OPTIMAL RAP CONTENT
FOR MINNESOTA GRAVEL ROADS

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The objective of this project was to provide a better understanding of how various virgin aggregate and recycled asphalt pavement (RAP) mixtures for surface layers affect the performance of gravel or crushed rock roads and, with further analysis, to determine the optimal RAP content for Minnesota gravel roads. This project included a literature review, preliminary laboratory testing, economic and feasibility analysis, and two field studies. Several studies regarding the use of RAP materials for road surfaces were reviewed. Then, laboratory tests on various RAP materials, one virgin aggregate, and mixtures of RAP materials and virgin aggregate were conducted to observe the effect of RAP on the index properties of the materials and the engineering properties of the mixtures. Initially, six test sections were constructed with various surface aggregates in two locations. Virgin RAP-aggregate blends having 15% to 60% RAP contents were placed as surface aggregate. Then, three more test sections were constructed using RAP-aggregate blends having 50%, 70%, and 80% RAP contents. Several field tests, including lightweight deflectometer, dynamic cone penetrometer, scrape, and dustometer tests, were performed to evaluate the test sections. This report provides insights regarding the effect of using RAP material on surface layers to reduce the use of virgin aggregates. It was concluded that the optimal RAP content for unpaved road surfaces changes according to the properties of the materials used, testing methods, and site conditions.
OPTIMAL RAP CONTENT FOR MINNESOTA GRAVEL ROADS

FINAL REPORT

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EXECUTIVE SUMMARY

The objective of this research project was to develop an understanding of how the use of various mixtures of gravel or crushed rock and recycled asphalt pavement (RAP) for road surfacing material affect the performance and economics of unpaved roads. This document is the final report presenting the findings of a research effort performed to determine an optimal RAP content for Minnesota gravel roads. To perform this study more effectively, the topic was divided into five main sections: (1) literature review, (2) preliminary laboratory testing, (3) economic and feasibility analyses, (4) preliminary field study, and (5) secondary field study.

In the literature review, a review of the use of RAP as surface, base, and subbase layer aggregates was performed. Several road applications of RAP that provided benefits in terms of dust reduction and/or improvements in engineering properties of roadways were identified. In previous studies, the use of RAP in road surfaces was found to be to be effective in that fugitive dust emissions were reduced. In addition, it was found that RAP was more economically advantageous as a surface course material than as a base material. The use of RAP was found to be beneficial in cold regions or in areas with high water tables because of the reduction in moisture susceptibility in the presence of RAP.

In addition, as part of the literature review an internet survey was prepared and sent to Minnesota counties to determine the scale of RAP applications in roadways and the relevant RAP contents used. In general, it was found that various RAP contents were used in surface layer applications and that there is a lack of information about the optimal RAP content for surface layer applications.

In the preliminary laboratory testing, several tests were performed on three RAP materials and a virgin aggregate that were collected from two different locations in Minnesota to better understand the properties of these materials and their relationships with each other. Two of the RAP materials were similar materials with different gradations (unprocessed coarser RAP and processed finer RAP), and another RAP material was unprocessed and relatively coarser. Virgin aggregate contained considerable amounts of fines. Gradation, moisture content, binder content, and bulk density tests were carried out on each material. Then, RAP materials were mixed with virgin aggregate separately at various RAP contents to carry out California Bearing Ratio (CBR) and unconfined compression (UC) testing. The asphalt contents of the RAP materials were in the range of 5.7% to 7.0%.

While different RAP contents (depending on the RAP material) in the blends of virgin aggregate and RAP materials were observed to give the highest unconfined compressive strength (UCS) values, using 30% of each RAP provided the second highest strength values consistently. Overall, it was concluded from the CBR tests that an increase in the RAP content of a mix was directly proportional to a decrease in the CBR value. For the two similar RAP materials with different gradations, using finer RAP in the mixes yielded higher CBR values and provided better binding capability with virgin aggregate particles.

In the economic and feasibility analyses, a maintenance cost estimate was selected as a relevant method. Cost estimate calculations were made for the maintenance of an existing crushed rock road surface of a one-mile road. Two cases, in which two different surface aggregates were used, were
evaluated and compared for economic and feasibility analysis. One surface aggregate type was selected as 100% virgin aggregate and another was selected as a blend of 50% virgin aggregate and 50% RAP. Yearly routine grading activities and re-rocking (every five years) were also considered in the cost analysis. Detailed information about other assumptions based on other relevant studies was provided.

After the analysis, a 1.5% increase in the overall cost was concluded when using 50% RAP compared to using 100% virgin aggregates. However, when the effect of using RAP on road performance (e.g., reduction in fugitive dust), which would eliminate the requirement for re-graveling or re-rocking by reducing the loss of surface materials, was also considered, some savings could be obtained.

In the primary field study, six different test sections (in addition to several control sections), four in Goodhue County and two in Carlton County, with different subgrade soil properties were constructed. Test sections were constructed with different contents of RAP materials in the surface layer to observe the effects of RAP on the performance of the built test sections. RAP contents were 15%, 30%, 45%, and 60% for the sections in Goodhue County, and 30% and 50% RAP for the sections in Carlton County. Surface layer thicknesses were 1 in. and 4 in. for the test sections built in Goodhue County and Carlton County, respectively.

While no specific trend was observed between the RAP content and the amount of free surface aggregates, overall, using RAP with aggregates yielded a decrease in the free surface aggregates compared to the control sections. According to lightweight deflectometer (LWD) test data, in Goodhue County, lower elastic moduli were observed at higher RAP contents. In Carlton County, an increase in elastic moduli was observed over time. According to dynamic cone penetrometer (DCP) test data, in both counties, test sections with lower RAP contents provided higher DCP-CBR values. In both counties, an increase in the RAP content yielded lower amounts of fugitive dust, according to the dustometer test.

In addition to the primary field study, a supplementary laboratory study was also performed under the same task. In addition to the CBR values obtained from the DCP tests (DCP-CBR), laboratory CBR tests were also performed. An increase in the RAP content yielded lower CBR values for the materials collected from Goodhue County. However, for the materials collected from Carlton County, the virgin aggregate showed lower CBR values compared to the 30% and 50% RAP mixtures. From the gradation test, it was found that the virgin aggregate collected from Carlton County was poorly graded sand, and it was concluded that adding RAP actually improved the stability of poorly graded virgin aggregate. Based on the experience from the Carlton County test sections, it was found that RAP can be used to improve the gradation of materials that lack relatively large-size particles if the RAP material includes a sufficient amount of them.

In the secondary field study, three different RAP-Class 5 aggregate blends containing 50%, 70%, and 80% RAP were used as surface materials to construct three more test sections on County Road (CR) 44 in Goodhue County. A control section was also constructed using only Class 5 aggregate surface material. Surface layers were designed to be 3 in. thick. Higher RAP contents than those used in the primary field study were used to extend the scope of the project. The following tests were performed to evaluate the optimal RAP content: DCP, LWD, dustometer, scrape, and International Roughness Index (IRI) tests. In
addition, visual observations and a supplementary laboratory study were also performed as a part of the field study.

According to the DCP test data, on the CR 44 test sections, relatively stiffer top soil layers with DCP-CBR values considerably higher than 100% were observed compared to the test sections built for the primary field study. Differences in the stiff top layer thicknesses were detected for the 70% and 80% RAP sections by comparing the calculated DCP-CBR values before and after construction.

According to the LWD test data, the 50% RAP section showed the highest elastic moduli among the RAP sections. The 70% RAP section provided the lowest elastic moduli. Lower elastic moduli were observed in the RAP sections over time. This behavior of the RAP sections indicated the degradation of RAP materials over time, which caused the performance degradation.

According to the dustometer data, the 50% RAP section generated the lowest amount of fugitive dust among all sections immediately after construction. The amount of the collected fugitive dust increased as the RAP content increased. One year after construction, the lowest amount of dust was collected from the 70% RAP section. The 80% RAP section produced the highest amount of dust among the RAP sections in tests performed at different dates.

According to the scrape test data, the 50% RAP section contained the highest amount of free surface aggregates three months after construction. However, the 70% and 80% RAP sections provided lower amounts of free surface aggregates than the control section. This indicated that using a higher RAP content in the surface layer provided better binding between the aggregate particles and RAP materials. However, an increase in the free surface materials was observed in the 70% and 80% RAP sections over time (similar free surface amounts were observed in the 50% RAP section), which indicated that a relatively higher content of RAP lost its binding properties and caused an increase in free surface materials over time. The control section showed the lowest amount of free surface aggregates one year after construction.

According to the IRI tests, the lowest IRI values were observed in the control section three months after construction. However, around one year after the construction, the 70% RAP and 80% RAP sections showed lower IRI values, which indicated that a higher RAP content improved the binding between the aggregates and RAP materials, which led to a smoother road surface.
CHAPTER 1: GENERAL INTRODUCTION

In the State of Minnesota, the total length of all roads is 132,250 miles, and approximately half of these roads (about 66,000 miles) are gravel or crushed rock roads. These roads play a vital role in connecting the remote farmlands with the mainstream economy. However, due to increased traffic and loads from heavy agricultural equipment, these roads are facing durability issues.

Under heavier loads, the bond fails between the fine and coarse aggregate particles on the road surface, and problems related to dust and excessive floating aggregate occur. To address these problems, alternative surface courses that could provide better performance are sought. In addition, the State of Minnesota faces issues regarding depleted virgin aggregate sources. Due to the resulting scarcity of virgin aggregate, hauling distances for good-quality virgin aggregates have increased, and this has increased the overall cost of constructing new roads and maintaining the existing ones. The cost of constructing and maintaining roads has also increased with increasing fuel costs.

There have been several studies about finding alternative materials to reduce the use of virgin aggregates in road-related construction and maintenance activities. One of the common findings of such studies is that recycled materials, when used appropriately, can provide good-quality, durable, and cost-effective construction materials to replace virgin aggregates. In addition, using recycled materials benefits the environment by saving natural sources, reducing fuel consumption, and extracting added value from existing materials with recycling (Saeed 2008).

