</td><td>102</td><td>1.09</td><td>1.13</td></tr>
<tr><td>Bear Mountain-compacted</td><td rowspan="2">93</td><td>104</td><td>99</td><td>1.12</td><td>1.06</td></tr>
<tr><td>Bear Mountain-uncompacted</td><td>112</td><td>101</td><td>1.20</td><td>1.09</td></tr>
</table>

The following observations can be made about the results of the testing for gravel unit weight.

- Overall, the range in unit weight after construction (E1) for all gravel materials is relatively low (98 to 112 lb/ft^3).
- For the STAAP+crusher fines-compacted gravel, the after-construction unit weight is greater than the stockpile unit weight, although not as great as would be expected (considering that it was compacted). Second, there was no change in unit weight from after construction (E1) to final inspection (E4).
- For the STAAP-compacted gravel, the after-construction unit weight reflects an increase in unit weight over the stockpile unit weight (E0) that is commensurate with effects of compaction. Second, there is a small reduction in unit weight from after construction (E1) to final inspection (E4).
- For the STAAP-uncompacted gravel, the after-construction unit weight is greater than the stockpile unit weight and within the expected range (considering that it was not

compacted). Second, there is a slight increase in unit weight from after construction (E1) to final inspection (E4).

- For the Bear Mountain-compacted gravel, the after-construction unit weight is greater than the stockpile unit weight, although not as great as expected (considering that it was compacted). Second, there is a small reduction in unit weight from after construction (E1) to final inspection (E4).
- For the Bear Mountain-uncompacted gravel, the after-construction unit weight is greater than the stockpile unit weight, even greater than the after-construction unit weight for the Bear Mountain-compacted gravel. Second, there is a large reduction in unit weight from after construction (E1) to final inspection (E4).

South Dakota's standard specifications do not have a requirement on the unit weight (or density) of the gravel material, so it is not a critical property for gravel road construction. As indicated above, the unit weights measured for the Custer County gravels after construction are relatively low. Over time and traffic, the unit weight for the STAAP plus crusher fines gravel increased slightly while the unit weights for the remaining gravels increased significantly.

Absorption and Specific Gravity

Absorption and specific gravity tests were measured by SDDOT only on the stockpile samples. The results are summarized in table 32. Each result shown is based on a single test for each gravel.

Table 32: Custer County absorption and specific gravity results.

Material	Absorption (%)		Specific Gravity	
	Fine Agg.	Coarse Agg.	Fine Agg.	Coarse Agg.
Bear Mountain	1.3	2	2.69	2.62
STAAP	2.7	1.5	2.525	2.61
STAAP + crusher fines	1.8	1.1	2.593	2.641

There are no gravel specification requirements for absorption or specific gravity. The absorption values shown above indicate the presence of low voids in the aggregate, while the specific gravities are in the typical range for all aggregates. These properties will likely have no effect on the gravel performance.

Soundness and Resistance to Wear

Sulfate soundness and resistance to wear (L.A. abrasion) tests were performed on the stockpile samples for all three Custer County materials. These results are summarized in table 33. Each result shown is based on a single test for each gravel.

Table 33: Custer County soundness and resistance to wear.

Material	Soundness (% loss)		Resistance to Wear
	Fine Agg.	Coarse Agg.	
Bear Mountain	6	4	34
STAAP	5	5	28
STAAP + crusher fines	6	10	27

Soundness and resistance to wear are significant aggregate tests because they give an indication of the rate at which an aggregate will degrade under exposure to freezing/thawing and traffic, respectively. Following is a comparison of the test results for the Custer County gravels.

- Soundness – The South Dakota standard specifications requirement for sodium sulfate soundness is 15% maximum for the both the fine and coarse aggregate material. The soundness test results shown above indicate values in the range of 4 to 10, so all three gravels met this requirement.
- Resistance to wear – The specification requirement for L.A. Abrasion is a maximum of 40. The values for the three aggregates are in the range of 27 to 34, so all three gravels also satisfy the wear resistance requirement.

5.3.3.3. Brookings County Test Site

The eastern region is represented by Brookings County. The test site was located on a 1-mile long stretch of 214th Street just east of 464th Avenue and south of the Town of Volga. The test site was constructed in October 2011.

5.3.3.3.1. Traffic

Traffic counts on this site were 155 vehicles per day. The measurements were made by SDDOT between June 16 and July 12, 2011. There is no information on the split between trucks and automobiles.

5.3.3.3.2. Material Selection

The gravel materials selected for use in the three Brookings County test sites were obtained from two pits. The substandard material came from the Bowes pit; however, it is not sold as a gravel surfacing material. The standard material came from the Dupraz pit. The above-standard material was also obtained from the Dupraz pit; it was amended with a natural clay obtained from an area used for landfills.

5.3.3.3.3. Layout

From west to east, the following are the test sections at the Brookings County site:

- Bowes-compacted.
- Bowes-uncompacted.

- Dupraz-compacted.
- Dupraz-uncompacted.
- Dupraz plus clay-compacted.

Four of the test sections were 950 feet long with 50-foot transition zones between them. The Dupraz-compacted was 850 feet long due to space constrictions. A 500-foot buffer zone was created at the west end to avoid a test section being too close to a stop sign where vehicle braking could lead to washboarding. Additional construction information and a plan view map showing the layout of the site is presented in Appendix D.

5.3.3.3.4. Material Testing

Gradation

Pre-construction gradation test results for the three gravel materials are summarized in table 34 and graphically illustrated in figure 8.

Table 34: Brookings County stockpile key gradation points.

Sieve Size	State Specs	Dupraz	Dupraz plus clay	Bowes
3/4 in	100	100.0	98.7	100.0
1/2 in	-	90.9	88.1	94.4
#4	50-78	67.2	59.1	77.4
#8	37-67	51.9	50.7	64.4
#40	13-35	19.9	28.2	26.6
#80	-	9.6	19.9	-
#200	4-15	6.9	16.3	10.1

Note: Shaded areas indicate out of specification gradation points.

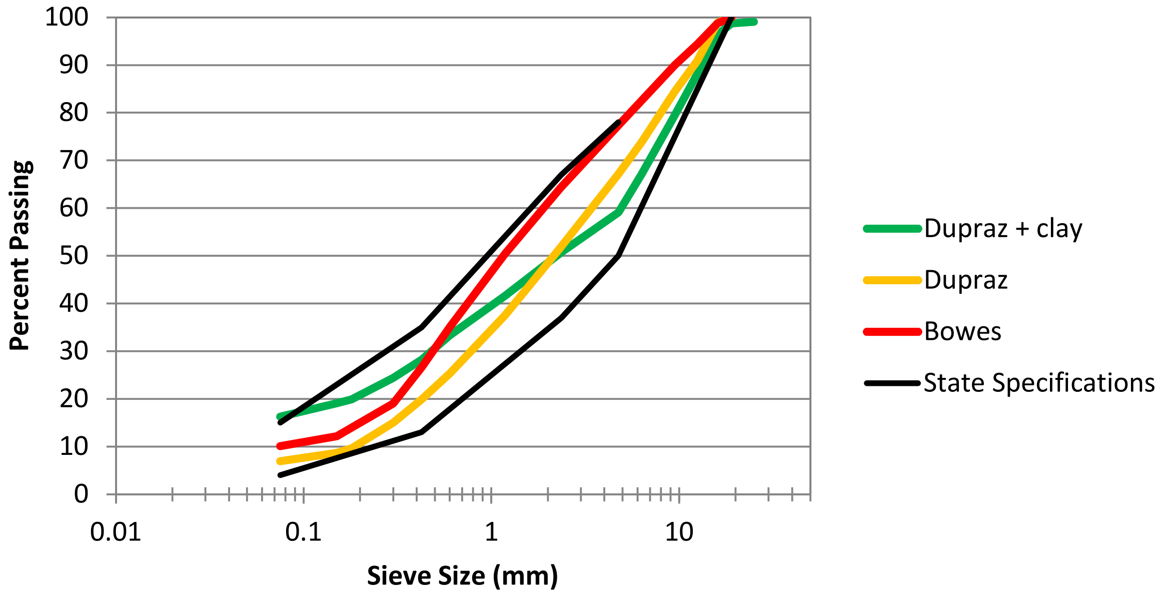

Figure 8: Brookings County gravel gradation curves.

Of the three counties, the Brookings County gravel materials have the most difference between them in terms of gradation. The Bowes and Dupraz materials are within the allowable gradation ranges at all points, but the Dupraz plus clay material is slightly out of compliance for both the #200 sieve and the ¾-inch sieve.

In addition to the pre-construction testing, SDDOT performed gradation testing on samples obtained from each of the four inspection periods (E1, E2, E3, and E4). Tables 35 through 39 provide the gradation results for each of the periods. Each gradation curve is the result of a test on a single gravel sample. Because of the interest in evaluating the change in gradation over time, the average change in gradation per month for each sieve was determined and included in each of the tables.

Table 35: Bowes-compacted key gradation points over time.

	Percent Passing by Event Number					Average Change in Gradation per Month
Sieve Size	E0	E1	E2	E3	E4	
3/4 in	100	96.7	95.9	97.1	97.3	-0.06
1/2 in	94.4	86.7	84.5	92.3	88.4	-0.06
#4	77.4	67.9	65	78.6	73.9	0.14
#8	64.4	55.9	52.4	67.2	64.1	0.26
#40	26.6	20.6	19.3	28.1	27.3	0.21
#80	-	9.3	9.6	14.7	12.5	0.21
#200	10.1	7.1	7.4	10.2	8.3	0.01

Table 36: Bowes-uncompacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	100	97.2	97.5	96.9	94.9	-0.18
1/2 in	94.4	87	89.1	88.4	85.9	-0.24
#4	77.4	66.4	68.1	74.7	67.7	-0.14
#8	64.4	54.6	57.4	64.6	57.1	-0.04
#40	26.6	18.9	23.8	25.6	23.4	0.05
#80	-	9.4	12.8	12.1	11.4	0.08
#200	10.1	7.4	10	8.3	8.3	-0.03

Table 37: Dupraz-compacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	100	100	100	100	100	0.00
1/2 in	90.9	92.4	93.8	92.4	93.4	0.08
#4	67.2	67.8	69.3	69.6	74	0.29
#8	51.9	56.4	57.1	56.2	62	0.35
#40	19.9	26	25.3	24.3	29.1	0.27
#80	9.6	16.6	15.8	14.4	17.7	0.21
#200	6.9	13	12.2	10.5	13	0.14

Table 38: Dupraz-uncompacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	100	99.6	99.9	100	100	0.01
1/2 in	90.9	92	93.3	93.5	93.5	0.11
#4	67.2	67.8	71.1	69.8	72.7	0.24
#8	51.9	55.1	58.7	57.5	61.3	0.37
#40	19.9	25.6	27.9	26.1	28.1	0.25
#80	9.6	15.4	17.1	15.2	15.8	0.17
#200	6.9	11.5	12.9	11.1	11.3	0.11

Table 39: Dupraz plus clay-compacted key gradation points over time.

Sieve Size	Percent Passing by Event Number					Average Change in Gradation per Month
	E0	E1	E2	E3	E4	
3/4 in	98.7	98.8	99.5	100	99.8	0.06
1/2 in	88.1	91.9	92.7	90.8	92.4	0.11
#4	59.1	71.2	65.3	69.5	65.8	0.11
#8	50.7	61.5	54.9	58.8	54.6	0.00
#40	28.2	32.8	30.1	31.5	29.7	-0.01
#80	19.9	23.1	20.9	21.7	21	-0.01
#200	16.3	18.8	16.9	17.2	16.7	-0.03

The following observations are made about the results of the gravel material gradation testing over time, focusing solely on the sieves that show a change.

- Three of the five gravel aggregates used at the Brookings test site exhibited significant gradation differences between the initial stockpile samples and samples taken after construction (E1). The three gravels are the Bowes-compacted, the Bowes-uncompacted, and, to a slightly lesser extent, the Dupraz plus clay-compacted. These differences made it difficult to determine the actual change in gradation over time.
- The Bowes-compacted gravel (table 35) seems to show a *slight* increase over time in the percent passing on three sieves: the #8, #40, and #80.
- The Bowes-uncompacted gravel (table 36) shows a *slight* decrease over time in the percent passing three sieves: ¾-inch, ½-inch, and #4. It also shows a *small* increase over time on the #80 sieve.
- The Dupraz-compacted gravel (table 37) shows a *small* increase over time in the percent passing on the #4, #40, and #80 sieves and a *moderate* increase over time on the #8 sieve.
- The Dupraz-uncompacted gravel (table 38) shows a *small* increase over time in the percent passing on the #4 and #40 sieves and a *moderate* increase over time in the percent passing the #8 sieve.
- The Dupraz plus clay-compacted gravel (table 39) shows *no* significant change in the gradation over time on any of the sieves.

SDDOT performed gradation testing to confirm that the gravel material met the gradation requirements established for the experiment and provided a basis for evaluating the change in gravel gradation over time. For this study it is assumed that any increases or decreases in the percent passing a particular sieve are attributable to the effects of vehicle trafficking and maintenance operations.

- Both the Dupraz and Bowes gravel materials conformed to the SDDOT specifications, but the Dupraz plus clay gravel did not based on the small percent of particles that were retained on the ¾-inch sieve and an excess amount of material passing the #200 sieve.
- The gradation results for the Dupraz plus clay gravel do not show any change over time.
- The Dupraz-compacted gravel shows a small increase in the percent passing the #4, #40, and #80 sieves and a moderate increase in the percent passing the #8 sieve. The Dupraz-uncompacted gravel exhibits an almost identical pattern of gravel deterioration.
- The Bowes-compacted gravel shows a slight increase in the percent passing on the #8, #40, and #80 sieves, while the Bowes-uncompacted gravel shows a slight decrease over time in the percent passing the ¾-inch, ½-inch, and #4 sieves. It also shows a small increase in the percent passing the #80 sieve.

Plasticity Index

The PI test results over time for the Brookings County test site are summarized in table 40. Each PI value shown is the result of a test by SDDOT on a single sample of gravel material.

Table 40: Brookings County PI results over time.

Material – Method	E0	E1	E2	E3	E4
Bowes-compacted	4	0	0	0	0
Bowes-uncompacted		0	0	0	0
Dupraz-compacted	4	0	0	0	0
Dupraz-uncompacted		0	5	0	0
Dupraz+clay-compacted	7	7	7	4	7

As can be seen, the three primary gravel materials all had some measurable plasticity at the beginning of the test. However, with the exception of the Dupraz plus clay-compacted, the remaining materials exhibited no plasticity after construction. The Dupraz+clay-compacted gravel material essentially maintained the same level of plasticity throughout the test period.

PI testing was conducted to determine if the gravel materials met the requirements established for the experiment design and to evaluate a change in material plasticity over time that might impact performance.

- By definition, the stockpile PI for all five gravels met the criteria for each gravel quality level defined for this experiment. However, each section's PI value was either on a low or high threshold.
- After construction, the PIs for all of the gravels, with the exception of the Dupraz-compacted, became non-plastic, which would put each of the four in the substandard classification.

CBR

CBR values for the Brookings County test site are summarized in table 41. Each CBR value shown (with the exception of those identified with a star) represents the average of three tests performed by SDDOT on separate samples of gravel material.

Table 41. Brookings County CBR results, measured at 0.1 inches.

	Stockpile (E0)				Final Inspection (E4)				Ratio of Final CBR to Stockpile CBR	
	Soaked		Unsoaked		Soaked		Unsoaked			
Material – Method	Avg	COV	Avg	COV	Avg	COV	Avg	COV	Soaked	Unsoaked
Bowes-compacted	47.3	12%	46.3	9%	19.5*	44%	54.7	14%	0.41	1.18
Bowes-uncompacted					36.5*	18%	53.7	5%	0.77	1.16
Dupraz-compacted	34.0	10%	49.3	15%	23.0	27%	38.5*	1%	0.68	0.78
Dupraz-uncompacted					17.0*	0%	36.0	24%	0.50	0.73
Dupraz+clay-compacted	11.0	7%	9.7	39%	7.7	16%	2.3	20%	0.70	0.24

*Data based on two tests instead of three.

The following observations can be made about the CBR results.

- The variability of the CBR results from the stockpile is low (COV of 7 to 12%) for the soaked samples and higher (COV of 9 to 39%) for the unsoaked samples.
- The variability of the CBR results from the final inspection is high (COV of 0 to 44%) for the soaked samples and moderate (COV of 1 to 24%) for the unsoaked samples.
- Overall, the variability of the CBR results is higher for the final inspection tests compared to the stockpile tests.
- The CBR values (soaked) for the Bowes and Dupraz gravels are within the expected range for a gravel material. The CBR value (soaked) for the Dupraz+clay gravel, however, is lower than the expected range for a gravel material.
- For the Bowes-compacted gravel, the CBR results from stockpile to final inspection tests reflect a large reduction in strength for the soaked samples and a moderate increase in strength for the unsoaked samples.
- For the Bowes-uncompacted gravel, the CBR results from stockpile to final inspection tests indicate a moderate decrease in strength for the soaked samples and a moderate increase in strength for the unsoaked samples.
- For the Dupraz-compacted gravel, the CBR results from stockpile to final inspection tests indicate a moderate drop in strength for both the soaked samples and unsoaked samples.
- For the Dupraz-uncompacted gravel, the CBR results from stockpile to final inspection tests indicate a large reduction in strength for the soaked samples and a moderate decrease in strength for the unsoaked samples.
- For the Dupraz+clay-compacted gravel, the CBR results from stockpile to final inspection tests indicate significant reductions in strength for both the soaked and unsoaked samples.
- Overall, the CBR results indicate a general loss in gravel strength from stockpile to final inspection tests, especially for the soaked samples.

Since there was no minimum CBR requirement for the gravels, the primary purpose of the CBR testing was to monitor the strength of gravel to determine if it was correlated with section performance. For this analysis, the focus was on CBR test results determined under soaked conditions using 0.1 inch of piston penetration.

The initial CBR values indicate that the two Dupraz and two Bowes gravels have good strength. However, the Dupraz with clay-compacted gravel exhibits relatively low strength. By the end of the experiment, all five gravel showed moderate to large decreases in strength.

Fractured Faces

SDDOT measured fractured faces on samples from the stockpile material (E0) and samples obtained during the final inspection period (E4). Samples from the first inspection period (E1) were supposed to be tested too; however, the data were misplaced. The results of the testing for fractured face counts are summarized in table 42. Each result shown is based on a test of a single sample of gravel material.

Table 42: Fractured faces testing results for Brookings County aggregates.

Material – Method	Stockpile (E0)	1st Inspection (E1)1	Final Inspection (E4)
Bowes-compacted	61% 1-surf 51% 2-surf	-	60% 1-surf 52% 2-surf
Bowes-uncompacted		-	55% 1-surf 40% 2-surf
Dupraz-compacted	72% 1-surf 66% 2-surf	-	60% 1-surf 56% 2-surf
Dupraz-uncompacted		-	67% 1-surf 62% 2-surf
Dupraz+clay-compacted	70% 1-surf 61% 2-surf	-	44% 1-surf 39% 2-surf

[1] Data for fractured faces for E1 in Brookings County were misplaced.

The following observations can be made about the change in fractured face test results from the stockpile (E0) to final inspection:

- Bowes-compacted gravel – no difference.
- Bowes-uncompacted gravel – small reduction.
- Dupraz-compacted gravel – moderate reduction.
- Dupraz-uncompacted gravel – small reduction.
- Dupraz+clay-uncompacted – large reduction.

The purposes of testing for fractured faces on the gravel materials was to confirm that the SDDOT specification (i.e., minimum 30% of the aggregate retained on the #4 sieve with one or more fractured faces) was met by each of the gravels and to evaluate the change in percent fractured faces over time.

- The percent fractured faces (one face) for all three gravels was in the range of 61 to 72%. Thus, the 30% minimum requirement was satisfied.
- By the end of the experiment, the percent fractured faces (for one face) for all five test sections decreased slightly, but stayed well above the 30% minimum requirement.

Unit Weight

SDDOT measured the unit weight of all gravel materials before construction (E0), after construction (E1), and during the final inspection (E4). The results are presented in table 43. Each unit weight shown is based on a test performed on a single gravel sample.

Table 43: Brookings County unit weights over time.

	Unit Weight (lb/ft^3)			Ratio of Unit Weights	
Material – Method	E0	E11	E4	E1/E0	E4/E0
Bowes-compacted	100	--	114	--	1.14
Bowes-uncompacted	100	--	116	--	1.16
Dupraz-compacted	100	--	116	--	1.16
Dupraz-uncompacted	100	--	117	--	1.17
Dupraz+clay-compacted	97	--	116	--	1.20

[1] Unit weight data for E1 were misplaced.

Without information on the gravel unit weights after construction (E1), it is not possible to make many observations on the change in unit weight over time. One observation that can be made is that the unit weights at the end of the test period (E4) are within the expected range for gravel materials. A second observation is that the unit weights for all gravel materials by the end of the experiment (E4) are about the same.

South Dakota's standard specifications do not have a requirement on the unit weight (or density) of the gravel material, so it is not a critical property for gravel road construction. As indicated in table 43, the unit weights determined for Brookings County gravels after construction are relatively low. Over time and traffic, the unit weight for all the gravels increased by 15 to 20%.

Absorption and Specific Gravity

Absorption and specific gravity were measured only on the stockpile samples. The results are summarized in table 44. Each result shown is based on a single test for each gravel.

Table 44: Brookings County absorption and specific gravity results.

Material	Absorption		Specific Gravity	
	Fine Agg.	Coarse Agg.	Fine Agg.	Coarse Agg.
Bowes	1.1	2.2	2.554	2.585
Dupraz	1.5	2.3	2.552	2.588
Dupraz+clay	3.7	2.2	2.45	2.6

There are no gravel specification requirements for absorption or specific gravity. The absorption values shown in table 44 indicate low absorption for the Dupraz and Bowes aggregates and moderate absorption for the Dupraz plus clay gravel. The specific gravities are in the typical range for gravels. These properties will likely have little effect on gravel performance.

Soundness and Resistance to Wear

SDDOT performed sulfate soundness and resistance to wear (L.A. abrasion) tests on the stockpile samples for all three Brookings County gravel materials. These results are summarized in table 45. Each result shown is based on a single test for each gravel.

Table 45: Brookings County soundness and resistance to wear.

Material	Soundness		Resistance to Wear
	Fine Agg.	Coarse Agg.	
Bowes	6	8	25
Dupraz	7	10	27
Dupraz + clay	6	12	34

Soundness and resistance to wear are significant aggregate tests because they give an indication of the rate at which an aggregate will degrade under exposure to freezing/thawing and traffic, respectively. The following is a comparison of the test results for the Brookings County gravels:

- Soundness – The South Dakota standard specifications requirement for sodium sulfate soundness is 15% maximum for the both the fine and coarse aggregate material. The soundness test results shown in table 45 indicate values in the range of 6 to 7 for the fine aggregate and 8 to 12 for the coarse aggregate. Accordingly, all three gravels met these requirements.
- Resistance to wear – The specification requirement for L.A. Abrasion is a maximum of 40. The values for the three aggregates are in the range of 25 to 34, so all three gravels also satisfy the wear resistance requirement.

5.4. Basis for Gravel Road Performance Assessment

5.4.1. Inspection Protocol

To characterize the condition of each gravel road test section, five distresses were evaluated during each inspection period. These included washboarding (corrugation), raveling (wash or loose aggregate), rutting, potholing, and dusting. Each distress was rated from 0 (worst) to 10 (best) based on severity levels used in the previously discussed FHWA-CFL National Wildlife Refuge road survey (Woll et al. 2008). For rutting, washboarding, and raveling, the distress levels were based on the average depth of the distress. Pothole ratings were based on the depth, width, and quantity. Dusting was a subjective measure. The severity levels and rating criteria for each of these distresses are summarized in figure 9.

To consider variation within the experimental sections, each was subdivided into 150- to 200-foot long subsections. The conditions were relatively uniform within each test section, so that representative ratings could be obtained. The distress ratings for each subsection were averaged to determine an average for each section.

Dust: Assess dust with respect to driving safety by following a vehicle at 25 mph and rating uneasiness.

0	Vehicle generating dust cannot be seen - Must stop for dust to clear
1-2	Dangerous loss of visibility - Significant uneasiness at driving 25 mph
3-4	Significant loss of visibility – Some uneasiness at driving 25 mph
5-6	Some loss of visibility – Little to no uneasiness at driving 25 mph
7-8	Very little loss of visibility – No uneasiness at driving 25 mph
9	A little low rising dust, but no loss of visibility
10	No Dust

Washboarding: Loose corrugations consisting of parallel alternating crests of loose, fine-sandy material and troughs of compacted material at right angles to the direction of travel; or fixed corrugations consisting of compacted crests and troughs of hard, fine sandy-gravel material. Six trough measurements (divided equally between the 2 or 3 wheel paths) are recorded and averaged.

0	> 60 mm
1	50 - 60 mm
2	40 - 50 mm
3	30 - 40 mm
4	25 - 30 mm
5	20 - 25 mm
6	15 - 20 mm
7	10 - 15 mm
8	5 - 10 mm
9	< 5 mm deep
10	Wash boarding is not visible

Rutting: Rutting is evaluated by measuring the rut depth with a straightedge and ruler. Average of four measurements.

0	> 60 mm deep
1	50 - 60 mm
2	40 - 50 mm
3	30 - 40 mm
4	25 - 30 mm
5	20 - 25 mm
6	15 - 20 mm
7	10 - 15 mm
8	5 - 10 mm
9	< 5 mm deep
10	Not measurable

Raveling: Raveling is evaluated by measuring the thickness of loose material. This is achieved by scraping a path through the material to the hard surface and measuring the thickness of the adjacent loose material with a straightedge and ruler. Measure at four locations and average.

0	> 60 mm thick
1	50 - 60 mm
2	40 - 50 mm
3	30 - 40 mm
4	25 - 30 mm
5	20 - 25 mm
6	15 - 20 mm
7	10 - 15 mm
8	5 - 10 mm
9	< 5 mm thick
10	Loose material is not visible

Potholing: Potholes are evaluated by measuring the pothole depth with a straightedge and ruler.

0	Impassable
1	Many, > 100 mm deep
2	Many, 80 - 100 mm deep
3	Many, 65 - 80 mm deep
4	Some, 50 - 65 mm deep
5	Some, 35 - 50 mm deep
6	Some, 20 - 35 mm deep
7	A few, 10 - 20 mm deep
8	A few, 5 - 10 mm deep
9	A few, < 5 mm deep
10	Potholes are not evident

Figure 9: Visual performance survey rating methodology.

5.4.2. Distress Weighting

Although each of the distresses are rated on a 1 to 10 scale, not all affect the overall condition of the road or its maintenance needs in the same way. So, rather than consider all of the distresses equally in evaluating performance, an analysis was performed to assign a greater weight to those distress measures which had a greater impact on maintenance decisions.

Accordingly, a survey was distributed to experienced county highway supervisors in South Dakota and ten responses were obtained. The survey asked respondents to rank the five distresses based on how they generated user complaints and the need for maintenance, and also asked for weighting percentages to develop a composite overall distress score.

All but one respondent indicated that washboarding was the highest ranked distress in terms of user complaints, with raveling being the second most important distress. Rutting was of least concern, with potholing and dusting being equally ranked between rutting and raveling. The survey responses are summarized in table 46.

All respondents agreed that dusting is of least priority in terms of maintenance triggers. Seven of the respondents ranked washboarding first, with three respondents putting rutting first. Rankings for the others varied, but overall rutting and raveling tied for second, with potholing coming in fourth. The results are summarized in table 47.

Finally, respondents were asked to assign a percent value to each distress (totaling 100 percent) so that a weighted average overall condition number could be developed. Weighting trends follow the maintenance ranking patterns, with washboarding being most important and dusting being least important. Eight respondents gave washboarding the highest weighting or tied for the highest weighting value. In all but one response, dusting was the lowest or tied for the lowest weighting percentage, with three responses assigning zero percent of the overall condition score. All of the results are summarized in table 48.

Table 46: Survey responses on user complaint rank.

County	User Complaint Rank				
	Wash-boarding	Rutting	Raveling	Potholing	Dusting
Clay	1	3	2	4	5
Miner	1	5	2	4	3
Beadle	1	4	2	3	5
Day	1	5	3	2	4
Fall River	1	3	2	4	5
Codington	1	5	3	4	2
McCook	2	3	4	5	1
Lawrence	1	5	4	3	2
Campbell	1	2	3	4	5
Deuel	1	5	4	2	3
Average	1.1	4	2.9	3.5	3.5
Standard Deviation	0.32	1.15	0.88	0.97	1.51
Overall	1	5	2	3 (tie)	3 (tie)

Table 47: Survey responses on maintenance trigger rank.

County	Maintenance Trigger Rank				
	Wash-boarding	Rutting	Raveling	Potholing	Dusting
Clay	3	1	2	4	5
Miner	1	3	4	2	5
Beadle	1	3	2	4	5
Day	1	4	3	2	5
Fall River	1	3	2	4	5
Codington	2	1	4	3	5
McCook	2	1	3	4	5
Lawrence	1	4	3	2	5
Campbell	1	3	2	4	5
Deuel	1	4	2	3	5
Average	1.4	2.7	2.7	3.2	5
Standard Deviation	0.70	1.25	0.82	0.92	0.00
Overall	1	2 (tie)	2 (tie)	4	5

Table 48: Survey responses on distress weighting.

County	Distress Weight				
	Wash-boarding	Rutting	Raveling	Potholing	Dusting
Clay	20%	30%	40%	10%	0%
Miner	40%	20%	20%	20%	0%
Beadle	50%	10%	25%	10%	5%
Day	30%	20%	30%	20%	0%
Fall River	35%	25%	20%	10%	10%
Codington	30%	30%	10%	20%	10%
McCook	25%	40%	15%	10%	10%
Lawrence	30%	10%	10%	30%	20%
Campbell	85%	10%	2%	2%	1%
Deuel	50%	5%	20%	20%	5%
Average	40%	20%	19%	15%	6%
Standard Deviation	0.19	0.11	0.11	0.08	0.06

Based on the distress weighting results, an overall or composite rating score (R_{COMP}) was developed and is shown below.

$$R_{COMP} = 0.40*R_{WB} + 0.20*R_{RUT} + 0.19*R_{RAV} + 0.15*R_{PH} + 0.06*R_{DUST}$$

where:

R_{WB} = Washboard distress rating.

R_{RUT} = Rutting distress rating.

R_{RAV} = Raveling distress rating.

R_{PH} = Pothole distress rating.

R_{DUST} = Dusting distress rating.

5.4.3. Quantifying Gravel Loss by Cast-Off

One mechanism by which gravel is lost is by the material being cast or thrown off the road surface, by one or more of the following: traffic, regular maintenance, and snow removal. In order to estimate the amount of material lost from each test cell by cast-off, SDDOT constructed collection boxes off the shoulder of each test cell. The cast-off measurement device is essentially a strip of landscaping fabric (apron) staked to the fore slope of the ditch immediately adjacent to the shoulder. The strip ends several feet above the bottom of the ditch, to ensure that water flow will not damage the measurement device or wash away material. A three-sided wall surrounds the end of the apron to catch cast-off material that would otherwise roll down the fabric and be lost. Figure 10 shows one of the cast-off boxes from the Custer County test site. SDDOT regularly collected and weighed the material in the boxes. The weight of the material collected from the box was then extrapolated to a loss rate over time, based on the time since the boxes were last emptied.

For calculations, it was assumed that the amount collected in each box was representative of the whole section. Also, the first foot of sample in the collection apron was discarded at each inspection, since this material would be reincorporated into a typical road during routine maintenance.

Figure 10: Cast-off collection box located in Custer County.

5.5. Test Site Road Maintenance

Maintenance records provided by SDDOT indicate that gravel road maintenance was performed by County maintenance crews on all three test sites during the course of the experiment. Following is a summary of the dates when work was performed at each site.

5.5.1. Hand County Test Site

This site was constructed in October 2010 and was last monitored in May 2012. In between, this test site was bladed on multiple occasions. The recorded dates and associated labor (in man-hours) for this work are shown in table 49. For convenience, this table also shows the performance monitoring dates.

Table 49: Record of gravel road maintenance at Hand County test site.

Date of Work	Labor (man-hours)
Oct 2010 (E1)	--
3/28/11	2
4/28/11	2
June 2010 (E2)	--
6/24/11	2.5
7/5/11	2
7/12/11	2
7/27/11	2
8/8/11	2
8/17-18/11	4
8/24-25/11	5
8/29/11	11
9/1/11	10
9/6/11	2
9/22/11	2
Oct 2011 (E3)	--
11/15/11	2
12/5/11	2
1/26/12	3
2/8/12	2
3/12/12	3
3/22/12	1.5
4/11/12	1.5
5/1/12	2
May 2012 (E4)	--

The data in table 49 indicate that the Hand County test sections were frequently maintained between their construction and the end of the experiment. The table also shows that there was one period at the end of August 2011 and the beginning of September 2011 where a relatively large maintenance effort was conducted. Unfortunately, County's maintenance records did not provide any indication of how the maintenance effort was distributed between the five sections. Nor were there any condition survey measurements directly before or after any of the activities, as had been recommended in the original set up of the experiment. Accordingly, it was not possible to make a valid assessment of the effect of maintenance on the performance of each test section.

5.5.2. Custer County Test Site

This test site was constructed in June 2011 and was last monitored in October 2012. Between these dates, the test sections were bladed on several occasions. The recorded dates and associated labor for this work are shown in table 50. For convenience, this table also shows the four performance monitoring dates.

Table 50: Record of gravel road maintenance at Custer County test site.

STAAP (Medicine Mountain Rd) Sections		Bear Mountain (Saginaw Rd) Sections	
Date of Work	Labor (man-hours)	Date of Work	Labor (man-hours)
June 2011 (E1)	--	June 2011 (E1)	--
8/30 to 9/1/11	21	9/1/11	8
9/14/11	6	Oct 2011 (E2)	--
Oct 2011 (E2)	--	3/29/12	16
10/9/11	4	May 2012 (E3)	--
4/30/12	41	Oct 2012 (E4)	--
May 2012 (E3)	--	--	--
Oct 2012 (E4)	--	--	--

This table shows that the three STAAP sections (located along Medicine Mountain Rd) were maintained four times while the Bear Mountain test sections (located along Saginaw Rd) were maintained only two times. In addition, table 50 shows that larger maintenance efforts were required in late August 2011 and April 2012 for the STAAP test sections and in March 2012 for the Bear Mountain test sections. The County's maintenance records did not indicate how maintenance efforts were distributed amongst the test sections. Also, there were no condition survey measurements before or after any of the activities. Consequently, it is not possible to make a valid assessment of the effect of maintenance on the performance of each test section.

5.5.3. Brookings County Test Site

This test site was constructed in October 2011 and received its last performance monitoring in June 2013. Between those dates, the test sections received a significant amount of maintenance attention, mostly to address washboarding problems. Table 51 summarizes the maintenance information provided by the SD DOT office in that District. As can be seen, the maintenance history is not only identified by date, but also by which test section was maintained and the primary reason for the activity. The following list indicates the experimental characteristics associated with each section:

- Section 1 – Substandard-compacted
- Section 2 – Substandard-uncompacted
- Section 3 – Standard-uncompacted
- Section 4 – Standard-compacted
- Section 5 – Above-standard-compacted

Table 51: Record of gravel road maintenance at Brookings County test site.

Date of Work	Test Section(s) Maintained	Reason for Maintenance
Oct 2011 (E1)	--	--
11/8/11	#1	Washboarding
12/5/11	#1 and #2	Washboarding
12/13/11	#1	Washboarding
12/22/11	#1	Washboarding
12/27/11	#1	Washboarding
1/3/12	#1	Washboarding
1/3/12	#2, #3, #4, and #5	Regular Maintenance
1/9/12	#1	Washboarding
1/30/12	All sections	Needed attention
3/8/12	#1 and #2	Washboarding
3/8/12	#5	Pulled gravel
3/22/12	#1 and #2	Washboarding
3/22/12	#3, #4, and #5	High crown
4/4/12	#1	Washboarding
May 2013 (E2)	--	--
5/21/12	#1 and #2	Washboarding
5/21/12	All sections	Pulled gravel
7/16/12	#1 and #2	Washboarding
8/6/12	#1 and #2	Washboarding
8/13/12	#1 and #2	Washboarding
8/20/12	#1 and #2	Washboarding
9/18/12	#1, #2, and #3	Washboarding
9/18/12	#4 and #5	Pulled gravel
Oct 2012 (E3)	--	--
10/29/12	#1 and #2	Washboarding
10/29/12	#3, #4, and #5	Pulled gravel
11/13/12	#1 and #2	Washboarding
11/20/12	#1, #2, and #3	Washboarding
11/20/12	#4	Regular maintenance
June 2013 (E4)	--	--

For convenience, the table also shows the dates when performance monitoring was performed. Unfortunately, the County's maintenance records do not indicate how much maintenance effort (or labor) was applied to each section. In addition, no condition survey measurements were performed before or after the maintenance activities. As with the other two sites, it was not possible to make a valid assessment of the effect of maintenance on the performance of each test section.

5.6. Test Section Performance Observations

This section presents the gravel road performance results for each of the five test sections within the Hand, Custer, and Brookings County test sites. The results include the five primary distresses evaluated during the condition surveys (i.e., washboarding, rutting, raveling, potholing, and dusting) as well as the composite rating score. It also includes the test section performance based on the amount of gravel cast off during the course of the experiment.

5.6.1. Hand County

This section provides the performance results for the five test sections that make up the Hand County test site. In reviewing the performance of the experimental sections, it is important to recognize the effect of road maintenance and traffic. Maintenance was applied at certain times (see Table 49) but, since no performance measurements were made before or after, it is not possible to determine the actual effects. It is also important to note that the maintenance records do not reflect how the effort was distributed between sections. It is possible that each section received the same amount of effort (such as the same number of grader passes); however, it is also possible that maintenance was focused on those sections that needed it the most. Accordingly, for the Hand County sections, the effect of maintenance is only addressed in general terms where it is appropriate. The impact of traffic level on the Hand County sections is not a consideration in terms of performance impacts because each section received approximately the same level of traffic.

5.6.1.1. Washboarding

Figure 11 shows the graph of post-construction washboard ratings obtained during the three inspection periods (E2, E3, and E4). Examination of the graph indicates:

- There is no apparent development of washboarding between construction and the first data collection event (E2) eight months later. Some maintenance was performed at four and five months after construction; however, there is no data to determine its effect.
- Since the washboard ratings for each section are all the same at E2, it appears that compaction did not have an effect on the development of washboarding.
- After E2, all but one of the washboard ratings are above 9.5. Only the Oakley (substandard)-compacted section shows a significant decrease in washboarding (at E3), but it is still a relatively high rating of 8.8. Overall, this suggests that gravel type did not have an effect on washboard performance.