Recycled asphalt pavement (RAP), a byproduct of milling of old/failed asphalt roads, is one of the recycled materials that has been commonly used in various road-related projects, such as hot mix asphalt (HMA) and base/subbase layer construction. Higher stiffness values are observed when RAP is incorporated into road materials, and the increase in stiffness can help to reduce the required thickness of certain road layers and to increase the service life of roads if no reduction in sublayer thicknesses is made. In light of the increasing demand for good-quality road surfaces in agricultural regions along with the scarcity of virgin aggregates, RAP has also been used on gravel road surfaces as a viable alternative material. Reductions in fugitive dust emissions with the use of RAP have been reported.

RAP that is not used on asphalt roads is kept in stockpiles until further use. If no other use is found, the stockpiles continue to increase in size. Additional problems, such as inventory management costs and chemicals leaching out of the stockpiles and into the surface water, also arise with this practice. Using RAP in the surface courses of gravel roads could possibly address the previously mentioned problems regarding both gravel roads and RAP stockpiling. In the State of Minnesota, local transportation agencies have been encouraged to consider using RAP for road construction in order to increase the use of this material.

RAP is collected from several sources: milling, full-depth pavement removal, and waste hot mix asphalt materials generated at the plant (Copeland 2011). There are different types of RAP materials that come from milling projects, depending on how the milling is performed. The milling that is performed only on the upper layer of an asphalt road produces what is known as classified RAP, which does not have
contaminations or impurities. The milling that is performed to a greater depth and that contains soil and other impurities is called unclassified RAP. Classified RAP can be used readily for hot mix asphalt without processing, while unclassified RAP requires additional processing before it can be used in hot mix asphalt, which increases the cost of the use of this RAP. It can be concluded that unclassified RAP and excess stockpiled RAP that will probably not be used for hot mix asphalt roads could possibly be used to improve gravel or crushed rock roads. In many cases, in the future it may be possible for RAP to be available within a feasible transportation distance at a reasonable cost.

There are many ways that RAP can be used for paved roads, such as in hot mix asphalt, hot in-place recycling, cold mix asphalt produced at a central processing facility (not a commonly used method in the State of Minnesota), and cold-in-place recycling. For unpaved roads, RAP can be incorporated in three ways:

1. **Blade mixed**

   The surface is scarified to a depth of 2 to 3 in. using a motor grader, and then RAP is placed in a windrow, preferably with bottom-discharge trucks. Then, RAP and scarified aggregates are blended and spread with a motor grader. Road shape and crown is established by the motor grader.

2. **Stockpile mixed**

   RAP and aggregates are blended together in a pug mill. Alternatively, loaders can build a stockpiled mixture by alternately taking buckets of material from separate stockpiles of virgin aggregate and RAP. Another method is to use a cold feed system from a hot mix asphalt plant. Bins are charged with virgin aggregate and RAP, and the system is operated so that material is fed from each bin onto the conveyor in proper proportions. The conveyor then stacks a stockpile or loads a truck. The existing roadway is shaped with a motor grader. The RAP and aggregate mixture is hauled to a section and placed in windrows with bottom-discharge trucks or spread through the tailgate of an end dump truck. Then, shaping and compaction is accomplished.

3. **Reclaimer mixed**

   The existing road surface is scarified. RAP is hauled to a section and placed in windrows with bottom-discharge trucks or spread through the tailgate of an end dump truck. Then, a motor grader is used to spread the RAP out and a rotary mixer reclaimer is used to blend the underlying, existing surface with the RAP. In the end, the motor grader is used to shape the road cross-section. Considerable compaction will be required, mostly using purpose-built compaction equipment such as pneumatic rollers.

The primary objective of this research was to assess the use of RAP as a material that can be incorporated into gravel road surfaces to increase the strength of the road structure and to reduce dust. Making a gravel road more durable and lowering the amount of fugitive dust would increase road safety, lower maintenance costs, and provide other benefits to road users, taxpayers, and other stakeholders. To achieve these objectives, mix designs with various RAP contents were developed and
tested in the laboratory, and then trial field sections were built accordingly. Several field tests were performed on the built test sections, and their results were analyzed to determine the optimal RAP content.
CHAPTER 2: LITERATURE REVIEW

2.1 FINDINGS

Recycled aggregate properties that have been determined to affect the performance of gravel road layers are shear strength, frost susceptibility, durability, stiffness, and toughness (Saeed 2008). Guidelines regarding the use of RAP are presented in a Federal Highway Administration (FHWA) report (Chesner et al. 1998). Some important considerations from this FHWA report and other selected references are summarized below:

- **Pavement cutting** – When a reclaimer is used to mix existing asphalt pavement with base materials, the depth of processing must be closely monitored because cutting too deep can incorporate subbase material into the blend while cutting too shallow increases the percentage of RAP in the blend.
- **Bearing capacity** – Bearing capacity decreases as the RAP content increases. RAP produced by milling or pulverizing has a lower bearing capacity than crushed RAP due to the comparatively fine gradation for milled or pulverized RAP.
- **Compacted density** – Compacted density decreases as the RAP content increases.
- **Moisture content** – Moisture content depends on how the RAP is processed. If the RAP is crushed (as opposed to being milled or pulverized), it has coarser particles and a lower moisture content because the asphalt on the aggregates inhibits water absorption. If milling is used to produce the RAP, the moisture content in the RAP increases as the proportion of fine aggregates increases.
- **Permeability** – Permeability decreases as the RAP content increases.
- **Durability** – Durability increases as the RAP content increases but increases more if additives are added.

The typical physical properties of RAP are shown in Table 2.1. Less than 40% of typical RAP materials are retained on a #8 sieve. This relatively low percentage may be due to the reduction in particle size that occurs during the milling process.
### Table 2.1 Typical physical properties of RAP

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Weight</td>
<td>1940 – 2300 kg/m³ (120 - 140 pcf)</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>Normal: Up to 5% Maximum: 7% – 8%</td>
</tr>
<tr>
<td>Asphalt Content</td>
<td>Normal: 4.5% – 6%</td>
</tr>
<tr>
<td>Asphalt Penetration</td>
<td>Normal: 10 – 80% at 25°C (77°F)</td>
</tr>
<tr>
<td>Absolute Viscosity or Recovered Asphalt Cement</td>
<td>Normal: 4000 – 25000 poises at 60°C (140°F)</td>
</tr>
</tbody>
</table>

### Mechanical Properties

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Compacted Unit Weight</td>
<td>1600 – 2000 kg/m³ (100 – 125 pcf)</td>
</tr>
<tr>
<td>California Bearing Ratio (CBR)</td>
<td>100% RAP: 20% – 25%</td>
</tr>
<tr>
<td></td>
<td>40% RAP: 150% or Higher</td>
</tr>
</tbody>
</table>

Source: Schaertl and Edil 2009

As part of a study conducted in Wyoming, the performance of RAP on gravel roads at three sites was examined. RAP from 3 sources and using 15 material and dust suppressant combinations were examined (Koch et al. 2011). Three different construction methods using various combinations of equipment were used, including using a motor grader alone to blend RAP and aggregate on the road; combining a motor grader with a reclaimer to blend aggregate on the road; and blending virgin aggregate and RAP at a stockpile, placing on the road using a motor grader, and compacting with a roller. The construction method used was found to directly affect road performance. Assessments were accomplished by using dustometer equipment developed at Colorado State University (CSU) and conducting unpaved road condition index (URCI) surveys in addition to material testing. The use of RAP in the observed unpaved road surfaces proved to be effective, in that fugitive dust emissions were reduced. A cost analysis suggested that using RAP on unpaved roads was not economical when it could be recycled in a hot mix plant. When RAP was used on unpaved roads, it was found to be more economically advantageous as a surface course than as a base material. An adequate amount of binding action from the RAP and a certain proportion of virgin aggregate were required for a road surface made with a RAP and aggregate mixture to perform well. When an effective binding material was not available, dust, loose aggregate,
and washboarding were observed. Depending on the binding properties of the fines, as little as 20% RAP was observed to provide sufficient binding. The study recommended that if an aggregate has a comparatively low binding capacity, as indicated by a relatively low plasticity index (PI) and percentage passing the #200 sieve, about 50% RAP should be used.

RAP has also been used as a base course material for asphalt roads. The quantity of RAP and its source affect the mechanical properties of a base material that contains RAP only or a mixture of RAP and other aggregate (Guthrie et al. 2007). The presence of asphalt binder in the RAP causes the material to behave in a hydrophobic manner. Thus, RAP reduces the moisture susceptibility of base materials and therefore may be especially valuable in areas with high water tables. Another situation where the use of RAP may be helpful is in areas with poor drainage that undergo repeated freeze-thaw cycles in addition to sustained freezing temperatures, conditions that can encourage the formation of frost boils. While using RAP alone or with virgin aggregates tends to increase stiffness in some cases, lower CBR measurements have been reported in other cases. Therefore, depending on the RAP material used and the results of a preliminary performance evaluation, thick layers may be required to provide a more sustainable road structure. Stabilization agents such as asphalt emulsion, Portland cement, or combinations of lime and fly ash may need to be used to increase durability.

A study based in Oman (Taha et al. 1999) claimed that the dry density and CBR values of RAP-aggregate blends increase as the proportion of virgin aggregate increases, and a RAP content of about 10% was found to be a good starting point for road bases. RAP was also reported to provide comparatively good support as a subbase. A 100% RAP mixture was reported to have a CBR value of 11% (Taha et al. 1999). Table 2.2 shows the physical properties of the RAP and virgin aggregates that were examined in that study.