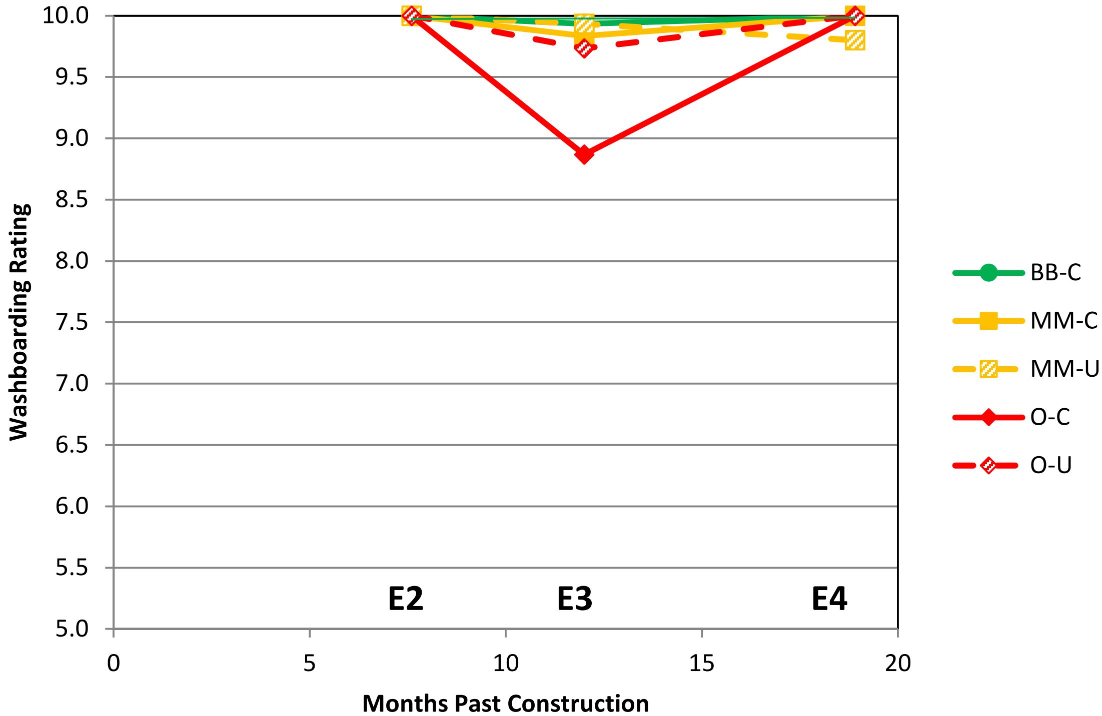

Figure 11: Washboard ratings over time for the Hand County test sections.

5.6.1.2. Rutting

Figure 12 provides a graph of the rutting ratings obtained during the three post-construction inspection periods. For this distress, there are some apparent differences in performance over time.

- Based on the observed ratings at E2 and assuming that the initial rutting ratings immediately after construction were near 10, then there must have been a large drop in rutting ratings (i.e., increase in rutting) during the first eight months after construction. Some maintenance was performed at four and five months after construction; however, there is no data to determine its effect.
- The ratings at E2 suggest that compaction did result in higher rut ratings (less rutting) during the first eight months after construction.
- The curves indicate that the Bone Bright (above-standard)-compacted, Martinmas (standard)-compacted, and Martinmas-uncompacted performed similarly at E3 and E4, while the Oakley (substandard)-compacted and Oakley uncompacted sections performed slightly worse.

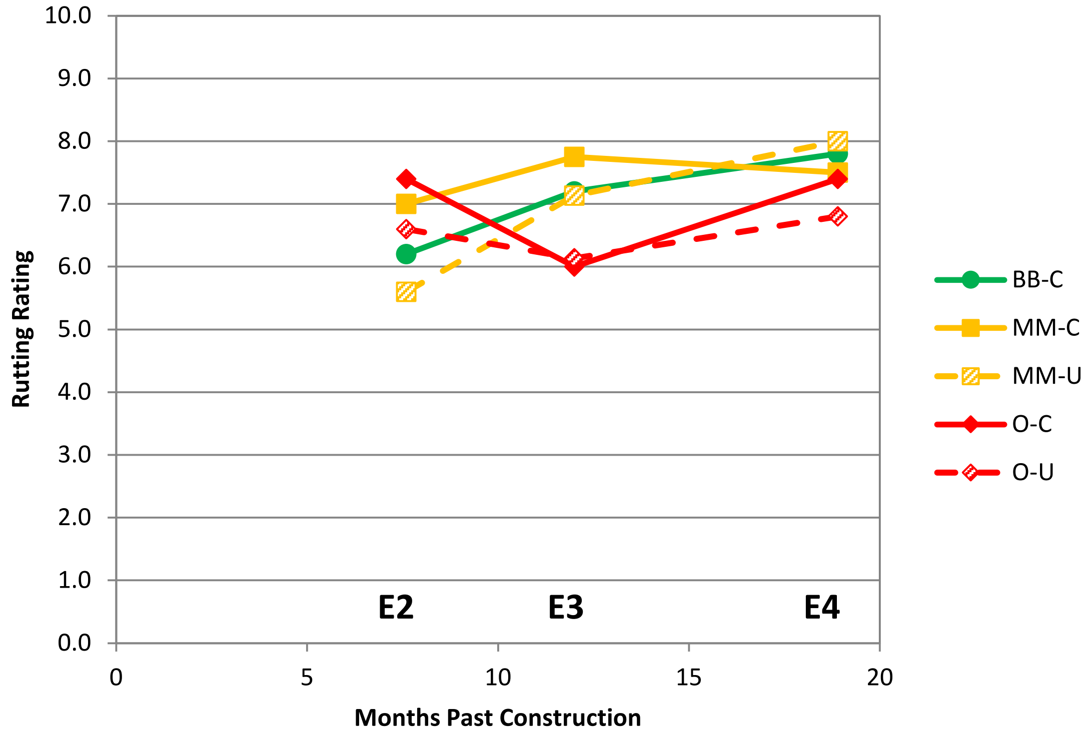

Figure 12: Rutting ratings over time for the Hand County test sections.

5.6.1.3. Raveling

Figure 13 shows a graph of the post-construction raveling ratings obtained during the three inspection periods. The graph shows that there are some performance differences between the test sections.

- Based on the range in ratings at E2 and assuming that the initial raveling ratings were near 10 after construction, then there must have been a drop in raveling ratings for all of the sections during the first eight months after construction. Some maintenance was performed at four and five months after construction; however, there is no data to determine its effect.
- Based on the ratings of the compacted and uncompacted sections at E2, there is no indication that compaction had any effect on raveling.
- The curves indicate that the two Martinmas (standard) sections performed the best in terms of raveling, while the two Oakley (substandard) sections performed the worst. The performance of the Bone Bright (above-standard) section appears to be better than the Oakley sections, but worse than the Martinmas sections.

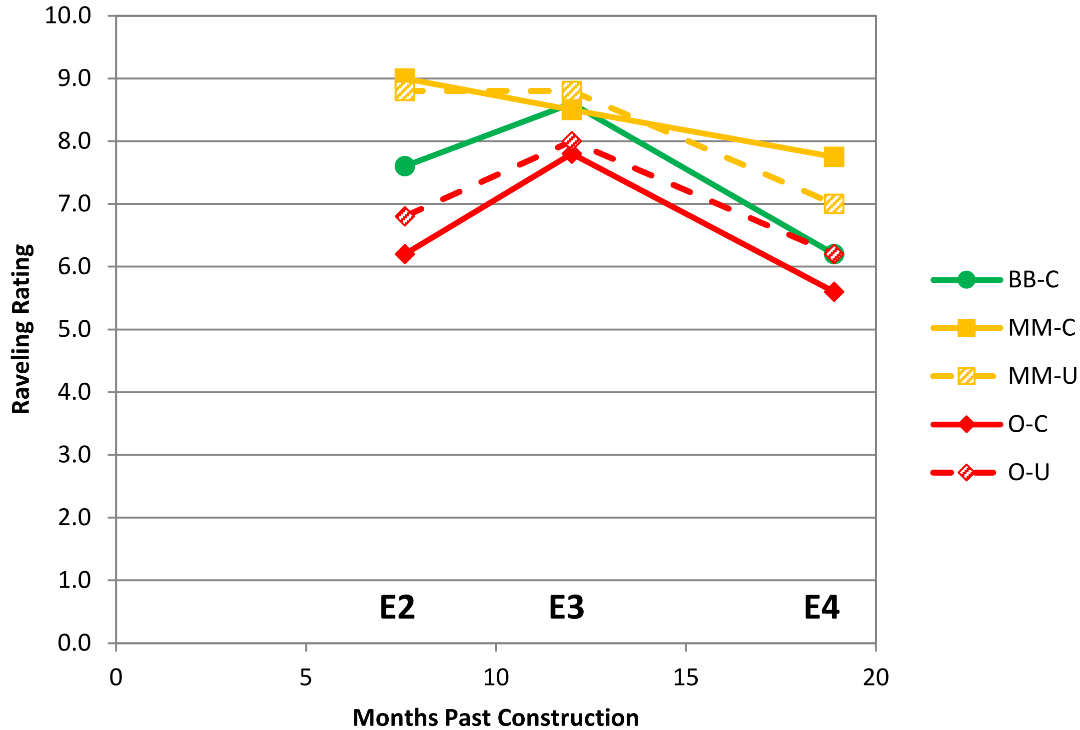

Figure 13: Raveling ratings over time for the Hand County test sections.

5.6.1.4. Potholing

Figure 14 provides a graph of the pothole ratings obtained during the three post-construction inspection periods. Examination of the graph indicates:

- The pothole ratings for all five test sections remained high at all 3 inspection periods. It is possible that maintenance work helped repair any potholes that developed; however, there is no data to determine its effect. It is also possible that very few potholes ever developed.
- Based on the ratings at E2, it appears that compaction did not have any effect on pothole development.
- The performance of the Bone Bright (above-standard) and Martinmas (standard) sections is basically the same, while the performance of the Oakley (substandard) sections is slightly worse.

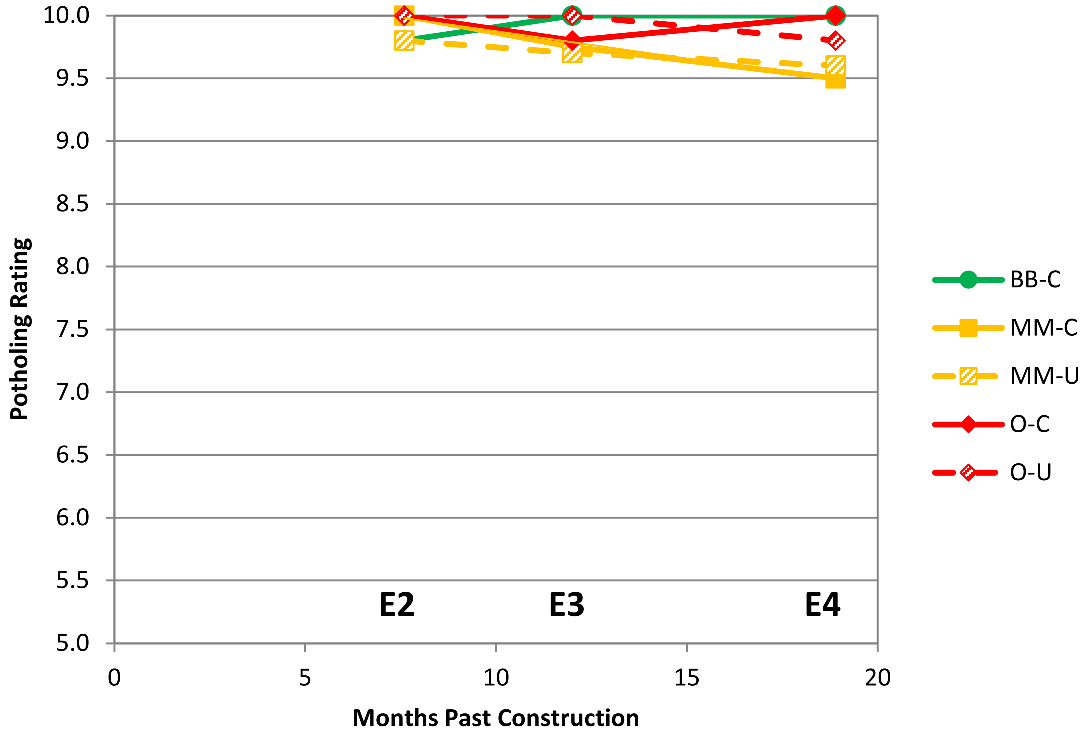

Figure 14: Pothole ratings over time for the Hand County test sections.

5.6.1.5. Dusting

Figure 15 shows a graph of the dusting ratings obtained during the three post-construction inspection periods. The graph shows that there are some significant differences in performance between the test sections.

- The dusting ratings for the E2 inspection period were the same (8.0) for all five test sections. Since the dusting rating at the time of construction was not determined, there is no basis to state that the gravel deteriorated during the eight months after construction. Maintenance was performed at four and five months after construction; however, there is no data to determine its effect.
- Because there is no difference in the ratings between the compacted and uncompacted sections at E2, it is reasonable to assume that compaction had no impact on dusting.
- The dusting rating curves indicate that the two Martinmas (standard) sections and the Bone Bright (above-standard) section performed about the same. In fact, the performance of the Martinmas-uncompacted section was identical to that of the Bone Bright-compacted section. The performance of the two Oakley (substandard) test sections was identical and both performed worse than the two Martinmas sections and the Bone Bright section.

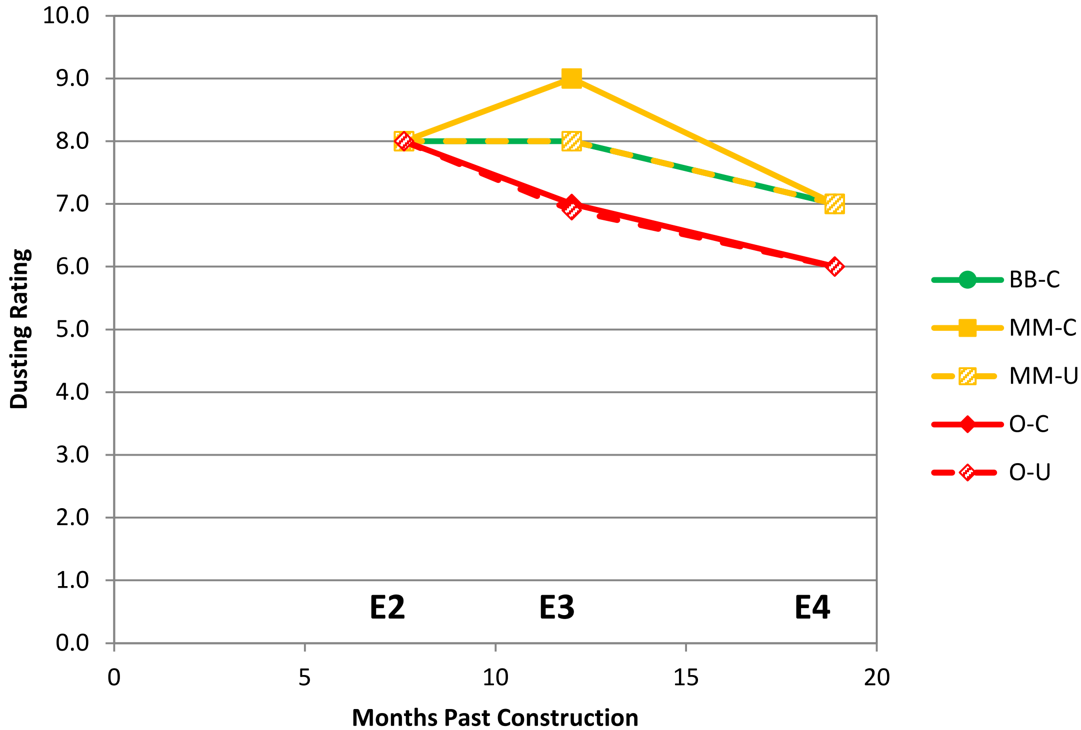

Figure 15: Dusting ratings over time for the Hand County test sections.

5.6.1.6. Overall

Figure 16 provides a graph showing the overall weighted (composite) ratings versus time for each of the five Hand County test sections. As can be seen, there are some notable differences in performance.

- Based on the range of overall weighted ratings for the E2 inspection period and assuming that the initial overall weighted ratings were near 10 after construction, there was a considerable drop in the overall ratings during the 8 months after construction. Reviewing the five other performance measures, this drop in the overall rating occurred primarily because of the observed drop in the ratings for rutting, raveling, and dusting.
- Based on the differences in overall weighted ratings between the compacted and uncompacted curves for both the Martinmas (standard) and Oakley (below standard) sections for the E2 period, there is no clear indication that compaction during construction had any effect on the overall weighted ratings.
- The graph indicates that the Bone Bright (above-standard) and both Martinmas (standard) sections performed about the same overall. The graph also indicates that the two Oakley (substandard) sections performed about the same; however, their performance was worse than the Martinmas and Bone Bright sections, especially after the E2 survey period.

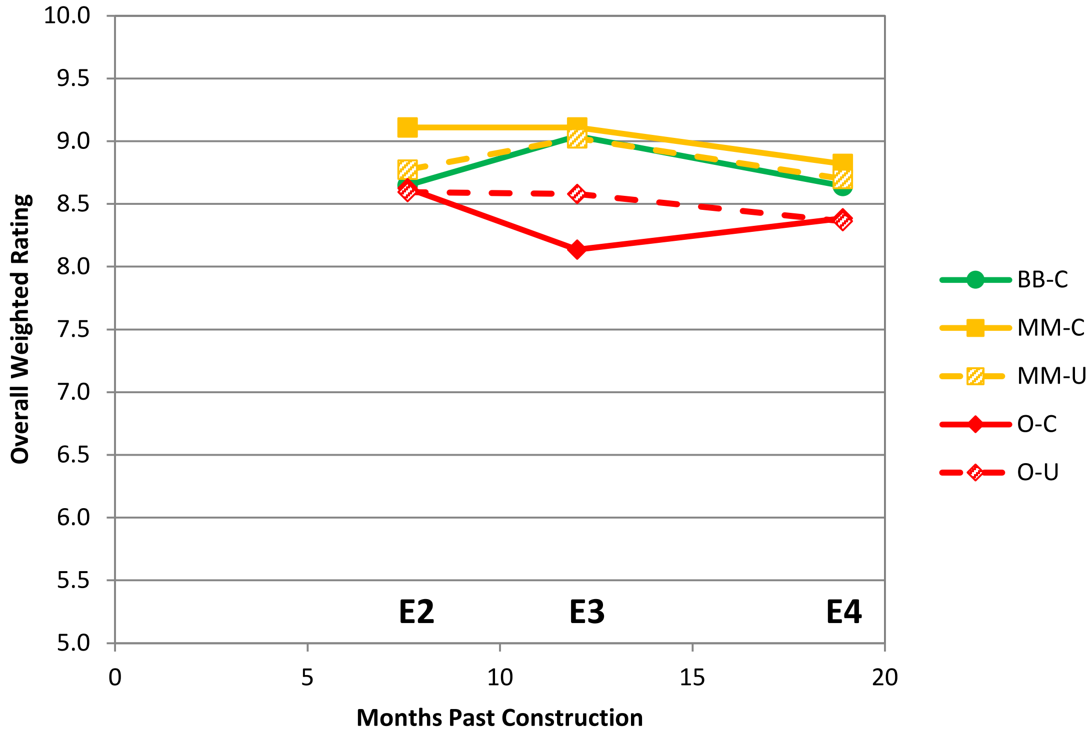

Figure 16: Overall weighted ratings over time for the Hand County test sections.

5.6.1.7. Gravel Loss by Cast-Off

The summary results from the gravel loss measurement are presented in figure 17. The most significant observation from these results is that the Bone Bright-compacted (above-standard) test section experienced the lowest rate of gravel loss (22 tons per year), while the Martinmas-compacted (standard) and Martinmas-uncompacted sections experienced a higher gravel loss of about 39 tons per year. At about 45 tons per year, the Oakley-compacted (substandard) and Oakley-uncompacted test sections exhibited the highest gravel loss.

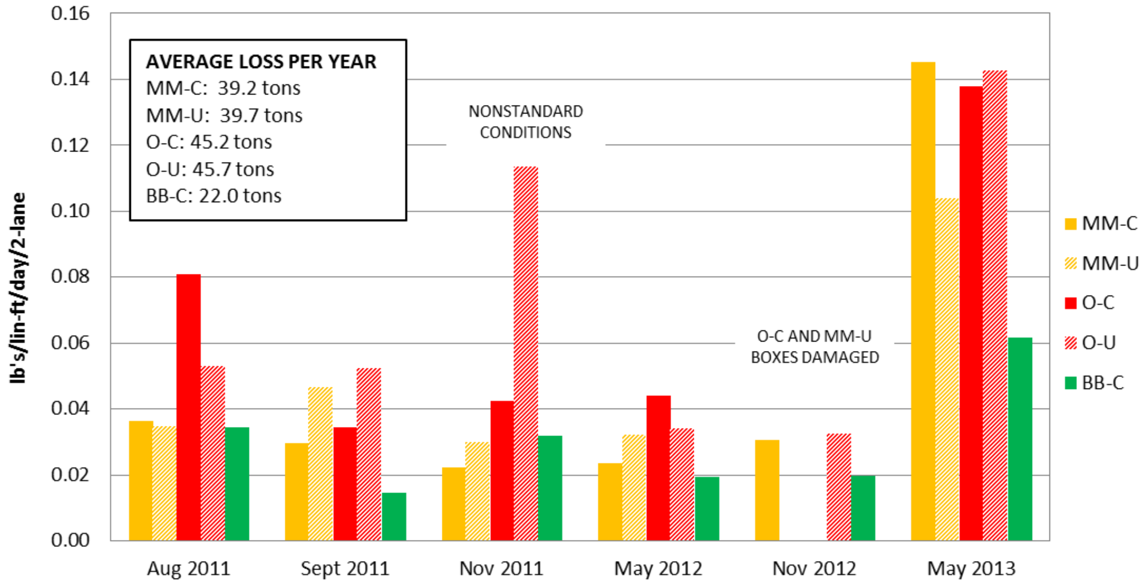

Figure 17: Gravel loss rates for Hand County test sections.

5.6.1.8. Hand County Summary Assessment

Following is a summary of the key findings from the assessment of the Hand County test site. These are based on a review of the performance charts without accounting for how the test sections may have received different levels of maintenance.

- The Martinmas gravel, which was initially characterized as standard, provided the best performance in terms of washboarding, rutting, raveling, dusting, and overall weighted rating as compared to the other gravels. Its performance in terms of potholing was also very good, but not quite as good as the other two gravels. In terms of gravel loss, it placed a distant second to the Bone Bright aggregate.
- The Bone Bright-compacted gravel, which was initially characterized as above-standard, was the second best performer overall. Its performance was relatively high in terms of washboarding, potholing, and gravel loss. For rutting, raveling, dusting, overall rating, it exhibited average performance.
- The Oakley gravel, which was characterized as substandard, exhibited poorer performance than the other gravels for gravel loss and all the distress ratings except potholing, where it appeared to be about the same as the Bone Bright gravel and slightly better that the Martinmas gravel.
- Assuming that the distress ratings at E2 are most representative of the effect of gravel road compaction on gravel road performance (because the effects of compaction dissipate over time), then the data show that compaction had little to no effect on washboarding, raveling, potholing, dusting, and the overall weighted rating. The data also indicate that compaction did have a significant effect on reducing rutting.

5.6.2. Custer County

This section provides the performance results for the five test sections that make up the Custer County test site. In reviewing the performance of the experimental sections, it is important to recognize that because the test sections were constructed along two different roads with two different levels of traffic and two different levels of maintenance, it is not valid to make head to head comparisons between the two sets of test sections. Medicine Mountain Rd, which includes the STAAP plus crusher fines (above-standard) and two STAAP (standard sections), carries 92 vehicles per day and received a total of 72 hours of effort during four different maintenance events. Saginaw Rd, which includes the two Bear Mountain (substandard) sections, carries 63 vehicles per day, and received a total of 24 hours of effort during two different maintenance events. In experimental terms, the type of aggregate, the level of traffic, and the level of maintenance are all confounded. Accordingly, it is not possible to determine whether any differences in performance are because of gravel type, traffic level, or maintenance level. Furthermore, because the maintenance records (see table 50) do not show how maintenance efforts were distributed between the sections along the two roads, it is not possible to determine the effects of maintenance on the performance of sections at the two gravel road locations.

5.6.2.1. Washboarding

Figure 18 shows a graph of the post-construction washboard ratings obtained during the three inspection periods (E2, E3, and E4). Examination of the graph indicates:

- Considering the high ratings throughout the experiment, the Bear Mountain (substandard) test sections performed well in terms of washboarding. Some maintenance was performed on all sections; however, there is no data to determine its effect.
- The high ratings at E2 (as well as E3 and E4) for the Bear Mountain compacted and uncompacted sections, suggest that compaction did not have any effect on performance.
- The washboard ratings at E2 indicate that the STAAP plus crusher fines (above-standard) section performed better that the other two STAAP (standard) sections for the first four months after construction. However, there is no apparent difference in performance between any of the STAAP sections after 10 months.
- The difference in washboard ratings between the STAAP (standard)-compacted and STAAP-uncompacted sections at E2 suggest that compaction did have an effect on performance during the first four months after construction.

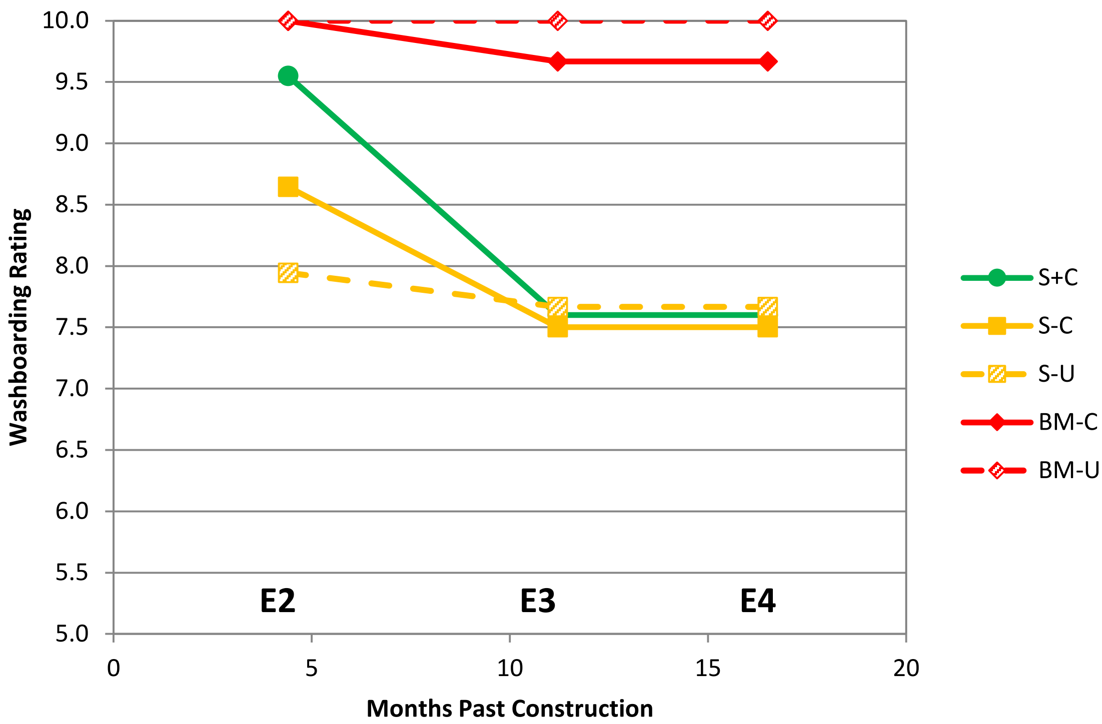

Figure 18: Washboard ratings over time for the Custer County test sections.

5.6.2.2. Rutting

Figure 19 provides a graph of the rutting ratings obtained during the three post-construction inspection periods (E2, E3, and E4), indicating clear trends in rutting over time for all of the test sections.

- Assuming that the initial rutting ratings were near 10 after construction, then the ratings at E2 indicate that there must have been a significant drop in rutting ratings during the first four months after construction (for all five test sections). Some maintenance was performed on all sections; however, there is no data to determine its effect.
- Overall, the Bear Mountain sections performed well in terms of rutting over the course of the experiment. It is likely that the increase in the rut rating from E2 to E3 is the result of significant maintenance performed in March 2012.
- The lack of a difference in the rutting rating for the Bear Mountain sections indicates that compaction had no effect on performance.
- For the three test sections along Medicine Mountain Rd, the rutting ratings show that the STAAP plus crusher fines (above-standard) section performed worse that the two STAAP (standard) sections, especially at the E3 and E4 periods.
- The difference in the rutting ratings at E2 between the STAAP-compacted and STAAP uncompacted sections indicates that compaction had a negative effect on the development of rutting during the first four months after construction.

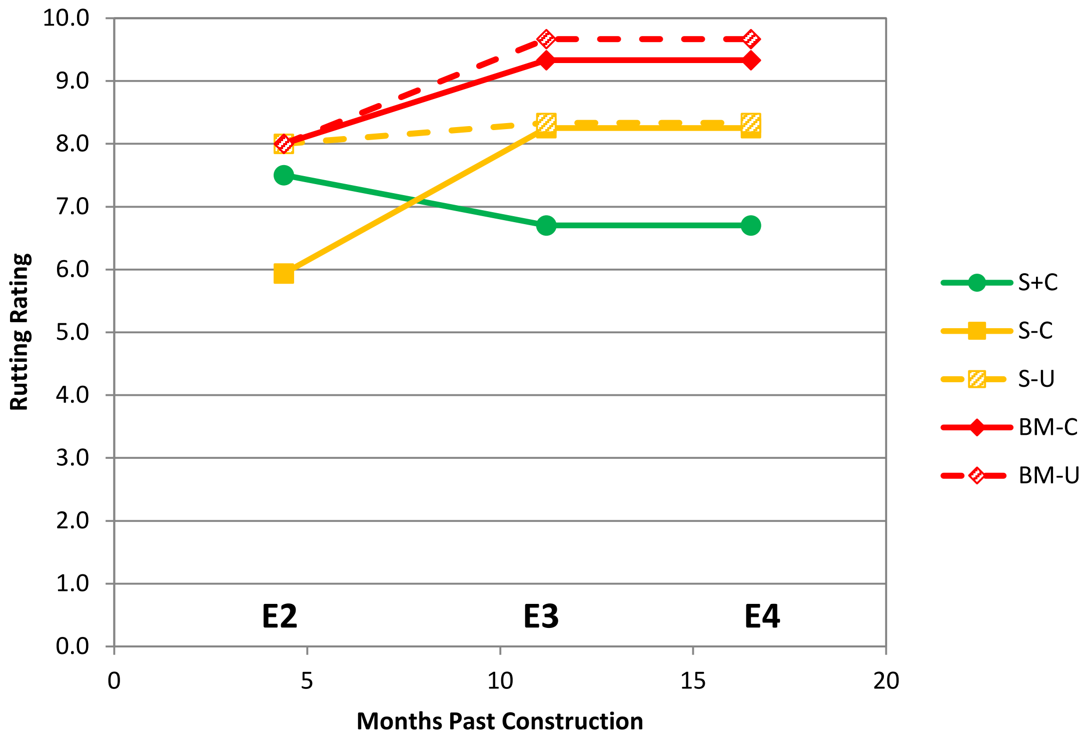

Figure 19: Rutting ratings over time for the Custer County test sections.

5.6.2.3. Raveling

Figure 20 shows a graph of the post-construction raveling ratings obtained during the three inspection periods (E2, E3, and E4). The graph shows that there are some minor performance differences between the test sections.

- Based on the raveling ratings at E2 and assuming that the initial raveling ratings were near 10 after construction, then there must have been a drop in raveling ratings for all of the sections during the first four months after construction. Some maintenance was performed on all sections; however, there is no data to determine its effect.
- The Bear Mountain sections showed very little difference in performance between E2 and E4. The rutting ratings at E2 suggest that compaction had a slightly negative (if not negligible) impact on performance for the first four months after construction.
- For the sections along Medicine Mountain Rd, the data indicate that the STAAP plus crusher fines (above-standard) section performed slightly better than the two STAAP (standard) sections. The rutting ratings at E2 suggest that compaction had a negative impact on performance over the first four months after construction.

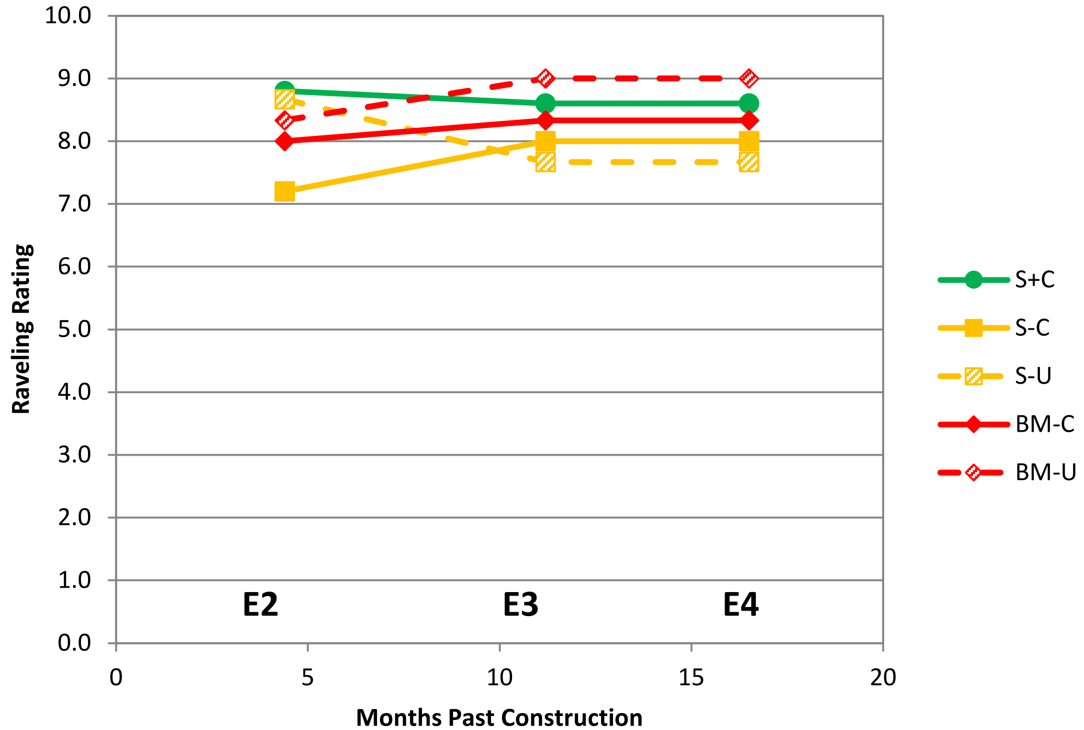

Figure 20: Raveling ratings over time for the Custer County test sections.

5.6.2.4. Potholing

Figure 21 shows a graph of the post-construction pothole ratings obtained during the three inspection periods (E2, E3, and E4). The graph shows some large performance differences between the test sections.

- Based on the potholing ratings at E2 and assuming that the initial potholing ratings were near 10 after construction, there was a significant drop in the potholing ratings for the Bear Mountain (substandard)-compacted and STAAP (standard)-compacted test sections. The other three sections showed little to no drop in pothole ratings. Some maintenance was performed on all sections; however, there is no data to determine its effect.
- The potholing ratings indicate a large difference in the performance between the two Bear Mountain (substandard) sections, with the Bear Mountain-compacted section performing much worse. In this case, it appears that compaction had a large negative impact on performance.
- For the sections located along Medicine Mountain Rd, there was a large difference in performance between the STAAP plus crusher fines (above-standard) and STAAP (standard) section. The STAAP plus crusher fines section performed very well, while the STAAP-uncompacted section performed poorly and the STAAP-compacted section performed the worst.

- Based on the difference in potholing ratings for the two STAAP sections at E2, compaction had a positive effect on performance over the first four months after construction. The potholing ratings for E3 and E4, on the other hand, indicate that compaction has a negative impact on performance.

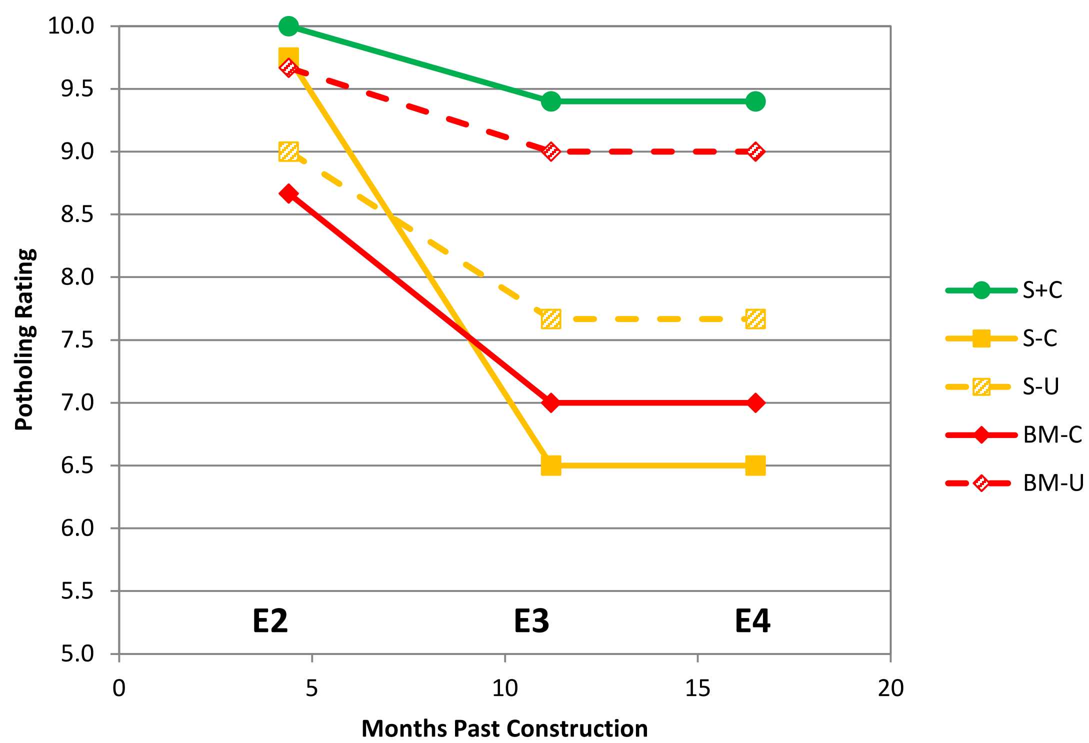

Figure 21: Potholing ratings over time for the Custer County test sections.

5.6.2.5. Dusting

Figure 22 shows a graph of the dusting ratings obtained during the three post-construction inspection periods (E2, E3, and E4). The graph shows that there is very little difference in performance.

- The performance of the two Bear Mountain sections is identical. Also, there is no indication that compaction had any effect on dusting performance.
- The performance of all three STAAP sections is identical. Again, there is no indication that compaction had any effect on dusting performance.
- Some maintenance was performed on all sections; however, there is no data to determine its effect.

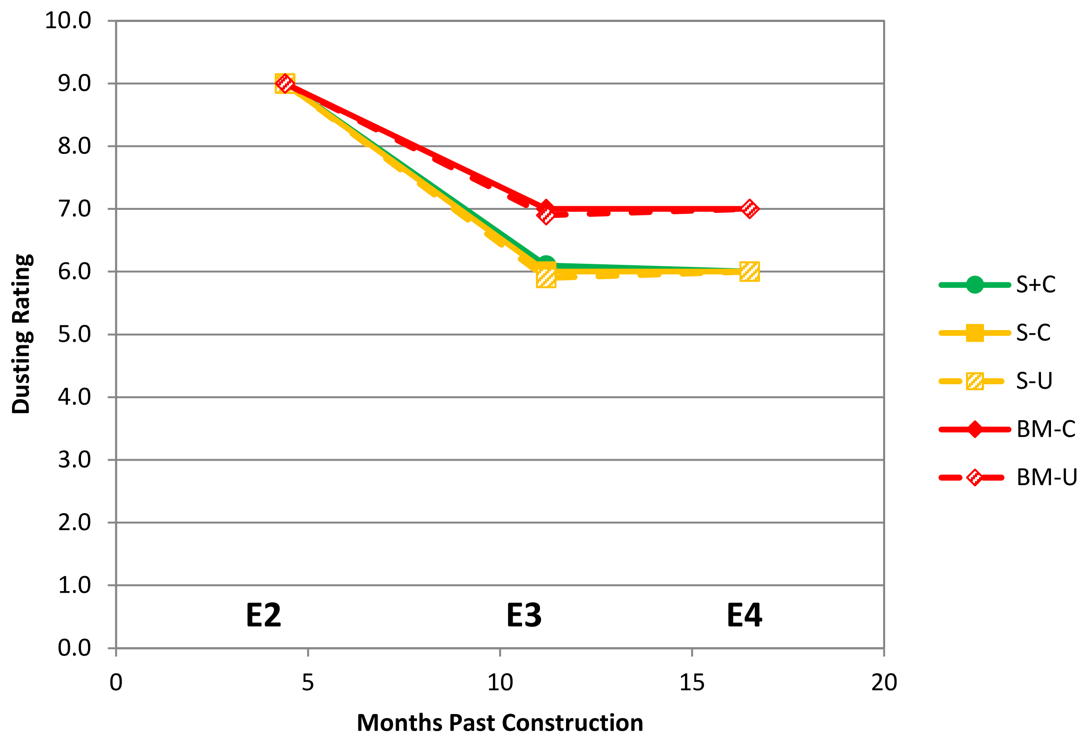

Figure 22: Dusting ratings over time for the Custer County test sections.