Table 2.2 Physical properties of RAP and virgin aggregates

<table>
<thead>
<tr>
<th>Property</th>
<th>RAP</th>
<th>Virgin Aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture Content (%)</td>
<td>0.23</td>
<td>0.86</td>
</tr>
<tr>
<td>Specific Gravity (SSD)</td>
<td>2.12</td>
<td>-</td>
</tr>
<tr>
<td>Water Absorption (%)</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Sand Equivalent (%)</td>
<td>97</td>
<td>67</td>
</tr>
<tr>
<td>Los Angeles (LA) Abrasion (%)</td>
<td>33.6</td>
<td>18.8</td>
</tr>
</tbody>
</table>

Source: Taha et al. 1999
2.2 INTERNET SURVEY

A short internet survey was sent to all Minnesota counties to determine which counties had experience with mixtures of gravel or crushed rock and RAP for gravel road surfaces. Eighteen responses were returned, and they are provided in Appendix A. Eleven respondents indicated that their county had used RAP mixtures in various applications. Table 2.3 summarizes the information obtained from these respondents.

Table 2.3 Minnesota counties with existing unpaved RAP sections

<table>
<thead>
<tr>
<th>Name of County</th>
<th>Place of Application</th>
<th>RAP Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Le Sueur County</td>
<td>On surface course</td>
<td>50 – 100</td>
</tr>
<tr>
<td>Traverse County</td>
<td>Repair of soft spots</td>
<td>100</td>
</tr>
<tr>
<td>Benton County</td>
<td>Shoulders</td>
<td>10</td>
</tr>
<tr>
<td>Mahnomen County</td>
<td>On surface course</td>
<td>100</td>
</tr>
<tr>
<td>Aitkin County</td>
<td>On surface course</td>
<td>100 (with emulsion on the surface)</td>
</tr>
<tr>
<td>Chippewa County</td>
<td>On surface course</td>
<td>10</td>
</tr>
<tr>
<td>Nobles County</td>
<td>On surface Course</td>
<td></td>
</tr>
<tr>
<td>Goodhue County</td>
<td>Shoulders</td>
<td>67</td>
</tr>
<tr>
<td>Clearwater County</td>
<td>Base course covered with Class 1 aggregate</td>
<td>50</td>
</tr>
<tr>
<td>Hennepin County</td>
<td>On surface course</td>
<td>100 (millings from a mill and overlay)</td>
</tr>
<tr>
<td>St. Louis County</td>
<td>On surface course</td>
<td>50</td>
</tr>
</tbody>
</table>

Of the respondents that stated that their county had not used RAP mixtures, one indicated an interest in using RAP mixtures in the future and one described a related use of RAP for road construction.
In Wyoming, it was found that using RAP on unpaved roads is not economically feasible when an alternative exists to use it in hot mix plants (Koch et al. 2011). However, there is typically a limit for the proportion of RAP that can be used in hot mix asphalt, and that is about 30% in some cases in the State of Minnesota. Therefore, using RAP for unpaved roads may be economically feasible. If the cost of RAP is less than the cost of virgin aggregate (including hauling expenses), if the life cycle cost analysis for using RAP on unpaved roads is favorable due to the greater durability of such roads, and if using RAP improves road performance sufficiently to avoid paving, then using RAP may be an attractive option for improving unpaved road performance.
CHAPTER 3: PRELIMINARY LABORATORY TESTING

3.1 INTRODUCTION

The interaction of asphalt binder and aggregates in an aggregate mass is difficult to understand because the properties of both constituents change with the material history, location, weather conditions, and traffic volume. In order to understand the relationship between RAP and virgin aggregates and to find the optimal RAP content for Minnesota gravel roads, the properties of these materials and their relationships with each other were investigated. RAP and gravel road samples were selected, and laboratory tests were carried out on the materials. In addition, laboratory and field studies were performed on Goodhue County shingle test sections in order to draw a comparison between RAP and shingles considering asphalt binder as a common thread between them. The analyses regarding the use of shingles are provided in Appendix B.

3.2 MATERIALS

3.2.1 Minneapolis (MPLS) RAP

Two RAP materials were obtained from the Tiller Corporation asphalt plant located in Maple Grove, MN, and are designated MPLS RAP#1 and MPLS RAP#2 (Figure 3.1).

![Figure 3.1 MPLS RAP#1 (left) and MPLS RAP#2 (right)]

MPLS RAP#1 included large particles of aggregates. In addition, this material was classified as unprocessed RAP with no crushing and screening. MPLS RAP#2 was processed and milled RAP that appeared to be relatively finer than MPLS RAP#1. MPLS RAP#1 and MPLS RAP#2 actually contained similar materials with different gradations.

3.2.2 Jackson RAP and Jackson Aggregates

These materials were obtained from Jackson County, MN, and are shown in Figure 3.2.
Figure 3.2 Jackson RAP (left) and Jackson virgin aggregate (right)

Jackson RAP included some relatively large particles because the material was not crushed and screened, and thus it was somewhat similar to MLPS RAP#1. Jackson aggregate included a considerable amount of fine materials and was relatively dry.

3.3 RESEARCH APPROACH

The laboratory testing plan was divided into two stages, as shown in Table 3.1 and Table 3.2. In stage one, the individual laboratory tests listed in Table 3.1 were carried out on each material to be used for the mix. In stage two, samples of various mix designs were prepared in order to carry out the tests listed in Table 3.2.

Table 3.1 Stage one: Individual properties of materials

<table>
<thead>
<tr>
<th>Test</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPLS RAP#1</td>
</tr>
<tr>
<td>Gradation</td>
<td>x</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>x</td>
</tr>
<tr>
<td>Binder Content</td>
<td>x</td>
</tr>
<tr>
<td>Bulk Density</td>
<td>x</td>
</tr>
</tbody>
</table>
### Table 3.2 Stage two: Engineering properties of mix designs

<table>
<thead>
<tr>
<th>Test</th>
<th>Mix Design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPLS RAP#1 + Jackson Aggregate</td>
</tr>
<tr>
<td></td>
<td>MPLS RAP#2 + Jackson Aggregate</td>
</tr>
<tr>
<td></td>
<td>Jackson RAP + Jackson Aggregate</td>
</tr>
<tr>
<td>CBR</td>
<td>x</td>
</tr>
<tr>
<td>Unconfined Compression Test</td>
<td>x</td>
</tr>
</tbody>
</table>

#### 3.4 TESTS AND THEIR RESULTS

**3.4.1 Gradation**

Standard procedures for particle size analysis as per ASTM C117 and ASTM C136 were carried out because the fineness of the aggregates was important. A comparison between the material gradations of the samples can be seen in Figure 3.3.

![Gradation of the materials used in this study](image)

Jackson RAP was found to contain the highest amount of gravel particles (about 69%). MPLS RAP#1 also contained a relatively high amount of gravel particles (about 47%). MPLS RAP#2 and Jackson aggregate
had a much higher proportion of sand (MPLS RAP#2 and Jackson aggregate contained about 70% and 73% sand, respectively) compared to the other materials.

3.4.2 Moisture Content

The moisture content of each material was calculated as per ASTM D2216; these were relatively low because asphalt absorbs little water and imparts hydrophobic properties to the RAP. Also, Jackson aggregate was relatively dry when it was obtained and therefore had a very low moisture content. The observed moisture contents are provided in Table 3.3.

Table 3.3 Moisture contents of materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Moisture Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPLS RAP#1</td>
<td>0.16</td>
</tr>
<tr>
<td>MPLS RAP#2</td>
<td>0.22</td>
</tr>
<tr>
<td>Jackson RAP</td>
<td>0.21</td>
</tr>
<tr>
<td>Jackson Aggregate</td>
<td>0.26</td>
</tr>
</tbody>
</table>

3.4.3 Binder Content

In order to estimate the asphalt binder contents of the various RAP materials, ignition tests were conducted with reference to ASTM D6307. In the first step of the ignition process, RAP samples were kept in an ignition oven and heated to allow evaporation of all asphalt binder. The next step was to conduct binder weight calculations. Figure 3.4 shows the ignition oven and a RAP sample placed in the oven.
Figure 3.4 Ignition test

Error! Not a valid bookmark self-reference. provides the ignition test results. It was concluded that Jackson RAP contained the highest RAP content (6.8% on average).

Table 3.4 Ignition test results

<table>
<thead>
<tr>
<th></th>
<th>MPLS RAP#1</th>
<th>MPLS RAP#2</th>
<th>Jackson RAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Number</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Weight of Sample (g)</td>
<td>2382.2</td>
<td>2127.5</td>
<td>2453.7</td>
</tr>
<tr>
<td>Weight of Sample After Ignition (g)</td>
<td>2246.6</td>
<td>1989.9</td>
<td>2296.5</td>
</tr>
<tr>
<td>Asphalt Content (%)</td>
<td>5.7%</td>
<td>6.5%</td>
<td>6.4%</td>
</tr>
<tr>
<td>Average Asphalt Content (%)</td>
<td>6.2%</td>
<td>6.0%</td>
<td>6.8%</td>
</tr>
</tbody>
</table>

3.4.4 Bulk Density

Using ASTM C29, the bulk density (loose unit weight) of the materials was calculated. As expected, the materials that were more densely graded tended to have the highest bulk densities. Test results are shown in Table 3.5.
Table 3.5 Loose unit weight of materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Bulk Density (pcf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPLS RAP#1</td>
<td>108.11</td>
</tr>
<tr>
<td>MPLS RAP#2</td>
<td>132.13</td>
</tr>
<tr>
<td>Jackson RAP</td>
<td>117.09</td>
</tr>
<tr>
<td>Jackson Aggregate</td>
<td>145.5</td>
</tr>
</tbody>
</table>

3.4.5 Unconfined Compression (UC) Test

In order to determine the strength of each of the RAP-aggregate mixtures with various RAP contents, specimens were prepared using the Marshall hammer method (ASTM D6926) and then tested according to ASTM D2166. Test specimens were prepared at their optimum moisture contents, and only 35 blows were given on each side of the compaction mold because this number of blows was found to be appropriate for specimens that represent low traffic roads. After compaction, specimens having a 4 in. diameter and a 2.5 to 3 in. height (with all of the dimensions measured carefully using a Vernier caliper) were extracted with a hydraulic jack. After extraction, they were covered with aluminum foil to retain their moisture and mellowed for 1 day prior to testing. It was observed that the specimens were not able to hold their shapes easily due to the properties of the materials (low fines contents and non-plastic properties). The test specimens, Marshall hammer, and test equipment are shown in Figure 3.5.
Figure 3.5 Specimen preparation and UC test equipment

The test results of the MPLS RAP#1 + Jackson aggregate, MPLS RAP#2 + Jackson aggregate, and Jackson RAP + Jackson aggregate mixes are shown in Figure 3.6, Figure 3.7, and Figure 3.8, respectively. The highest strength value was observed in the specimen in which 50% Jackson RAP was used. The weakest material was the specimen in which 20% Jackson RAP was used.

Figure 3.6 Stress-strain curve of MPLS RAP#1 + Jackson aggregate mix
Using 20% MPLS RAP#1 yielded the highest strength among its mix design group (Figure 3.6). In addition, using 50% MPLS RAP#2 and Jackson RAP provided the highest strength values among their mix design groups (Figure 3.7 and Figure 3.8, respectively). While various RAP contents (20% and 50% depending on the RAP material used) were observed to give the highest strength values, using 30% RAP achieved the second highest strength consistently.
Defining “optimal RAP content” and understanding what exactly is optimal is an important aspect of this investigation. Road sections with very high stiffness may not be desirable. Gravel and crushed rock roads need to allow some material movement so they can be shaped using a motor grader. Gravel roads that are too stiff are prone to develop potholes and other distresses under traffic loads, which are difficult to repair with a motor grader because the blade tends to tear stiff material into chunks that are difficult to manipulate using standard motor grader maintenance procedures.

3.4.6 California Bearing Ratio (CBR)

Unsoaked CBR tests were carried out with the CBR apparatus shown in Figure 3.9.

![Figure 3.9 CBR test equipment](image)

The CBR test results for the MPLS RAP#1 + Jackson aggregate, MPLS RAP#2 + Jackson aggregate, and Jackson RAP + Jackson aggregate mixes are provided in Figure 3.10, Figure 3.11, and Figure 3.12, respectively. In addition, summaries of the CBR test results for these mixes are provided in Table 3.6, Table 3.7, and Table 3.8 in the same order. In these tables, the CBR percentages were calculated considering 0.1 in. and 0.2 in. penetrations, and the maximum value was considered to be the final CBR.
Figure 3.10 CBR test results for MPLS RAP#1 + Jackson aggregate mix

Table 3.6 Summary of CBR test results for MPLS RAP#1 + Jackson aggregate mix

<table>
<thead>
<tr>
<th></th>
<th>0% RAP</th>
<th>10% RAP</th>
<th>20% RAP</th>
<th>30% RAP</th>
<th>40% RAP</th>
<th>50% RAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBR at 0.1&quot;</td>
<td>37%</td>
<td>20.0%</td>
<td>11.5%</td>
<td>13.2%</td>
<td>7.8%</td>
<td>9.9%</td>
</tr>
<tr>
<td>CBR at 0.2&quot;</td>
<td>55%</td>
<td>27.1%</td>
<td>18.3%</td>
<td>17.2%</td>
<td>10.6%</td>
<td>12.0%</td>
</tr>
<tr>
<td>Final CBR</td>
<td>55%</td>
<td>27.1%</td>
<td>18.3%</td>
<td>17.2%</td>
<td>10.6%</td>
<td>12.0%</td>
</tr>
</tbody>
</table>
Figure 3.11 CBR test results for MPLS RAP#2 + Jackson aggregate mix

Table 3.7 Summary of CBR test results for MPLS RAP#2 + Jackson aggregate mix

<table>
<thead>
<tr>
<th></th>
<th>0% RAP</th>
<th>10% RAP</th>
<th>20% RAP</th>
<th>30% RAP</th>
<th>40% RAP</th>
<th>50% RAP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CBR at 0.1”</strong></td>
<td>37%</td>
<td>21.6%</td>
<td>19.5%</td>
<td>19.5%</td>
<td>8.1%</td>
<td>10.1%</td>
</tr>
<tr>
<td><strong>CBR at 0.2”</strong></td>
<td>55%</td>
<td>35.6%</td>
<td>29.4%</td>
<td>22.4%</td>
<td>10.8%</td>
<td>12.2%</td>
</tr>
<tr>
<td><strong>Final CBR</strong></td>
<td>55%</td>
<td>35.6%</td>
<td>29.4%</td>
<td>22.4%</td>
<td>10.8%</td>
<td>12.2%</td>
</tr>
</tbody>
</table>
In all cases, Jackson aggregate without any RAP addition (shown as 0% in the figures) was able to take more load, which resulted in a higher CBR compared to the corresponding mixes with various RAP contents. Based on these tests, it was concluded that increases in RAP content in the mix (valid until 40% RAP for MPLS RAP#1 and MPLS RAP#2) were directly proportional to decreases in the final CBR value. Relatively higher CBR values were observed with the use of 50% MPLS RAP#1 and MPLS RAP#2 compared to using 40% of these materials (in separate mixtures). Various mixes with various amounts of RAP showed that MPLS RAP#2 yielded better results than MPLS RAP#1.

To better understand and compare all of the mixes prepared and tested, a general comparison was made, shown in Figure 3.13.
It was observed that the highest CBR value among all of the mixes prepared at various RAP percentages was observed in the mix in which 10% MPLS RAP#2 was used (CBR = 35.6%). As stated previously, MPLS RAP#1 and MPLS RAP#2 were the same material with different gradations (MPLS RAP#2 was finer than MPLS RAP#1). Therefore, it was concluded that using finer RAP in the mixes yielded higher CBR values and provided better binding capability with the soil aggregates.

### 3.5 SUMMARY

Both the index and engineering properties of three different RAP materials and their mixes with soil aggregate were investigated. MPLS RAP#1 and MPLS RAP#2 were the same materials but had different gradations, and Jackson RAP was collected from another source. While MPLS RAP#1 was an unprocessed RAP containing coarser particles, MPLS RAP#2 was a processed material with finer particles. Jackson RAP was the coarsest among the collected RAP materials.

According to the UC test results, using 20% MPLS RAP#1, 50% MPLS RAP#2, and 50% Jackson RAP in mixes separately provided the highest strength values. In addition, using 30% of each material yielded the second highest strength values in all mixes. Therefore, it was concluded that 30% would be the optimum RAP content unless maximum UC strength is desirable.

As stated previously, the cylindrical specimens prepared for the UC testing did not hold their shapes easily due to their material properties (lacking binding materials and cohesion). CBR testing was found to be the most suitable test because the specimens were confined in molds during testing. Unpaved
roads are typically surfaced with aggregate mixtures that tend to be cohesive; however, a non-cohesive mix is formed by the introduction of RAP material. In addition, RAP tends to retain less moisture (due to its hydrophobic tendencies) compared to soil aggregates, which inhibits moisture-related binding.

The CBR test results for the RAP-aggregate mixes followed the trend noted in the literature review. As per the literature review, the CBR values of RAP-aggregate mixes tend to decrease as the RAP content increases. However, for both MPLS RAP mixes, the CBR values decreased as the RAP content increased to 40% and then exhibited a modest increase when 50% RAP was used. MPLS RAP#2 provided higher CBR values than MPLS RAP#1 because MPLS RAP#2 had finer particles providing better bonding. Considering all of the test result summarized above, it was concluded that the optimal RAP content for gravel roads would change according to the properties of the RAP and the testing method.
CHAPTER 4: ECONOMIC AND FEASIBILITY ANALYSIS

4.1 INTRODUCTION

Many studies have been undertaken to estimate the cost of maintaining a gravel road. One such study suggested that if the annual average daily traffic (AADT) is above approximately 200, then it is likely not to be economically feasible to maintain a gravel or crushed rock road and other alternatives should be considered (Jahren et al. 2005). In order to evaluate the economic feasibility of using RAP on unpaved roads, it is necessary to select a relevant evaluation method. In this study, a maintenance cost estimate was selected for this purpose.

4.2 MAINTENANCE AND COST ESTIMATES

To simplify the following discussion, calculations are provided for a one-mile section of road, and it was assumed that one alternative was to continue the maintenance of the existing crushed rock road surface. A cross-section of a typical road is provided in Figure 4.1.

\[ \text{Figure 4.1 Typical roadway cross-section} \]

The maintenance cost estimates summarized below were taken from Jahren et al. (2005). Routine grading activities (each year) and re-rocking (every five years) were included in the cost estimates. The following subsections include a list of the assumptions made, calculations of the motor grader work hours, maintaining/grading costs, and re-graveling and surfacing costs. Many aspects of these calculations were based on the methods presented in the Caterpillar Performance Handbook (Caterpillar 1999).

4.2.1 Assumptions

The following assumptions are based on Jahren et al. (2005):

- A one-mile-long roadway with a 24 ft top was assumed: \((24 \text{ ft}) \times (5,280 \text{ ft}) = 126,720 \text{ ft}^2\) of surface.
- A nominal 2 in. of new gravel is assumed for re-graveling requiring 1,000 yd\(^3\)/mile or 1,000 tons/mile.
• The ratio of the thickness of loose gravel to compacted gravel is 1.28:1; therefore, a 2 in. compacted gravel lift requires placement of 2.56 in. of loose gravel (Skorseth and Selim 2000a).
• Based on conversations during interviews with county personnel, gravel costs were determined to be approximately $7.00/yd$^3$.
• The road is graded 3 times per month from April to October, for a total of 21 times.
• The cost for the motor grader is $40/hour, including fuel, oil, etc.:
  o The motor grader travels at about 4 mph during grading operations.
  o A 12 ft moldboard with a carrying angle of 60 degrees is assumed.
  o Three passes of the motor grader are needed per mile.
• The cost for a motor grader operator is $30/hour, including fringe benefits:
  o The motor grader operates at an efficiency of a 45 minutes/hour (0.75). This assumes a time spent deadheading to and from the maintenance areas and the standard construction equipment operating efficiency of a 50 minutes/hour.
• The cost for a truck is $40/hour, including fuel, oil, etc.:
  o A 12 yd$^3$ capacity is assumed.
• The cost for a truck driver is $25/hour, including fringe benefits:
  o Round trip for one load of material takes about 1.25 hours.