5.6.2.6. Overall

Figure 23 provides a graph showing the overall weighted (composite) ratings versus time for each of the five Custer County test sections, and indicates some notable differences in performance.

- Since the initial overall weighted ratings must have been near 10 after construction, a significant drop in ratings took place between construction and the first inspection period (E2). This rating decrease is a reflection of the drop in washboarding, rutting, and raveling ratings that took place during the four months after construction.
- The results indicate that the Bear Mountain sections performed well over the 17-month experimental period. The results at E2 suggest that compaction did not have much effect on performance over the first four months after construction. However, the results at E3 and E4 indicate that compaction had a negative impact on performance.
- For the sections along Medicine Mountain Rd., the results indicate that the STAAP plus crusher fines (above-standard) section performed satisfactorily over the 17-month experimental period. The two STAAP sections performed slightly worse. Based on the overall weighted rating scores at E2, there is no clear indication that compaction had a significant impact on performance.

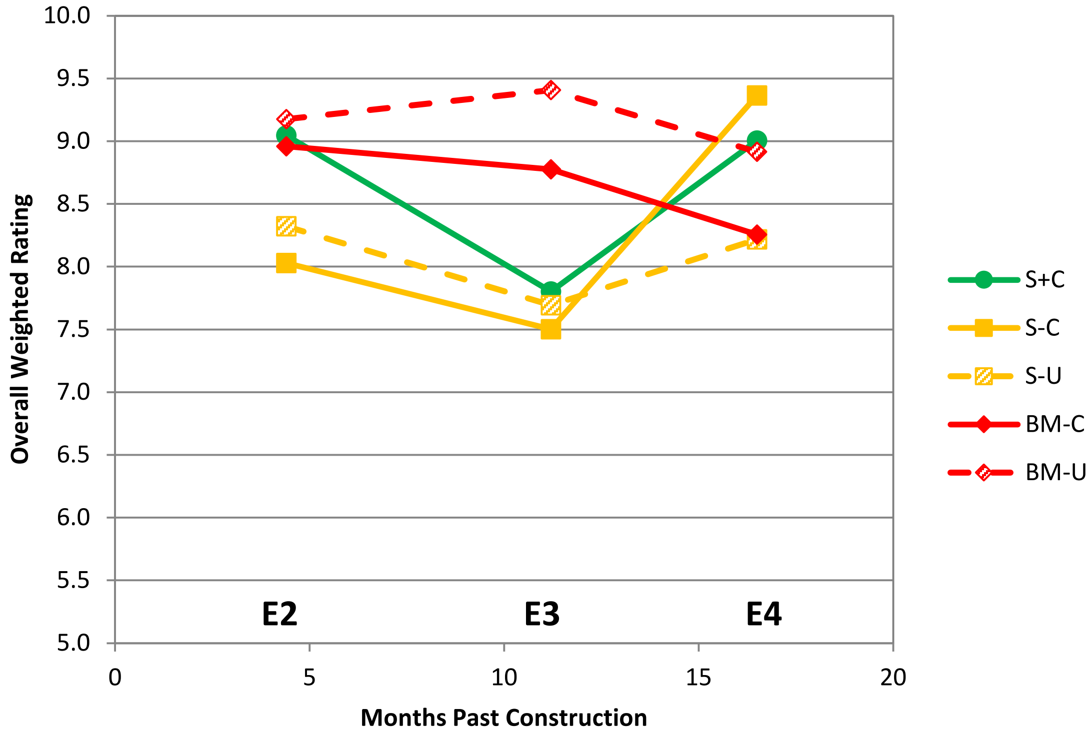

Figure 23: Overall weighted ratings over time for the Custer County test sections.

5.6.2.7. Gravel Loss by Cast-Off

The summary results from the gravel loss measurement are presented in figure 24. The primary finding from these results is that the Bear Mountain-compacted and Bear Mountain-uncompacted test sections experienced very low rates of gravel loss of 4.1 and 5.7 tons per year, respectively.

The STAAP sections also exhibited relative low rates of gravel loss. The STAAP-compacted and STAAP-uncompacted sections experienced losses of 6.6 and 11.1 tons per year, respectively. At 8.9 tons per year, the STAAP plus crusher fines-compacted test section exhibited gravel loss at a rate between the two STAAP sections.

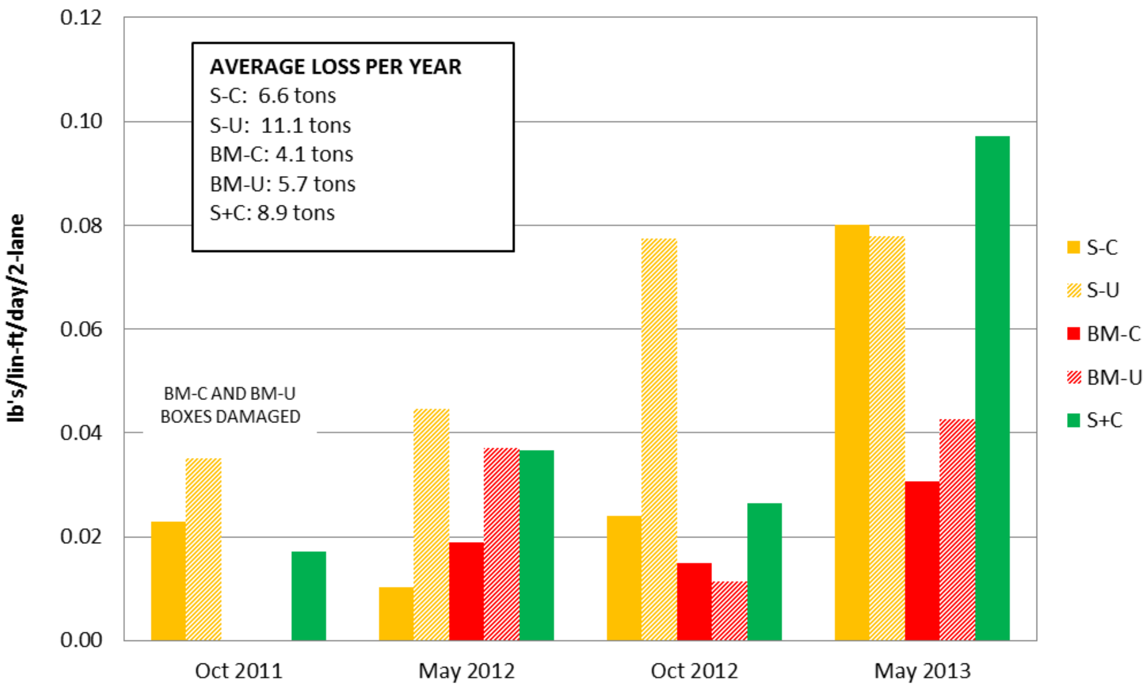

Figure 24: Gravel loss rates for each test section in Custer County over the testing period.

5.6.2.8. Custer County Summary Assessment

As noted previously, the test sections at the Custer County test site were split between two road sections with different site conditions, making it impossible to make a valid comparison of the performance of the Bear Mountain gravel test sections with the STAAP gravel test sections. The different traffic levels, soil conditions, and possible other environmental factors associated with each site can affect the performance as much as (or even more than) the type of gravel. The following is a summary of key findings:

- The Bear Mountain gravel, which was initially characterized as substandard, provided very good performance in terms of washboarding, rutting, dusting, overall weighted, and gravel loss. The one deficiency observed was that the Bear Mountain-compacted test section performed poorly in terms of potholing.
- Overall, the STAAP plus crusher fines-compacted test section, which was initially characterized as above-standard, appears to be a good performer. It performed very well in terms of potholing and raveling, but was poor in rutting and gravel loss.
- The STAAP gravel, which was initially characterized as standard, exhibited relatively poor performance in terms of washboarding, raveling, potholing, dusting, and gravel loss.
- Overall, the data suggests that the uncompacted gravel sections performed better than the compacted gravel sections.

5.6.3. Brookings County

This section provides the performance results for the five experimental test sections that make up the Brookings County test site. In reviewing the performance of the test sections at the Brookings County test site, it is important to recognize the effect of road maintenance and traffic. Maintenance was applied at certain times (see table 51) and attention was given by maintenance crews to identifying which sections got maintenance and why that maintenance was applied. However, there is no indication of how much maintenance effort was applied at each time. Also, since no performance data were collected before or after the maintenance activities, it is not possible to make accurate statements about the effect of maintenance on the performance of the individual test sections. Accordingly, the effect of maintenance is only addressed in general terms where it is appropriate. The impact of traffic level on the Brookings County sections is not a consideration in terms of performance impacts because each section received approximately the same level of traffic.

5.6.3.1. Washboarding

Figure 25 shows a graph of the post-construction washboard ratings obtained during the three inspection periods (E2, E3, and E4). As can be seen, there are some clear performance trends for each of the sections.

- There is almost no development of washboarding between construction and the first data collection event (E2) seven months later.
- Based on the maintenance records, none of the three Dupraz (standard and above-standard sections) specifically required maintenance to repair washboarding. On the other hand, the Bowes (substandard)-compacted test section was maintained 10 times before E2 to address washboarding while the Bowes-uncompacted test section was maintained three times to address washboarding. It is also useful to note that the two Bowes sections required maintenance nine more times to address washboarding before the end of the experiment. The only other section that required maintenance for washboarding (twice) was the Dupraz (standard)-uncompacted.
- Considering the high ratings and that they required almost no maintenance to address washboarding, all three of the Dupraz sections performed very well. The two Bowes sections, on the other hand, performed considerably worse.
- With the possible exception of the two Bowes sections, it does not appear that compaction had a meaningful effect on washboard performance.

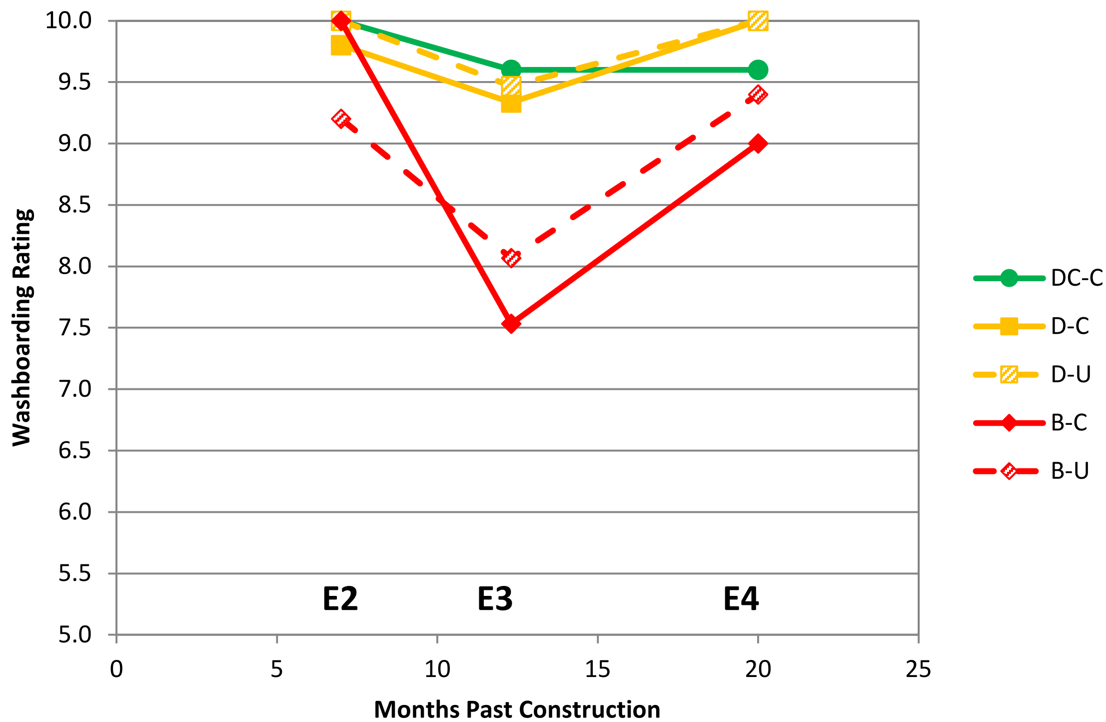

Figure 25: Washboard ratings over time for the Brookings County test sections.

5.6.3.2. Rutting

Figure 26 provides a graph of the rutting ratings obtained during the three post-construction inspection periods (E2, E3, and E4).

- Assuming the initial rutting ratings were near 10 right after construction, then three of the test sections, Dupraz (standard)-compacted, Bowes (substandard)-compacted, and Dupraz plus clay (above-standard)-compacted experienced a significant drop in the ratings (increase in rutting) between construction and the E2 inspection period. The two remaining sections, Dupraz-uncompacted and Bowes-uncompacted, do not show a significant drop in rutting ratings.
- After E2, the rutting rating for all sections was between 8.0 and 9.0 and there does not seem to be a significant difference between any of the sections.
- Maintenance was performed on all five sections during the experiment; however, the records do not indicate that any maintenance was specifically done to address rutting. Nevertheless, the maintenance that was done to address washboarding and other deterioration would have affected rutting. Accordingly, consideration must be given to the fact that the Bowes sections (particularly the one that was compacted during construction) received much more attention than the two Dupraz and the Dupraz plus clay sections.
- Based upon the rutting ratings at E2, the uncompacted test sections performed better the compacted sections. After E2, there is no apparent difference in performance.

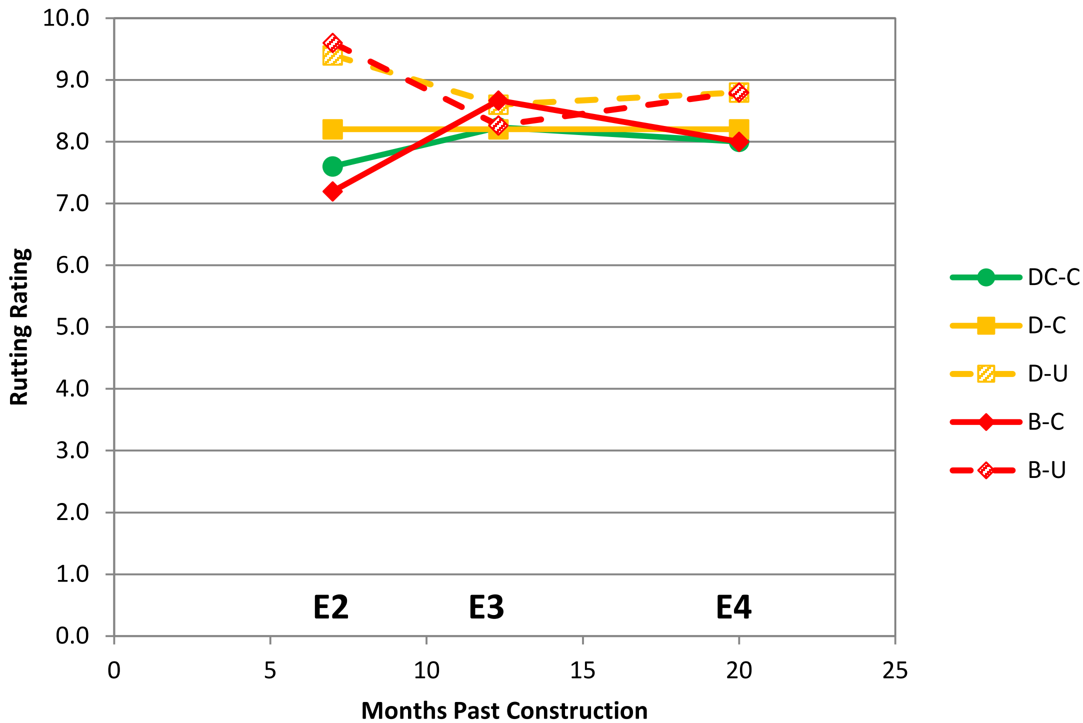

Figure 26: Rutting ratings over time for the Brookings County test sections.

5.6.3.3. Raveling

Figure 27 shows a graph of the post-construction raveling ratings obtained during the three inspection periods (E2, E3, and E4).

- Based on the raveling ratings at E2 and assuming that the initial raveling ratings were near 10 after construction, the drop in the raveling ratings ranged from small to large after construction.
- The graph indicates that three of the sections – the two Dupraz sections and the Bowes (substandard)-uncompacted section – exhibit the same performance. The Dupraz clay-compacted section performed the best, while the Bowes-compacted section performed the worst.
- Maintenance was performed on all five sections during the experiment; however, the records do not indicate that any maintenance was specifically done to address raveling. Nevertheless, the maintenance that was done to address washboarding and other deterioration had to affect raveling. Accordingly, consideration must be given to the fact that the Bowes sections (particularly the compacted one) received much more attention than the two Dupraz and Dupraz plus clay sections.
- The graphs suggest that the uncompacted sections performed better than the compacted sections.

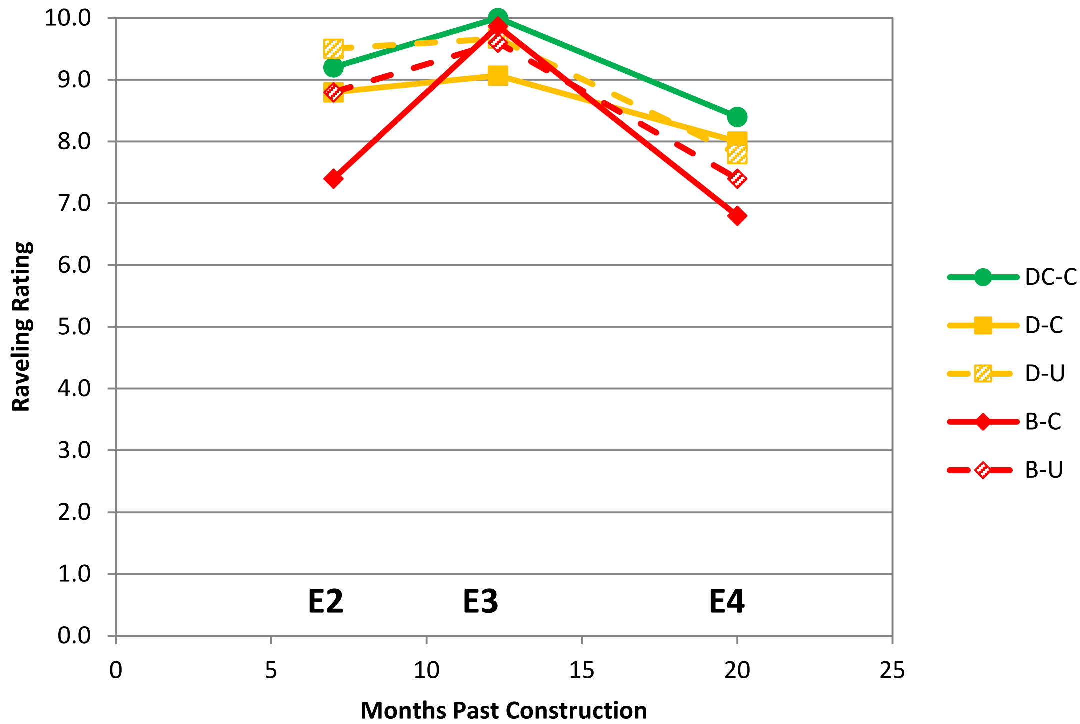

Figure 27: Raveling ratings over time for the Brookings County test sections.

5.6.3.4. Potholing

Figure 28 shows a graph of the post-construction pothole ratings obtained during the three inspection periods (E2, E3, and E4). The graph shows some large performance differences between the test sections.

- In light of the low pothole ratings in the E2 and E4 inspection periods, the Dupraz plus clay (above-standard)-compacted section appears to be prone to the development of potholes. According to the maintenance records, it received maintenance three times before E2 (regular maintenance, pulled gravel, and high crown). Between E2 and E3, it received maintenance twice (pulled gravel). The last maintenance was less than a month before the E3 data collection event, so this likely explains the high pothole rating at E3. After E3, it only received maintenance once, and that was at least seven months before E4, when the rating dropped to 6.2.
- The Dupraz (standard)-compacted test section is also a poor performer. It received maintenance twice before E2 (regular maintenance and high crown), twice between E2 and E3 (pulled gravel), and twice after E3 (pulled gravel and regular maintenance). It is interesting that the same maintenance that likely increased the rating of the Dupraz plus clay section had no apparent effect on this section.

- The Bowes (substandard)-compacted section generally performed reasonably well in terms of potholing; however, its performance was likely affected by all the maintenance it received to address washboarding.
- The Dupraz (standard)-uncompacted and Bowes (substandard)-uncompacted test sections performed the best in terms of pothole ratings. However, it is important to note that all the maintenance that Bowes-uncompacted section received to address washboarding (as compared to the Dupraz-uncompacted section) likely improved its pothole performance.
- In this instance, the data show that the uncompacted test sections performed much better than the compacted test sections.

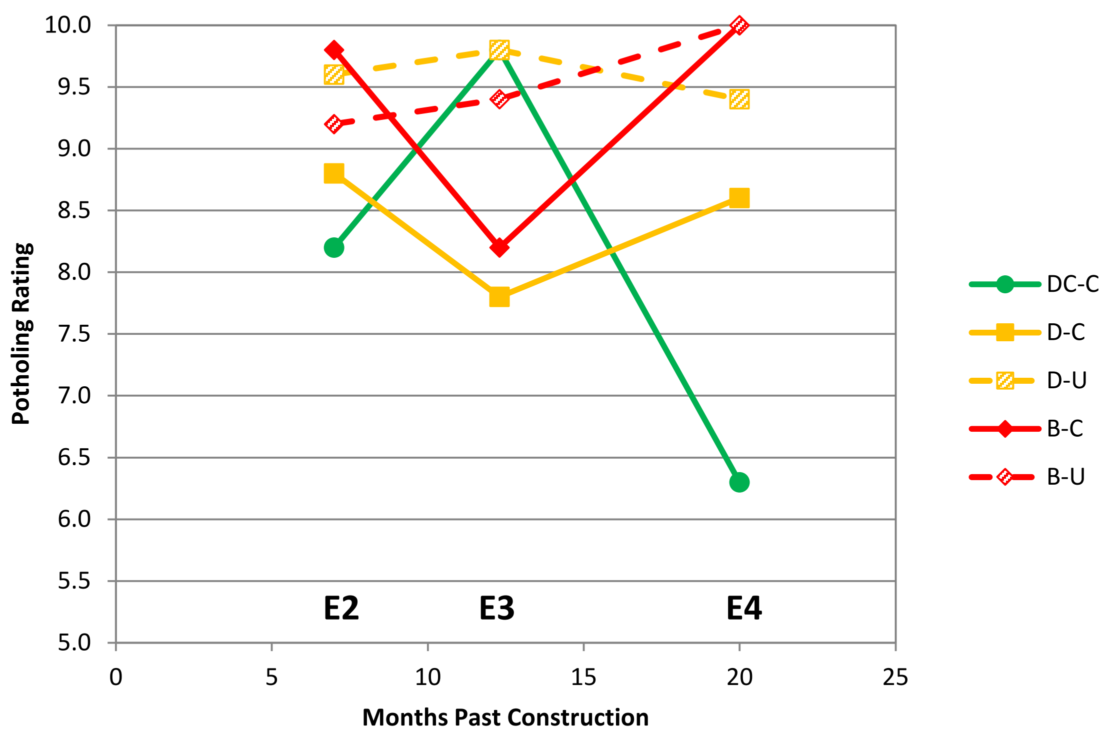

Figure 28: Potholing ratings over time for the Brookings County test sections.

5.6.3.5. Dusting

Figure 29 shows a graph of the dusting ratings obtained during the three post-construction inspection periods (E2, E3, and E4). Unfortunately, dusting data was available for only three test sections, Bowes-compacted, Duprav-compacted, and Duprav with clay-compacted.

- The dusting ratings between E2 and E3 are identical for all three test sections. The ratings at E4 show that the Dupraz plus clay (above-standard)-compacted section performed the best while the Dupraz (standard)-compacted section performed the second best. The Bowes (substandard)-compacted section is a close third.

- Since the dusting rating at the time of construction was not determined, there is no basis to indicate how much the gravel deteriorated between the time of construction and E2. The Bowes-compacted section received considerably more maintenance than the other two sections over the course of the project; however, it is not possible to determine how much this maintenance might have affected the dusting ratings.
- Because there was no difference in the performance between the compacted and uncompacted test sections in terms of dusting rating, there is no evidence to indicate whether compaction during construction had an effect on the dusting rating.

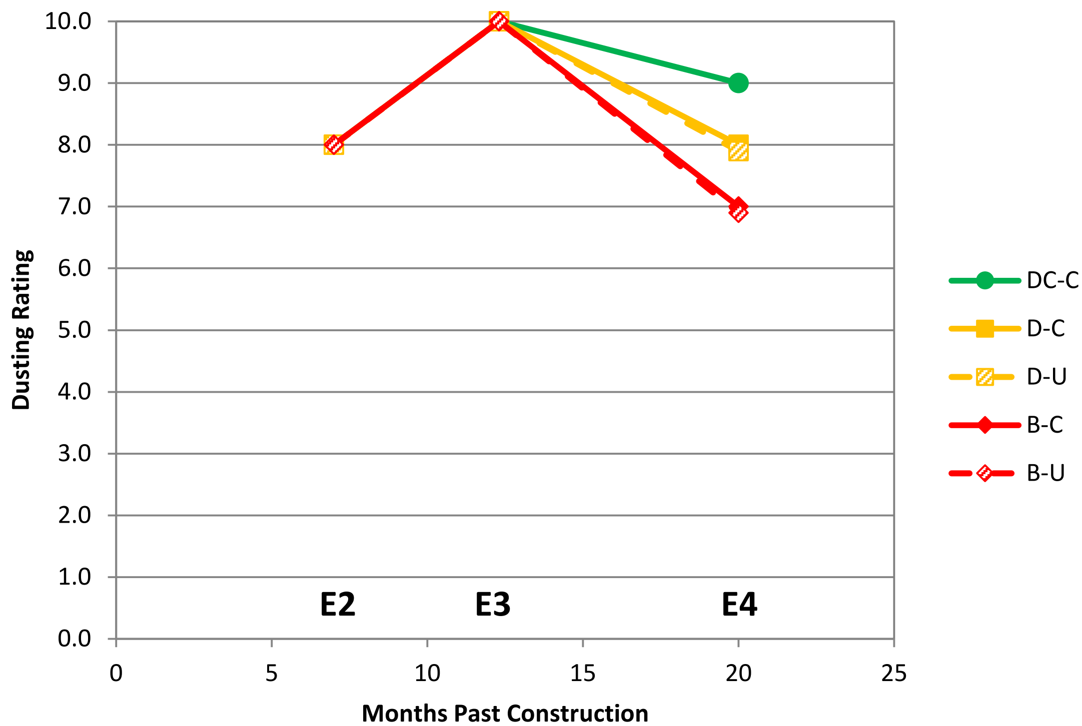

Figure 29: Dusting ratings over time for the Brookings County test sections.

5.6.3.6. Overall

Figure 30 provides a graph showing the overall weighted (composite) ratings versus time for each of the five Brookings County test sections. As can be seen, there are some notable performance trends.

- Assuming that the initial overall weighted ratings were near 10 soon after construction, there was a small to medium drop in ratings between construction and the E2 inspection period. This drop is a reflection of the drop in washboarding, rutting, raveling, and dusting ratings that occurred between construction and the E2 inspection period.

- Based on the graph, it appears that the Dupraz (standard)-uncompacted test section provided the best overall performance, followed by the Dupraz (standard)-compacted test section.
- The Bowes (substandard)-compacted test section provided the poorest overall performance, with the Bowes (substandard)-uncompacted test section providing slightly better performance.
- The performance of the Dupraz plus clay-compacted test section appears to be within that of the Dupraz and Bowes test sections.
- Examination of the graph indicates that the uncompacted test sections provided better overall performance than the compacted test sections.

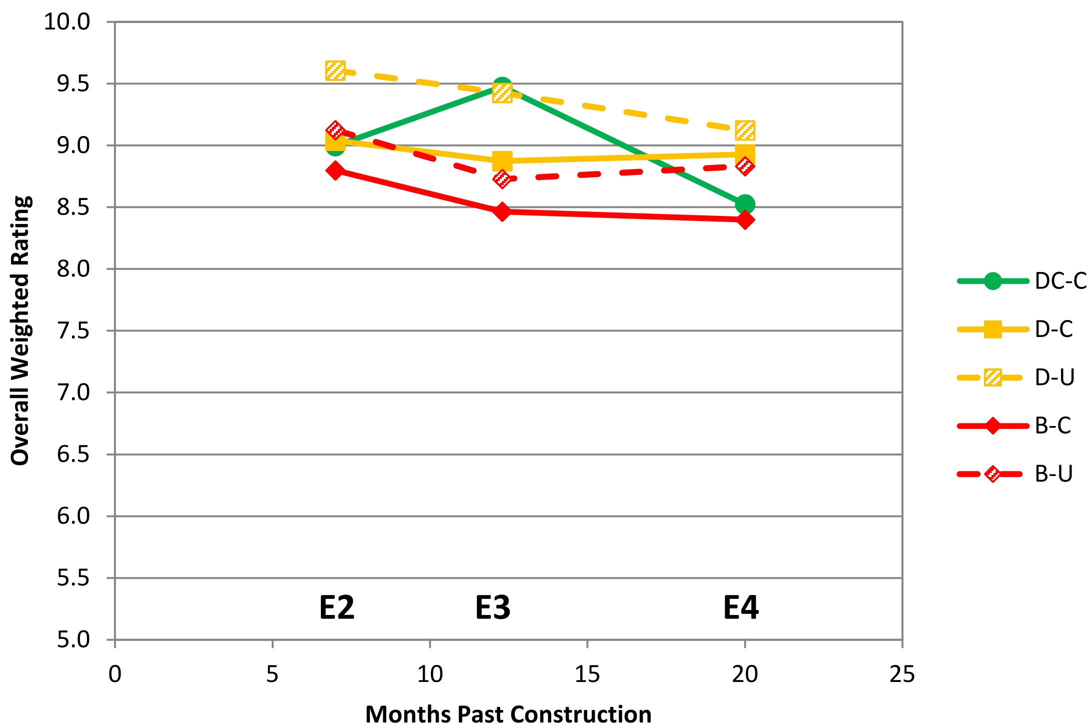

Figure 30: Overall weighted ratings over time for the Brookings County test sections.

5.6.3.7. Gravel Loss by Cast-Off

The summary results from the gravel loss measurements are presented in figure 31. The primary finding from these results is that the Dupraz plus clay-compacted test sections experienced the least rate of gravel loss at 7.2 tons per year. The Dupraz-uncompacted and Dupraz-compacted sections experienced a higher gravel loss of 12.6 and 13.3 tons per year, respectively. Lastly, the Bowes-uncompacted and Bowes-compacted test sections exhibited the highest gravel loss at respective rates of 17.3 and 18.1 tons per year.

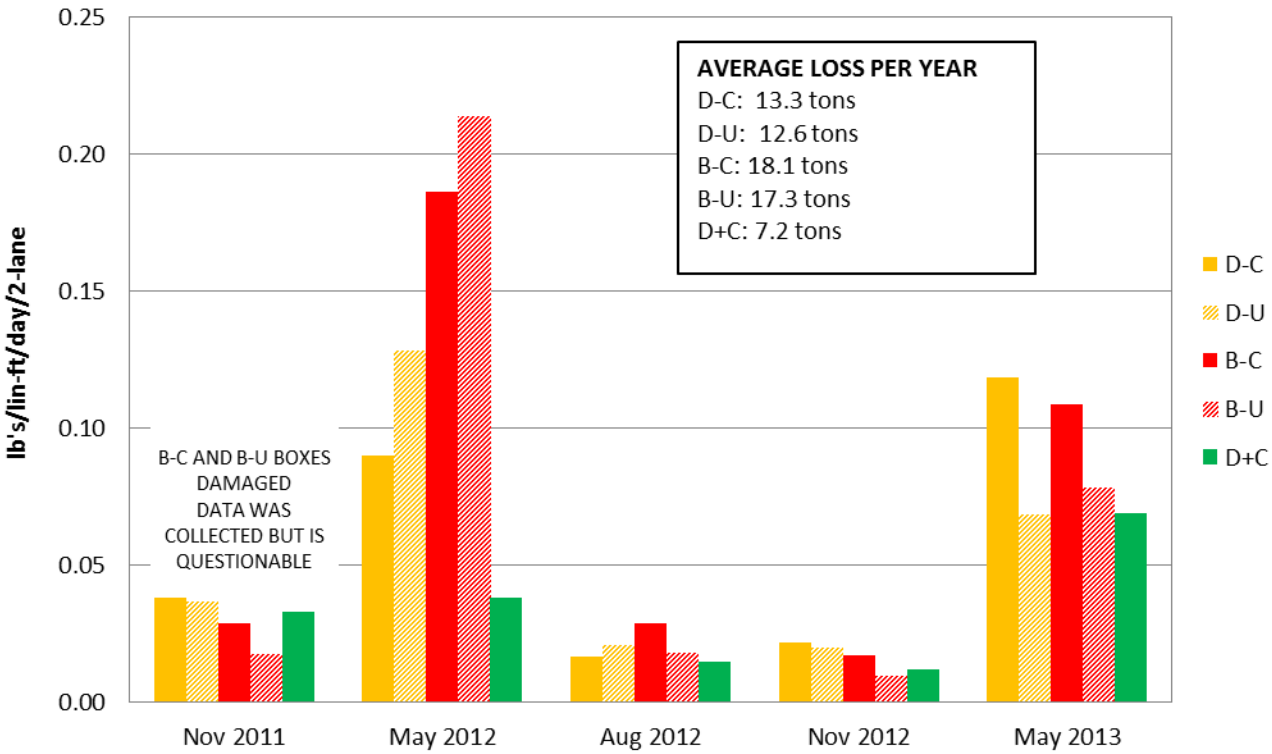

Figure 31: Gravel loss rates for each test section in Brookings County over the testing period.

5.6.3.8. Brookings County Summary Assessment

Following is a summary of the key findings from the assessment of the Brookings County test site.

- The choice for best performing gravel is not as clear for the Brookings County test site as it was for the other two Counties. The Dupraz plus clay gravel, which was initially characterized as above-standard, provided the best performance in terms of washboarding, raveling, dusting, and gravel loss and was second highest in terms of overall weighted rating. However, its performance in terms of rutting and potholing was poor.
- The Dupraz gravel, which was initially characterized as standard, was the second best performer. It performed very well in terms of washboarding, raveling, rutting, and dusting and was best in terms of overall weighted score. However, it had one test section that performed poorly in terms of potholing and was a distant second in terms of gravel loss.
- The Bowes gravel, which was initially characterized as substandard, was the poorest performer. It exhibited the poorest performance in washboarding, raveling, overall weighted, and gravel loss. Lastly, the Bowes sections—particularly the compacted gravel section—required much more maintenance effort to address washboarding than the other gravels.

- Since the uncompacted gravel sections performed better than their counterpart compacted gravel sections in every instance, there is evidence to conclude that gravel roads should not be compacted—at least not in Brookings County with the gravels used in this experiment.
- It was possible to consider the effects of maintenance because information on how maintenance activities were distributed between the test sections was provided.

5.7. Statistics-Based Performance Comparisons

5.7.1. Introduction

In the review of test section performance presented in the last section, observations were made based on visual examination of the performance curves for each test section, with no consideration given to whether the observed differences were statistically significant. Accordingly, this section provides the results of a more statistically rigorous analysis approach to determine if:

1. The initial compaction had a significant effect on performance.
2. The substandard or above-standard gravels performed significantly better or worse than the standard gravels.

The six primary performance measures evaluated were washboarding, rutting, raveling, potholing, dusting, and overall rating. In comparing the performance of the different gravels, it should be noted that a confidence level of 90 percent was used throughout the analyses.

5.7.2. Determination of Whether Initial Compaction Had a Significant Effect

To determine if compaction (rolling) of the gravel had an effect on performance, the original experiment called for the construction of "sister" sections at each site. For the standard and below-standard gravels, one sister section was constructed with compaction and the second was constructed without. (The above-standard gravel was only constructed using compaction). The initial examination of the results indicated that there was not much difference in the performance between the compacted and uncompacted sections. However, for this analysis, a statistical approach was used to determine if the performance differences were statistically significant. Specifically, a Students t-test was used to determine if the average difference in performance between the compacted and uncompacted sections (for the five key performance measures) was significant. In statistical terms, the approach was used to test the hypothesis that the average difference in performance (compacted score minus uncompacted score) was zero.

For the initial analysis, the data from all E2, E3, and E4 combinations were tested. The results of this analysis, as presented in table 52, show that only 21 of the 90 combinations (23 percent) exhibited a significant difference in performance between the sections built with compaction and the sections built without. Of the 21, only 5 show a positive difference. This means that, as a whole, compaction did not improve performance.

Table 52: Summary results of comparison between compacted and uncompacted sections.

County	Comparison	Performance Measure	t-Test Result (Average Difference)		
			E2	E3	E4
Hand	Standard compacted	Overall	Not significant (0.34)	Not significant (0.08)	Not significant (0.12)
		Washboarding	No difference (0.00)	Not significant (-0.10)	Not significant (0.20)
		Raveling	Not significant (0.20)	Not significant (-0.30)	Not significant (0.75)
		Rutting	Not significant (1.40)	Not significant (0.62)	Not significant (-0.50)
		Potholing	Not significant (0.20)	Not significant (0.05)	Not significant (-0.10)
	Substandard compacted	Overall	Not significant (0.03)	Significant (-0.44)	Not significant (0.02)
		Washboarding	No difference (0.00)	Significant (-0.87)	No difference (0.00)
		Raveling	Not significant (-0.60)	Not significant (-0.20)	Not significant (-0.60)
		Rutting	Not significant (0.80)	Not significant (-0.13)	Significant (0.60)
		Potholing	No difference (0.00)	Not significant (-0.20)	Not significant (0.20)
Brookings	Standard compacted	Overall	Significant (-0.57)	Significant (-0.55)	Not significant (-0.19)
		Washboarding	Not significant (-0.20)	Not significant (-0.13)	No difference (0.00)
		Raveling	Significant (-0.70)	Significant (-0.60)	Not significant (0.20)
		Rutting	Not significant (-1.20)	Significant (-0.40)	Not significant (-0.60)
		Potholing	Not significant (-0.80)	Not significant (-2.00)	Not significant (-0.80)
	Substandard compacted	Overall	Significant (-0.33)	Not significant (-0.26)	Significant (-0.43)
		Washboarding	Significant (0.80)	Not significant (-0.53)	Not significant (-0.40)
		Raveling	Significant (-1.40)	Not significant (0.27)	Significant (-0.60)
		Rutting	Significant (-2.40)	Not significant (0.40)	Significant (-0.80)
		Potholing	Not significant (0.60)	Significant (-1.20)	No difference (0.00)
Custer	Standard compacted	Overall	Not significant (0.07)	Not significant (-0.19)	Significant (1.15)
		Washboarding	Not significant (0.70)	Not significant (-0.17)	Significant (2.31)
		Raveling	Not significant (-1.47)	Not significant (0.33)	Significant (0.78)
		Rutting	Not significant (-2.06)	Not significant (-0.08)	Not significant (0.36)
		Potholing	Not significant (0.75)	Not significant (-1.17)	No difference (0.00)
	Substandard compacted	Overall	Not significant (-0.22)	Significant (-0.63)	Not significant (-0.66)
		Washboarding	No difference (0.00)	Not significant (-0.33)	Not significant (-1.00)
		Raveling	Not significant (-0.33)	Not significant (-0.67)	Not significant (-1.00)
		Rutting	Not significant (0.00)	Not significant (-0.33)	Not significant (0.22)
		Potholing	Not significant (-1.00)	Significant (-2.00)	Not significant (-0.67)

Considering the way the test sections were constructed, maintained, and monitored, perhaps the best indication of whether compaction has a significant effect on performance is in comparing the sections using only the data obtained during the first data collection period after initial construction (E2). The reason is that the data collected during this period were less affected by maintenance efforts than the data collected during E3 and E4. When the results are viewed from this perspective, they show that compaction did not have a significant effect on performance for any of the performance measures in any of the Hand County or

Custer County test sections. In other words, the performance data at E2 (eight months after construction for Hand County and five months after construction for Custer County) indicate that there was no value to applying compactive effort in constructing these sections.