4.2.2 Calculation of Motor Grader Work Hours

\[ A = S \times (L_e - L_o) \times 5280 \times E \]

where,

\[ A = \text{Hourly operating area (ft}^2/\text{hour}) \]
\[ S = \text{Operating speed (mph)} = 4 \text{ mph} \]
\[ L_e = \text{Effective blade length (ft)} = 10.4 \text{ ft (Caterpillar 1999)} \]
\[ L_o = \text{Width of overlap (ft)} = 2.4 \text{ ft for three passes} \]
\[ E = \text{Job efficiency} = 0.75 \]

\[ A = (4 \text{ mph}) \times [(10.4 \text{ ft}) - (2.4 \text{ ft})] \times (5,280 \text{ ft/mile}) \times 0.75 = 126,720 \text{ ft}^2/\text{hour} \]

Time (t) to blade a one-mile road with a 24 ft wide top:

\[ t = \frac{\text{Surfacing area}}{\text{Hourly operating area}} = \frac{126,720 \text{ ft}^2}{126,720 \text{ ft}^2/\text{hr}} = 1 \text{ hr} \]
A one-mile stretch of road is bladed 21 times throughout the year. Annual time (T) spent on one mile of roadway:

\[ T = 1 \text{ hour/mile} \times 21 \text{ miles} = 21 \text{ hours} \]

### 4.2.3 Maintaining/Grading Costs

- **Equipment:** \((\$40/\text{hour}) \times 21 \text{ hours} = \$840/\text{year} \approx \$800/\text{year}\)
- **Labor:** \((\$30/\text{hour}) \times 21 \text{ hours} = \$630/\text{year} \approx \$600/\text{year}\)

**Total:** \(\$800/\text{year} + \$600/\text{year} = \$1,400/\text{year}\)

### 4.2.4 Re-graveling/Surfacing Costs

- **Material:** \((\$7/\text{yd}^3) \times (1,000 \text{ yd}^3/\text{mile}) = \$7,000\)
- **Equipment:** Number of loads \(= (1 \text{ load}/12 \text{ yd}^3) \times (1,000 \text{ yd}^3/\text{mile}) = 83.33 \approx 84 \text{ loads}\)
  - \(84 \text{ loads} \times 1.25 \text{ hours} = 105 \text{ hours}\)
  - \(105 \text{ hours} \times \$40/\text{hour} = \$4,200\)
- **Labor:** \((\$25/\text{hour}) \times 105 \text{ hours} = \$2,625 = \$2,600\)

**Total re-graveling/surfacing costs = \$7,000 + \$4,200 + \$2,600 = \$13,800**

Table 4.1 shows the primary costs for maintaining a gravel or crushed rock road, including grading and resurfacing, for a five-year re-graveling cycle.
Table 4.1 Maintaining/grading and re-graveling/surfacing costs for five-year cycle

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grading</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment</td>
<td>$800</td>
<td>$800</td>
<td>$800</td>
<td>$800</td>
<td>$800</td>
<td>$800</td>
<td>$4,800</td>
</tr>
<tr>
<td>Labor</td>
<td>$600</td>
<td>$600</td>
<td>$600</td>
<td>$600</td>
<td>$600</td>
<td>$600</td>
<td>$3,600</td>
</tr>
<tr>
<td>Resurfacing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td>$7,000</td>
<td></td>
<td></td>
<td>$7,000</td>
<td>$7,000</td>
<td>$14,000</td>
<td></td>
</tr>
<tr>
<td>Equipment</td>
<td>$4,200</td>
<td></td>
<td></td>
<td></td>
<td>$4,200</td>
<td>$8,400</td>
<td></td>
</tr>
<tr>
<td>Labor</td>
<td>$2,600</td>
<td></td>
<td></td>
<td></td>
<td>$2,600</td>
<td>$5,200</td>
<td></td>
</tr>
<tr>
<td>Annual Totals</td>
<td>$15,200</td>
<td>$1,400</td>
<td>$1,400</td>
<td>$1,400</td>
<td>$1,400</td>
<td>$15,200</td>
<td>$36,000</td>
</tr>
<tr>
<td>Cumulative Costs</td>
<td></td>
<td>$1,400</td>
<td>$2,800</td>
<td>$4,200</td>
<td>$5,600</td>
<td>$20,800</td>
<td></td>
</tr>
</tbody>
</table>

Source: Jahren et al. 2005

Notice that the majority of the costs associated with maintaining a such a road occur when new surfacing material is hauled and spread. Depending on the quality of the material being used and the amount lost each year, this resurfacing operation may occur at various intervals for each county (Jahren et al. 2005).

The cost of a typical five-year maintenance cycle can be found by summing the costs for years 2, 3, 4, 5, and 6, which yields $20,800 (Table 4.1). The average annual cost can be calculated by dividing by five years. The result is $4,160 per year (Jahren et al. 2005).

If the use of RAP is taken as a second option (Figure 4.2), the material cost for the virgin aggregate is deleted and the cost for the RAP mixture is inserted. The cost for the RAP materials may be better estimated after the percentage of RAP in the materials is selected.
Using RAP is considered economically feasible when the total cost of the RAP is less than that of the gravel or crushed rock road. If 1,000 yd$^3$ of surfacing material is needed and the RAP content is desired to be 50%, then 500 yd$^3$ of RAP and 500 yd$^3$ of regular aggregate would be needed. If the cost of the RAP materials is $7.65/yd^3$ (average market price in 2015),

\[
\text{Material cost for 50% RAP mix} = (7$/yd^3$) \times (500 \text{ yd}^3) + (7.65$/yd^3$) \times (500 \text{ yd}^3) = 7,325
\]

Under these assumptions, the cost of a typical five-year maintenance cycle will be $21,125 and the average annual cost will be $4,225. This would be a 1.5% increase in costs. The foregoing analysis was made under the assumption that maintenance requirements would not be reduced and that the re-graveling or re-rocking cycle remains at five years. If the use of the RAP mixture reduces the maintenance and re-graveling or re-rocking requirements, it is possible that some savings could result. In this example, if the cost of maintenance activities and the volume of gravel or crushed rock that would have to be purchased and replaced could be reduced by 1.5%, net savings would result.

Fugitive dust emissions, in addition to being unpleasant to road neighbors, is an important way that material is lost from a gravel or crushed rock road. First, the fugitive dust is part of the material that has been purchased, and it is being lost to the road surface and would have to be replaced to maintain the binding properties of the surface material. Second, when the fine binding material is removed, the coarse fraction of the road surface becomes more unstable and is subject to being lost during summer and winter maintenance activities as well as during traffic operations and environmental or weather events. If a surfacing material that includes RAP in the mixture is successful in mitigating fugitive dust emissions, it might also reduce the requirements for hauling new materials during regular re-graveling or re-rocking operations.

Even if monetary savings cannot be demonstrated, road officials may choose to recommend a higher cost surfacing material, such a RAP and gravel or crushed rock mixture, because of the advantage that road users and neighbors obtain from having a better road surface that mitigates fugitive dust emissions.

### 4.3 SUMMARY

Because the information needed to do a detailed cost-benefit analysis was unavailable, the costs of maintaining two basic road sections with and without RAP were considered to demonstrate how an analysis could be conducted to provide a cost comparison. In the example demonstrated in this chapter,
the costs were slightly higher when a mixture of RAP and gravel or crushed rock was used. Small savings in maintenance and re-graveling or re-rocking costs could make the use of the RAP mixture more economical than the use of the original surfacing material. The results of the analysis in a particular situation will change depending on the particular costs associated with that situation. In any case, road officials should consider advantages and disadvantages that are difficult to quantify in deciding when to use different surfacing alternatives. In some cases, higher costs for an alternative surface mixture might be justified if fugitive dust emissions are reduced and a better road surface is provided for road users and neighbors.
CHAPTER 5: PRIMARY FIELD STUDY

5.1 INTRODUCTION

Blending RAP with existing road surface materials reduces the amount of virgin aggregate required and thus reduces costs and increases the sustainability of the road. If road performance improves, the amount of required maintenance will likely decrease, allowing maintenance efforts to be diverted to areas of higher need. Better road performance also leads to lower vehicle maintenance costs, which benefits road users. Better road performance also increases safety by increasing visibility (by producing less dust) and providing better traction and vehicle handling (by ensuring a firmer road surface with fewer potholes and less floating aggregate and corrugation). If road users are satisfied with better performing gravel surfaces, there may be less public pressure to make costly investments in paving.

There are various subgrade soils in the State of Minnesota showing various index and engineering properties. It is difficult to obtain a single optimal RAP content value for the entire state because the quality of the subgrade affects the performance of a composite road considerably. To address this issue, six different test sections, four in Goodhue County and two in Carlton County, with different subgrade soil properties (Figure 5.1) were constructed to perform a field study.

![Subgrade soils in Goodhue and Carlton Counties](image)

Figure 5.1 Subgrade soils in Goodhue and Carlton Counties

While roads in Goodhue County predominantly contain silty glacial sediment subgrade, roads in Carlton County contain sand and gravel subgrade (Minnesota Geological Survey 2006). According to the traffic data for these counties, the AADT is 45 and 145 for the Carlton and Goodhue test sections, respectively (MnDOT 2015). Field test sections were constructed with varying contents of locally available RAP
materials in the surface layer in order to observe the effects of RAP on the performance of these test sections.