For the Brookings County test sections, the standard (Dupraz) gravel showed a significant difference in raveling and overall performance. However, because of the negative differences, these results indicate that section compaction significantly reduced raveling and overall performance. For the substandard (Bowes) gravel, the effect on performance was significant for four of the performance measures. Of the four, section compaction only had a positive effect on washboarding. Again, the E2 performance data (seven months after construction) show that there was essentially no value to applying compactive effort to these sections.

5.7.3. Determination of Whether Performance Differences are Significant

Section 5.6 of this report provided graphical illustrations of the performance of five experimental sections for each of the three test sites and for six different performance measures: washboarding, raveling, rutting, potholing, dusting, and an overall (composite) rating. The ratings associated with each performance measure were based upon three to five field measurements obtained from each experimental section during three different times (E2, E3, and E4) after the start of the experiment. Observations and comparisons were then made by comparing the performance curves generated from the average performance values at each survey event. The basic problem with this approach to comparing performance is that it masks the effect variability. In other words, if the variability is high for a given performance measure, then there is an increased likelihood that the difference in performance between one section and another is not significant.

To address the problem with the variability in performance, two different statistical approaches were employed. In the first, a test was performed to determine if the difference in average performance between an above-standard section and the standard section at each time period was zero. In the case of a substandard section, the test was performed to determine if the difference in average performance relative to the standard section at each time period was zero. In statistical terms, the null hypothesis was established that the average difference is zero and was then tested to see if it was true. If the test results showed that the hypothesis was false, then it can be stated with statistical confidence that the performance of the above-standard (or substandard section) was better (or worse) than the standard section. However, in order to analyze all three time periods together, the average of the three to five assessments made per test cell were used rather than the individual data points.

The second approach uses the individual assessments taken at different locations within each test cell at each time period, and then tests whether the cell performed better or worse than the standard cell. This approach uses all the collected data, but is less straightforward to interpret because it gives a result for each time period rather than one assessment per cell per performance measure. However, since maintenance was performed at all test sections throughout the duration of the project, differences in performance may not have always been obvious at each inspection. Therefore, considering each time period individually helps identify more trends in performance.

Inherent in both of these statistical approaches is the assumption that the performance of all of the test sections never dropped below an unacceptable level. This is considered a valid assumption because maintenance was performed on a routine basis to avoid any unacceptable levels of gravel road distress or deterioration.

5.7.3.1.1. Test for Significance by Comparing Mean Performance for All Time Periods

In this approach, the average performance measure for each cell at each time period (event) is calculated from the individual rating locations. The difference in performance at each time period was calculated for each test pair. In this example, the standard compacted and substandard compacted test cells from Hand County are compared. The test statistic t is calculated from the mean and standard deviation of the three difference values, and compared to the $t_{critical}$ from a table. Since the absolute value of t is greater than $t_{critical}$, we reject the null hypothesis that the means are equal, and accept the alternate hypothesis that the difference in performance is statistically significant. This is demonstrated in table 53.

Table 53. Raw field data and t-test for Hand County raveling measurements in the standard compacted and substandard compacted test cells.

Material	Method	Cell Code	Event Code	Material Type	Raveling A	B	C	D	E	Mean
Martinmas	Compacted	MM-C	E2	Standard	9.0	9.0	9.0	9.0	--	9.00
Martinmas	Compacted	MM-C	E3	Standard	8.5	8.0	8.5	9.0	--	8.50
Martinmas	Compacted	MM-C	E4	Standard	8.0	7.0	8.0	8.0	--	7.75
Oakley	Compacted	O-C	E2	Substandard	6.0	7.0	6.0	4.0	8.0	6.20
Oakley	Compacted	O-C	E3	Substandard	8.0	8.0	8.0	7.0	8.0	7.80
Oakley	Compacted	O-C	E4	Substandard	6.0	6.0	4.0	4.0	8.0	5.60

Difference in Mean Performance			All Time Periods		t-test		
E2	E3	E4	Mean	Std Dev	T	$t_{critical}$ (table)	Interpretation
9.00-6.20 =2.80	8.50-7.80 =0.70	7.75-5.60 =2.15	1.88	1.075	-3.034	2.292	Difference is significant

5.7.3.1.2. Test for Significance by Comparing Performance for Individual Time Periods

In the previous approach, any variation of performance within the test cell, i.e., between locations A, B, C, and so on, was masked by the use of an average value. For example, one test cell with one area of severe potholing but good throughout may have location ratings of 10, 10, 4, 10, and 10. Another location may have equal potholing present at a very minor level and have location ratings of 9, 9, 9, 9, and 9. Both sections would have an average Event rating of 9, and would be treated by the first analysis approach in the same way.

In order to account for this kind of performance data variability, the second analysis approach was pursued. In this case, a two-sample, unpaired t-test was performed using Excel, and the t-value was not manually calculated. Rather, the Excel formula returns the probability that two sets of data actually have the same mean once the variability is accounted for. Since a 90% confidence level is being used, an output of less than 10% means that the means are not equal, and the difference is significant. Table 54 demonstrates how the data are used in this test.

Table 54: Raw field data and t-test setup for Brookings County potholing for the above-standard compacted and standard compacted test cells.

County	Material	Method	Cell Code	Event Code	Material Type	Potholing A	B	C	D	E
Brookings	Dupraz+clay	Compacted	DC-C	E2	Above-standard	7	5	9	10	10
Brookings	Dupraz+clay	Compacted	DC-C	E3	Above-standard	10	10	10	9	10
Brookings	Dupraz+clay	Compacted	DC-C	E4	Above-standard	5	4.5	8	8	6
Brookings	Dupraz	Compacted	D-C	E2	Standard	9	10	9	10	6
Brookings	Dupraz	Compacted	D-C	E3	Standard	10	10	8	5	6
Brookings	Dupraz	Compacted	D-C	E4	Standard	10	9	8	7	9

Data Comparison	Time Period	Data Input	t-test Output	Average Difference	t-test result
Standard versus Above-standard Compacted	E2	A through E ratings for Dupraz+ clay at E2 versus A through E ratings for Dupraz at E2.	63.6%	0.60	No significant difference
	E3	A through E ratings for Dupraz+ clay at E3 versus A through E ratings for Dupraz at E3.	12.2%	-2.00	No significant difference
	E4	A through E ratings for Dupraz+ clay at E4 versus A through E ratings for Dupraz at E4.	3.6%	2.30	Significant difference; above-standard performed worse than standard

5.7.3.1.3. Summary Results

Table 55 provides a summary of all the performance comparison results using a simple comparison of means as well as the two approaches described above. It also includes key information such as gravel properties, estimated traffic, and maintenance activities that are specific to each test site and are useful in reviewing the results. The summary performance results in this table are presented in a 3 by 6 array (3 county sites with 6 performance measures). Within a given block of the array, there is information that allows for section to section comparisons based on the following three methods:

- Method 1: Section Performance Rating – This column shows the mean and standard deviation for one of the six performance ratings. These ratings are calculated from the measured performance values (usually five at each site) and each of the post-construction measurement events (E2, E3, and E4). A direct comparison of the mean values provides a simple basis for comparing the performance of one section versus another. Again, this method does not take into consideration the variability of performance. In table 55, the red color code indicates that the mean performance of the section is lower than the mean performance of the corresponding standard section. Similarly, a green color code indicates that the mean performance of the section is higher than the mean performance of the standard section. It should be noted that the magnitude of the difference between the two means is inconsequential in assigning the red or green color code. As such, a small, insignificant difference may be interpreted as meaningful. A yellow color code indicates that the two means are identical.

- Method 2: Performance Comparison (Overall) to Standard – The information under this heading indicates whether a given above-standard (or substandard) section performed the same (S), better (B) or worse (W) overall than the corresponding standard section. The method, which was described earlier as the first approach, determines whether the average performance difference over E2, E3, and E4 (shown in parentheses) is close enough to zero to state that the sections are performing the same. If the average difference is significant, then the section can be said to have performed better or worse than the standard section, depending on whether the difference is positive (worst) or negative (better). The cell is also color-coded to indicate whether the performance is worse (red), better (green), or the same (yellow).
- Method 3: Performance Comparison (By Event) to Standard – The information under the "Performance Comparison (Overall) to Standard" heading indicates whether a given above-standard (or substandard) section exhibited the same (S), better (B), or worse (W) performance than the corresponding standard section at a given field data collection event (E2, E3, or E4). It also shows (in parentheses) the magnitude of the difference in the performance rating from the standard section. (This method was described earlier as the second approach). If a given above-standard or substandard section exhibited the same performance (statistically) as the standard section, it was assigned an S. If the section exhibited significantly better performance at a given event, it was assigned a B and the text was color coded green. If the section exhibited significantly worse performance, it was assigned a W and the text was color-coded red. The results presented under the "Performance Comparison (by Event) to Standard" heading provides the results of statistical comparisons of the performance data from each field data collection event which can be helpful in explaining the "Performance Comparison (Overall) to Standard" differences.

Following are some important considerations when reviewing the summary results in table 55.

- Since the standard section(s) serve as the basis for all of the performance comparisons, those sections are not assigned any letter or color codes.
- Because the performance ratings can vary widely from section to section (and from event to event), there is no standard difference between the means that result in a better or worse designation. In one instance where the variability is low, the difference may be as little as 0.30. In the case where the variability is high, the difference may be as high as 1.00.
- Other than showing the average section performance and standard deviation, no performance comparison between the Bear Mountain (substandard) sections and the STAAP (standard) sections is provided. This is because the Bear Mountain and STAAP sections were on two different roadway segments and experienced two different levels of traffic as well as two different subgrade soil conditions. Thus, the performance differences cannot be attributed to the gravel alone.

Table 55: Summary of performance comparisons.

County	Gravel Name (Intended Quality)	Method	Stockpile Test Results*: % Passing 3/4" Sieve	Stockpile Test Results*: % Passing #200 Sieve	Stockpile Test Results*: Plasticity Index (PI)	Traffic Data: Total Vehicles per Day	Traffic Data: Trucks per Day	No. of Maint. Events	Overall Rating: Section Perf. Rating (Mean & Std Dev)	Overall Rating: Perf. Comp. (Overall) to Standard	Overall Rating: Perf. Comp. (by Event) to Standard	Washboarding: Section Perf. Rating (Mean & Std Dev)	Washboarding: Perf. Comp. (Overall) to Standard	Washboarding: Perf. Comp. (by Event) to Standard	Raveling Rating: Section Perf. Rating (Mean & Std Dev)	Raveling Rating: Perf. Comp. (Overall) to Standard	Raveling Rating: Perf. Comp. (by Event) to Standard	Rutting Rating: Section Perf. Rating (Mean & Std Dev)	Rutting Rating: Perf. Comp. (Overall) to Standard	Rutting Rating: Perf. Comp. (by Event) to Standard	Potholing Rating: Section Perf. Rating (Mean & Std Dev)	Potholing Rating: Perf. Comp. (Overall) to Standard	Potholing Rating: Perf. Comp. (by Event) to Standard	Dusting Rating: Section Perf. Rating (Mean & Std Dev)	Dusting Rating: Perf. Comp. (Overall) to Standard	Dusting Rating: Perf. Comp. (by Event) to Standard
Hand (Central)	Bone Bright (Abv Std)	Comp	98.3	8.0	9	81 [85 M-F, 48 S-S]	59 [64 M-F, 48 S-S]	22	8.78 (0.25)	S (0.24)	E2: W (+0.46) E3: S (+0.07) E4: S (+0.18)	9.98 (0.09)	S (-0.03)	E2: N/A (0.00) E3: S (-0.10) E4: N/A (0.00)	7.47 (1.19)	S (+0.95)	E2: W (+1.40) E3: S (-0.10) E4: W (+1.55)	7.07 (0.87)	S (+0.35)	E2: S (+0.80) E3: S (+0.55) E4: S (-0.30)	9.93 (0.26)	S (-0.18)	E2: S (+0.20) E3: S (-0.25) E4: S (-0.50)	7.67 (0.58)	S (+0.33)	E2: N/A (0.00) E3: N/A (0.00) E4: N/A (0.00)
	Martin-mas (Std)	Comp	98.7	10.9	4				9.01 (0.30)	N/A	E2 avg = 9.11 E3 avg = 9.11 E4 avg = 8.82	9.94 (0.19)	N/A	E2 avg = 10.00 E3 avg = 9.83 E4 avg = 10.00	8.42 (0.63)	N/A	E2 avg = 9.00 E3 avg = 8.50 E4 avg = 7.75	7.42 (0.79)	N/A	E2 avg = 7.00 E3 avg = 7.75 E4 avg = 7.50	9.77 (0.60)	N/A	E2 avg = 10.00 E3 avg = 9.75 E4 avg = 9.50	8.00 (1.00)	N/A	E2 avg = 8 E3 avg = 9 E4 avg = 7
		Un-Comp							8.83 (0.30)	N/A	E2 avg = 8.77 E3 avg = 9.02 E4 avg = 8.70	9.91 (0.27)	N/A	E2 avg = 10.00 E3 avg = 9.93 E4 avg = 9.80	8.20 (1.01)	N/A	E2 avg = 8.80 E3 avg = 8.80 E4 avg = 7.00	6.91 (1.45)	N/A	E2 avg = 5.60 E3 avg = 7.13 E4 avg = 8.00	9.70 (0.59)	N/A	E2 avg = 9.80 E3 avg = 9.70 E4 avg = 9.60	7.67 (0.58)	N/A	E2 avg = 8 E3 avg = 8 E4 avg = 7
	Oakley (Sub Std)	Comp	97.3	7.0	4				8.38 (0.40)	W (+0.63)	E2: W (+0.48) E3: W (+0.97) E4: S (+0.43)	9.62 (0.69)	S (+0.32)	E2: N/A (0.00) E3: W (+0.97) E4: N/A (0.00)	6.53 (1.55)	W (+1.88)	E2: W (+2.80) E3: W (+0.70) E4: W (+2.15)	6.93 (0.82)	S (+0.48)	E2: S (-0.40) E3: W (+1.75) E4: S (+0.10)	9.93 (0.26)	S (-0.18)	E2: N/A (0.00) E3: S (-0.05) E4: S (-0.50)	7.00 (1.00)	S (+1.00)	E2: N/A (0.00) E3: N/A (0.00) E4: N/A (0.00)
		Un-Comp							8.51 (0.20)	W (+0.32)	E2: S (+0.18) E3: W (+0.45) E4: W (+0.34)	9.91 (0.20)	S (0.00)	E2: N/A (0.00) E3: S (+0.20) E4: S (-0.20)	7.00 (1.07)	W (+1.20)	E2: W (+2.00) E3: W (+0.80) E4: S (+0.80)	6.51 (0.70)	S (+0.40)	E2: S (-1.00) E3: W (+1.00) E4: W (+1.20)	9.93 (0.26)	S (-0.23)	E2: S (-0.20) E3: S (-0.30) E4: S (-0.20)	7.00 (1.00)	S (+0.67)	E2: N/A (0.00) E3: N/A (0.00) E4: N/A (0.00)
Custer County (Western)	STAAP+ crsh fines (Abv Std)	Comp	100.0	12.5	3	92	No Data	11	8.62 (0.67)	S (-0.20)	E2: B (-0.66) E3: S (-0.30) E4: S (+0.36)	8.85 (1.11)	S (-0.33)	E2: B (-0.90) E3: S (-0.10) E4: S (+0.02)	8.67 (0.44)	S (-0.60)	E2: S (-1.60) E3: S (-0.60) E4: S (+0.40)	7.60 (0.92)	S (+0.21)	E2: S (-1.56) E3: S (+1.55) E4: W (+0.65)	9.60 (0.74)	S (-0.85)	E2: S (-0.25) E3: B (-2.90) E4: S (+0.60)	7.67 (1.53)	S (+0.33)	E2: N/A (0.00) E3: N/A (0.00) E4: N/A (0.00)
	STAAP (Std)	Comp	100.0	13.3	6				8.42 (0.85)	N/A	E2 avg = 8.03 E3 avg = 7.50 E4 avg = 9.36	8.52 (1.14)	N/A	E2 avg = 8.65 E3 avg = 7.50 E4 avg = 9.42	8.00 (2.49)	N/A	E2 avg = 7.20 E3 avg = 8.00 E4 avg = 9.00	7.81 (2.12)	N/A	E2 avg = 5.94 E3 avg = 8.25 E4 avg = 9.25	8.75 (1.82)	N/A	E2 avg = 9.75 E3 avg = 6.50 E4 avg = 10.00	8.00 (1.73)	N/A	E2 avg = 9 E3 avg = 6 E4 avg = 9
		Un-Comp							8.08 (0.56)	N/A	E2 avg = 8.32 E3 avg = 7.69 E4 avg = 8.22	7.57 (1.26)	N/A	E2 avg = 7.94 E3 avg = 7.67 E4 avg = 7.11	8.19 (0.63)	N/A	E2 avg = 8.67 E3 avg = 7.67 E4 avg = 8.22	8.41 (1.15)	N/A	E2 avg = 8.00 E3 avg = 8.33 E4 avg = 8.89	8.89 (1.62)	N/A	E2 avg = 9.00 E3 avg = 7.67 E4 avg = 10.00	8.00 (1.73)	N/A	E2 avg = 9 E3 avg = 6 E4 avg = 9
	Bear Mountain (Sub Std)	Comp	97.6	13.7	0	63		6	8.66 (0.80)	N/A	E2 avg = 8.96 E3 avg = 8.78 E4 avg = 8.26	9.15 (1.42)	N/A	E2 avg = 10.00 E3 avg = 9.67 E4 avg = 7.78	8.41 (0.64)	N/A	E2 avg = 8.00 E3 avg = 8.33 E4 avg = 8.89	8.70 (1.33)	N/A	E2 avg = 8.00 E3 avg = 9.33 E4 avg = 8.78	7.67 (1.58)	N/A	E2 avg = 8.67 E3 avg = 7.00 E4 avg = 7.33	8.67 (1.53)	N/A	E2 avg = 9 E3 avg = 7 E4 avg = 10
		Un-Comp							9.17 (0.31)	N/A	E2 avg = 9.18 E3 avg = 9.41 E4 avg = 8.91	9.59 (0.64)	N/A	E2 avg = 10.00 E3 avg = 10.00 E4 avg = 8.78	9.07 (0.74)	N/A	E2 avg = 8.33 E3 avg = 9.00 E4 avg = 9.89	8.74 (0.94)	N/A	E2 avg = 8.00 E3 avg = 9.67 E4 avg = 8.56	8.89 (1.27)	N/A	E2 avg = 9.67 E3 avg = 9.00 E4 avg = 8.00	8.67 (1.53)	N/A	E2 avg = 9 E3 avg = 7 E4 avg = 10
Brookings County (Eastern)	Dupraz + clay (Abv Std)	Comp	98.7	16.3	7	155	No Data	6	9.00 (0.53)	S (-0.05)	E2: S (+0.04) E3: B (-0.60) E4: W (+0.40)	9.73 (0.40)	S (-0.02)	E2: S (-0.20) E3: S (-0.27) E4: S (+0.40)	9.20 (0.75)	B (-0.58)	E2: S (-0.40) E3: B (-0.93) E4: S (-0.40)	7.94 (0.84)	S (+0.26)	E2: S (+0.60) E3: S (-0.03) E4: S (+0.20)	8.10 (2.09)	S (+0.30)	E2: S (+0.60) E3: S (-2.00) E4: W (+2.30)	9.00 (1.00)	S (-0.33)	E2: N/A (0.00) E3: N/A (0.00) E4: N/A (0.00)
	Dupraz (Std)	Comp	100.0	6.9	4				8.95 (0.39)	N/A	E2 avg = 9.04 E3 avg = 8.87 E4 avg = 8.56	9.71 (0.45)	N/A	E2 avg = 9.80 E3 avg = 9.33 E4 avg = 10.00	8.62 (0.69)	N/A	E2 avg = 8.80 E3 avg = 9.07 E4 avg = 8.00	8.20 (0.84)	N/A	E2 avg = 8.20 E3 avg = 8.20 E4 avg = 8.20	8.40 (1.68)	N/A	E2 avg = 8.80 E3 avg = 7.80 E4 avg = 8.60	8.67 (1.16)	N/A	E2 avg = 8 E3 avg = 10 E4 avg = 8
		Un-Comp							9.38 (0.27)	N/A	E2 avg = 9.61 E3 avg = 9.42 E4 avg = 8.80	9.82 (0.31)	N/A	E2 avg = 10.00 E3 avg = 9.47 E4 avg = 10.00	8.99 (0.95)	N/A	E2 avg = 9.50 E3 avg = 9.67 E4 avg = 7.80	8.93 (0.55)	N/A	E2 avg = 9.40 E3 avg = 8.60 E4 avg = 8.80	9.60 (0.83)	N/A	E2 avg = 9.60 E3 avg = 9.80 E4 avg = 9.40	8.67 (1.16)	N/A	E2 avg = 8 E3 avg = 10 E4 avg = 8
	Bowes (Sub Std)	Comp	100.0	10.1	4			14-20	8.55 (0.27)	W (+0.39)	E2: S (+0.24) E3: S (+0.41) E4: W (+0.53)	8.84 (1.13)	S (+0.87)	E2: S (-0.20) E3: W (+1.80) E4: W (+1.00)	8.02 (1.43)	S (+0.60)	E2: W (+1.40) E3: B (-0.80) E4: W (+1.20)	7.96 (0.84)	S (+0.24)	E2: S (+1.00) E3: S (-0.47) E4: S (+0.20)	9.33 (0.98)	B (-0.93)	E2: S (-1.00) E3: S (-0.40) E4: B (-1.40)	8.33 (1.53)	S (+0.33)	E2: N/A (0.00) E3: N/A (0.00) E4: N/A (0.00)
		Un-Comp							8.89 (0.43)	W (+0.49)	E2: W (+0.48) E3: W (+0.70) E4: S (+0.29)	8.89 (0.89)	W (+0.93)	E2: W (+0.80) E3: W (+1.40) E4: W (+0.60)	8.60 (1.06)	S (+0.39)	E2: W (+0.70) E3: S (+0.07) E4: S (+0.40)	8.89 (0.71)	S (+0.04)	E2: S (-0.20) E3: S (+0.33) E4: S (0.00)	9.53 (0.74)	S (+0.07)	E2: S (+0.40) E3: S (+0.40) E4: S (-0.60)	8.33 (1.53)	S (+0.33)	E2: N/A (0.00) E3: N/A (0.00) E4: N/A (0.00)

*Note: Red stockile test results indicate values out of compliance with state gravel surfacing material specifications.

5.7.3.1.4. Summary Observations

This section provides observations on the performance of the above-standard and substandard gravel materials relative to the standard gravel material at each test site. For each comparison, the compacted gravel materials were compared to the standard compacted gravel and the uncompacted gravels were compared to the standard uncompacted gravel.

The comments are based on the results presented in table 55. In this discussion, the focus is on the statistics-based comparisons derived from application of Method 2. The value of the Method 3 results is that they show performance details at each of the data collection events (E2, E3, and E4) and they can help explain the Method 2 results. Because of their impact on the road user's perception of the road quality, these observations will focus on the quality of the gravel materials with respect to the washboarding and potholing performance ratings.

If the experiment had produced the "expected" results, all the above-standard sections would have performed significantly better than the standard sections and been color-coded green. Similarly, all of the substandard sections would have performed significantly worse and been color-coded red. Overall, table 55 shows multiple deviations from the expected results.

Hand County Test Site

All of the Hand County sections experienced essentially the same level of traffic during the experiment. Accordingly, traffic is considered a non-factor in evaluating the performance of the different gravel materials. In addition, because there was no information on how maintenance was distributed between the sections, it is also necessary to treat maintenance as a non-factor. Inherent in this is the assumption that maintenance was equally distributed between the sections. Accepting that traffic and maintenance are non-factors, the following observations can be made about gravel performance at the Hand County test site.

- Bone Bright (above-standard) gravel – Because the mean values for the Overall, Raveling, Rutting and Dusting ratings for the Bone Bright-compacted gravel are lower than the Martinmas (standard) compacted gravel, the Method 1 comparison would indicate that the Bone Bright gravel did not perform as well as the Martinmas gravel. However, when the variability of the ratings is considered using Method 2, the result is that none of the four performance measures for the Bone Bright gravel are significantly worse than the Martinmas gravel. Even the Raveling difference of +0.95 was not large enough to be significant. Also, since there are no significant differences in the Washboarding and Potholing ratings for the two gravels, it is valid (at the 90 percent confidence level) to conclude that the Bone-Bright gravel performed the same as the Martinmas gravel. This is not the expected finding since the PI values of the Bone Bright and Martinmas gravels were 9 and 4, respectively.
- Oakley (substandard) gravel – Based on the Method 2 approach, the Overall and Raveling ratings for the Oakley-compacted and Oakley-uncompacted gravels are significantly less than the corresponding Martinmas (standard)-compacted and Martinmas-uncompacted gravels. For the four remaining ratings (Washboarding, Rutting, Potholing, and Dusting), none of the differences were found to be significant.

If emphasis is placed on the Washboarding, Rutting, Potholing and Dusting ratings, it is valid to conclude that the Oakley (compacted and uncompacted) gravels performed the same as the corresponding Martinmas gravels. If the emphasis in on the Overall and Raveling ratings, then the conclusion is that the Oakley (compacted and uncompacted) gravels performed worse than the corresponding Martinmas gravels. The PI values were 4 for both the Martinmas and Oakley gravels, so if PI is a key indicator of gravel performance, then the findings are reasonable.

Custer County Test Site

The above-standard and standard sections in Custer County were located along the one road segment and received the same level of traffic and maintenance. The substandard sections were located along a different road segment that experienced a lower level of traffic and less maintenance during the experiment. They may have also experienced different soil and moisture conditions than the standard sections. Both road segments received maintenance; however, there was no data on how the maintenance was distributed between the sections. Accordingly, maintenance was considered a non-factor (which assumes that maintenance was equally distributed among the sections).

- STAAP+crusher fines (above-standard) gravel – Using the Method 2 approach, all of the ratings for the STAAP+crusher fines-compacted gravel were the same as STAAP (standard)-compacted gravel. Accordingly, it is valid (at the 90 percent confidence level) to conclude that there is no difference between the two gravels. The PI values for the STAAP+crusher fines and STAAP gravel materials were 3 and 6, respectively. Based on this, it was expected that the performance of the STAAP+crusher fines material would be worse than the STAAP material.
- Bear Mountain (substandard) gravel – Because the traffic and maintenance on the sections built with the Bear Mountain gravel are very different from the STAAP (standard) sections, it is not statistically valid to compare the performance and use it as a basis for determining whether the Bear Mountain compacted and uncompacted gravels are worse or better than the STAAP gravels.

Brookings County Test Site

All five Brookings County sections were located along the same road segment and received essentially the same level of traffic. This means that traffic is a non-factor. Unlike the Hand County and Custer County test sites, however, information was available on how the maintenance was distributed between the test sites. The data showed that the level of maintenance required by the substandard sections was much higher. Accordingly, this does impact the assessment of the performance and the quality of the gravels.

- Dupraz+clay (above-standard) gravel – Based on the Method 2 approach, the analysis results show that the performance of the Dupraz+clay-compacted section was the same as the Dupraz (standard)-compacted section for five of the six performance ratings (Overall, Washboarding, Rutting, Potholing, and Dusting). For raveling, the rating for the Dupraz+clay-compacted sections was significantly higher than the Dupraz-compacted section. Based on these results, with particular emphasis on

Washboarding and Potholing, it is valid (at the 90 percent confidence level) to conclude that the Dupraz+clay-compacted and the Dupraz-compacted gravels are the same. If Raveling is a concern, it is also valid to conclude that the Dupraz+clay-compacted gravel is better than the Dupraz-compacted gravel. The PI of the Dupraz+clay gravel was 7 while the PI of the Dupraz gravel was 4. Thus, based on the associated gravel quality associated with these values, the expectation was that the Dupraz+clay material would perform better than the Dupraz material.

- Bowes (substandard) gravel – The results of the analyses using Method 2 show that Bowes-compacted gravel performed the same as the Dupraz (standard)-compacted gravel in terms of the Washboarding, Raveling, Rutting, and Dusting ratings. In terms of the Overall rating, however, the performance was significantly worse, and for Potholing, the performance was significantly better. However, since the Bowes-compacted section required two to three times more maintenance than the Dupraz-compacted section, it is valid to conclude that the Bowes-compacted gravel is a lesser quality material. For the Bowes-uncompacted gravel, the performance in terms of Raveling, Rutting, Potholing, and Dusting was the same as the Dupraz-uncompacted gravel. On the other hand, the Overall and Washboarding ratings were significantly worse. These ratings, along with the fact that the Bowes-uncompacted sections also received two to three times more maintenance, indicate that the Bowes-uncompacted gravel is also a lesser quality material than the Dupraz-uncompacted gravel material. The PI for both the Dupraz and the Bowes gravel materials was 4. Accordingly, the expectation was that the performance would be about the same.

5.8. Comparison of Findings with SD-LTAP Investigation

In 2012, a team led by Ken Skorseth of the South Dakota Local Transportation Assistance Program (SD-LTAP) at South Dakota State University gathered some data from the Brookings test sites, made comparisons, and included the findings in a presentation for a national ASCE webinar. The SD-LTAP researchers gathered data from two sections at the Brookings County test site. One of the sections was constructed with the Dupraz+clay (above-standard) compacted gravel while the second was constructed with the Bowes (substandard) compacted gravel. The reported date of the data collection was July 27, 2012, which is approximately two months after the first data collection (E2) event.

Following are the results of the test/performance data included in the SD-LTAP presentation with a discussion of how they compare with the findings of this study.

- Loose aggregate (float) test – This test is intended to estimate the amount of loose gravel on the road surface. It is measured manually by using a shovel to collect the loose gravel along a 10-in wide transverse strip across the road surface. The collected material is then weighed and used as a basis to estimate potential gravel loss. SD-LTAP staff performed this test and their results showed that there were 72 lbs of loose gravel on the Bowes (substandard) section and only 12 lbs of loose gravel on the Dupraz+clay (above-standard) section.

  The float test was not conducted as part of this research project. However, it can be compared with the results of the "gravel loss by cast-off" test, which is also designed to estimate the quantity of loose gravel. The test result reported in this study was 18.1 tons per year for the Bowes-compacted section and 7.2 tons per year for the Dupraz+clay section. The results of the two studies can be compared by evaluating the ratios of the test measurements. The float test performed by SD-LTAP shows a ratio of about 5 times more loose gravel on the Bowes section than the Dupraz+clay section. The gravel loss test performed under this study shows a ratio of 2.5. Given the differences in the two test methods, it is reasonable to conclude that the results are consistent.

- Performance comparison – The SD-LTAP investigation reported that no corrugation (washboarding) was observed on the Dupraz+clay section since it was constructed. It did not indicate how much corrugation was observed on the Bowes sections; however, it did report that the average ratio of blade maintenance between a Bowes section and the Dupraz+clay section was 4 to 1. The SD-LTAP results compare very favorably with the results of this study. The washboard rating at E2 (just before the SD-LTAP study) was 10.0 for the Dupraz+clay section. The maintenance records indicate that the Dupraz+clay section received some form of maintenance (regular, pulled gravel, and high crown) on five occasions prior to the SD-LTAP study. Although blading was likely involved, it was not specifically targeted at addressing washboarding. The Bowes sections, on the other hand, received considerable maintenance, most of it to address washboarding. The Bowes-compacted section was maintained 12 times prior to the SD-LTAP study.

5.9. Key Findings and Conclusions

Section 5 of this report documents the findings of eight major areas related to the research carried out under this study. Each area included some discussion of key observations and, more importantly, the conclusions that could be drawn from a review of the findings. Below is a summary of the key findings and conclusions for each section that had a direct bearing on achieving Objective 2.

1. Literature Review (Section 5.1) – The primary purpose of the literature review was to establish the prevailing and best practices with regard to gravel surfacing. The focus was on the design, construction, rehabilitation, maintenance, and stabilization of gravel surfacing practices that might result in improved practices in South Dakota. However, the key finding of the literature review was identification of the method for conducting the condition surveys as part of the field experiment. It provided the guidelines needed for monitoring washboarding, raveling, rutting, potholing, dusting, and gravel loss.
2. Survey Approach and Results (Section 5.2) – As an extension to the literature review to gather more information on specific practices in South Dakota, an electronic survey of local agencies in the State along with some follow-up telephone interviews was conducted. With information gathered from 17 counties and 3 cities, the survey did generate useful information on the materials, construction, and maintenance practices they employ. Overall, the key findings of the survey showed that the agencies recognized the cost effectiveness of using higher-quality gravel materials and performing testing to ensure their materials met specifications. Another key finding

was that many agencies considered the use of higher plasticity materials to be advantageous.

3. Test Section Construction and Monitoring Results (Section 5.3) – SDDOT and the research team members gave considerable attention to designing the field experiment, selecting the experimental sites, laying out and constructing the test sections, and performing the laboratory testing needed to characterize the properties of the materials used in the test sections. Most aspects of the aspects of this activity went very well, especially the identification of the test sites, the testing of the materials, and the construction of the test sections. However, there were some basic problems with the experiment design that, ultimately, had a major impact on the project findings.
    a. Use of plasticity index to define the quality of the gravel – While it is understood that the use of gravels with a higher PI value (within a certain range) result in better gravel road performance, the use of PI to discriminate between the substandard, standard, and above-standard gravels did not work well for this experiment. Considering the variability of the test for PI and the variability of the materials in the stockpile, it was concluded that the use of the 0-4, 4-7, and 7-12 ranges was not practical.
    b. Use of two road locations for the test sections at the Custer County test site – The experiment was primarily intended to evaluate the effects of gravel quality on gravel road performance. Unfortunately, by separating the test sections at the Custer County test site between two roads with different traffic levels and different environmental conditions, it became impossible to attribute the performance of each section solely to the gravels used at their respective locations.
    c. Section layout – Not all of the sections at a given site had uniform geometry that may have affected performance. Some sections had some horizontal curvature issues and some were affected by intersection with other gravel roads. Again, these differences in gravel road performance can impact the assessment of the effect of the type of gravel.
4. Basis for Gravel Road Performance Assessment (Section 5.4) – Five different gravel road distress ratings (washboarding, rutting, raveling, potholing, and dusting) and one distress measurement (gravel loss by cast-off) were used as the primary basis for rating the performance of the gravel road test sections in this experiment. The five distress ratings were carried out mostly on a visual basis which resulted in assigning a 0 to 10 rating, while loss of gravel by cast-off was measured by weight of gravel captured on the shoulder. The unique part of this effort was the development of a composite rating formula that uses weighting coefficients on each of the individual distress ratings to produce an overall rating. The weighting coefficients were developed using the results of a survey of 10 experienced county highway supervisors. Overall, the inspection protocols provided a consistent method of rating the gravel roads. However, the study findings lead to two conclusions:
    a. Based on the apparent rate at which some forms of distress developed during the first few months after construction, the condition surveys should have been performed earlier and more frequently. For purposes of performance

monitoring, the condition surveys should have been performed before and after each maintenance activity.

   b. To put each distress rating into perspective, critical levels should have been defined. These include levels that would trigger some form of maintenance activity (to address safety or ride quality) and levels that are considered unacceptable (i.e., reason for road closure).

5. Test Site Road Maintenance (Section 5.5) – Maintenance on each of the test sites was carried out by the local county maintenance crews at each site. It is assumed that the maintenance was performed when one or more distresses at a site reached or approached a trigger level, such as a high level of washboarding or rutting. The maintenance records for each of the three sites indicate the dates at which maintenance was performed. For Hand County and Custer County, the records also provide an estimate of the labor (in man-hours) that was expended. For Brookings County, the records also include information on which test sections were maintained and what the reason was for each. For example, test section 1 received maintenance to address washboarding. The main conclusion that can be drawn here is that the maintenance information should have been collected on a consistent basis between test sites and the data should have recorded on a section-by-section basis (as in the case of Brookings County).

6. Test Section Performance Observations (Section 5.6) – For each test site, a series of graphs were presented that depict the individual distress ratings for each test section over the course of the experiment. The distress ratings represent the average of the distress ratings recorded in the field for each test section and, from a general perspective, provide a valid basis for assessing the performance of any individual section. By examining the results for one type of distress rating at a given site, the graphs also provide a basis for comparing the performance of one section versus another. However, in comparing the performance of test sections using the average distress rating curves, the variability in performance is overlooked. If the range in distress ratings for a given section at a given time was small, then the visual method of comparison might be accurate. On the other hand, if the range of distress ratings is high, then it can lead to incorrect conclusions about the performance of one section versus another. Section 5.6 provides numerous observations and comments on the performance comparisons between the different gravel materials and the two levels of compaction that assume a low range in distress ratings. Unfortunately, analysis of the field data for this experiment showed that the range of distress ratings for a given site was often high (standard deviation greater than 1). This means that many of the observations that one gravel material performed better (or worse) that another gravel may not be correct and is why a statistical approach to comparing the performance became necessary.

7. Statistics-based Performance Observations (Section 5.7) – Statistical analyses of the test section performance data were performed to address some of key questions.

   a. The first analysis was to determine if gravel compaction during construction had a statistically significant effect on performance. The results for the data showed that only 23 percent of all the combinations of test site, gravel type, distress rating type, and data collection time resulted in a significant difference. This is a strong indication that compaction did not have a significant impact on performance. For those that did show a significant difference, only a few showed that compaction had a positive effect on performance. Based on these findings, it was reasonable to conclude that compaction does not result in improved gravel road performance—at least not in the time period during over which the condition surveys were performed. It is possible that compaction had a positive effect on performance during the first few months after construction (before the condition surveys began), but there was no data to determine this.

b. Using the standard gravel material for each test site as the basis, the second analysis was performed to determine if the above-standard gravel performed significantly better and if the substandard gravel performed significantly worse. Following is a summary of the conclusions for each test site.

   i. Hand County test site

      - The Bone-Bright (above-standard)-compacted gravel performed the same as the Martinmas (standard)-compacted gravel for all distress ratings. Since the PI of the Bone Bright gravel was 9 and the PI of the Martinmas gravel was 4, the expectation was that the Bone-Bright gravel would perform significantly better than the Martinmas gravel.
      - The Oakley (substandard)-compacted and uncompacted gravels performed the same as the Martinmas (standard)-compacted and uncompacted gravel materials in terms of the Washboarding, Rutting, Potholing, and Dusting ratings and worse in terms of the Overall and Raveling ratings. These conclusions are based on the assumption that each test section received the same level of maintenance during the experiment. The PI values for both gravels was the same (4), so the expectation was that the performance would be the same.

   ii. Custer County test site

      - The STAAP+crusher fines (above standard)-compacted gravel material performed the same as the STAAP (standard)-compacted gravel for all distress ratings. This conclusion is based on the assumption that each test section received the same level of maintenance during the experiment. Since the PI of the STAAP+crusher fines gravel material was 3 and the PI for the STAAP gravel was 6, the expectation was that the performance of the STAAP+crusher fines would be worse than the STAAP gravel.
      - No conclusion can be drawn about the comparison between the Bear Mountain (substandard) gravel materials with respect to

the STAAP gravels, because the test sections were constructed on two different road sections.

iii. Brookings County test site

- The Dupraz+clay (above standard)-compacted gravel material performed the same as the Dupraz (standard)-compacted gravel for the Overall, Washboarding, Rutting, Potholing, and Dusting ratings. For the Raveling rating, the performance was significantly higher. These sections received the same level of maintenance during the experiment. The PI values for the Dupraz+clay and Dupraz materials were 7 and 4, respectively. Accordingly, the expectation was that the Dupraz+clay material would perform better than the Dupraz material.
- The Bowes (substandard)-compacted gravel performed the same as the Dupraz (standard)-compacted gravel in terms of the Washboarding, Raveling, Rutting, and Dusting ratings. In terms of the Overall rating, the performance was significantly worse, and for Potholing, the performance was significantly better. Since the Bowes-compacted section required two to three times more maintenance than the Dupraz-compacted section, it is valid to conclude that the Bowes-compacted gravel is a lesser quality material. For the Bowes-uncompacted gravel, the performance in terms of Raveling, Rutting, Potholing, and Dusting was the same as the Dupraz-uncompacted gravel. On the other hand, the Overall and Washboarding ratings were significantly worse. These ratings, along with the fact that the Bowes-uncompacted sections also received two to three times the maintenance, support the conclusion that the Bowes-uncompacted gravel is also a poorer quality material than the Dupraz-uncompacted gravel. The PI values for both the Dupraz and Bowes gravel materials was 4, so the expectation was that they would perform the same.

8. Comparison of Findings with the SD-LTAP Investigation (Section 5.8) – For the two areas investigated by SD-LTAP researchers at the Brookings County test site (above standard versus substandard sections), there was clear agreement between the two studies.
    a. The float test results conducted by SD-LTAP compared favorably with the gravel by cast-off test results performed by SDDOT for this study.
    b. The comparison of performance in terms of washboarding considering the effects of maintenance were also consistent with the results reported in this study.

6. RECOMMENDATIONS

As indicated in Section 1, there were four original project objectives related to best practices, test section construction, monitoring, and performance, improved guidelines, and training materials. During the course of the research, the FHWA developed the new *Gravel Roads Construction and Maintenance Guide* (FHWA 2015) which essentially covers three of the project objectives. Accordingly, at the direction of SD DOT, this scope of this report was modified to only address the second objective.

Objective 2 was to assess the performance and costs of new, non-stabilized gravel surfacing test sections constructed with a) commonly used materials and methods that do not meet state specifications; b) materials and methods that comply with state specifications; and c) materials and methods that exceed state specifications. Section 5 of this report (Findings and Conclusions) provided a detailed description of all the work that was done to achieve Objective 2. Because of their direct bearing on Objective 2, the key parts of Section 5 were those that described the test section construction and monitoring results, the basis for gravel road performance assessment, test site road maintenance, test section performance observations, statistics-based performance comparisons, and key findings and conclusions. The latter two are especially important because they do address the questions about test section performance and gravel material performance comparisons. No attention was given to the cost aspects of the gravel materials used, primarily because the performance differences, in general, were not significant enough to justify a performance-cost assessment.

The remainder of this Section summarizes the problem areas encountered during the study and provides recommendations for further research.

6.1. Summary of Observations Regarding this Research

As discussed in Section 5, there were several project variables that did not have the expected effect on performance. For example, gravel compaction during construction did not result in better road performance compared to the sections that were not compacted. Also, the PI results were inconsistent, and only seemed to indicate that the PI by itself does not determine the quality of a gravel for surfacing.

The following observations and recommendations expand on the research results. These are not listed in order of importance.

- Conduct further research on objective measures of gravel surfacing performance: the researchers identified and applied a number of measures to reflect how gravel roads perform. The selected performance measures did not seem to track well with the project panel's experience-based ideas of performance. In particular, members of the panel saw significant performance differences at the Brookings site where the research team's measures showed similar performance. Perhaps further research should consider the impact of some combination of the PI, gravel gradation, CBR, and fractured faces, if not independently, then is some form of a gravel quality index.
- Continue research on appropriate methods of quantifying gravel loss: the researchers hoped to be able to quantify gravel loss. While one lesson learned from the research is that using the DCP to measure gravel thickness is neither particularly effective nor

accurate, the alternative – digging test pits – is time-consuming and requires considerable on-site resources. The cast-off method of collecting lost gravel on the shoulder seemed to provide consistent results with the results of the float test conducted by SD-LTAP researchers, but its application was also problematic in some instances.

- Greater variability in materials is essential if a follow-up experiment is considered: two characteristics in particular—gradation and PI—should be varied such that sites include materials well below, within, and outside of specified limits. Furthermore, if pre-construction testing on the materials shows that they do not meet the requirements of the experiment, then the materials should either be modified or replaced by materials that do.
- At least three stockpile samples should be used to characterize material properties prior to construction. This is especially true for calculation of the stockpile PI. Had three PI tests been done on each stockpile, it would have resulted in a much better representation mean and standard deviation of the gravel material.
- Control as much variability as possible in construction. There was a lot of variation in construction practices and this could have had a major impact on the results. For example, in Custer County, the test sections were constructed on two different roads with likely different soil conditions and certainly different traffic conditions. In Hand County and Brookings County, the existing gravel surfacing was removed or re-mixed with the subgrade prior to placement of the test gravel.
- Only perform the maintenance that is needed on test sections and collect complete maintenance data over time in order to determine cost effectiveness. In this study Brookings County performed maintenance only as needed on the cells which were showing problems, whereas Hand County generally graded the entire test section whenever it needed maintenance. Custer County provided limited maintenance records due to personnel turnover, but since the test cells were split over two separate roadway sections (a few miles apart) it is unlikely that they received the same maintenance.

  Other local features may have affected performance in unaccounted ways. These include the presence of driveways (and associated turning traffic), varying vegetation along the road (half the Brookings site was lined with corn fields, and the other half had tall trees on both sides of the roads – the trees provided more shade and blocked wind, so the road held onto more moisture), geometric changes (both Custer roadways were curved and hilly), and intersections (causing variable traffic speed).
- The condition surveys must be performed immediately before (and preferably immediately after) any major maintenance activity and not at arbitrary times between maintenance activities. This will provide for a much better assessment of the performance of gravel materials because it separates the maintenance effect from the gravel quality effect. In addition, the distress condition that is dictating the need for maintenance should be identified.
- Account for, or at least consider, variations in traffic patterns which could have an effect on performance: traffic patterns can have a significant effect on loose surface

aggregate/float/raveling. If the traffic remained in established wheel paths, there tends to be very little loose material, regardless of the test section. If there was more traffic wander, or large trucks driving close to the edge and pushing loose material around, there tends to be more loose material.

- Determine if it is possible to control roadway width: what was defined as the roadway width or traveled surface had a large impact on the performance measures. Some roads tend to develop large aggregate particles along the edge, probably from traffic patterns, but since this was outside the traveled wheelpaths it was more or less ignored by the performance measures.

6.2. Continuing Research Needs

Based on the research conducted to date, no further study of the three county test sites is recommended. It is highly improbable that continued monitoring or testing would provide inputs that are more useful than those that have already been reported.

6.3. Recommendations for Future Research

The following are specific recommendations if the study were to be repeated.

- Rather than focusing on a "one size fits all approach," consider developing a method of gravel selection that addresses the particular type of distress observed on an existing gravel road. For example, the best gravel resurfacing solution for a road that is experiencing a washboard problem may be different than a road experiencing a potholing problem.
- Eliminate the compacted versus uncompacted sections and only study the effects of gravel quality.
- Sample the stockpile materials from the same area of the stockpiles as the actual material used in test sites.
- Determine if there is a test for the plasticity effect of these materials that is more reliable and repeatable than the plasticity index (PI).
- Improve field material sampling: It was difficult to obtain enough material samples without any mixing of underlying gravel or of subgrade material. Because the gravel was so tightly compacted, mechanical methods were used to loosen the material (augers or trenching machine), likely further breaking down the material.
- If possible, blind the researchers as to the characteristics of the test sections. Failure to do so could create a subconscious bias toward gravels known to be "good performers" and against ones known to be "bad."
- Improvements are needed in the objective measurement of performance. At least a part of this improvement should be to confirm those objective measures which align well with how owners make gravel road maintenance decisions and how users view road performance. Part of this involves the determination of critical levels of the key distress ratings (especially washboarding, rutting, and potholing) that are considered unacceptable and triggers for maintenance work. This could be done as part of small

field study to investigate what conditions actually trigger maintenance crews to perform maintenance.

- Eliminate as much variability (in cross-section, alignment, driveways, vegetation, etc.) as possible along the test sites.
- Conduct more frequent condition monitoring and ensure that monitoring is performed immediately before (and preferably after) any maintenance activity that significantly affects the gravel road condition.
- Exercise better control over maintenance operations (and winter snow-clearing operations), and better monitor the frequency of maintenance operations and understand why the maintenance was performed.
- Include stabilization as a variable in future studies to determine if this is a cost-effective way to reduce the need for maintenance and control dusting.

7. RESEARCH BENEFITS

The SDDOT has a strong interest in improving its practices for the design, construction, maintenance, rehabilitation, and stabilization of gravel-surfaced roads. This study began in 2009 to investigate many of these practices, study the effect of gravel quality on road performance, and develop new gravel resurfacing guidelines. During the course of the study, the FHWA released its new *Gravel Road Construction and Maintenance Guide* (FHWA 2015). This document was very well received by SDDOT, as it provides the latest guidance on all of the key practices identified above. Because of this, the SDDOT is adapting the new *Guide* into practice and elected not to pursue three of this study's four original objectives. Accordingly, the focus of this report was on the remaining project objective:

> *Assess the performance and costs of new, unstabilized gravel surfacing test sections constructed with a) commonly used materials and methods that do not meet state specifications; b) materials and methods that comply with state specifications; and c) materials and methods that exceed state specifications.*

The statistics-based performance comparisons presented in Section 5.7 of this report provided considerable evidence that there was so much variability in the performance results, as well as uncertainty in how the quality of the gravel materials was characterized, that it was not possible to adequately determine if the above-standard gravel materials performed significantly better than the standard gravels and whether the substandard gravels performed significantly worse. It is very likely that if the recommendations offered in Section 6 were applied in a new experiment, there would be much less variability in test section performance, more certainty in the characterization of the gravel materials, and more meaningful results in the performance comparisons. This would also make it possible to consider gravel costs and identify the more cost-effective gravel materials. Overall, the main benefit of this study was all of the lessons learned that would result in a better gravel road field investigation and performance comparison project in the future. Such a project would provide specific benefits such as:

- Decreased need for regraveling due to decreased gravel loss.
- Slower consumption of limited gravel supplies due to decreased need for regraveling.
- Decreased need for regrading due to lower incidence of distresses related to decreased gravel loss and the use of a more stable road surface.
- Decreased maintenance costs due to less frequent regraveling and regrading.
- Improved service for the road user due to fewer distresses.
- Increased safety due to fewer distresses.

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Visser, A. T. and W. R. Hudson. 1981. "Performance, Design, and Maintenance Relationships for Unpaved Low-Volume Roads." *Transportation Research Record 898.* Transportation Research Board, Washington, DC.

Walker, D. 1989. *PASER Gravel Roads Manual.* Wisconsin Transportation Information Center, Madison, WI.

Woll, H., R. W. Surdahl, R. Everett, and R. Andresen. 2008. *Road Stabilizer Product Performance: Seedsakadee National Wildlife Refuge.* FHWA-CFL/TD-08-005. Federal Highway Administration, Central Federal Lands Highway Division, Lakewood, CO.

Zimmerman, K. A. and A. S. Wolters. 2004. *Local Road Surfacing Criteria.* SD2002-10-F; Final Report. South Dakota Department of Transportation, Pierre, SD. 112 p.

APPENDIX A. ANNOTATED BIBLIOGRAPHY

Berthelot, C. and A. Carpentier. 2003. "Gravel Loss Characterization and Innovative Preservation Treatments of Gravel Roads: Saskatchewan, Canada." ***Transportation Research Record 1819.*** **Transportation Research Board, Washington, DC. pp. 180-184.**

Recent restructuring of Canadian transportation has significantly increased commercial truck traffic on many rural roads in Saskatchewan, Canada. This increased traffic is having a detrimental effect on performance of the approximately 175,000 centerline kilometers of gravel roads collectively managed by provincial road agencies. The depletion of quality aggregate sources in many Saskatchewan regions is a primary contributor to the detrimental performance. Preservation and optimization of gravel are therefore becoming critical in sustaining an effective and efficient rural road system. Even minor improvements in gravel optimization could significantly reduce the amount of gravel required for an acceptable level of service and save millions of dollars per year for taxpayers. A study was undertaken to quantify typical gravel supply and demand characteristics in Saskatchewan, the factors influencing gravel loss, and innovative means of gravel road preservation. Several rural municipalities were interviewed on their gravel road preservation practices and gravel supply and demand. Test sections were constructed to evaluate relationships between gravel loss and heavy truck loadings and to investigate innovative gravel preservation techniques. The study determined that most rural municipalities suffer from aggregate shortages. Gravel with a larger top size took longer to break down, and higher gravel application rates reduced gravel displacement. Ionic stabilization of gravel roads improved gravel retention and reduced dust, and shoulder reclamation with commercial rock rakes could recover gravel from roadside slopes for reapplication to the road surface.

Embacher, R. A. 2006. "Duration of Spring Thaw Recovery for Aggregate-Surfaced Roads." ***Transportation Research Record 1967.*** **Transportation Research Board, Washington, DC. pp. 27-35.**

Low-volume roads in regions susceptible to freezing and thawing periods are often at risk of load-related damage during the spring thaw. Reduced support capacity during this period results from excess melt water that becomes trapped above underlying frozen layers. Many agencies place spring load restrictions (SLRs) during the thaw period to reduce damage to roadways. The period of SLRs set forth by the Minnesota Department of Transportation is effective for all flexible pavements; however, experience suggests that many aggregate-surfaced roads require additional time relative to flexible pavements to recover strength sufficient to carry unrestricted loads. An investigation was performed to improve local agency's abilities to evaluate the duration of SLR on aggregate-surfaced roadways. This was accomplished through seasonal measurements of in situ shear strengths, measured with the dynamic cone penetrometer, on various Minnesota county routes. In situ strength tests were conducted on selected county gravel roads over the course of 3 years. Strength levels recorded during the thaw-weakened period were compared with fully recovered periods that typically occur in late spring or summer. Results indicate that aggregate-surfaced roads generally require 1 to 3 additional weeks over that required by flexible pavements to reach recovered bearing capacity.

Erickson, H. and A. Drescher. 2001. *The Use of Geosynthetics to Reinforce Low Volume Roads*. MN/RC-2001-15. University of Minnesota, and Minnesota Department of Transportation, St Paul, MN. 124 p.

This report presents the results of a study that investigated the reinforcement function of geosynthetics for typical Minnesota low volume roadways. Researchers conducted a series of numerical simulations using the finite difference program FLAC. The numerical tests consisted of a static, circular nine kip loading over a variety of typical surfaced and unsurfaced road cross sections that were reinforced with geotextiles and geogrids. Researchers used elastic and elasto-plastic models with frictional interfaces to simulate the layered roadway system. The results of the study indicate that the addition of a geosynthetic does provide reinforcement to the roadway as long as the geosynthetic is stiffer than the subgrade material. However, for most of the cases studied, the benefit in terms of deflection reduction, was very small. Only for the poorest subgrades was the reinforcement benefit substantial.

Giummarra, G. J., Z. Hoque, and R. Roper. 2007. "Establishing Deterioration Models for Local Roads in Australia." Proceedings, Ninth International Conference for Low Volume Roads. Transportation Research Board, Washington, DC.

Although the concepts of transportation asset management are generic in nature, the adoption of asset management by local agencies (counties, county road commissions, cities, villages, towns, and townships) takes shape in as many ways as there are types of agencies. Asset management adoption brings about a melding of engineering, finance, and agency culture, with politics and accountability to the taxpaying public. Michigan is using an innovative approach to help local agencies incorporate the principles of asset management in their transportation management process—focusing first on pavements and later moving on to other assets. While most activities are not unique, innovation lies in bringing all activities together in a coordinated effort. This includes training opportunities for every level of stakeholder and providing the tools necessary for roadway data collection and asset management analysis. Early adopters are seeing direct results; others are at varying stages within the process of change. The benefits of adoption are noted by Tim O'Rourke, manager of the Rosscommon County, Michigan, Road Commission: "What you are really doing is telling a story. A story about levels of investment, a mix of maintenance fixes, and the condition of the road network in 10 years. It's a story people can understand." This paper details the components that have led to making local agency asset management work in Michigan and provides agency case examples.

Henning, T. F. P., G. J. Giummarra and D. C. Roux. 2008. *The Development of Gravel Deterioration Models for Adoption in a New Zealand Gravel Road Management System.* Research Report 348. Land Transport New Zealand, Wellington, New Zealand.

This report provides the outcomes from research based on the Land Transport New Zealand gravel road monitoring program that commenced during 2002 and included the cooperation of 51 local authorities. These sections were monitored on a six-month basis and all relevant data such as maintenance, rainfall where available and evaporation were incorporated into a national database. This research project included the provision of practical guidelines for the construction and maintenance of gravel roads. In addition, the gravel road data were analyzed and outcomes are presented. The resulting models are effective indications of gravel loss on a network scale but further research would be required for more detailed models. This can be achieved by collecting more information on the impact of routine maintenance such as blading. One of the main outcomes from this research is the addition of a key performance measure that indicates the change in cross profile or shape over time.

Henry, K. S., J. P. Olson, S. P. Farrington, and J. Lens. 2005. *Improved Performance of Unpaved Roads During Spring Thaw.* ERDC/CRREL TR-05-1. Cold Regions Research and Engineering Laboratory, Vermont Agency of Transportation, and Federal Highway Administration, Washington, DC. 179 p.

Unpaved roads in Vermont are subject to deterioration from seasonal freezing and thawing, and many towns have roads that suffer chronic serviceability problems during the so-called "spring thaw," or mud season. Several techniques thought to mitigate deterioration of unpaved roads during spring thaw were constructed on test sections of unpaved roads in two towns. Each potential remedy was aimed at providing some combination of limiting the availability of moisture in the winter, improving drainage during spring, and strengthening the upper portion of the road. Each technique used local and/or commercially available materials, and all were easy to construct, i.e., a town road crew could build them. For two spring thaw seasons, the authors compared strength estimates based on dynamic cone penetrometer tests and the percentage of the road surface rutted for treated and control sections. Methods that permanently improved the strength of the top 12 inches of the road or decreased the water content of the upper 12 inches of the road resulted in significant performance improvement during spring thaw. Cement and cellular confinement systems worked well by improving the strength of the upper layers of the soil. Two new techniques--geowrap, comprising clean sand sandwiched by geotextile separators placed 12-18 inches deep, and the patented Geosynthetic Capillary Barrier Drain--provided benefit by keeping the upper layers of the soil relatively dry. Geogrid and geotextile separators placed 12 inch deep and trench drains parallel to the road provided no observable benefit.

Huntington, G. and K. Ksaibati. 2005. "Gravel Roads Asset Management." *First National Conference on Pavement Preservation.* Transportation Research E-Circular No. E-C078. Transportation Research Board, Washington, DC. pp. 214-228.

In the winter of 2004, the Wyoming Technology Transfer Center in cooperation with the Wyoming Department of Transportation and Sheridan, Johnson, and Carbon Counties of Wyoming undertook a 3-year project to institute a geographic information system- (GIS-) based asset management program. It encompasses inventorying, rating, and optimization strategies for improved gravel roads, as well as for the limited mileage of asphalt and unimproved roads in the counties. The roughly 2,000 mi of roads in the three counties were located with a Global Positioning Satellite system and rated using the Wisconsin Transportation Information Center's Pavement Surface Evaluation and Ratings manuals, modified for Wyoming's conditions. In addition, expenditures on each road section are tracked through maintainers' daily reports. Signs, sign supports, cattleguards, approaches, and culverts were rated and located. Bridges were located. Interviews with maintainers were conducted to gather historical and routine maintenance information on each section. This report describes the current status of this asset management program and road surface management system. The goals of this program are two-fold, similar to those in widespread use for asphalt and concrete roads. First, it is to be used on a network level for financial and management decisions and strategies. Second, at the project level, it is to be used to make specific maintenance and construction recommendations on individual roads, largely through a life-cycle costing approach. Off-the-shelf GIS software is used to enter and manipulate the data collected. Adapting this software to surface management tasks was relatively simple, given the user-friendliness of the newer GIS packages. Recent modifications allow for multiple entries for a single feature. Cost estimates for routine activities, such as mowing, snowplowing, and reshaping gravel roads, allow the counties to make reasonable, detailed estimates of the cost of maintaining gravel roads under different conditions. For these and numerous other applications, the asset management system is streamlining county operations.

Huntington, G. and K. Ksaibati. 2007. "Gravel Roads Surface Performance Modeling." *Transportation Research Record 2016.* Transportation Research Board, Washington, DC. pp. 56-64.

Twenty gravel road study sections at 10 sites in north-central Wyoming were monitored from September 2005 through June 2006. Windshield or mobile, visual survey ratings of the sections and field measurements were taken weekly. Surfacing gravel samples were collected, and their gradations were determined. Traffic speeds and volumes by class were collected with a two-tube system. (A two-tube system counts traffic by receiving signals from two tubes placed 8 ft apart across the road. By a comparison of the times at which signals are received from each tube, the speed of the traffic can be determined, as can the number and spacing of axles.) Statistical analyses generated regression models that allowed the prediction of the service life of an unmaintained gravel road. Traffic speeds, traffic volumes, and surfacing gravel properties were shown to have the greatest influence on gravel roads' deterioration rates. For these typical Wyoming county roads with good geometry, good drainage, and adequate gravel thicknesses, the typical failure mode was shown to be either potholes or washboards (corrugations). The typical life of gravel roads without maintenance was shown to be in the range of several months to 1 year. Climatic effects were shown to be related to precipitation more than seasonality, at least in Wyoming's dry-freeze climate.

Huntington, G. and K. Ksaibati. 2009. "Annualized Road Works Cost Estimates for Unpaved Roads." *Journal of Transportation Engineering.* Vol. 135, No. 10. American Society of Civil Engineers, Reston, VA. pp. 702-710.

Providing locally elected officials with reasonable information about the cost of maintaining and improving an unpaved road network is part of the job for those directly responsible for maintaining such a network. This paper describes a simple method for generating estimates of the annualized maintenance and construction costs incurred by small agencies, three Wyoming counties in this case. Several simple inputs are used to estimate the total annualized cost of operating an unpaved road network. Road segments are assigned to one of four functional classes. Treatment costs and frequencies are determined for each functional class. These inputs are used to generate annualized network-level cost estimates for each county. The most difficult aspect of this procedure is generating reasonable treatment cost and frequency information, particularly for rehabilitation and reconstruction costs. The process of generating these inputs, along with the process of assigning roads to functional classes, is described in this paper. Comparisons between the estimates generated using the method presented in this paper and actual costs incurred by two of the counties both demonstrate the feasibility of this method and highlight aspects of this procedure that will benefit from further refinement. Tailoring treatment costs and frequencies to in-place cost tracking methods will make for more precise projection of future costs, particularly for maintenance tasks. The methods presented here are particularly useful for smaller agencies without the resources to undertake highly sophisticated, expensive asset management programs. This methodology may be applied to a wide and diverse range of agencies.

Huntington, G. and K. Ksaibati. 2009. "Improvement Recommendations For Unpaved Roads." ***Transportation Research Board 88th Annual Meeting.*** **09-1999. Transportation Research Board, Washington, DC. 17 p.**

As part of a pilot asset management program for three Wyoming Counties, the Wyoming Technology Transfer Center developed a method for recommending surfacing and drainage improvements to unpaved roads. Based on current surface and drainage conditions and the costs of performing upgrades, a list of unpaved roads in need of improvement is generated along with the costs of these upgrades. Road surface and drainage conditions were evaluated with "windshield" surveys using the Wisconsin Pavement Surface Evaluation and Rating (PASER) method. Roads with inadequate surface quality for their functional class are selected for improvement. An improvement-type decision matrix with functional class and distress conditions as inputs was developed. This matrix is used to select appropriate improvement activities. The methodology developed in this study was applied in the three counties included in this pilot study. The recommended improvement lists generated using this method have been used both to assist with prioritizing county road and bridge activities and to present policy makers with reasonable assessments of each county's road network's improvement needs. Other counties and local agencies can easily apply the methodology developed in this paper after adjusting the decision matrix and activity costs to reflect their local conditions.

Jahren, C. T. 2001. ***Best Practices for Maintaining and Upgrading Aggregate Roads in Australia and New Zealand.*** **MN/RC-P2002-01. Minnesota Department of Transportation, St Paul, MN. 75 p.**

This report documents the best practices of Australia and New Zealand in maintaining and upgrading aggregate roads. Compared to the United States, Australia and New Zealand have fewer resources to invest in road construction and maintenance. As a result, both countries have developed systems for economically constructing and maintaining roads. Although differences exist in climate, traffic, and road user expectations, studying the best practices of Australia and New Zealand offers opportunities to apply relevant practices.

Johnson, E. N. and R. C. Olson. 2009. ***Best Practices for Dust Control on Aggregate Roads. MN/RC 2009-04.*** **Minnesota Department of Transportation, and Minnesota Department of Transportation, St Paul, MN. 54 p.**

This study evaluated the performance and cost of commonly used dust palliatives using a mobile air sampling technique. Treatments of calcium chloride, magnesium chloride, and organic polymer-plus-binder were evaluated at standard application rates during the first year and at variable rates during the second year. The treatments were applied to a variety of subject roads that were located throughout Minnesota. Average daily traffic levels varied from 25 to 700 vehicles per day. The overall data trend showed that treatments reduced dust levels and measurements showed that aggregate surface moisture content was the best predictor of dust control efficiency. Positive relationships were measured between dust control efficiency and other variables in the study, generally reinforcing the concept that higher application rates may be more successful on gravels containing greater amounts of material passing the #200

sieve. A negative relationship was measured between dust control efficiency and sand equivalency, showing that treatments on gravels containing more sand material were less effective. In addition to dust control, study participants observed a secondary benefit of surface stabilization, which lasted for a period of time. Treated sections that developed surface stabilization were able to reduce maintenance activities to intersection areas only.

Jones, D. and P. Paige-Green. 2000. *Pavement Management Systems: Standard Visual Assessment Manual for Unsealed Roads*. Report No. CR-2000/66. Committee of Land Transport Officials, Pretoria, South Africa.

TMH12 provides guidelines for the visual assessment of the condition of unsealed roads at network and/or project level for use in unsealed road management systems. A modular approach to information collection is introduced. Attributes of distress are defined and requirements for training and calibration of visual assessors, quality control, assessment procedures and road segment information data are specified. The different assessment parameters are classified and detailed descriptions of degree and distress, including photographic plates illustrating each condition, for each parameter are given. Examples of assessment forms are provided. Simple guidelines on material identification using an engineering geological classification are included. The use of the data collected in management systems and maintenance management planning falls outside the scope of the document.

Jones, D., P. Paige-Green, and E. Sadzik. 2003. "Development of Guidelines for Unsealed Road Assessment." *Transportation Research Record 1819*. Transportation Research Board, Washington, DC.

The assessment of unsealed roads in South Africa has, up to now, been done on an ad hoc basis with a variety of individual standards and has produced highly subjective results. A standard visual assessment manual has been developed to provide a single, unified objective system of unsealed road evaluation in South Africa and southern Africa. The assessment techniques, as well as standard descriptors of the various distress modes, are clearly defined in the document. Examples of the content and application of the document are provided and discussed.

Keller, G. R. 2008. "Environmental and Engineering Design Best Practices for Low-Volume Roads." *ARRB Conference, 23rd, 2008, Adelaide, South Australia, Australia*. ARRB Group Limited, Vermont South, Australia. 16 p.

Low-volume roads have long been known to contribute to substantial erosion and sediment production, as well as create other problems such as channel modifications, slope instability, or land use changes. Roads are a basic part of rural infrastructure and are needed for rural development, access to areas, resource extraction, movement of goods and services, etc. Well-built roads that are environmentally sensitive can be accomplished, but they require good design, attention to detail, a holistic perspective, trained and experienced people, and the application of roads best management practices. This paper discusses many of those "best practices." Good road engineering that is relatively environmentally friendly involves a blend of three basic components: 1. application of basic engineering and design concepts, including good planning and location, drainage analysis, stable slopes, and proper selection of roadway materials; 2. environmental awareness and application of practical environmental mitigation measures, such as environmental analysis, erosion and sediment control, fish passage and wildlife crossings, and invasive species control; and 3. use of appropriate, innovative technologies to facilitate work and make it more cost-effective, such as GIS mapping, use of geosynthetics, trenchless technologies, mechanically stabilized earth structures, and simple in-situ site characterization tools.

Keller, G. and J. Sherar. 2003. "Low-Volume Roads Engineering: Best Management Practices." ***Eighth International Conference on Low-Volume Roads. Transportation Research Record No. 1819.*** **Federal Highway Administration and Transportation Research Board, Washington, DC. pp. 174-181.**

The concept and application of best management practices (BMPs) for low-volume roads projects were studied. BMPs are techniques or design practices that will prevent or reduce nonpoint pollution, maintain water quality, and help produce well-built roads. A "Low-Volume Roads Engineering Best Management Practices Field Guide" was developed to address those key practices. Roads that are not well planned or located, not properly designed or constructed, not well drained, not well maintained, or not made with durable materials often produce negative impacts, most of which are preventable with good engineering and road management practices. A number of key practices and design techniques can be used to prevent adverse impacts of roads. First a road must serve the needs of the user through good transportation system planning. Long-term cost-effectiveness and minimized impacts are then achieved through application of good design and maintenance practices, including a road location that avoids problematic areas such as slides or springs; positive surface drainage; adequately sized and appropriate drainage crossing structures; stable cut and fill slopes; use of erosion control measures; roadway surface stabilization; and materials source development with subsequent site reclamation.

Ksaibati, K., G. Huntington, and B. Weaver. 2006. "Performance and Evaluation of Gravel Roads." ***Transportation Research Board 85th Annual Meeting*****. 06-2487. Transportation Research Board, Washington, DC.**

The Wyoming Technology Transfer Center has undertaken a study that evaluates and predicts deterioration of gravel roads. Twenty 1000-ft gravel road sections on Wyoming county roads have been visually rated and measured on a weekly basis. Gradation and plasticity of the road surfacing, base, and subgrade have been evaluated in the laboratory. Most of the information about gravel roads' performance is qualitative, based on the judgment of experts. This paper adds to the quantitative knowledge by assigning numeric values to various performance measures and analyzing these measures as a function of time and other factors. Fifteen independent variables describing the gravel road sections' traffic, surfacing aggregate, subgrade materials, and drainage are used to predict the rate at which the dependent variables, overall condition, potholes, rutting, and washboards, deteriorate. P-values are used to evaluate each individual independent variable's effect on each of the dependent variables. Using these variables, relatively simple equations describing surface deterioration achieved R2 values of 61% for overall condition and 66% for potholes. Deterioration of the overall condition is predicted by heavy truck traffic, the percentage of coarse sand in the surfacing aggregate, drainage, and gravel thickness. Pothole formation is predicted from average daily traffic, gravel thickness, plasticity of the surfacing aggregate, and crown shape. Interesting findings in this paper include the detrimental effects of effective drainage, at least during a dry summer, and the insignificance of traffic on washboard formation.

Mills, K., M. Pyles, and R. Thoreson. 2007. "Aggregate Surfacing Design and Management for Low-Volume Roads in Temperate, Mountainous Areas." *Transportation Research Record 1989*. Transportation Research Board, Washington, DC. pp. 154-160.

An integrated aggregate design and management system for forest roads in wet, mountainous terrain requires special considerations. Typically, subgrade soils, drainage conditions, and compactive effort vary along the length of new and existing roads. There are fewer testing opportunities for obtaining design parameters in these remote areas. Nevertheless, relatively small depths of aggregate can provide high performance. This design requires characterization of subgrade materials before or during construction. It uses steep road grades to advantage for effective drainage of the subgrade and aggregate. The design is used in conjunction with drainage practices that minimize erosion from reaching streams. Compaction effectiveness can be limited by soil moisture that is wet of optimum for compaction during the short construction period, requiring that aggregate depths be adjusted accordingly. To be used by practitioners, the design must be simple and not very conservative. Aggregate properties vary widely, and gradation specifications must be adjusted on the basis of these properties. Aggregate roads require timely inspection and should be graded only when they are rutted or major defects are present. Drainage and subgrade problems also need to be addressed during maintenance of the surface.

Muench, S. T., J. P. Mahoney, W. Wataru, L. Chong, and J. Romanowski. 2007. "Best Practices for Long-Lasting Low-Volume Pavements." *Journal of Infrastructure Systems*. Vol. 13, No. 4. American Society of Civil Engineers, Reston, VA. pp. 311-320.

A majority of U.S. and international roads are low volume. Pavements on these roads, which are often owned or managed by local agencies with limited resources, represent a large transportation infrastructure asset and could benefit from lower life-cycle costs and better performance. The concept of long-lasting or "perpetual" pavements, often applied to high-volume pavements, is likely to produce similar benefits for low-volume pavements. Careful consideration of current long-lasting pavement research and existing practice can produce a straightforward set of best practices for use by local agency practitioners in designing, constructing, preserving, financing, and marketing long-lasting low-volume pavements. These best practices are: 1) a maximum traffic loading; 2) a minimum subgrade support; 3) a minimum pavement structure; 4) construction quality; 5) financing; and 6) marketing. A case study involving the city and county of Honolulu illustrates how these best practices can be put into use in developing and implementing a long-lasting low-volume pavement strategy.

Paterson, W. D. O. 1987. *The Highway and Maintenance Standards Models (HDM-III), Volume III, Road Deterioration and Maintenance Effects: Models for Planning and Management*. World Bank Transportation Department, Washington DC.

No abstract provided.

Rukashaza-Mukome, M. C., J. M. Thorius, C. T. Jahren, G. D. Johnson, and D. J. White. 2003. "Cost Comparison of Treatments Used to Maintain or Upgrade Aggregate Roads." ***Mid-Continent Transportation Research Symposium.*** **Center for Transportation Research and Education, Ames, IA. 10 p.**

This study uses data from counties in Minnesota to investigate spending to maintain low-volume roads. Data from this investigation will allow county and local governments to make informed decisions on when it may be economically advantageous to upgrade and pave aggregate roads. The reviewed activities include maintenance grading, regraveling, dust control/stabilization, reconstruction/regrading, paving and associated maintenance activities. The expected end product is a set of relationships that can be modified to address local conditions, which will include a cumulative maintenance cost per mile. These relationships are expected to show how the maintenance costs of aggregate roads, lightly surfaced roads, and hot-mix asphalt roads vary with type of surface, age and traffic. This relationship will also be used as a tool to assist in decisions about whether or not to upgrade an aggregate road to a bound surface. Research to this point has provided enough information to give rough averages and ranges for the total maintenance cost/mile of low-volume roads. However, further research is needed to find out how counties classify their cost and whether results can be generalized.

Rushing, J. F., A. Harrison, J. S. Tingle, Q. Mason, and T. McCaffrey. 2006. "Evaluation of Dust Palliatives for Unpaved Roads in Arid Climates." ***Journal of Performance of Constructed Facilities.*** **Vol. 20 No. 3. American Society of Civil Engineers, Reston, VA. pp. 281-286.**

An evaluation of commercial and experimental dust palliatives was conducted to determine their effectiveness for mitigating fugitive dust on roads in arid climates. Several types of chemicals were tested including polymer emulsions, lignosulfonates, chloride salts, synthetic fluids, an asphalt emulsion, a polysaccharide solution, a polyacrylamide, and a guar gum. Each product was placed in an individual test section at a rate of 3.8 L/m squared using an admix construction method (grade/spray/till/compact/spray). Fourteen test sections were constructed and observed at 30-day intervals to monitor product performance. Data from both stationary and mobile particle collectors were analyzed to determine the ability of each product to suppress dust for extended periods. Several products are recommended for use on roads in arid climates as a result of this evaluation.

Selim, A. A., O. K. Skorseth, and R. Muniandy. 2003. "Long-Lasting Gravel Roads: Case Study From the United States." ***Eighth International Conference on Low-Volume Roads*****.** ***Transportation Research Record 1819.*** **Federal Highway Administration and Transportation Research Board, Washington, DC. pp. 161-165.**

Gravel surfacing is commonly used on low-volume roads in rural areas of the United States to form farm-to-market networks that contain more than a million miles of unpaved roads. Some of these roads carry appreciable amounts of trucks and farm machinery. Some of these roads, if properly designed and constructed, can last a long time. One such road is in Hand County, South Dakota. This road was constructed in 1963 and has never been rehabilitated or reconstructed since its construction, and it has shown excellent performance for more than 37 years. This road normally carries less than 200 vehicles per day, but significant numbers of heavy trucks use the road. This exceptional performance led to an investigation of the reasons

why that road lasted as long as it did without major maintenance or rehabilitation. Although this type of road construction is common in other nations, under different names, the practice of constructing this type of road in the United States was done without documented specifications. The main objectives of the study were to determine all factors that contributed to the longevity and the remarkable performance of this road through field and laboratory investigations. Field investigations with a dynamic cone penetrometer (DCP) revealed that both the quality and the quantity of aggregate base were more than adequate. Although the subgrade soil was classified as A6 according to AASHTO soil specifications, it provided good support according to DCP data. Tests of the flatness and elongation of the coarse aggregate and the angularity of the fine aggregate also revealed satisfactory results. Gradation tests also revealed compliance with specifications.

Skorseth, K. and A. A. Selim. 2000. *Gravel Roads: Maintenance and Design Manual.* South Dakota Department of Transportation, Pierre, SD and Federal Highway Administration, Washington, DC. 106 p.

The purpose of this manual is to provide clear and helpful information for maintaining gravel roads. Very little technical help is available to small agencies that are responsible for managing these roads. Gravel road maintenance has traditionally been "more of an art than a science" and very few formal standards exist. This manual contains guidelines to help answer the questions that arise concerning gravel road maintenance such as: What is enough surface crown? What is too much? What causes corrugation? The manual is designed for the benefit of elected officials, managers, and grader operators who are responsible for designing and maintaining gravel roads. The information is as nontechnical as possible without sacrificing clear guidelines and instructions on how to do the job right. The manual is presented in the following sections: (I) Routine Maintenance and Rehabilitation; (II) Drainage; (III) Surface Gravel; (IV) Dust Control/Stabilization; and (V) Innovations. Numerous photographs accompany the text and an index is provided.

Surdahl, R. W., J. H. Woll, and R. Marquez. 2005. *Road Stabilizer Product Performance: Buenos Aires National Wildlife Refuge*. FHWA-CFL/TD-05-011. Federal Highway Administration, Central Federal Lands Highway Division, Lakewood, CO.

Six different soil stabilizers were individually applied each on a 1.6 km (1mi) section to a depth of 150 mm (6 in) at the Buenos Aires National Wildlife Refuge in south central Arizona. These six products were monitored at 6-month intervals for a period of 2 years.