### 5.2 TEST SECTIONS

#### 5.2.1 Goodhue County

The test sections in Goodhue County were constructed on County Road 55. Test sections 0.33 to 0.37 miles long consisting of various mixtures of crushed rock and RAP materials were separated by control sections (Figure 5.2).

![Figure 5.2 Goodhue County test section plan](image)

Test section mixtures were 15%, 30%, 45%, and 60% RAP, with the remainder of the mixtures (the control mixtures) being crushed limestone. About 250 tons of materials were placed on each test section, resulting in a thickness of approximately one inch, assuming that the compact density was 120 lb/ft³ and the average width was 25.5 ft. A longer control section (0.4 miles long) on 500th street was also built.

Construction was accomplished under a regular contract for furnishing and placing crushed rock held by Kielmeyer Construction Inc. The material was placed and spread on the sections using bottom dump trucks and a motor grader (Figure 5.3).
Figure 5.3 Test section construction in Goodhue County

RAP material was provided by Mathy Construction Co. The RAP was delivered to Kielmeyer Construction Inc.’s quarry by Mathy Construction Co. from a location in Olmsted County and crushed and blended with crushed rock at the quarry prior to placing. In front of some farm residences, a calcium chloride treatment was later placed (Figure 5.4).

Figure 5.4 Placement of calcium chloride treatment in Goodhue County

5.2.2 Carlton County

The test sections in Carlton County were situated on East County Road 103. As shown in Figure 5.5, there were 30% and 50% RAP test sections having lengths of 0.7 and 0.3 miles, respectively. A control section was also provided for comparison with the test sections built with the blend of RAP and Class 1 aggregate materials consisting of around 9% (by weight) of materials passing the #200 sieve.
The 30% RAP-aggregate and 50% RAP-aggregate mixes were taken from the county's Barnum and Carlton stockpiles, respectively (Figure 5.6).

The construction process adopted was similar to that used in Goodhue County: the material was placed by bottom dump trucks, and then a motor grader was used to spread the material. However, the material was not compacted. Before laying the surface material, a 2 in. thick red clay layer was placed on the subgrade, as recounted by the maintenance supervisor of the county. Then, a 4 in. layer of RAP-aggregate blend was placed on top of both sections.
5.3 FIELD TESTING

Several field trips were planned to collect field test data, record the construction processes and methods that were followed, and document other aspects of the test sections. As shown in Figure 5.7, the field trips were divided into two phases and included visits both before and after construction.

<table>
<thead>
<tr>
<th>Preconstruction road tests (Field &amp; Lab tests)</th>
<th>New material to be used (Lab tests)</th>
<th>Documenting Construction (Process/methods)</th>
<th>Post Construction road tests (Field &amp; Lab tests)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5.7 Field trip plan**

5.3.1 Road Cross-Section Survey

To record the geometric properties of the sections, a cross-sectional survey was performed using optical surveying equipment. The cross slope and crown of each test section were calculated based on these readings.

Because cross slope and crown play an important role in shedding water off the road during a rainfall event, these features can be considered as indicators for road performance. The recommended crown is approximately 1/2 in. per ft (or 4%) (Skorseth and Selim 2000b).

Survey results for the Goodhue County test sections are provided in Figure 5.8.
As shown in Figure 5.8, all test sections had a reasonably good cross slope, except for the 30% RAP test section, which had a cross slope of 1.86%. It should be noted that the width of the 15% RAP test section was comparatively wider (32 ft) than the average width of the other sections (25.5 ft). A similar cross-sectional survey was carried out on the Carlton County test sections, as shown in Figure 5.9.
Figure 5.9 Cross-sectional survey results for Carlton County test sections

It was observed that the control section had a relatively flat cross slope (1.88%) compared to the other sections. In addition, the cross slope of the 30% RAP section was also low (2.3%).

5.3.2 Scrape Test

A modified garden hoe, as shown in Figure 5.10, was used to scrape and collect free surface material throughout the selected cross-sections of the roads.

Figure 5.10 Modified garden hoe for scrape test
The modified tool consisted of two side plates welded to a regular garden hoe. Three scrapes at random locations were performed on each test section to estimate the total amount of floating material on the road surface, and then the average weights (per unit width) of the floating material collected from each section were compared. This method provides an indication of the amount of floating material found in each test section.

Based on the test results shown in Table 5.1, it was concluded that the test sections using RAP with aggregates yielded lower amounts of floating material than the control sections.

**Table 5.1 Float calculation for scrape test**

<table>
<thead>
<tr>
<th>Location</th>
<th>Section</th>
<th>Floating Material (lb) (Average of 3 scrapes)</th>
<th>Road Width (ft)</th>
<th>Floating Material (lb/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goodhue County</td>
<td>Control 1</td>
<td>8.901</td>
<td>24</td>
<td>0.371</td>
</tr>
<tr>
<td></td>
<td>Control 500th</td>
<td>11.510</td>
<td>22</td>
<td>0.523</td>
</tr>
<tr>
<td></td>
<td>15%</td>
<td>9.459</td>
<td>22</td>
<td>0.295</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>7.296</td>
<td>22</td>
<td>0.332</td>
</tr>
<tr>
<td></td>
<td>45%</td>
<td>7.798</td>
<td>22</td>
<td>0.354</td>
</tr>
<tr>
<td></td>
<td>60%</td>
<td>6.989</td>
<td>26</td>
<td>0.268</td>
</tr>
<tr>
<td>Carlton County</td>
<td>Control</td>
<td>12.123</td>
<td>24</td>
<td>0.505</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>14.762</td>
<td>26</td>
<td>0.567</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>6.873</td>
<td>26</td>
<td>0.264</td>
</tr>
</tbody>
</table>

In the Carlton County test sections, using 30% RAP with aggregates yielded a higher amount of floating material, while using 50% RAP with aggregates yielded relatively lower amounts of floating material. No specific trend was observed between the RAP content and the amount of collected floating material per foot in both test sections.
5.3.3 Modified Pavement Surface Evaluation and Rating (PASER) Chart

The Pavement Surface Evaluation and Rating (PASER) method is a visual rating system by which observed road conditions can be recorded. The results depend on the judgment of the observer recording the data and are therefore subjective. The PASER chart used in this study for visual road condition assessment is provided in Appendix C. Figure 5.11 and Figure 5.12 show the PASER data obtained from the Goodhue County and Carlton County test sections, respectively.

Figure 5.11 PASER data for Goodhue County test sections

Figure 5.12 PASER data for Carlton County test sections
Under this rating system, higher ratings are more favorable. The highest possible rating for rutting, washboarding, potholes, and loose aggregate is 9. For dust and crown and roadside drainage, the highest possible rating is 3 (3 = no visible dust while 0 = considerable dust). As seen in Figure 5.11, the PASER results indicated that comparatively less dust and loose aggregate were visible on the 45% RAP and 60% RAP sections in Goodhue County. As shown in Figure 5.12, the ratings indicated that comparatively less loose aggregate was seen on the RAP sections in Carlton County. In addition, only the 50% RAP section showed a lower amount of dust in the same county. However, the RAP sections were rated to have considerably more rutting and washboarding (Figure 5.12).

### 5.3.4 Lightweight Deflectometer (LWD) Test

In order to calculate the stiffnesses of test sections, test protocol ASTM E2583 was executed using a lightweight deflectometer (LWD). This is considered an important measurement for pavement design because the stiffness characteristics of various materials are different due to their different load carrying capacities. Below are the details of the method by which the elastic modulus was calculated for this investigation.

**Determination of elastic modulus (Vennapusa and White 2009):**

\[
E_{LWD} = \frac{(1 - v^2) \sigma_0 \alpha f}{d_0}
\]

where,

- \(E_{LWD}\) = Elastic modulus (MPa)
- \(v\) = Poisson's ratio (assumed as 0.40)
- \(\sigma_0 = 0.1\) MPa (300 mm Ø Plate @ 71 cm drop height)
- \(0.2\) MPa (200 mm Ø Plate @ 50 cm drop height)
- \(\alpha\) = Plate radius (150 mm [Ø = 300 mm] or 100 mm [Ø = 200 mm])
- \(f\) = Shape factor (assumed as 2)
- \(d_0\) = Average deflection after 3 drops (mm)

LWD test data were collected from the Goodhue County test sections in a cross-sectional manner, where both shoulders and both wheel paths of the roads are represented by four data points in the cross-section (Figure 5.13).
In many cases, the shoulder stiffness values were lower than the stiffness values obtained from the wheel paths. In addition, the recorded stiffness values were generally lower for the sections in which higher RAP contents were used, which would be expected due to the non-cohesive property of the RAP mixes.

Similar to the data collected from the Goodhue County test sections, cross-sectional LWD data were also collected from the Carlton County test sections (Figure 5.14).

Both 150 mm and 100 mm diameter plates were used on different dates (labeled as 6/9 and 9/3, respectively, in the figure). As shown in Figure 5.14, it was observed that higher stiffness values were
recorded by the LWD tests performed on September 3 (labeled as 9/3 in the figure) compared to the
tests performed on June 9 (labeled as 6/9 in the figure). In other words, stiffness values increased with
time for each test section. While the increases in the stiffness values were relatively higher for the 30%
RAP and control sections, relatively lower increases were observed in the 50% RAP section.

5.3.5 Dynamic Cone Penetrometer (DCP) Test

Dynamic cone penetrometer (DCP) test (ASTM D6951) data can be correlated to CBR values (DCP-CBR)
and can show how the stiffness changes as the probe penetrates the layers of the surface, base, and
subgrade layers. Separations between the gravel and subgrade layers can be determined based on
sudden changes in the DCP-CBR values.