Visual evaluation included effectiveness in controlling dust, washboarding, and raveling. Materials tests and evaluation included Moisture/Density, Gradation, Liquid Limit, Plastic Limit, R-Value, CBR, and silt loading. Final analysis included an overall ranking of the six materials and their performance.

Roadway stabilization or dust abatement products are classified into the following seven basic categories: 1) Water; 2) Water absorbing; 3) Organic Petroleum; 4) Organic Non-petroleum; 5) Electrochemical; 6) Synthetic Polymer; 7) Clay Additives. For this specific semi-arid desert location and non-plastic roadway material, the best performing product was a formulation of an organic non-petroleum plus water absorbing material.

Tingle, J. S. and S. Jersey. 2007. "Empirical Design Methods for Geosynthetic-Reinforced Low-Volume Roads." ***Transportation Research Record 1989*****. Transportation Research Board, Washington, DC. pp. 91-101.**

Low-volume road managers are forced to focus their limited resources on higher-capacity infrastructure, with minimal funding for repairing, maintaining, or improving unpaved low-volume roads as a result. Insufficient funding requires road managers to consider the use of innovative stabilization and reinforcement materials to reduce operational costs and minimize maintenance requirements. Geosynthetic materials have been used for many years to improve the quality of low-volume roads in an effort to reduce the amount of aggregate required or to extend the service life of the pavement. The objective of this paper is to review the use of geotextiles and geogrids in unpaved roads, compare common design approaches, discuss advantages and limitations of current design methods, and seek directions for future research efforts to improve the implementation of geosynthetic technologies. This paper summarizes prior research activities to establish the historical performance of geosynthetic-reinforced unpaved roads. Once the performance benefits have been generally supported, current design methods for separation and reinforcement, including advantages and limiting assumptions, are discussed. The sensitivity of the design methods to specific input parameters is examined to provide users with an understanding of the impact of design assumptions on the resulting structural design. Design methods are compared by performing designs with different methods for a variety of site conditions. Finally, the paper discusses the essential requirements for the development of more advanced design methods.

Tingle, J., J. K. Newman, S. Larson, C. Weiss, and J. Rushing. 2007. "Stabilization Mechanisms of Nontraditional Additives." ***Transportation Research Record 1989*****. Transportation Research Board, Washington, DC.**

Because of the high cost of quality construction materials, transportation engineers are often forced to seek alternative designs using substandard materials, commercial construction aids, alternative pavement materials, and innovative design practices. Nontraditional soil stabilization additives are being marketed as viable solutions for stabilizing marginal materials as a low-cost alternative to traditional construction materials. Nontraditional additives are diverse in their composition and the way they interact with soil. Unfortunately, little is known about their interaction with geotechnical materials and their fundamental stabilization mechanisms. The objective of this research was to advance current understanding of the chemical and physical bonding mechanisms associated with selected nontraditional stabilizers. The research consisted of conducting qualitative analyses of hypothesized stabilization mechanisms, examining historical literature for supporting documentation, and performing laboratory experiments to improve the understanding of how these nontraditional additives stabilize soils. Laboratory experiments included image analyses, physical characterization, and chemical analyses to determine the primary constituents of the mineral, soil, stabilizer, and stabilized soil composite. The focus of this effort was to provide insight into the proposed mechanisms by using the laboratory data to examine proposed mechanisms from the historical literature and to provide additional hypotheses for the interaction between nontraditional additives and different soil types.

Visser, A. T. and W. R. Hudson. 1981. "Performance, Design, and Maintenance Relationships for Unpaved Low-Volume Roads." ***Transportation Research Record 898*****. Transportation Research Board, Washington, DC.**

Although paved roads are widely studied, unpaved roads are far more widely used throughout the world. Recently, problems have been encountered in transferring experience and technology with unpaved roads to environments other than those in which they were obtained. In addition, low available funding demands that these funds be used with maximum benefit, and this requires the use of pavement management system methodology. An approach for evaluating unpaved road performance and deterioration is developed. The method is based on an extensive study in Brazil, and equations for predicting roughness, rut depth, and gravel loss are developed. Important criteria for the passability of an unpaved road and a minimum gravel thickness to protect the roadbed are presented. The maintenance and design system (MDS) presented combines these relationships with user cost equations in a systematic manner, which permits an evaluation of the interaction of the factors. Most important, traffic was found to have the greatest influence on regraveling and blading strategies as well as on the total cost of unpaved roads. The MDS has been tested by comparing predicted and actual maintenance on the unpaved road network in the Bronkhorstspruit District of South Africa and excellent agreement was found, which signifies that on average the MDS developed for Brazilian conditions can be applied to South African conditions.

Walker, D. 1989. ***PASER Gravel Roads Manual*****. Wisconsin Transportation Information Center, Madison, WI.**

This manual is intended to assist local officials in understanding and rating the surface condition of gravel roads. It describes types and causes of distress and provides a simple system to visually rate the road segment's condition. The rating procedure can be used as condition data for the Wisconsin DOT local road inventory and as part of a computerized pavement management system like PASERWARE.

Woll, H., R. W. Surdahl, R. Everett, and R. Andresen. 2008. ***Road Stabilizer Product Performance: Seedsakadee National Wildlife Refuge*****. FHWA-CFL/TD-08-005. Federal Highway Administration, Central Federal Lands Highway Division, Lakewood, CO.**

Roadway stabilization or dust abatement products are classified into seven categories: 1) Water, 2) Water Absorbing, 3) Organic Petroleum, 4) Organic Non-petroleum, 5) Electrochemical, 6) Synthetic Polymer, 7) Clay Additives. Six different soil stabilizers from the above categories of 2, 4, 5, and 6 were individually applied each on a 0.8-km (0.5-mi) section to a depth of 125 mm (5 in) at the Seedskadee National Wildlife Refuge in south western Wyoming. These six products were monitored for a period of two years. Both subjective and objective monitoring systems were used to evaluate the products' effectiveness in controlling dust, wash boarding, raveling, rutting, and potholing. Materials tests and evaluation included Moisture/Density, Gradation, Liquid Limit, Plastic Limit, R-Value, CBR, and silt loading. Final analysis included an overall ranking of the six products and their performance, comparisons of silt load results and dust observations, and a correlation study of the subjective and objective monitoring systems. For this specific semi-arid desert location and non-plastic crushed aggregate surfacing material, the evaluation of each product's performance in order from the highest rank was 1) an Organic Non-Petroleum (Lignosulfonate), 2) Water Absorbing/Organic Non-Petroleum mix (Mag/Lig), 3) Water

Absorbing/Organic Non-Petroleum mix (Caliber), 4) Electrochemical Enzyme (Permazyme), 5) Electrochemical Enzyme (Terrazyme), and 6) Synthetic Polymer (Soil Sement.)

Wolters, A. S., K. A. Zimmerman, D. L. Huft, and P. A. Oien. 2005. "Development of Surfacing Criteria for Low-Volume Roads in South Dakota." ***Transportation Research Record 1913*****. Transportation Research Board, Washington, DC. pp. 109-116.**

On a daily basis, local road agencies in South Dakota face the challenge of how to maintain low-volume roads cost-effectively. Specifically, agencies are faced with the decision of determining when it is most economical to maintain, upgrade, or downgrade a road's existing surface. To assist decision makers with maintenance and rehabilitation decisions, the South Dakota Department of Transportation (SDDOT) initiated a study in 2002 to investigate surfacing criteria for low-volume roads. The overall objective of this research is to create a process that allows users to compare the costs associated with different types of roads to provide assistance in deciding which surface type (hot-mix asphalt, blotter, gravel, or stabilized gravel) is most economical under a specific set of circumstances. In addition to incorporating economic factors into the analysis, the process allows the user to consider other noneconomic factors that are more subjective and difficult to quantify. The process used during this study is flexible enough to allow users to consider any combination of agency costs incurred by the agency for maintaining its roads, user cost factors such as vehicle operating costs or crash potential, and noneconomic factors such as politics and housing densities. The methodology was created with agency cost and user cost models developed on the basis of specific road section information supplied by various local agencies in South Dakota, average daily traffic and crash occurrence information supplied by the SDDOT, information obtained through a literature search, and input from members of the project's technical panel.

Worel, B. J., T. R. Clyne, T. R. Burnham, D. M. Johnson, D. M. Tompkins. 2007. "Low-Volume-Road Lessons Learned: Minnesota Road Research Project." ***Transportation Research Record 1989*****. Transportation Research Board, Washington, DC. pp. 198-207.**

The Minnesota Department of Transportation built the Minnesota Road Research Project (MnROAD) and its low-volume road (LVR) between 1990 and 1993. The 2.5-mi LVR consists of a two-lane roadway that originally contained gravel, hot-mix asphalt, and concrete test sections designed for low-volume road research. Each of these test sections is trafficked by a controlled five-axle tractor-semitrailer to simulate conditions of rural roads in two load configurations, resulting in the same equivalent axle loads. Over the years, a number of activities and studies have taken place that have used information from MnROAD's LVR. The first 10 years of findings related to the LVR in the areas of facility, hot-mix asphalt, portland cement concrete, aggregate surfacing, seasonal load limits, and non-pavement-related lessons learned are summarized.

Zimmerman, K. A. and A. S. Wolters. 2004. ***Local Road Surfacing Criteria*****. SD2002-10-F; Final Report. South Dakota Department of Transportation, Pierre, SD. 112 p.**

On a daily basis, local road agencies in South Dakota face the question of how to cost-effectively maintain low-volume roads. Specifically, decision makers are faced with the challenge of determining when it is most economical to maintain, upgrade, or downgrade a

road's existing surface. In order to assist decision makers with these types of decisions, the South Dakota Department of Transportation (SDDOT) initiated a research study in 2002 to investigate surfacing criteria for low-volume roads. The overall objective of this research study is to create a process that allows the user to compare the costs associated with different types of roads to provide assistance in deciding which surface type (hot-mix asphalt, blotter, gravel, or stabilized gravel) is most economical under a specific set of circumstances. In addition to incorporating economic factors into the analysis, the process also allows the user to consider other non-economic factors that are more subjective and difficult to quantify, such as political factors, growth rates, housing concentration, mail routes, and industry/truck traffic. The process used during this study is flexible enough to allow users to consider any combination of agency costs incurred by the agency for maintaining its roads, non-agency (user) cost factors such as vehicle operating costs or crash potential, and non-economic factors such as politics and housing densities. The underlying methodology developed during this project for making road surface type decisions is based upon life-cycle cost analysis techniques that focus on selecting the most cost-effective road surface to meet a specific need. The methodology was created using agency cost and user cost models that were developed based upon specific road section information supplied by various local agencies in South Dakota, average daily traffic and crash occurrence information supplied by the SDDOT, information obtained through a literature search, and input from members of the Technical Panel. The primary deliverables for this study include a Technical Brief that summarizes the manual procedure for determining the appropriate surface type for a road section based upon the average conditions, and a software tool that allows the user to analyze economic and non-economic factors at specific locations to determine the appropriate surface type.

Zimmerman, K. A. and A. S. Wolters. 2004. *Local Road Surfacing Criteria*. SD2002-10-TB. South Dakota Department of Transportation, Pierre, SD.

This Tech Brief presents a step-by-step process to assist counties in South Dakota in making road surface type decisions. The manual procedure allows the user to consider any combination of agency costs, user costs, and other non-economic factors, such as political factors, housing concentration, and industry/truck traffic, when determining the appropriate surface type for a given roadway section. The models used as the basis of this procedure are based upon the average construction and maintenance costs, treatment timings, crash costs, and vehicle operating costs submitted by counties in South Dakota during the data collection efforts of this study with some modifications by the Technical Panel. In addition to the manual procedures outlined in this document, a software tool has been developed that is also available for conducting the analysis. The software tool allows an agency to further customize the types of treatments and the costs that will be applied over the life of a road section. The basis for this manual procedure and the software tool are summarized in the Final Report.

APPENDIX B. SURVEY RESULTS AND INVITED PARTICIPANTS

Invited Participants

Table B-1: Tribal governments invited.

Last Name	First Name	Tribal Government
Kelly	Dave	Oglala Sioux Tribe
Jewitt	Albert	Cheyenne River Sioux Tribe
Hill-George	Charnel	Sisseton-Wahpeton Sioux Tribe
Hare Jr.	Wesley	Yankton Sioux Tribe
Allen	Sam	Flandreau Santee Sioux Tribe
Wright	Sherman	Rosebud Sioux Tribe
Rouillard-Wells	Toni	Lower Brule Sioux Tribe
Red Tomahawk	Pete	Standing Rock Sioux Tribe
Big Eagle	Duane	Crow Creek Sioux Tribe

Table B-2: Cities invited with populations over 5,000.

Last Name	First Name	Title	City
Bobzien	Robin	City Engineer	City of Aberdeen
Brown	Jon	City Engineer	City of Brandon
Lanning	Jackie	City Engineer	City of Brookings
Wever	Mike	City Engineer	City of Huron
Comes	Chad	City Engineer	City of Madison
McGannon	Tim	City Engineer/Planning	City of Mitchell
Childs	John	Dir	City of Pierre
Tech	Dale	City Engineer	City of Rapid City
Mathis	Kyle	City Engineer	City of Spearfish
Nohava	Randy	Public Works Director	City of Sturgis
Dominguez	Jose	City Engineer	City of Vermillion
Kuhl	Kevin	Public Services Director	City of Yankton
Drake	Tom	City Engineer	Watertown

Table B-3: County governments invited.

Last Name	First Name	Title	County
Lynn	Bettelyoun	County Highway Supt	Shannon
Marc	Blum	County Highway Supt	Moody
Brad	Bowers	County Highway Supt	Harding
Chris	Christensen	County Highway Supt	Jackson
Tom	Hermes	County Highway Supt	Dewey
Gene	Homan	County Highway Supt	Mellette
Norman	Riley	County Highway Supt	Todd
Bruce	Royer	County Highway Supt	Jones
Alan	Sorensen	County Highway Supt	Yankton
Wade	Stambach	County Highway Supt	Ziebach
Pat	Stickland	County Highway Supt	Roberts
Lenny	Uhrich	County Highway Supt	Edmunds
Byrne	Pat	County Highway Supt	Bennett
Weismantel	Janet	County Engineer	Brown
Polley	Rod	County Highway Supt	Clay
Hintz	Jamie	County Highway Supt	Deuel
Seiler	Randy	County Highway Supt	Fall River
Wanner	Steve	County Highway Supt	Faulk
Schultz	Kerwin	County Highway Supt	Grant
Degen	Clinton	County Highway Supt	Hanson
Meyer	Michael	County Highway Supt	Hughes
Hazen	John	County Highway Supt	Hutchinson
Vavra	Gregory	County Highway Supt	Jerauld
Sorenson	David	County Highway Supt	Kingsbury
Mathison	Scott	County Highway Supt	Lake
Birk	Dick	Public Works	Lawrence
Winson	Bill	County Highway Supt	Marshall
Rohwedder	Roger	County Highway Supt	Mc Pherson
Blum	Marc	County Highway Supt	Moody
Tanner	Ronnie	County Highway Supt	Potter
Leinen	Tom	County Highway Supt	Spink
Sullivan	Leo	County Highway Supt	Stanley
Maier	Marty	County Highway Supt	Sully
Sund	Roger	County Highway Supt	Tripp
Schulte	Ronald	County Highway Supt	Turner
Falk	Larry	County Highway Supt	Aurora
Batien	Jerry	County Highway Supt	Beadle
Hovorka	Dennis	County Highway Supt	Bon Homme
Jensen	Larry	County Highway Supt	Brookings
Rasmussen	Shannon	County Highway Supt	Brule
Adams	Don	County Highway Supt	Butte

Table B-3: County governments invited (continued).

Last Name	First Name	Title	County
Kost	Clinton	County Highway Supt	Campbell
Superintendent		County Highway Supt	Charles Mix
Howardson	John	County Highway Supt	Clark
Small	Rick	County Highway Supt	Codington
Schell	Benny	County Highway Supt	Corson
Culberson	John	County Highway Supt	Custer
Weinberg	Russel	County Highway Supt	Davison
Fromelt	Chuck	County Highway Supt	Day
Sparks	Travis	County Highway Supt	Douglas
Cassidy	Steve	County Highway Supt	Gregory
Neville	Wallace	County Highway Supt	Haaken
Hanson	Merl	County Highway Supt	Hamlin
Blachford	Ron	County Highway Supt	Hand
Rada	Jerry	County Highway Supt	Hyde
Bonnema	Allan	County Highway Supt	Lincoln
Lengkeek	Bill	County Highway Supt	Lyman
Kreutzfeldt	Michael	County Highway Supt	McCook
McGirr	Ken	County Highway Supt	Meade
Krempges	Ron	County Highway Supt	Miner
Meister	Bobby	Public Works Director	Minnehaha
Junge	Hiene	County Highway Supt	Pennington
Buer	Tracy	County Highway Supt	Perkins
Goergen	Lee	County Highway Supt	Sanborn
Roggow	Raymond	County Highway Supt	Union
Geotz	Penny	County Highway Supt	Walworth

Survey Results

Table B-4: Classification Questions (questions 1-3).

Agency Type	Entity	Respondent
City	Aberdeen	Robin Bobzien
County	Bon Homme	Dennis A Hovorka
City	Brandon*	Jon Brown
County	Butte	Don Adams
County	Codington**	Rick Small
County	Custer	John Culberson
County	Deuel	Jamie Hintz
County	Douglas	Scott Tegethoff
County	Fall River	Randy Seiler
County	Grant**	Kerwin Schultz
County	Gregory	Steven Cassidy
County	Hamlin	Merl Hanson
County	Hand	Ron Blachford
County	Lincoln	Allan G. Bonnema
County	McCook	Michael Kreutzfeldt
County	Minnehaha***	Bob Meister
County	Pennington	Hiene Junge
County	Sanborn	Lee Goergen
City	Vermillion	Jose Dominguez
County	Walworth	Penny Goetz

* Response was from a civil engineering consultant who serves as the city engineer.
** Codington and Grant counties each had two responses from the same individual which were combined for this analysis.
*** Incomplete response. County responded that they do not manage any gravel roads. Minnehaha county is not included in any other summary tables or counts.

Table B-5: Number of responses.

Category	Responses
Invited	66 counties 13 cities 9 tribal governments
Full response to survey	16 counties 3 cities
Partial response to survey	1 county

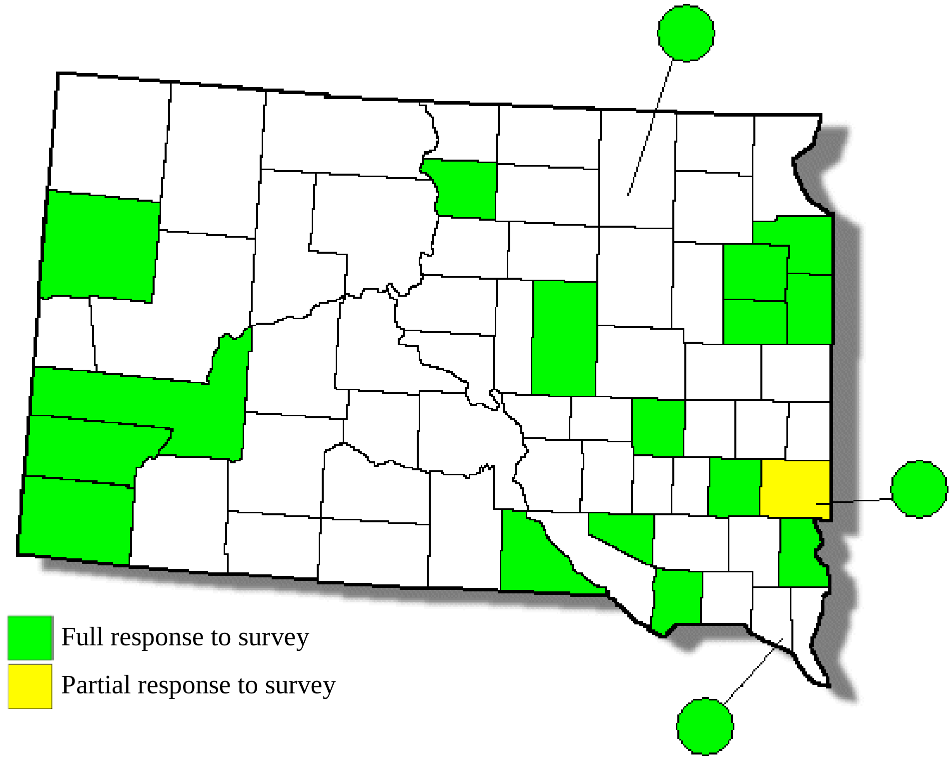

Figure B-1. Map of survey respondents (cities are shown as circles with leaders to their approximate location).

Overall, 17 of the 66 counties in South Dakota responded in one way or another to the survey. One of the responses was from Minnehaha county, where Sioux Falls is located, responding only that they did not manage any aggregate-surfaced roads. This represents a 24% response rate (26% if Minnehaha county is included). Of the 13 cities with populations over 5,000 which were invited to participate in the survey, 3 responded, or 23%. None of the 9 tribal governments responded to the survey.

By SDDOT regions, 4 of the counties (Fall River, Custer, Butte, and Pennington) are in the Rapid City Region in the western part of the state. Only Walworth county responded from the Pierre Region in the central part of the state. In the northeastern part of the state, 5 counties (Hand, Grant, Codington, Deuel, and Hamlin) and 1 city (Aberdeen) responded from the Aberdeen Region. In the southeastern part of the state, 7 counties (Minnehaha, Lincoln, McCook, Sanborn, Douglas, Bon Homme, and Gregory) and one city (Vermillion) responded from the Mitchell Region.

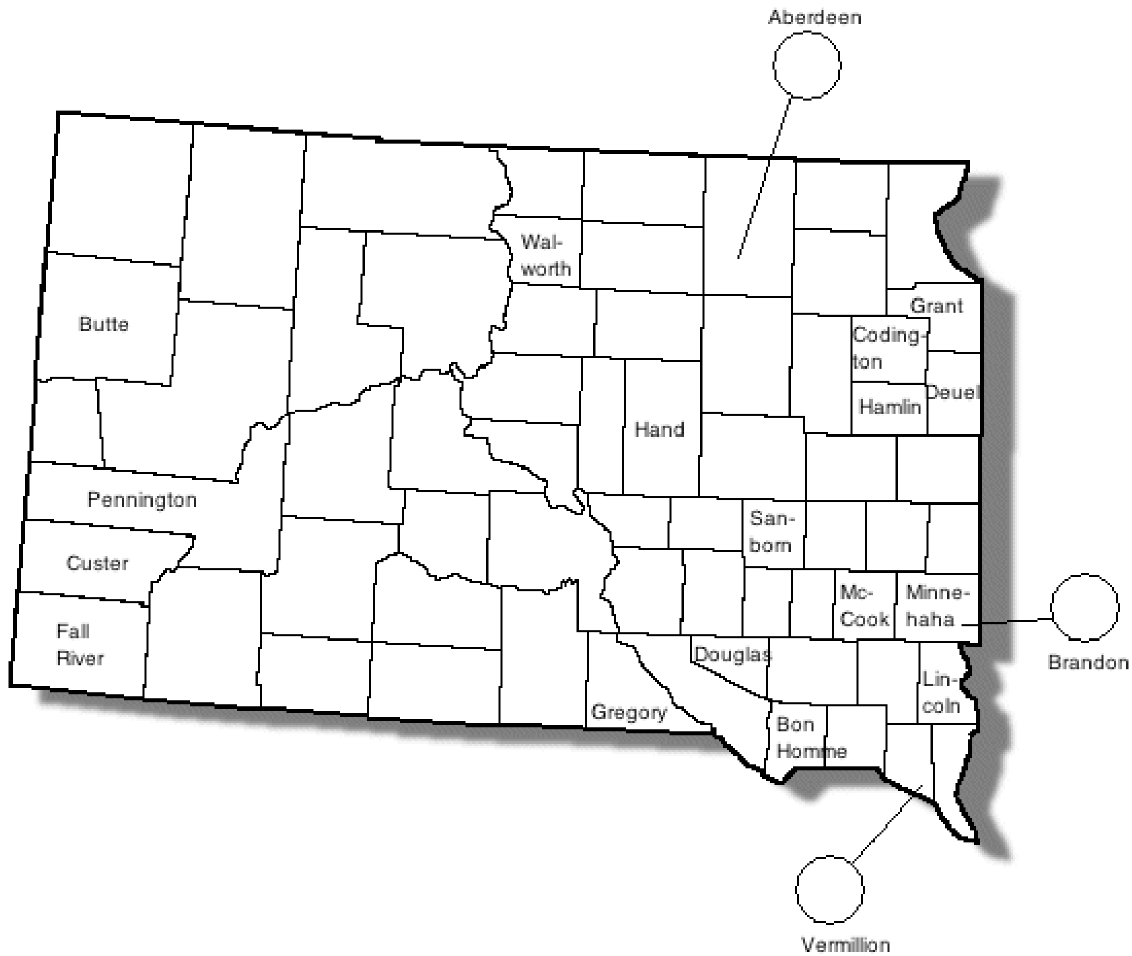

Figure B-2: Labeled map of cities and counties that responded to the survey.

Table B-6: Percentage (by weight) of type of material used (question 4).

County or City	% SDDOT Gravel Surfacing Spec	% Unprocessed or "bank run"	% Asphalt millings or concrete grindings
City of Aberdeen	50%	50%	
Bon Homme County	90%	10%	
City of Brandon	100%		
Butte County	100%		
Codington County	99%		1%
Custer County	100%		
Deuel County	100%		
Douglas County	100%		
Fall River County	100%		
Grant County	90%	10%	
Gregory County	90%	10%	
Hamlin County	100%		
Hand County	98%	2%	
Lincoln County	100%		
McCook County	100%		
Pennington County	100%		
Sanborn County	75%	25%	
City of Vermillion	25%		75%
Walworth County	90%	10%	

Table B-7: Response summary: percentage (by weight) of type of material used (question 4).

Response	Count
100% state spec	9 counties 1 city
≥ 90% state spec ≤ 10% bank run	5 counties
≥ 90% state spec ≤ 10% asphalt millings or concrete grindings	1 county
75% state specs 25% bank run	1 county
≤ 50% state specs	2 cities

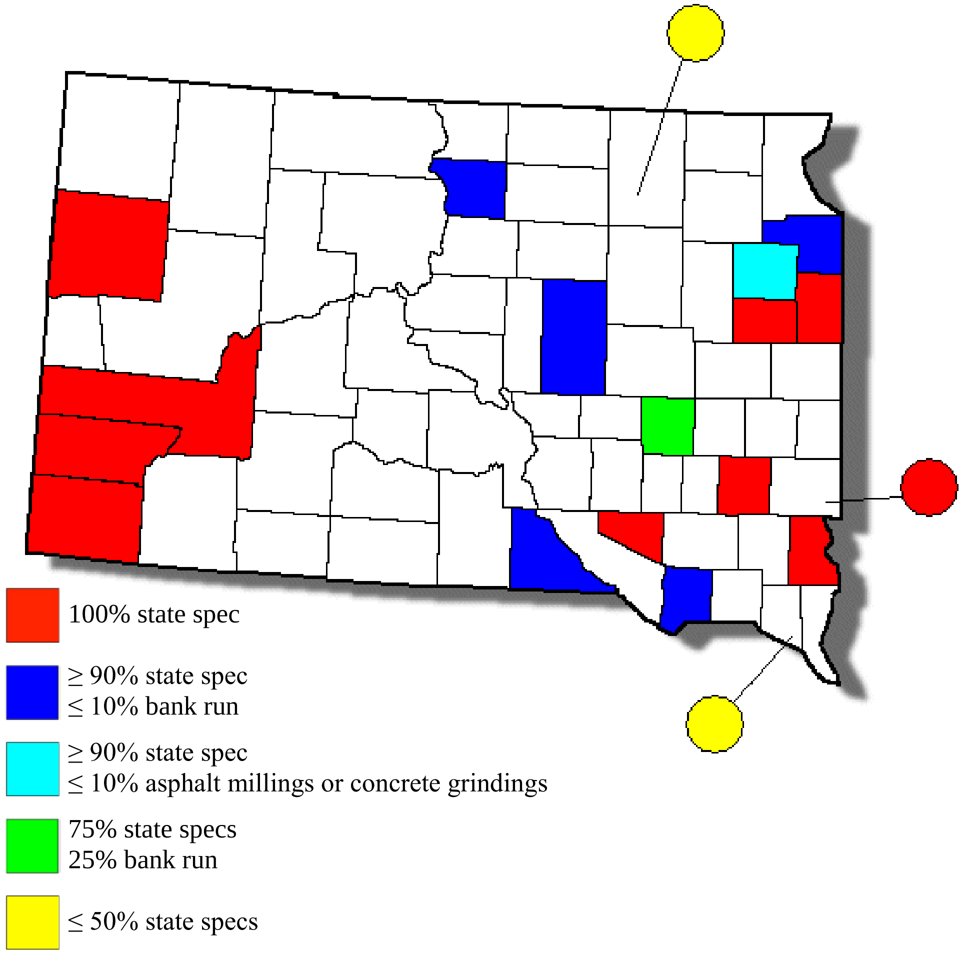

Figure B-3: Response map: percentage (by weight) of type of material used (question 4).

Table B-8: Modifications to the state gravel surfacing specification (question 5).

County or City	Modify SDDOT Spec?	Plasticity Index	Other Changes
City of Aberdeen	No		
Bon Homme County	Yes	6 - 16	
City of Brandon	Yes	≥ 5	
Butte County	No		
Codington County	No		
Custer County	No		
Deuel County	Yes	"Higher plasticity if possible"	
Douglas County	Yes	8 - 12	
Fall River County	No		
Grant County	No		
Gregory County	Yes	10 - 14	Increase maximum size from 3/4 inch to 1 inch
Hamlin County	No		
Hand County	No		
Lincoln County	No		
McCook County	No		
Pennington County	No		
Sanborn County	No		
City of Vermillion	Yes	No change	Use asphalt and concrete
Walworth County	No		

Table B-9: Response summary: modifications to the state gravel surfacing specification (question 5).

Response	Count
Yes	4 counties 2 cities
No	12 counties 1 city

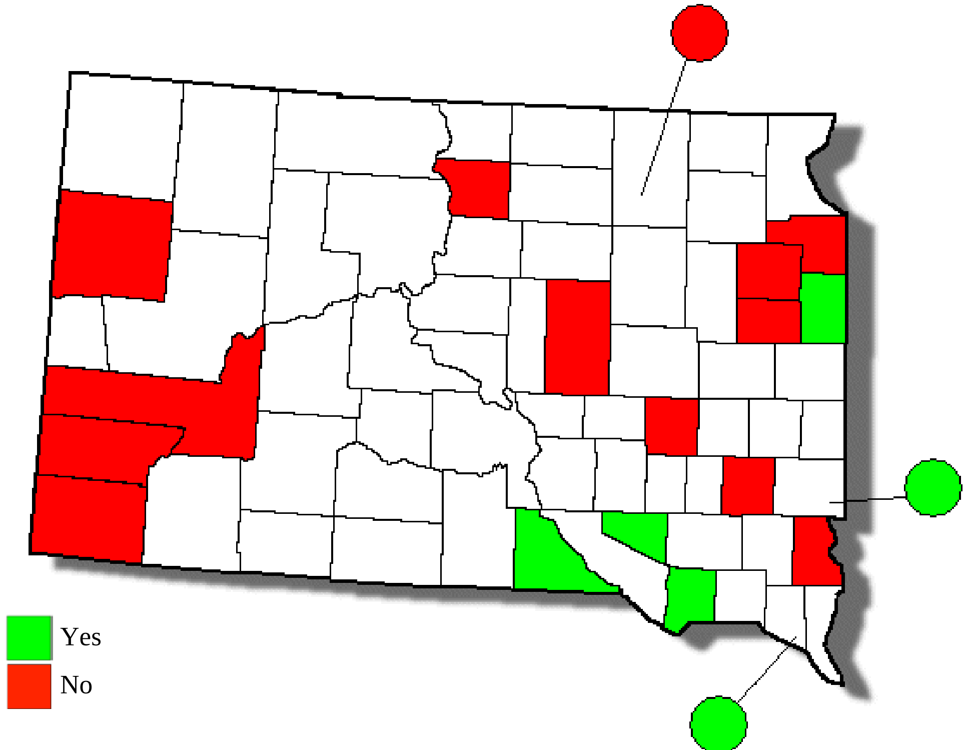

Figure B-4: Response map: modifications to state gravel surfacing specification (question 5).

Four counties and one city responded that they use material with higher plasticity, though the amounts varied, as shown in table B-6. The state specification normally requires a PI between 4 and 12, and according to Ken Skorseth's experience, a marked improvement occurs with PI over 7. One county (Gregory) responded that they also allow material up to 1 inch in diameter, whereas the spec only allows material up to ¾ inch. The other city that responded (Vermillion) stated that they have not tested their material, but what they use is concrete grindings and asphalt millings.

Table B-10: Modified allowed plasticity indexes for counties that use modified specifications.

County or City	Allowable PI
Bon Homme	6-16
Gregory	10-14
Douglas	8-12
Deuel	"Higher plasticity if possible"
Brandon	≥ 5

Table B-11: Primary factor in deciding when to use processed or spec material and when to use unprocessed material (question 6).

County or City	Response
City of Aberdeen	Traffic volume of road
Bon Homme County	Other: use it only for back fill
City of Brandon	Other: specify crushed material for all applications.
Butte County	Only processed is used / no answer
Codington County	Only processed is used / no answer
Custer County	Only processed is used / no answer
Deuel County	Only processed is used / no answer
Douglas County	Classification of road
Fall River County	Only processed is used / no answer
Grant County	Other: backfill or subgrade filler
Gregory County	Availability of materials
Hamlin County	Only processed is used / no answer
Hand County	Other: bank run is used for fill or soft spots & is covered with at least 3 inches of crushed
Lincoln County	Only processed is used / no answer
McCook County	Only processed is used / no answer
Pennington County	Only processed is used / no answer
Sanborn County	Availability of materials
City of Vermillion	Only processed is used / no answer
Walworth County	Classification of road

Table B-12: Response summary: primary factor in deciding when to use processed or spec material and when to use unprocessed material (question 6).

Response	Count
Classification of road	2 counties
Traffic volume of road	1 city
Availability of materials	2 counties
Other	3 counties
Public complaints	No responses
No answer / do not use “bank run”	9 counties 2 cities

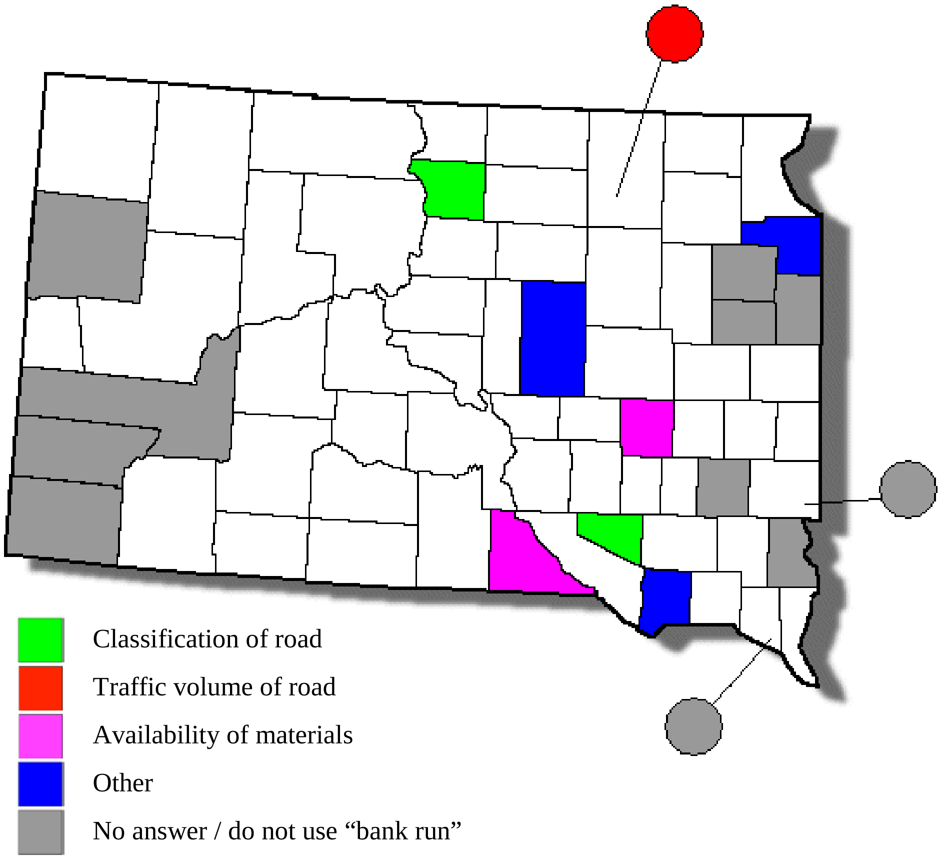

Figure B-5: Response map: primary factor in deciding when to use processed or spec material and when to use unprocessed material (question 6).

Table B-13: Frequency of surface aggregate testing (question 7).

County or City	Testing Frequency
City of Aberdeen	All of the time
Bon Homme County	Most of the time
City of Brandon	Rarely
Butte County	Rarely
Codington County	Some of the time
Custer County	Most of the time
Deuel County	Most of the time
Douglas County	Most of the time
Fall River County	Most of the time
Grant County	All of the time
Gregory County	Most of the time
Hamlin County	Some of the time
Hand County	All of the time
Lincoln County	All of the time
McCook County	All of the time
Pennington County	All of the time
Sanborn County	Some of the time
City of Vermillion	Never
Walworth County	All of the time

Table B-14: Response summary: frequency of surface aggregate testing (question 7).

Response	Count
All of the time	6 counties 1 city
Most of the time	6 counties
Some of the time	3 counties
Rarely	1 county 1 city
Never	1 city

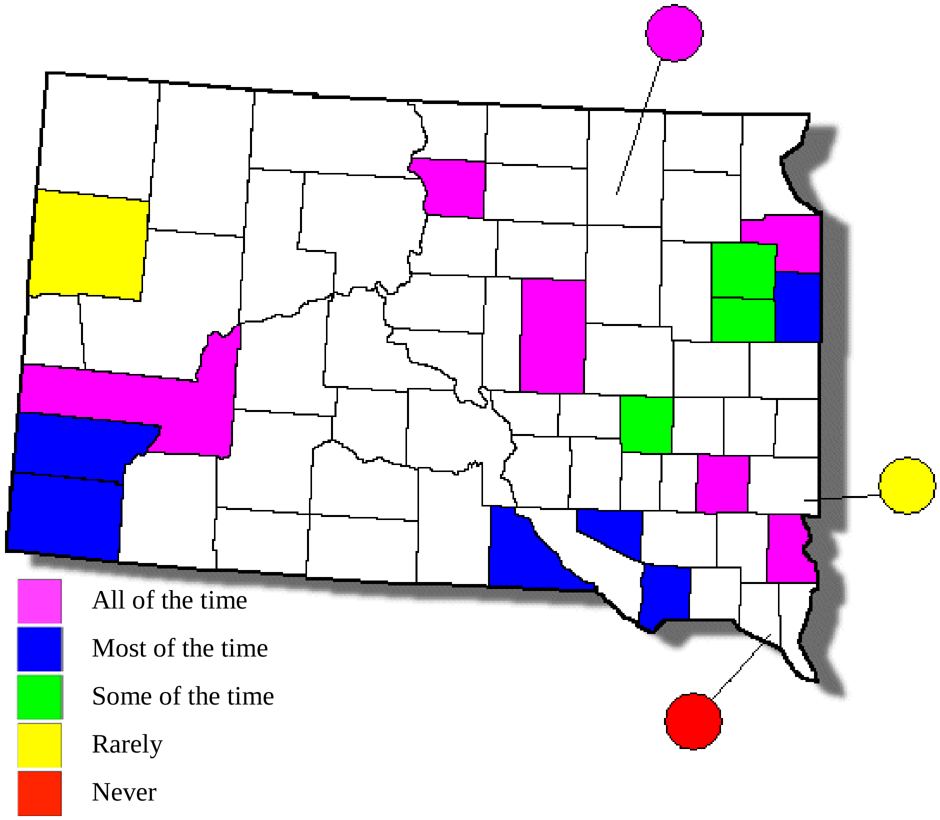

Figure B-6: Response map: frequency of surface aggregate testing (question 7).

Table B-15: Location for material sampling (question 8).

County or City	Material Sampling Location
City of Aberdeen	Stockpile
Bon Homme County	(Other) Crusher
City of Brandon	Stockpile
Butte County	Stockpile
Codington County	Stockpile
Custer County	(Other) We are taking them off the belt
Deuel County	Stockpile
Douglas County	Stockpile
Fall River County	Stockpile
Grant County	(Other) Stockpile & compacted surface
Gregory County	Stockpile
Hamlin County	Stockpile
Hand County	Stockpile
Lincoln County	Stockpile
McCook County	(Other) Belt during crushing
Pennington County	Stockpile
Sanborn County	Stockpile
City of Vermillion	No answer
Walworth County	Compacted surface

Table B-16: Response summary: location for material sampling (question 8).

Response	Count
Stockpile	11 counties 2 cities
Windrow	No responses
Compacted surface	1 county
Belt	2 counties
Other	2 counties
No answer	1 city

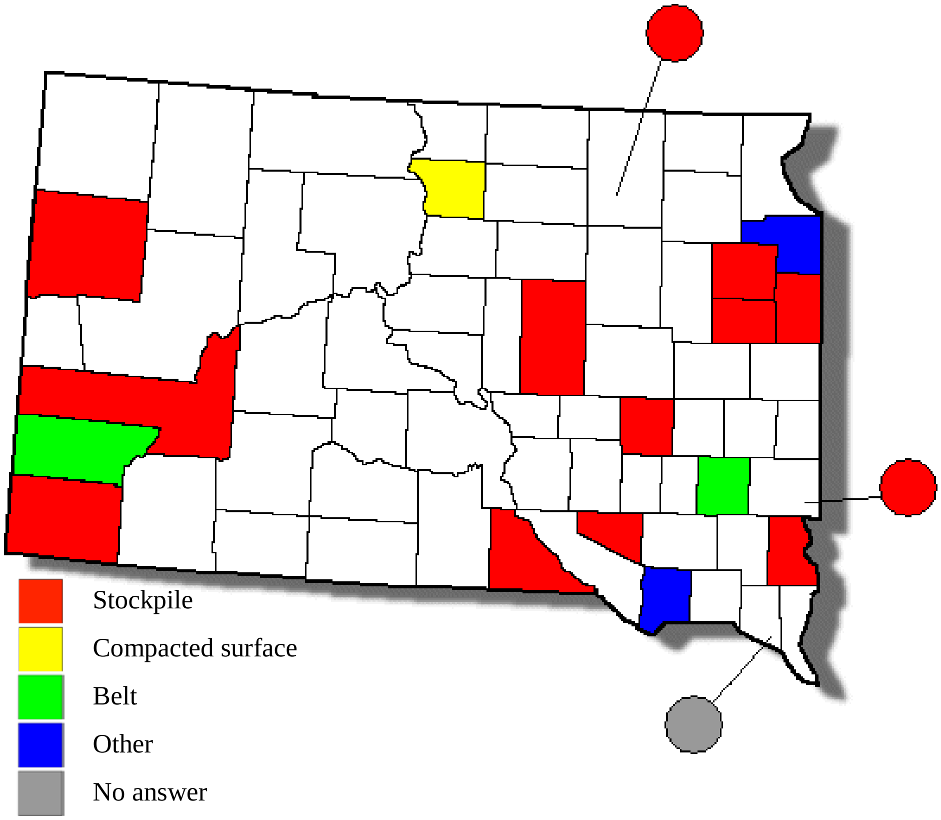

Figure B-7: Response map: location for material sampling (question 8).

Table B-17: Testing frequency for projects (question 9).

County or City	Project Testing Frequency
City of Aberdeen	Tests are taken based on the tonnage of material used
Bon Homme County	A few times as the aggregate is processed
City of Brandon	Once or twice per project
Butte County	A few times as the aggregate is processed
Codington County	A few times as the aggregate is processed / No specified frequency
Custer County	No specified frequency
Deuel County	A few times as the aggregate is processed
Douglas County	A few times as the aggregate is processed
Fall River County	A few times as the aggregate is processed
Grant County	A few times as the aggregate is processed
Gregory County	A few times as the aggregate is processed
Hamlin County	No specified frequency
Hand County	A few times as the aggregate is processed
Lincoln County	A few times as the aggregate is processed
McCook County	Tests are taken based on the tonnage of material used
Pennington County	A few times as the aggregate is processed
Sanborn County	No specified frequency
City of Vermillion	No testing is regularly done
Walworth County	No testing is regularly done

Table B-18: Response summary: testing frequency for projects (question 9).

Response	Count
Once or twice per project	1 city
A few times as the aggregate is processed	10 counties
Tests are taken based on the tonnage of material used	1 county 1 city
No specified frequency	3 counties
Varies based on traffic volume of the road being surfaced	No responses
No testing is regularly done	1 county 1 city
A few times as the aggregate is processed / No specified frequency	1 county

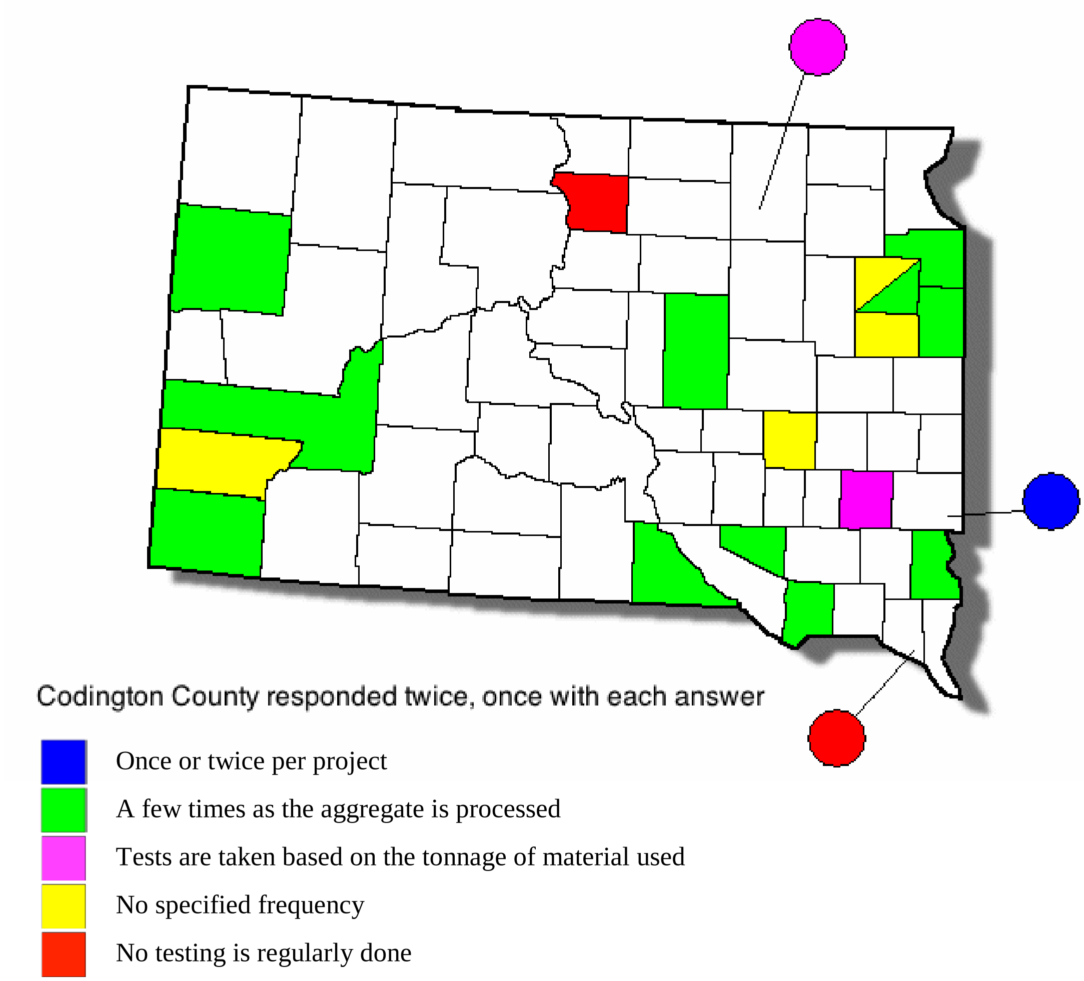

Figure B-8: Response map: testing frequency for projects (question 9).

Table B-19: Tests performed on road surface aggregates (question 10).

County or City	Gradation	Plasticity	Fractured faces
City of Aberdeen	x	x	x
Bon Homme County	x	x	
City of Brandon	x	x	
Butte County	x	x	x
Codington County	x	x	
Custer County	x	x	x
Deuel County		x	x
Douglas County		x	
Fall River County	x	x	x
Grant County	x	x	x
Gregory County	x	x	
Hamlin County	x	x	x
Hand County	x	x	
Lincoln County	x	x	
McCook County	x	x	
Pennington County	x	x	
Sanborn County			x
City of Vermillion			
Walworth County			

Table B-20: Response summary: tests performed on road surface aggregates (question 10).

Response	Count
Gradation, plasticity, and fractured faces	5 counties; 1 city
Gradation and plasticity	7 counties; 1 city
Plasticity and fractured faces	1 county
Plasticity	1 county
Fractured faces	1 county
Wear	No responses
No testing	1 county; 1 city

Table B-21: Total count of each test performed on road surface aggregates (question 10).

Test	Count
Gradation	12 counties; 2 cities
Plasticity	14 counties; 2 cities
Fractured faces	7 counties; 1 city
Wear	No responses
No testing	1 city; 1 county

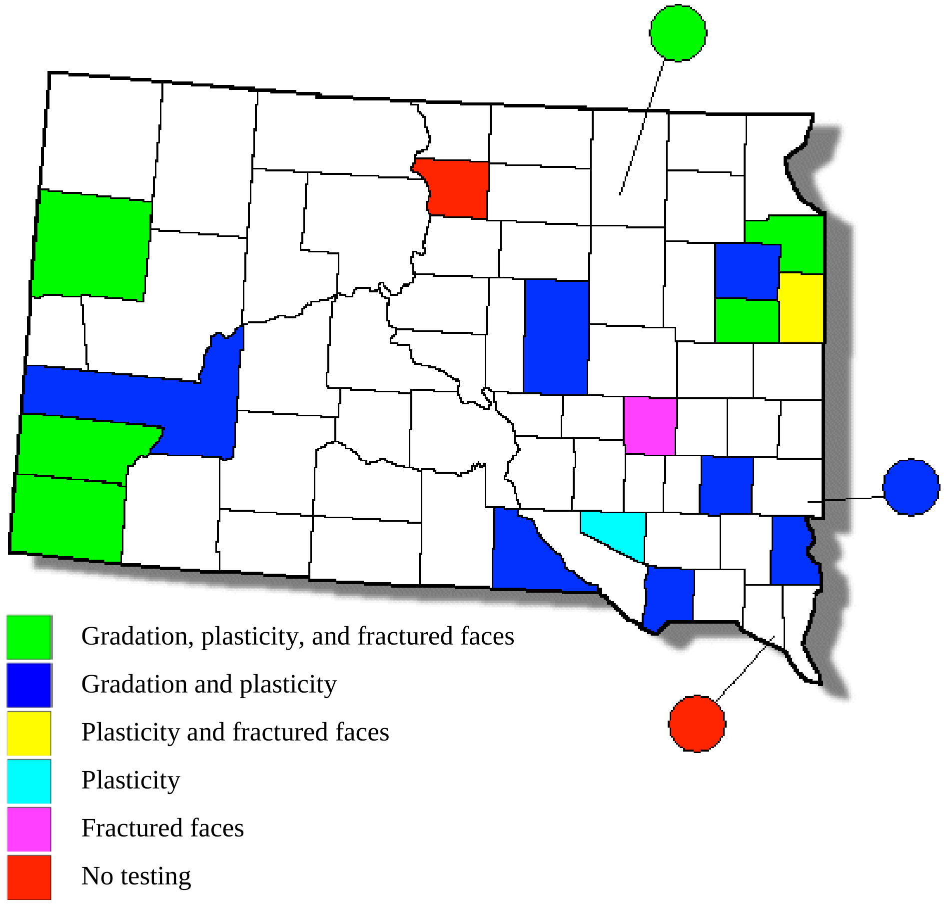

Figure B-9: Response map: tests performed on road surface aggregates (question 10).

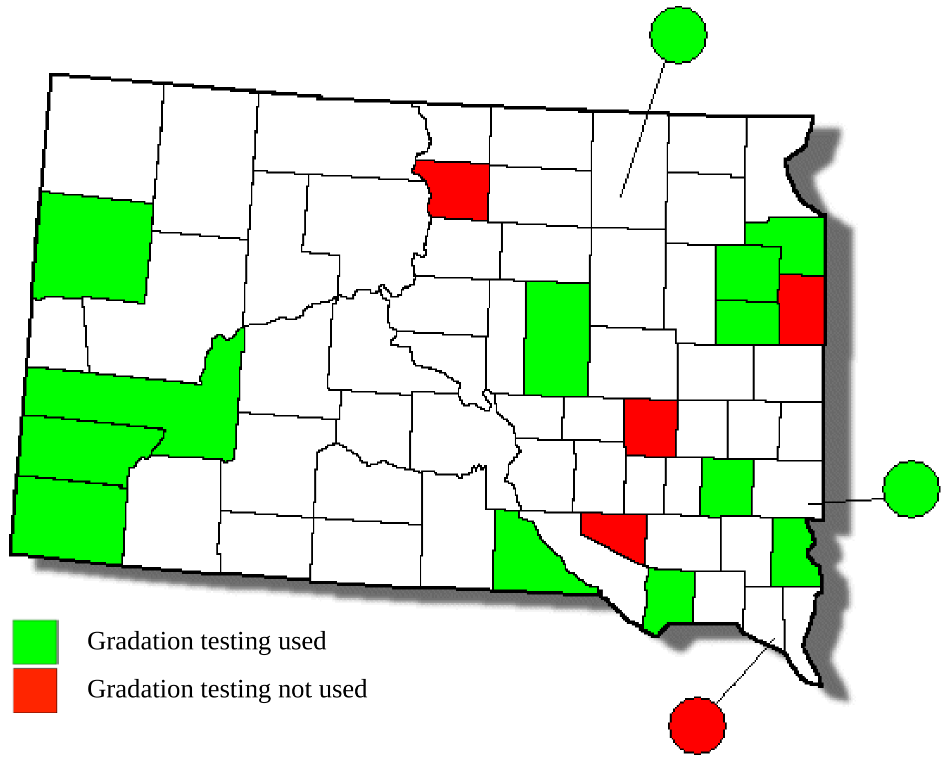

Figure B-10: Map of respondents that test for gradation (question 10).

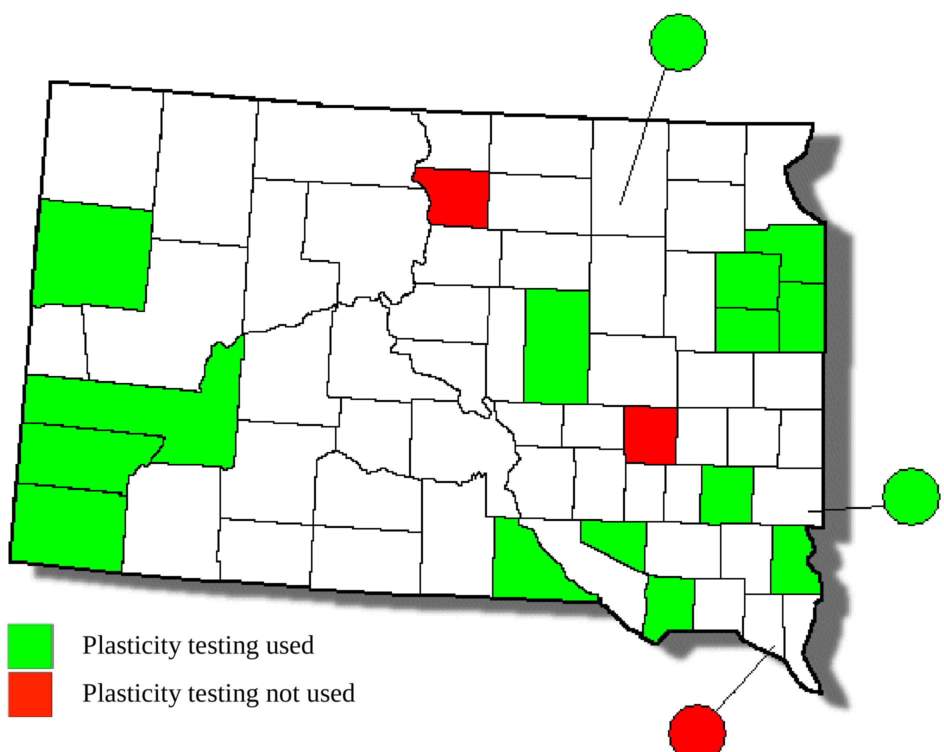

Figure B-11: Map of respondents that test plasticity (question 10).

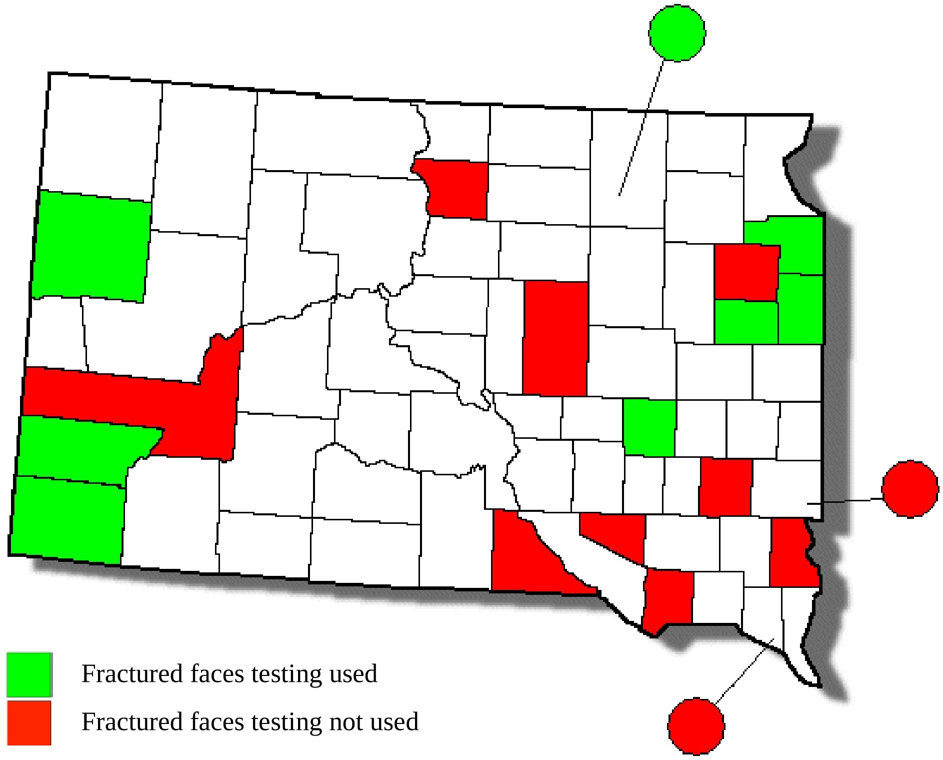

Figure B-12: Map of respondents that use fractured faces testing.

Table B-22: Use of compaction during placement and maintenance (questions 12 and 13).

County or City	Compaction during initial placement	Compaction during maintenance
City of Aberdeen	Yes	Yes
Bon Homme County	No	No
City of Brandon	Yes	No
Butte County	No	No
Codington County	No	No
Custer County	Yes	Yes
Deuel County	Yes	No
Douglas County	No	No
Fall River County	Yes	Yes
Grant County	Yes	No
Gregory County	No	No
Hamlin County	No	No
Hand County	No	No
Lincoln County	No	No
McCook County	Yes	No
Pennington County	Yes	Yes
Sanborn County	No	No
City of Vermillion	Yes	No
Walworth County	No	No

Table B-23: Response summary: use of compaction during placement (question 12).

Response	Count
Yes	6 counties 3 cities
No	10 counties

Table B-24: Response summary: use of compaction during maintenance (question 13).

Response	Count
Yes	3 counties 2 cities
No	13 counties 1 city

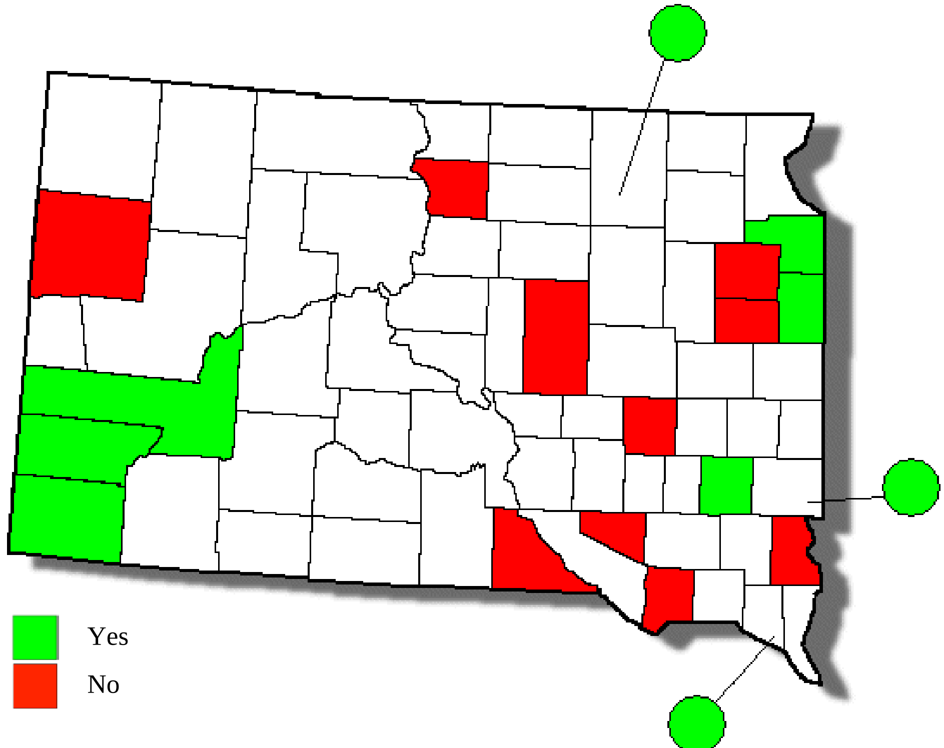

Figure B-13: Response map: use of compaction during placement (question 12).

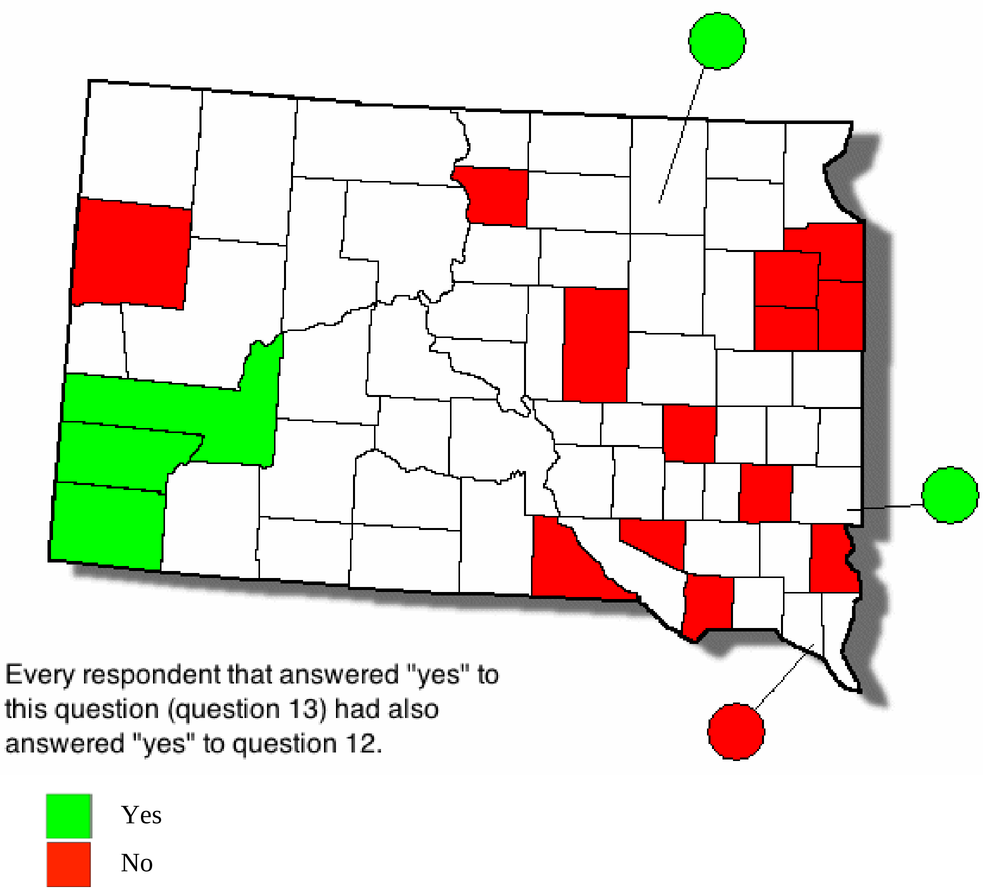

Figure B-14: Response map: use of compaction during maintenance (question 13).

Table B-25: Steps taken to obtain optimum moisture content (question 14).

County or City	Methods to obtain optimum moisture
City of Aberdeen	Watering
Bon Homme County	No
City of Brandon	Both
Butte County	N/A - We don't compact
Codington County	Windrowing
Custer County	Windrowing
Deuel County	Both
Douglas County	N/A - We don't compact
Fall River County	Windrowing
Grant County	Both
Gregory County	No
Hamlin County	No
Hand County	N/A - We don't compact
Lincoln County	Both
McCook County	Both
Pennington County	Both
Sanborn County	No
City of Vermillion	Windrowing
Walworth County	Both

Table B-26: Response summary: steps to obtain optimum moisture content (question 14).

Response	Count
Watering	1 city
Windrowing	3 counties 1 city
Both	6 counties 1 city
No	4 counties
N/A - We don't utilize compaction for construction or maintenance of gravel surfaces.	3 counties

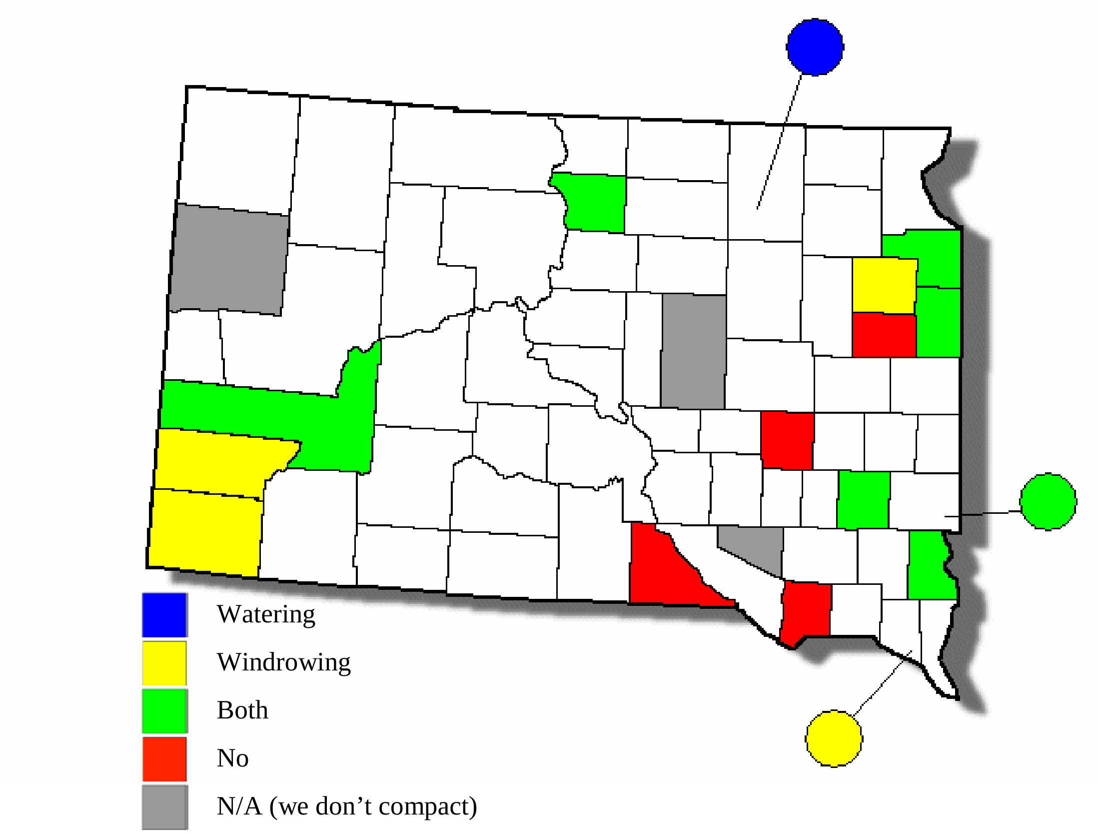

Figure B-15: Response map: steps taken to obtain optimum moisture content (question 14).

Table B-27: Extent of stabilizer use (question 15).

County or City	Roads stabilized
City of Aberdeen	Some
Bon Homme County	None
City of Brandon	Some
Butte County	Little
Codington County	None
Custer County	Some
Deuel County	Little
Douglas County	Little
Fall River County	Little
Grant County	Little
Gregory County	Little
Hamlin County	None
Hand County	None
Lincoln County	Some
McCook County	Little
Pennington County	None
Sanborn County	None
City of Vermillion	None
Walworth County	None

Table B-28: Response summary: extent of stabilizer use (question 15).

Response	Count
All	No responses
Most	No responses
Some	2 counties 2 cities
Little	7 counties 1 city
None	7 counties

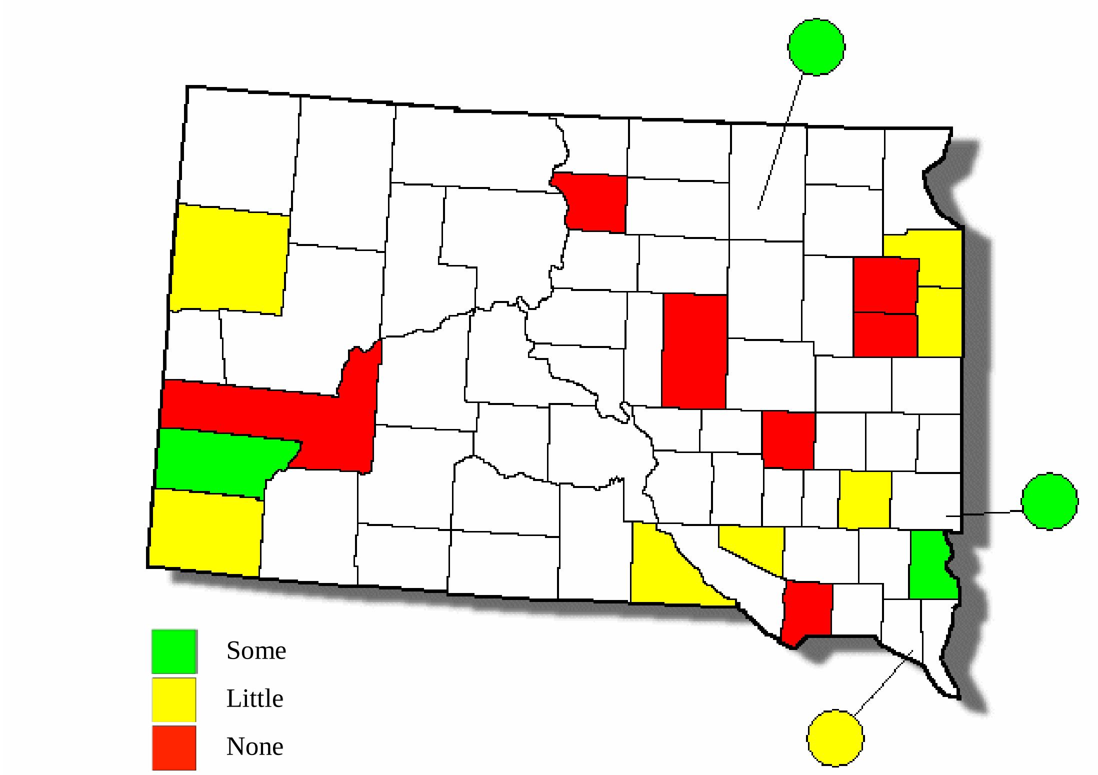

Figure B-16: Response map: extent of stabilizer use (question 15).

Table B-29: Major factor in determining when maintenance grading is required and annual number of maintenance gradings (questions 16 and 17).

County or City	Major factor in requiring grading	Annual number of maintenance gradings
City of Aberdeen	Surface Defects (Washboard, Rutting, Potholes)	3 to 6
Bon Homme County	(Other) Combination of surface defects, rain events, complaints, and schedule cycle	3 to 6
City of Brandon	Surface Defects (Washboard, Rutting, Potholes)	3 to 6
Butte County	Surface Defects (Washboard, Rutting, Potholes)	Not based on a schedule
Codington County	Scheduled cycle	11 or more
Custer County	(Other) We use a combination of surface defects, complaints, anticipated or received moisture so there is no set major factor.	Not based on a schedule
Deuel County	Scheduled cycle	7 to 10
Douglas County	Surface Defects (Washboard, Rutting, Potholes)	1
Fall River County		3 to 6
Grant County	Scheduled cycle	11 or more
Gregory County	Surface Defects (Washboard, Rutting, Potholes)	7 to 10
Hamlin County	Scheduled cycle	11 or more
Hand County	Scheduled cycle	11 or more
Lincoln County	Scheduled cycle	11 or more
McCook County	Scheduled cycle	11 or more
Pennington County	Surface Defects (Washboard, Rutting, Potholes)	7 to 10
Sanborn County	Average daily traffic levels -- regardless of distress	11 or more
City of Vermillion	Scheduled cycle	2
Walworth County	Scheduled cycle	7 to 10

Table B-30: Response summary: major factor in determining when maintenance grading is required (question 16).

Response	Count
Surface defects	4 counties 2 cities
Dust	No responses
Rain event	No responses
Complaints	No responses
Scheduled cycle	8 counties 1 city
Average daily traffic levels (regardless of distress)	1 county
Combination	2 counties
No response	1 county

Table B-31: Response summary: annual number of maintenance gradings (question 17).

Response	Count
1	1 county
2	1 city
3 to 6	2 counties 2 cities
7 to 10	4 counties
11 or more	7 counties
Not based on a schedule	2 counties

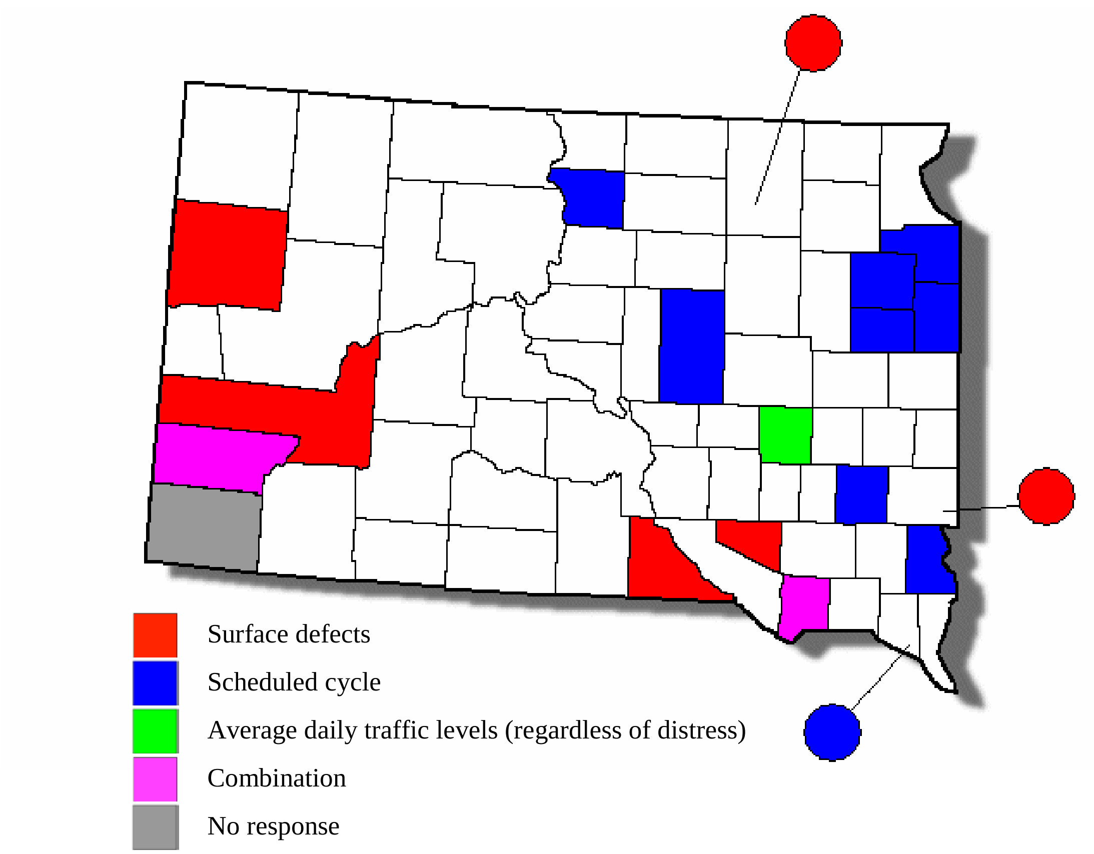

Figure B-17: Response map: major factor in determining when maintenance grading is required (question 16).