The DCP test results obtained from the Goodhue County test sections are provided in Figure 5.15, Figure
5.16, and Figure 5.17.
Figure 5.15 DCP test results for Goodhue County Control 1 (top) and 60% RAP sections (bottom)
Figure 5.16 DCP test results for Goodhue County RAP 45% (top) and 30% RAP sections (bottom)
Figure 5.17 DCP test results for Goodhue County 15% RAP (top) and control 500th sections (bottom)

The Control.1 section had a relatively harder gravel layer; however, sudden decreases in the DCP-CBR values were observed as the probe reached the subgrade layer (Figure 5.15). In contrast, the gravel layer of the 60% RAP section had a comparatively low DCP-CBR value (Figure 5.15). For the RAP 45% and RAP 30% sections (Figure 5.16), a similar pattern was evident where the gravel layer above the subgrade
maintained relatively higher DCP-CBR values, and then the DCP-CBR values dropped as the probe reached the subgrade. The 15% RAP section (Figure 5.17) was the hardest section encountered. Repeated trials on this section failed, and final readings were concluded with an incomplete west wheel path reading. The control 500th section was comparatively normal.

Figure 5.18 depicts a comparative DCP-CBR chart created by averaging the gravel and subgrade DCP-CBR values and selecting the highest. It can be clearly seen that the gravel DCP-CBR values were greater than those for the subgrade and that the RAP 15% section had the highest DCP-CBR values and the RAP 60% section had the lowest.

![Figure 5.18 Summary of the DCP-CBR values obtained from Goodhue County test sections](image)

The DCP test results obtained from the Carlton County test sections are shown in Figure 5.19 and Figure 5.20. In general, expected results were obtained from the Carlton County test sections.
Figure 5.19 DCP test results for Carlton County control section
A summary of the DCP test results obtained from the Carlton County test sections is provided in Figure 5.21. The highest DCP-CBR values were observed in the 30% RAP section, and the lowest DCP-CBR values were observed in the 50% RAP section. As observed in the Goodhue County test sections, the gravel DCP-CBR values were higher than those for the subgrade.
Figure 5.21 Summary of the DCP-CBR values obtained from Carlton County test sections

5.3.6 International Roughness Index (IRI)

For the test sections in both Goodhue and Carlton Counties, the Roadroid mobile phone application was used to estimate the International Roughness Index (IRI) values (Forslöf and Jones 2015). A car was driven on both sides of the road, and the average estimated IRI (eIRI) value was calculated using the Roadroid application. It is important to note that eIRI was used in this study to compare different sections. A longitudinal IRI profile of each test section was then generated to understand the roughness of the sections.

As seen in Figure 5.22, the eIRI values obtained from the Goodhue County test sections had more peaks in the RAP sections than in the control section.

Figure 5.22 Average eIRI longitudinal profile of Goodhue County test sections

The longitudinal IRI profile of the Carlton County test sections was difficult to interpret because the section lengths were different (Figure 5.23).
The average eIRI values for the Goodhue County test sections were 1.19, 1.13, 1.13, 1.11, and 1.06 for the RAP 60%, RAP 45%, RAP 30%, RAP 15%, and control sections, respectively. The average eIRI values for the Carlton County test sections were 1.19, 1.4, and 1.35 for the RAP 30%, RAP 50%, and control sections, respectively.

### 5.3.7 Dustometer Data

Dust is an important parameter that affects road performance. The turbulence created by moving vehicles lifts up the fines from the road surface in the form of dust, which is then deposited elsewhere, possibly on the shoulders, ditches, and neighboring properties. When the fines are removed, loose aggregate also accumulates in the middle of the road. This repetitive cycle degrades the road surface and increases the required maintenance effort.

The CSU dustometer, which is basically an assembly of a vacuum pump and filter mounted to the rear of a truck (Morgan 2005), was used on both the Goodhue and Carlton County test sections to provide a relative measurement of the amount of fugitive dust that is generated as traffic traverses the various test section surfaces.

In the Goodhue County test sections, three runs were conducted on each section to provide one mile of dust collection, as per the standard procedure (Figure 5.24).
Figure 5.24 Dustometer test results obtained from the Goodhue County test sections

A large amount of dust was noted during some of the runs. In Figure 5.24, each data point represents the amount of dust that was collected after each separate run. In Figure 5.25, each data point shows the sum of the amount of dust collected in three runs for each test section.

Figure 5.25 Regression analysis for the Goodhue County dustometer test results

A trend was observed in which the dust emission decreased as the RAP content increased. The regression analysis shown in Figure 5.25 gave an $R^2$ value of 0.73, which indicates a correlation between these two variables.

The dustometer data collected from Carlton County supported a similar finding. In Figure 5.26, which shows a separate data point for each of the three runs on each test section, there was a noticeable reduction in the dust as the RAP percentage increased.
In the regression analysis shown in Figure 5.27, each data point represents the sum of the collected dust amounts after each of the three runs made on each test section.

The data indicate a clear trend, with an $R^2$ value of 0.92, for the regression analysis. This trend provides evidence for a correlation between the dust amount and the RAP content. Increases in the RAP content yielded lower amounts of dust.
5.4 SUPPLEMENTARY LABORATORY TESTING

5.4.1 Gradation

Particle size analysis was performed on the samples collected from the test sections in both counties in accordance with ASTM D2487 (unified soil classification system [USCS]). The gradations of the materials used in the Goodhue County test sections are provided in Figure 5.28.

![Gradation of materials used in the Goodhue County sections](image)

All RAP materials except for the 100% RAP and 30% RAP had gradations that are similar to that of the crushed limestone material used in the control section. The 100% RAP material was coarser and the 30% RAP material was finer than the crushed limestone. Given the likelihood that RAP particles might clump together because of the adhesion of the included binder, the 100% RAP material would be expected to have a comparatively coarser gradation. The classifications of the materials and other relevant parameters are provided in Error! Not a valid bookmark self-reference.
Table 5.2 Classification of the materials used in the Goodhue County sections

<table>
<thead>
<tr>
<th>Material</th>
<th>$D_{60}$</th>
<th>$D_{30}$</th>
<th>$D_{10}$</th>
<th>$C_u$</th>
<th>$C_c$</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>15% RAP</td>
<td>19</td>
<td>4.76</td>
<td>0.42</td>
<td>45.2</td>
<td>2.8</td>
<td>GW</td>
</tr>
<tr>
<td>30% RAP</td>
<td>9.51</td>
<td>2</td>
<td>0.42</td>
<td>22.6</td>
<td>1</td>
<td>SW</td>
</tr>
<tr>
<td>45% RAP</td>
<td>19</td>
<td>2.38</td>
<td>0.42</td>
<td>45.2</td>
<td>0.7</td>
<td>GP</td>
</tr>
<tr>
<td>60% RAP</td>
<td>19</td>
<td>4.76</td>
<td>0.59</td>
<td>31.9</td>
<td>2.01</td>
<td>GW</td>
</tr>
<tr>
<td>100% RAP</td>
<td>19</td>
<td>19</td>
<td>2</td>
<td>9.5</td>
<td>9.5</td>
<td>GP</td>
</tr>
<tr>
<td>0% (Road rock)</td>
<td>19</td>
<td>2.38</td>
<td>0.42</td>
<td>45.2</td>
<td>0.7</td>
<td>GP</td>
</tr>
</tbody>
</table>

The gradations of the materials used in the Carlton County test sections are provided in Figure 5.29.

![Figure 5.29 Gradations of materials used in the Carlton County sections](image)

As expected, the 100% RAP was the coarsest of the four materials, whereas the Class 5 material (denoted as 0% in the figure) was the finest. The soil classifications and other parameters of the materials are provided in Error! Not a valid bookmark self-reference..
### Table 5.3 Classification of the materials used in the Carlton County test sections

<table>
<thead>
<tr>
<th>Material</th>
<th>D&lt;sub&gt;60&lt;/sub&gt;</th>
<th>D&lt;sub&gt;30&lt;/sub&gt;</th>
<th>D&lt;sub&gt;10&lt;/sub&gt;</th>
<th>C&lt;sub&gt;u&lt;/sub&gt;</th>
<th>C&lt;sub&gt;c&lt;/sub&gt;</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% RAP</td>
<td>9.51</td>
<td>2.38</td>
<td>0.59</td>
<td>15.98</td>
<td>1.00</td>
<td>GW</td>
</tr>
<tr>
<td>0% (Class 5)</td>
<td>2</td>
<td>2</td>
<td>0.42</td>
<td>4.76</td>
<td>4.76</td>
<td>SP</td>
</tr>
<tr>
<td>30% RAP</td>
<td>4.76</td>
<td>2</td>
<td>0.42</td>
<td>11.33</td>
<td>2.00</td>
<td>SW</td>
</tr>
<tr>
<td>50% RAP</td>
<td>4.76</td>
<td>2</td>
<td>0.42</td>
<td>11.33</td>
<td>2.00</td>
<td>SW</td>
</tr>
</tbody>
</table>

### 5.4.2 CBR Tests

The CBR values for the various materials from both counties were determined using a laboratory investigation to supplement the CBR values obtained from the DCP field testing (DCP-CBR). The laboratory CBR test results for the materials used in the Goodhue County test sections are provided in Figure 5.30, and the CBR value of each material is provided in Figure 5.31.

![Figure 5.30 CBR test results for the materials used in the Goodhue County sections](image-url)
The observed trend was that the materials containing lower amounts of RAP were able to resist higher loads in comparison to the materials containing higher amounts of RAP. Therefore, a decrease in the RAP content yielded higher CBR values.

The laboratory CBR test results for the materials used in the Carlton County test sections are provided in Figure 5.32, and the CBR value of each material is provided in Figure 5.33.
Unlike the trend observed in the materials used in the Goodhue County sections, the 30% RAP provided a higher CBR value than that observed in the 0% RAP (Class 5 aggregate). However, the expected trend was observed among the 30% RAP, 50% RAP, and 100% RAP materials. An increase in the RAP content yielded a decrease in the CBR value.