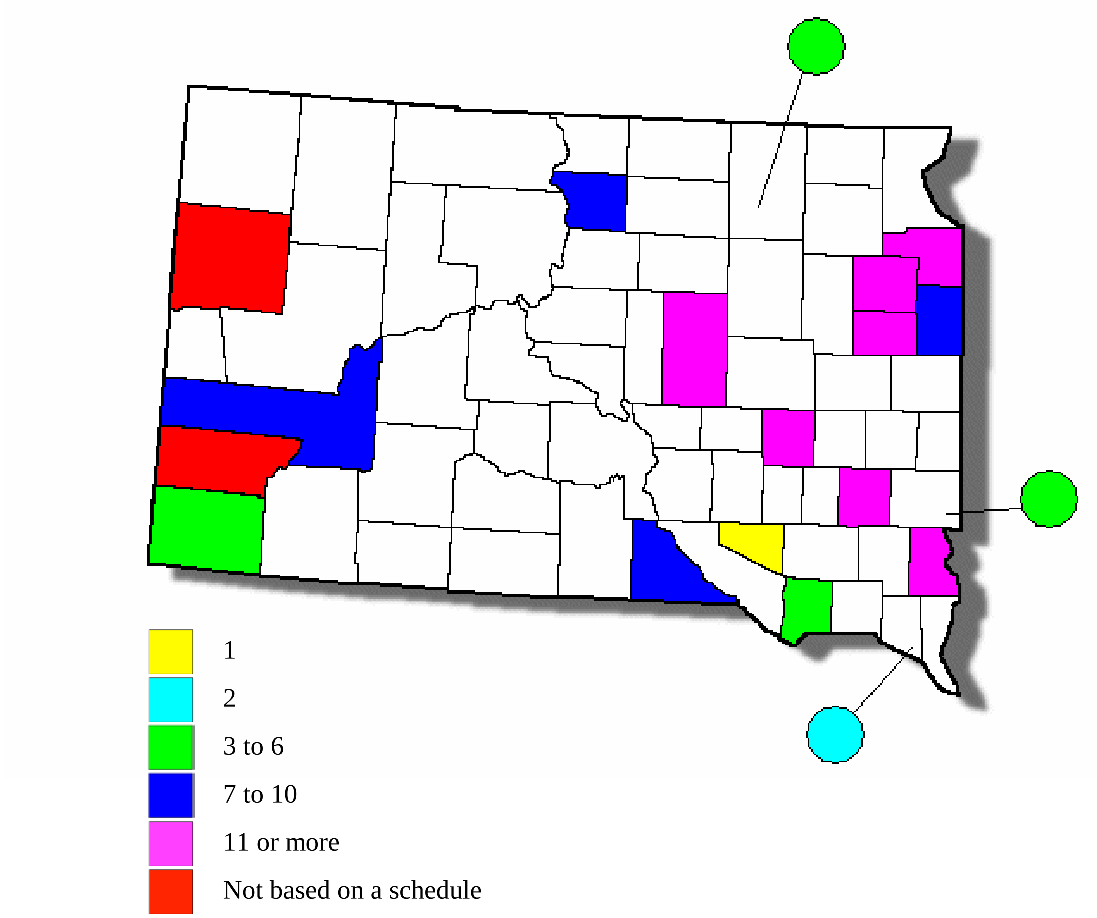

Figure B-18: Response map: annual number of maintenance gradings (question 17).

Table B-32: Agencies that maintain gravel roads differently based on classification or traffic (question 18).

County or City	Different treatment for traffic volume	Treatment method
City of Aberdeen	No	
Bon Homme County	Yes	Traffic volume, weather, condition of road surface, & amount of complaints
City of Brandon	Yes	No answer
Butte County	Yes	
Codington County	Yes	Higher ADTs get more frequent maintaining.
Custer County	Yes	A more heavily travelled road gets more frequent service.
Deuel County	Yes	Higher volume gets more attention
Douglas County	Yes	Designated haul roads get maintained once a week.
Fall River County	Yes	More traffic need more maintenance
Grant County	Yes	Scheduled more often for maintenance
Gregory County	No	
Hamlin County	Yes	Blade more
Hand County	No	
Lincoln County	No	
McCook County	No	
Pennington County	Yes	Low volume roads are not maintained as often.
Sanborn County	No	
City of Vermillion	No	
Walworth County	No	

Table B-33: Response summary: agencies that maintain gravel roads differently based on classification or traffic (question 18).

Response	Count
Yes	10 counties 1 city
No	6 counties 2 cities

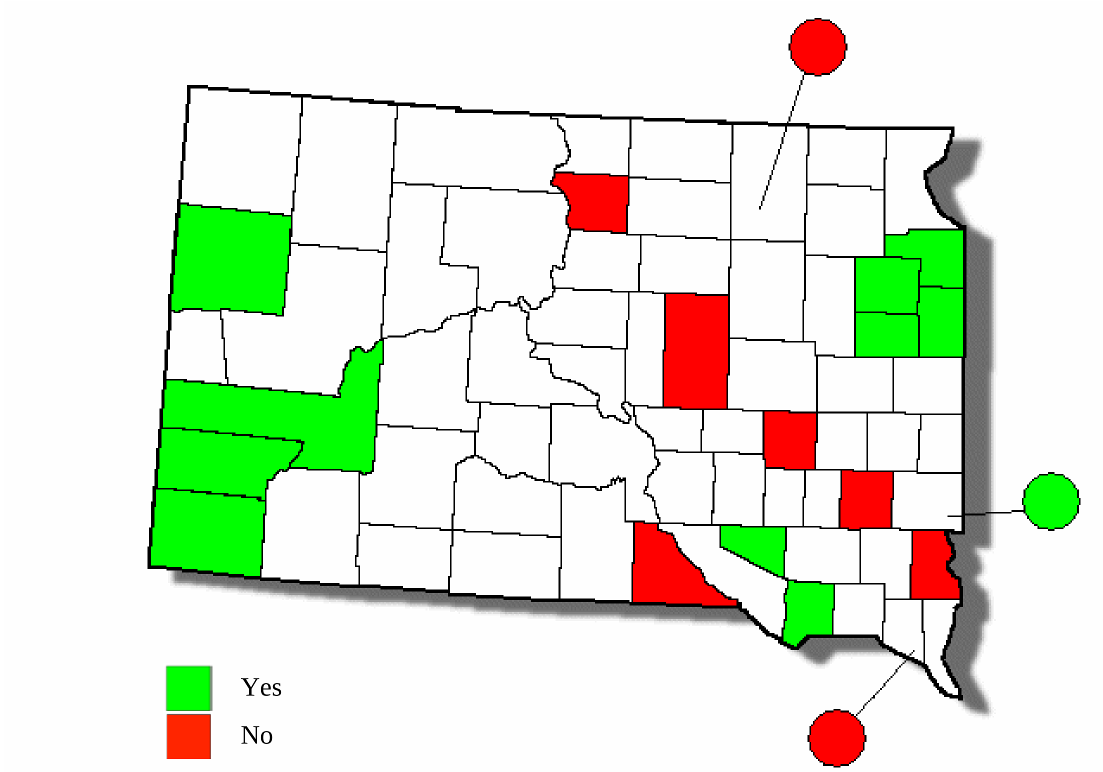

Figure B-19: Response map: agencies that maintain gravel roads differently based on classification or traffic (question 18).

Table B-34: Method for determining when regraveling is required (question 19).

County or City	Regraveling trigger
City of Aberdeen	Lack of adequate material for a grading operation
Bon Homme County	Exposed sub surface materials
City of Brandon	Exposed sub surface materials
Butte County	Lack of adequate material for a grading operation
Codington County	Lack of adequate material for a grading operation
Custer County	Exposed sub surface materials
Deuel County	Exposed sub surface materials
Douglas County	Lack of adequate material for a grading operation
Fall River County	Lack of adequate material for a grading operation
Grant County	Lack of adequate material for a grading operation
Gregory County	Lack of adequate material for a grading operation
Hamlin County	Lack of adequate material for a grading operation
Hand County	Exposed sub surface materials
Lincoln County	Thickness of aggregate
McCook County	Thickness of aggregate
Pennington County	Exposed sub surface materials
Sanborn County	Exposed sub surface materials
City of Vermillion	Lack of adequate material for a grading operation
Walworth County	Lack of adequate material for a grading operation

Table B-35: Response summary: method for determining when regraveling is required (question 19).

Response	Count
Thickness of aggregate	2 counties
Exposed subsurface materials	6 counties 1 city
Severe rutting	No responses
Lack of adequate material for grading operation	8 counties 2 cities
Other	No responses

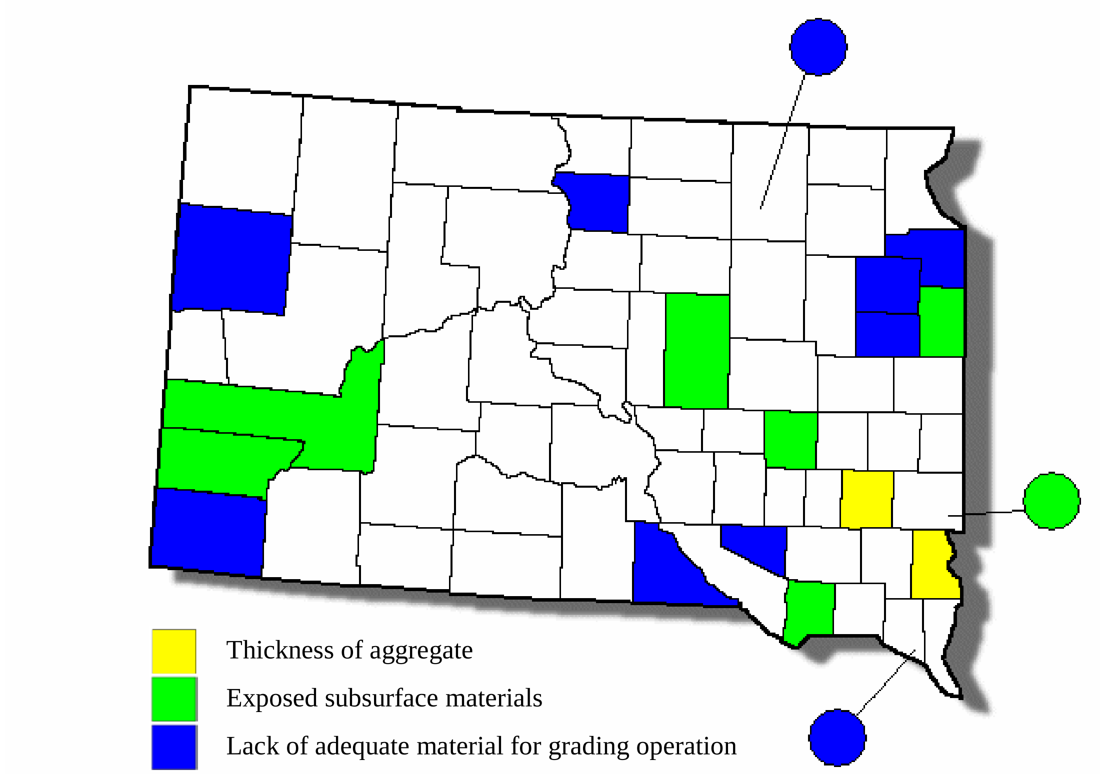

Figure B-20: Response map: determining method for regraveling (question 19).

Table B-36: Gravel placement method (question 20).

County or City	Gravel placement method
City of Aberdeen	End dump and spread,
Bon Homme County	(Other) End dump, windrow, mix, then spread
City of Brandon	End dump and spread,
Butte County	End dump and spread,
Codington County	Mix (windrow) existing and new then spread
Custer County	Mix (windrow) existing and new then spread
Deuel County	End dump and spread,
Douglas County	Mix (windrow) existing and new then spread
Fall River County	Mix (windrow) existing and new then spread
Grant County	End dump and spread,
Gregory County	End dump and spread,
Hamlin County	Belly dump and then spread
Hand County	Mix (windrow) existing and new then spread
Lincoln County	End dump and spread,
McCook County	Mix (windrow) existing and new then spread
Pennington County	End dump and spread,
Sanborn County	End dump and spread,
City of Vermillion	End dump and spread,
Walworth County	Belly dump and then spread

Table B-37: Response summary: gravel placement method (question 20).

Response	Count
End dump then spread	7 counties 3 cities
Belly dump then spread	2 counties
Mix (windrow) existing and new then spread	7 counties

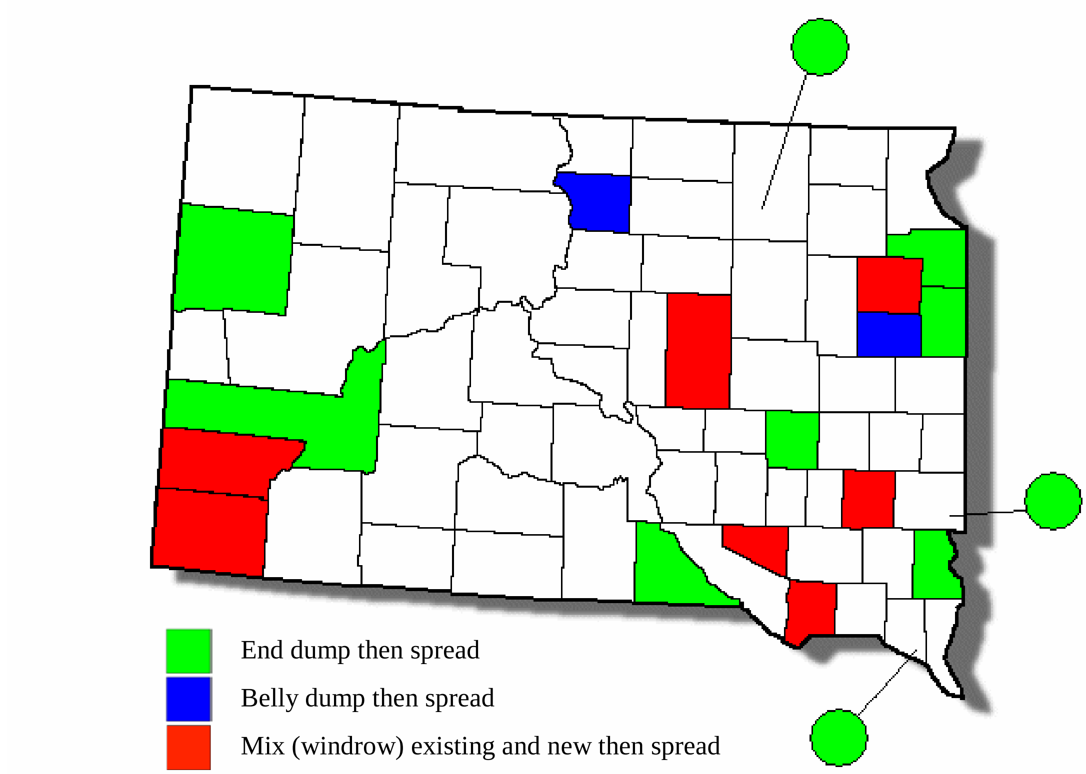

Figure B-21: Response map: gravel placement method (question 20).

Table B-38: Different treatments for hill and curves (question 21).

County or City	Hills and curves treated differently	Treatment method
City of Aberdeen	No	
Bon Homme County	Yes	Different grading methods
City of Brandon	No	
Butte County	Yes	Different grading methods
Codington County	Yes	Different grading methods
Custer County	Yes	We use crusher fines on some hills and corners and chloride on others.
Deuel County	Yes	Different grading methods
Douglas County	No	
Fall River County	No	
Grant County	Yes	More material
Gregory County	No	
Hamlin County	Yes	
Hand County	Yes	Different grading methods
Lincoln County	No	
McCook County	Yes	Different grading methods
Pennington County	No	
Sanborn County	No	
City of Vermillion	No	
Walworth County	Yes	Different grading methods

Table B-39: Response summary: counties or cities that treat hills or curves differently (question 21).

Response	Count
Yes	10 counties
No	6 counties 3 cities

Table B-40: Response summary: different treatments for hills and curves (question 21).

Response	Count
Different grading methods	8 counties
Different materials	1 county
More material	1 county
Hills and curves not treated differently	6 counties 3 cities

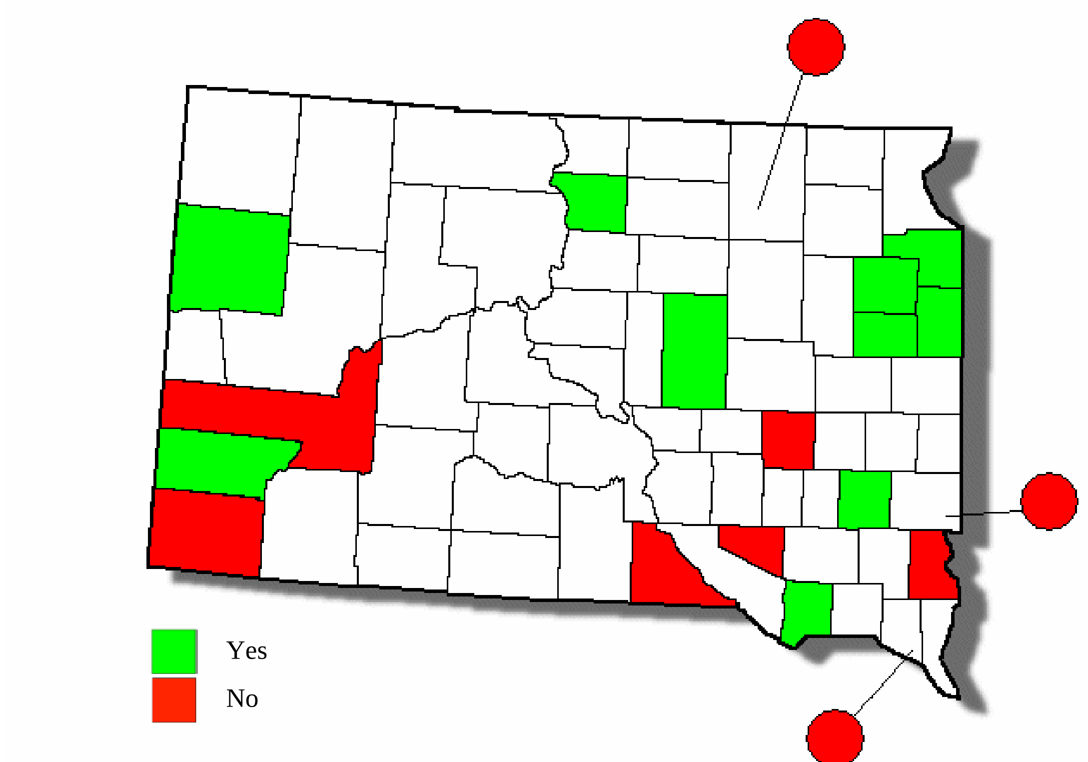

Figure B-22: Response map: counties/cities that treat hills or curves differently (question 21).

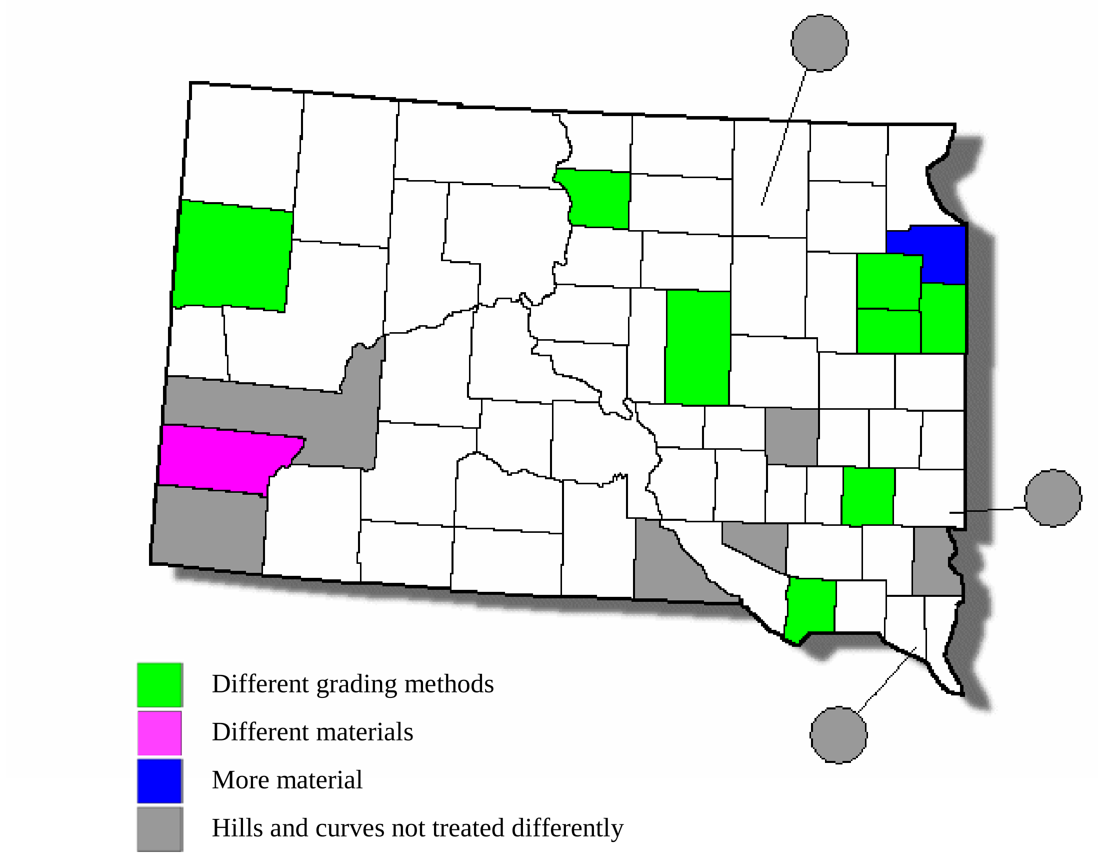

Figure B-23: Response map: different treatments for hill and curves (question 21).

Table B-41: Top local concerns related to gravel roads (question 22).

County or City	Top Local Concerns
City of Aberdeen	The number of times we have to go out to maintain them and the muddy conditions following rain events
Bon Homme County	Not having enough material to meet the needs of the roads & budget concerns. We only crush what budget allows.
City of Brandon	Heavy truck loading on the roads and washboarding due to high travel areas.
Butte County	Keep the roads smooth
Codington County	Aggregate quality
Custer County	Dust
Deuel County	Getting harder to find quality gravel, and speeds are too high on gravel roads.
Douglas County	Finding gravel with high enough PI value. And finding gravel that is close to work sites.
Fall River County	Specification
Grant County	Base not adequate for today's loads
Gregory County	Enough material on the road
Hamlin County	Lack of quality gravel
Hand County	
Lincoln County	
McCook County	Washing and erosion on hills, loose material and washboarding at starting and stopping points.
Pennington County	Washboard, rutting
Sanborn County	
City of Vermillion	Rutting, dust, travel of gravel into sidewalk and street, when regraveling fines sometimes flow into storm sewer system
Walworth County	

Table B-42: Innovative practices for construction or maintenance (question 23).

County or City	Innovative Practices
City of Aberdeen	None
Bon Homme County	Nothing out of the ordinary
City of Brandon	Magnesium Chloride and frequent maintenance.
Butte County	
Codington County	
Custer County	We chloride most of our new gravel. We have had considerable success with crusher fines.
Deuel County	None out of the ordinary
Douglas County	We use stinger bit blades.
Fall River County	We have walk & roll packers on our blades. We use them all the time.
Grant County	None in particular. Place fabric in short areas.
Gregory County	None
Hamlin County	Pull shoulders and rip and blend existing materials in weak spots and place gravel over those areas
Hand County	Water and add clay to existing aggregate when we have too much float
Lincoln County	
McCook County	We have several gravel sources within the county and depending upon plasticity we often blend materials from different sources. Blading hills only uphill.
Pennington County	We water and compact all newly placed aggregate.
Sanborn County	
City of Vermillion	On a majority of our gravel roads we use a mix of asphalt and concrete grindings.
Walworth County	

Table B-43: Gravel roads cost effectiveness (questions 24 and 25).

County or City	Most cost effective maintenance strategy	Cost data to support
City of Aberdeen	More expensive, processed aggregates	We don't have cost data
Bon Homme County	More expensive, processed aggregates	We have data but we are not willing to share it
City of Brandon	More expensive, processed aggregates	We don't have cost data
Butte County	More expensive, processed aggregates	We don't have cost data
Codington County	More expensive, processed aggregates	We don't have cost data
Custer County	More expensive, processed aggregates	We have data and are willing to share it
Deuel County	More expensive, processed aggregates	We don't have cost data
Douglas County	More expensive, processed aggregates	We don't have cost data
Fall River County	More expensive, processed aggregates	We don't have cost data
Grant County	More expensive, processed aggregates	We don't have cost data
Gregory County	More expensive, processed aggregates	We don't have cost data
Hamlin County	More expensive, processed aggregates	We don't have cost data
Hand County	More expensive, processed aggregates	We don't have cost data
Lincoln County	More expensive, processed aggregates	We don't have cost data
McCook County	Not sure	We don't have cost data
Pennington County	More expensive, processed aggregates	We have data and are willing to share it
Sanborn County	Less expensive, unprocessed aggregates	We don't have cost data
City of Vermillion	More expensive, processed aggregates	We don't have cost data
Walworth County	More expensive, processed aggregates	We don't have cost data

Table B-44: Response summary: gravel roads cost effectiveness (questions 24 and 25).

Response	Count
Use more expensive, processed aggregates that meet a specification	14 counties 3 cities
Less expensive, unprocessed aggregates that do not meet a specification	1 county
Not sure	1 county

Table B-45: Use of processed or unprocessed aggregates (questions 26 and 27).

County or City	Reason for using unprocessed aggregates	Reason for using processed aggregates
City of Aberdeen	We have a pit that has material that sets up fairly well and has pretty decent aggregate qualities.	For higher volume roads, the better aggregate that we use, will require less frequency for maintenance
Bon Homme County	Back fill or just fill	Our gravel in this county has too many larger rocks that you cannot place on road.
City of Brandon		We have found the fractured aggregate binds better and holds up better to traffic.
Butte County	To put the best gravel on the road	
Codington County		To maintain consistent quality
Custer County	Not Applicable	They "settle down" better and give us a better road surface. We like a tight road not loose marbles. Sometimes when we get really wet the higher PI can cause us problems but as I have explained to the Commission, we can manage our roads so they are good
Deuel County		Unprocessed materials in this area are full of large stones
Douglas County		It stays on the road better, very little float material on the surface.
Fall River County		It holds on the road a lot better.
Grant County	We use some out of bank for 1st 12" over fabric, then remainder class 5	For best possible stability
Gregory County	Location of material	Location of the pit
Hamlin County		Better quality surface and less maintenance required
Hand County	For soft spots and fill, we feel bank run does a better job.	We feel processed material provides a better driving surface, lasts longer, and we have less complaints.
Lincoln County		
McCook County	Don't use them	To provide a tight safe surface for the traveling public.
Pennington County		Improved driving surface, less maintenance
Sanborn County	Availability	Availability
City of Vermillion		Better quality control
Walworth County	Minimum maintenance roads. Soft spots are filled and then covered with processed aggregate	Long term stability

Survey Questions

Classification Questions

1. Name (fill in the blank):____

2. Agency (fill in the blank):____

3. Which of the following would best describe your agency (select one):
    A. County
    B. City
    C. Tribal Government
    D. Other____

Material Specification Questions

4. List the specification(s) or common names for surface aggregate materials for gravel roads that your agency uses, and list the approximate percentage of these materials, based on tonnage, that are used within your agency during a typical year? (Multiple answer):
    A. SDDOT Gravel Surfacing Specification: _____%
    B. Unprocessed or coarse screened "bank run" with little or no gradation requirements: _____%
    C. Local Agency Spec 1:_______________________ _____%
    D. Local Agency Spec 2:_______________________ _____%
    E. Local Agency Spec 3:_______________________ _____%
    F. Local Agency Spec 4:_______________________ _____%

5. Does your agency ever use a modified version of the South Dakota DOT Gravel Surfacing Specification for surface aggregate materials that you feel provides improved constructability and/or extends the life of the road surface (an example might be specifying higher plasticity or more material passing the #200 sieve)? (Select one)

    A. Yes
    B. No

    If "Yes" what modifications do you make to the South Dakota DOT Gravel Surfacing Specification?____

6. If your agency uses both "bank run" (uncrushed or unprocessed) and (processed) specification surface aggregate materials what is the primary factor in determining where to use each type? (select one):
    A. Traffic volume of road
    B. Classification of road
    C. Public complaints
    D. Availability of materials
    E. Other____

Material Testing Questions

7. What frequency does your agency test road surfacing aggregate for gravel road projects to determine if it meets specification? (select one):
    A. All of the time
    B. Most of the time
    C. Some of the time
    D. Rarely
    E. Never

8. Where are samples for material testing taken?
    A. Stockpile
    B. Windrow
    C. Compacted surface
    D. Other____

9. If your agency tests road surface aggregates which of the following describes the frequency of testing for the majority of your gravel road projects? (select one):
    A. Once or twice per project
    B. A few times as the aggregate is processed
    C. Tests are taken based on the tonnage of material used
    D. No specified frequency
    E. Varies based on traffic volume of the road being surfaced
    F. No testing is regularly done
    G. Other ____

10. If your agency runs tests on road surface aggregates for gravel road construction and maintenance, indicate which test you typically complete (select all that apply)?
    A. Gradation
    B. Plasticity
    C. Fractured faces
    D. Wear
    E. Other____
    F. Other 2____

11. If your agency uses specifications for any of the parameters listed in question 10 please list the name of the specification and a source where we can find a written copy of the specification. If your agency uses standard South Dakota DOT specifications you do not need to list a source

    ____

Construction Related Questions

12. For the majority of your gravel road projects, does your agency specify or utilize compaction of surface aggregate materials during <u>initial placement</u> of gravel layers? (select one):
    A. Yes
    B. No

13. For the majority of your gravel road projects, does your agency specify or utilized compaction of surface aggregate materials during <u>maintenance</u> of the roadway? (select one):
    A. Yes
    B. No

14. Does your agency take steps (watering or windrowing) to obtain the optimum moisture content during placement of surface aggregates prior to compaction? (select one):
    A. Watering
    B. Windrowing
    C. Both
    D. No
    E. N/A - We don't utilize compaction for construction or maintenance of gravel surfaces.

15. How much of your agency's gravel road system are stabilized using such stabilizers as calcium chloride, magnesium chloride, enzymes, bentonite, etc. used? (select one):
    A. All
    B. Most
    C. Some
    D. Little
    E. None

Maintenance Related Questions

16. What is the major factor for determining when maintenance grading is required on aggregate surface roads in your agency? (select one):
    A. Surface Defects (Washboard, Rutting, Potholes),
    B. Dust
    C. Rain Event
    D. Complaints
    E. Scheduled cycle
    F. Average daily traffic levels – regardless of distress
    G. Other____

17. If maintenance to aggregate surface roads is on a scheduled basis how many times yearly is it typically performed? (select one):
    A. 1
    B. 2
    C. 3 to 6
    D. 7 to 10
    E. 11 or more
    F. Not based on a schedule

18. Does your agency maintain aggregate surface roads differently based on the road classification or traffic volume? (select one):
    A. Yes
    B. No

    If Yes, how are the practices different?
    ____

19. How does your agency determine when re-graveling is required on aggregate surface roads? (select one):
    A. Thickness of aggregate,
    B. Exposed sub surface materials,
    C. Severe rutting,
    D. Lack of adequate material for a grading operation,
    E. Other____

20. What is the primary method for placing surface aggregate materials when re-graveling is required on a gravel road in your agency?
    A. End dump and spread,
    B. Mix (windrow) existing and new then spread
    C. Other____

21. When performing maintenance do you treat hills or curves differently than straight sections? (select one):
    A. Yes
    B. No

22. If yes, how do you treat them differently? (multiple answer):
    A. Different materials
    B. Different grading methods
    C. Other____

General Questions

23. What are your top local concerns related to aggregate surface roads?

    ____

24. What innovative practices for construction or maintenance of aggregate surface roads does your agency employ?

    ____

25. In your opinion is it more cost effective for your agency to build and maintain aggregate surface roads with: (select one):
    A. Less expensive, unprocessed aggregates that do not meet a specification
    B. Use more expensive, processed aggregates that meet a specification
    C. Not sure

26. Do you have cost data that you would be willing to share that support your answer to question number 24? (select one):
    A. No – we don't have cost data
    B. We have data but we are <u>not</u> willing to share it
    C. Yes- we have data and are willing to share it

27. If your agency uses unprocessed aggregates that do not meet a specification, what is the reason(s) for using them?

    ____

28. If your agency uses processed aggregates that meet a specification, what is the reason(s) for using them?

    ____

APPENDIX C. TELEPHONE INTERVIEWS

Follow up interviews were conducted by John Kiefer, P.E. via telephone. Interviews were recorded using a digital audio recorder with the interviewee's consent. Interviews were conducted with agencies that had indicated that they had innovative material, maintenance or construction practices on the gravel surfacing guidelines survey. Another pool of interview candidates was developed from an interview with Ken Skorseth from the South Dakota LTAP center. Mr. Skorseth identified several local agencies that use innovative practices at their agency.

Ken Skorseth-South Dakota LTAP

Conducted 10/7/10 (approx. length 40 minutes)
(did not participate in survey)

Summary of interview: Discussed persons and responses from the previous survey that were selected for the telephone interviews. Ken suggested that we also contact some specific agencies that had not responded to the survey but were likely to be using innovative practices for maintaining gravel roads. We discussed the "walk and roll packer" that was mentioned in the survey responses. This is a brand name of a pneumatic tire compacting device (typically has 8 to 11 tires) that attaches directly to the grader blade or ripper. This allows two tasks to be performed at one time with one operator and one piece of equipment. Although it is not as effective at compaction as a rubber tire roller unit it provides some amount of compaction where otherwise there would likely be none due to the cost of a separate piece of equipment and an operator. Ken mentioned that Custer County Highway Department uses a tow behind blading device for light maintenance. This unit is pulled behind a tractor or heavy duty pickup truck. It is thought that this unit will be faster and less costly than a grader.

Jose Dominguez-City of Vermillion

Conducted 10/7/10 (approx. length 15 minutes)
Audio File: Dominguez 101006_005.mp3

Answer to survey question: On the majority of our gravel roads we use a mix of asphalt and concrete grindings.

Summary of interview: The City of Vermillion has approximately one and one half to two miles of gravel surface roads. Most of their gravel surface roads have concrete curb and gutter as they were constructed with the intent to pave them in the future. They stockpile asphalt millings and concrete materials, in separate piles, obtained from other projects completed in town. Once a year they rent a crusher and crush these materials. The two piles of crushed materials are combined using a dozer. This material is then dumped and spread on the gravel roads using a grader. No attempt is made to mix this with the underlying gravel and no additional compaction is performed.

Michael Kreutzfeldt-McCook County Highway Department

Conducted 10/11/10 (approx. length 10 minutes)
Audio File: Kreutzfeldt 101010_000.mp3

Answer to survey question: We have several gravel sources within the county and depending on plasticity we often blend materials from different sources. Blading uphill only.

Summary of interview: This agency typically uses two different materials and blends them to obtain the desired plasticity. Blending is accomplished by placing two windrows and using a grader to roll across and back over the road surface. They use 1,000 ton per mile of materials in the process. Compaction is accomplished with two rubber tire rollers. For low volume roads, material with a lower PI is used. When a road has a high level of float, a higher PI material is used. The crushing of materials is contracted out and they test for gradation and plasticity. Only crushed materials are used. Maintenance on hills is performed by blading uphill on both sides of the road to attempt to replace the material that naturally migrates downhill. The cutting edge of the grader blade consists of the center eight feet fitted with carbide bits and one-half inch carbon on the outside four feet. They find that the carbide bit is not as good for shoulder maintenance. Also they have tried carbide faced but found that it does not work as well.

Randy Seiler-Fall River County Highway Department

Conducted 10/12/10 (approx. length 5 minutes)
Audio File: Seiler 101012_001.mp3

Answer to survey question: We have walk and roll packers on our blades. We use them all of the time.

Summary of interview: The Fall River County Highway Department uses walk and roll packers, which is a rubber tire device mounted behind the ripper, on their motor graders, to obtain compaction of gravel. It is their opinion that following road maintenance, that includes the use of the walk and roll packer, the traveling public tends to use the entire width of the road rather than only the center portion. If they feel that the desired compaction has not been achieved during blading they will run additional passes with the walk and roll packer. They attempt to perform maintenance when there is proper moisture in the gravel materials but do not add water.

Ralph Merchen-Custer County Highway Department

Conducted 10/12/10 (approx. length 15 minutes)
Audio File: Merchen (Custer) 101012_003.mp3

Answer to survey question: We chloride most of our new gravel. We have had considerable success with crusher fines.

Summary of interview: When placing new gravel they add calcium chloride brine to make the gravel tacky and then shape and compact. For low volume roads this will last up to three years but on high volume the best is one to possibly two years before maintenance is required. This method works best with new gravel rather than working with existing gravel materials. Due to availability magnesium chloride is also used. In the spring of the year roads treated with magnesium chloride tend to be greasy and in the summer will pothole. They also use a product referred to as “wetter water” that assists in the gravels ability to absorb water. At first it was used for dust control and now it is used with the magnesium chloride for stabilization. Gravel material consists of crushed limestone or hard rock (granite). The better hard rock gravel contains a gray clay material for binder. There are two types of limestone; the “red” limestone works better than the “white” limestone. They are using limestone crusher fines treated with magnesium chloride and then placed in a layer on top of the existing gravel. This is giving good service on low volume roads but on high volume roads dust is a problem. The crusher fines do not work as well as a good quality gravel material. For compaction a walk and roll packer unit is used. They also have two what they refer to as “groomers” or tow behind blades. These are units that are towed behind a tractor or large pickup truck and are used for light maintenance work. One of the operators has become quite proficient with its use while the other has not. They estimate that the amount of work performed with a grader in one week could be performed by the groomer in two days. There has been a significant amount of maintenance to the groomer required as it does not seem to be designed properly for this application.

Ron Olson-City of Mitchell

Conducted 10/12/10 (approx. length 5 minutes)
Audio File: Olson 101012_002.mp3
(did not participate in survey)

Summary of interview: The City of Mitchell has been recycling asphalt and concrete materials for approximately 18 years. They use this material as a surface course on low speed roads such as alleys with good results. They have also used this on a landfill haul road with limited success as it tended to washboard. Application consists of placing material, adding water as necessary and rolling to compact. Economics plays a role as it is less expensive to use the recycled materials than purchase virgin materials.

Brad Bowers-Harting County Highway Department

Conducted 10/13/10 (approx. length 10 minutes)
Audio File: Bowers 101013_000.mp3
(did not participate in survey)

Summary of interview: They use a product called “Base One” for stabilization. This is used primarily for base stabilization under sealcoat surfaced roads. The process consists of scarifying the gravel surface, adding Base One mixed with water, blading with a grader and then adding more Base One and water. After several days the surface is very hard. This type of stabilization has not been tried on gravel surface roads in their jurisdiction. They are an agency that also uses the walk and roll packers on their graders. Maintenance is performed on their gravel surface roads one or two times a year.

Dan Holsworth-City of Hermosa

Conducted 10/14/10
Audio File: Holsworth 101014_000.mp3
(did not participate in survey)

Summary of interview: The City of Hermosa, with approximately 4 to 5 miles of gravel surface streets, has used magnesium chloride brine in the past to control dust and stabilize their gravel roads. Over the past 6 or 7 years they have switch to a completely natural product called “EnviroDust” which is comprised primarily from soy bean oil. There was a bit of a learning curve to determine proper surface preparation and application rates but following this they have been very pleased with the performance. Preparation includes loosening the top one half inch to one inch of materials, apply the EnviroDust material and let set for 30 minutes (warm weather seems to work best), spread a thin layer of sand over the top and then roll with a rubber tire roller. This process seems to work better with gravel that contains less binder (sandy) materials than with the limestone materials. River rock gravel works well with this product. The EnviroDust materials is about twice as expense as magnesium chloride brine but treated roads last up to three years where magnesium treated roads tend to last less than one year. There have been some complaints about the odor from the EnviroDust but this is gone within a week or two.

Dick Birk-Lawrence County Highway Department

Conducted 10/14/10
Audio File: Birk 101014_001.mp3
(did not participate in survey)

Summary of interview: Due to their location and local geology the Lawrence County Highway Department is restricted in the type of gravel materials they use. These consist primarily of crushed hard rock with fines added. In their mountainous terrain magnesium chloride is used to stabilize the gravel and keep it on the road to reduce the need for replacement. Their method of treatment consists of blading with a grader equipped with Kennametal bits to loosen the top one and one half inch of material, shape the cross section, apply the magnesium chloride brine, roll the gravel across the road, roll the gravel back across the road and wheel roll for compaction. They also apply water before during and after this process as required to obtain the desired consistency. They feel that a rubber tire roller, to provide greater compaction, would be a benefit but they do not own one. This process seems to work well even on high volume roads and the treated roads show little damage following a rain. The treatment is applied yearly. They are experimenting with reducing the rate of application of the magnesium chloride while maintaining the same effect to reduce costs. This treatment seems to have a residual effect as the more years a road has been treated the longer it stays in acceptable condition.