5.4.3 Binder Content

In order to find the binder contents of the materials used in the test sections in both counties and the possible effect of the binder content on other material properties, ignition tests (AASHTO T 308) were conducted. Three tests were performed on each sample, and the average values are shown in Table 5.4 for the Goodhue County sections and Table 5.5 for the Carlton County sections. Higher binder contents were observed in the materials with higher RAP contents, as expected.
Table 5.4 Binder contents of the materials used in the Goodhue County test sections

<table>
<thead>
<tr>
<th>Material</th>
<th>Binder Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP 15%</td>
<td>0.46%</td>
</tr>
<tr>
<td>RAP 30%</td>
<td>1.06%</td>
</tr>
<tr>
<td>RAP 45%</td>
<td>3.04%</td>
</tr>
<tr>
<td>RAP 60%</td>
<td>3.68%</td>
</tr>
<tr>
<td>RAP 100%</td>
<td>5.52%</td>
</tr>
</tbody>
</table>

Table 5.5 Binder contents of the materials used in the Carlton County test sections

<table>
<thead>
<tr>
<th>Mix</th>
<th>Binder Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP 30%</td>
<td>2.74%</td>
</tr>
<tr>
<td>RAP 50%</td>
<td>4.54%</td>
</tr>
<tr>
<td>RAP 100%</td>
<td>6.12%</td>
</tr>
</tbody>
</table>

5.5 SUMMARY

The scrape test results showed that using RAP with aggregates generally reduced the amount of floating material present on the granular surfaces of the road sections (except for the 30% RAP section in Carlton County). However, varying RAP contents did not provide a specific trend in terms of floating material reduction.

According to the PASER results, using higher RAP contents (> 40%) provided an improvement in dust control and reduced the amount of loose aggregate. However, the RAP sections in Carlton County were rated to have more rutting and washboarding. In this case, it appears that the addition of RAP can exacerbate rutting and washboarding if the material it is mixed with is poorly graded sand and if the base is soft.

Due to the non-cohesive properties of RAP material, a reduction in the elastic modulus values obtained from the LWD testing was observed as RAP content increased. One exception was observed in the 60%
RAP section in Goodhue County. Higher modulus values were observed in the 60% RAP section compared to the 40% RAP section in that county. In addition, it was observed in Carlton County that elastic modulus values increased in all subsections over time.

According to the DCP test data, in Goodhue County the 15% RAP section had the highest DCP-CBR values and the 60% RAP section had the lowest values. However, in Carlton County the highest DCP-CBR values were observed in the 30% RAP section and the lowest DCP-CBR values were observed in the 50% RAP section.

The IRI profiles of the Goodhue County control sections were flatter compared to those of the RAP sections. However, no clearly noticeable trend was observed between the IRI values and RAP contents.

According to the dustometer test results, the amount of dust generated decreased as the percentage of RAP in a road surface mixture increased.

The laboratory CBR test results for the Goodhue County test section materials confirmed the trend found in the literature that CBR values decrease as RAP content increases. However, for Carlton County the CBR values were higher for the 30% RAP-aggregate road surfacing gravel mixture compared to the control section built with aggregate only. The road surfacing aggregate used in the 30% RAP-aggregate section was classified as poorly graded sand. Therefore, it was concluded that adding RAP actually improved the stability of the aggregate by adding large particles to the poorly graded sand. Based on the experience from the Carlton County test sections, it was found that RAP can be used to improve the gradation of materials that lack large particles if the RAP includes a sufficient amount of large particles.
CHAPTER 6: SECONDARY FIELD STUDY

6.1 INTRODUCTION

After the completion of the primary field study, three more test sections (and one control section) were built with three different RAP contents to extend the scale of this project. RAP-Class 5 aggregate blends containing 50%, 70%, and 80% RAP were used as surface aggregates. The aim of this secondary field study was to investigate the possible benefits of using higher RAP contents than those that were selected for the primary field study. In this chapter, the research effort performed to assess the use of higher RAP contents to reduce fugitive dust and surface irregularities and increase the stiffness of the road structure is summarized. In addition, a performance evaluation of various test sections constructed with the stated surface materials was conducted in an effort to identify an optimal RAP content that is expected to provide the most benefit.

To provide objective measures of road condition and performance, the following field tests were performed: DCP, LWD, dustometer, scrape (a nonstandard test performed in the primary field study), and IRI tests. In addition, visual observations were conducted as part of each field trip. Along with the field tests, sieve analyses/hydrometer tests and asphalt binder content determination tests were conducted on the materials collected from the field.

6.2 TEST SECTIONS

County Road (CR) 44 in Goodhue County was selected to be the road on which the test sections would be constructed. As stated in the previous chapter, there are various subgrade soils in the State of Minnesota that have various index and engineering properties that affect the overall performance of road systems. Therefore, a preliminary desk study regarding the subgrade soil conditions on CR 44 was conducted using the Web Soil Survey website (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). Figure 6.1 shows the distribution of various soil types obtained from this website (various codes were assigned for various soil types), and an explanation regarding the data obtained is provided in Appendix D.

Figure 6.1 Web Soil Survey desk study on CR 44

It was observed from the desk study that the existing soil/subgrade for these test sections was mainly CL and/or ML (low-plasticity clay and/or silt) according to the USCS (ASTM 2487) and A4, A6, or A7 (silty or
clayey soils that are generally rated as fair to poor for subgrades) according to the American Association of State Highway and Transportation Officials (AASHTO) Soil Classification System (AASHTO M 145).

The test sections are shown in Figure 6.2.

![Figure 6.2 CR 44 test section plan](image)

Descriptions of the test sections are as follows:

- Section 1 – Control section
- Section 2 – 50% Class 5 – 50% RAP section (abbreviation: 50% RAP section)
- Section 3 – 30% Class 5 – 70% RAP section (abbreviation: 70% RAP section)
- Section 4 – 20% Class 5 – 80% RAP section (abbreviation: 80% RAP section)

The length of each test section was designed to be 1,000 ft. The test sections were separated by 1,000 ft of aggregate, which is the typical road surfacing material that is used in Goodhue County. The thickness of the surface layers of both the Class 5 crushed limestone and RAP materials were targeted to be 3 in.

Selected pictures showing the construction process for the test sections are provided in Figure 6.3.

![Figure 6.3 Test section construction on CR 44](image)

*Praveen Gopiseti, Iowa State University*
The amounts of the materials placed on the sections are as follows:

- **50% RAP section**: 125 tons crushed limestone + 125 tons RAP
- **70% RAP section**: 75 tons crushed limestone + 175 tons RAP
- **80% RAP section**: 50 tons crushed limestone + 200 tons RAP

### 6.3 FIELD TESTING

In total, six field trips were planned and completed: one trip each before, during, and after construction to make observations and then three subsequent trips to monitor the longer-term performance of the test sections. The following activities were conducted during the field trips:

- **First field trip (07/19/2017 – pre-construction)**
  - Sample collection
  - DCP test
  - LWD test

- **Second field trip (07/27/2017 – construction)**
  - Sample collection
  - Visual observation

- **Third field trip (09/14/2017 – post-construction)**
  - Sample collection
  - DCP test
  - LWD test
  - Dustometer test
  - Visual observation

- **Fourth trip (10/31/2017)**
  - Scrape test
  - IRI test
  - Visual observation

- **Fifth trip (08/03/2018)**
  - Sample collection
  - DCP test
  - LWD test
  - Scrape test
  - Visual observation

- **Sixth trip (08/14/2018)**
Before the first field trip (pre-construction), seven test points were selected for each section (Figure 6.4).

![Figure 6.4 Planned test points at each section before construction (seven points)](image)

However, after construction it was observed that the actual length of each section was less than 1,000 ft and that the last test point was not located within the section limits. Therefore, tests were only conducted at the remaining six points for each section.

### 6.3.1 Dynamic Cone Penetrometer (DCP) Test

The DCP (ASTM D6951) is a device to measure the strength of soil in situ. The device consists of two 16 mm diameter shafts coupled near the mid-point, as well as a pointed cone tip that can be attached to the bottom of the lower shafts for stiffer soils. The underlying soil strength is determined by measuring the penetration of the lower shaft into the soil caused by dropping a hammer that slides on the top shaft onto an anvil. After each drop of the hammer (or after a group of drops, depending on the hardness of the road structure), the penetration value is obtained and recorded along with the number of drops. In this study, DCP data were used to estimate DCP-CBR values and thereby show the variation in DCP-CBR values at different depths and road layers. The transition between layers was determined based on sudden changes in the DCP-CBR values.

DCP tests were conducted on each test section before and after construction. Test data were analyzed to observe the relationships between the cumulative blows versus depth and DCP-CBR values versus depth. The following equations were used to correlate the DCP data to the estimated DCP-CBR values. The dynamic cone penetration index (DCPI), which is the penetration depth for a single drop of the hammer (in./blow), was used in the equations.

All soils except for CL soils show DCP-CBR < 10 and CH soils

- For DCP-CBR > 10 → DCP-CBR = \( \frac{292}{(DCPI \times 25.4)^{1.12}} \) in./blow

For CL soils with DCP-CBR < 10

- For DCP-CBR < 10 → DCP-CBR = \( \frac{1}{(0.432283 \times DCPI)^2} \) in./blow

As seen in Figure 6.5, the control section had a very stiff granular top layer (the calculated DCP-CBR was in the range of 100% and 10,000%) with a thickness of about 8 in.
While correlations between DCPI and DCP-CBR values are provided in ASTM D6951 for DCP-CBR measurements of less than 100%, layers that had DCP-CBR values exceeding 100% were observed in this study. That notwithstanding, higher CBR values are reported herein to provide readers with indications of the thickness of stiff layers and a possible very approximate estimate of layer stiffness. Only two DCP tests could be completed on each date (09/14/2017 [post-construction] and 08/03/2018) due to the high stiffness of the top layer. However, in the two tests completed, decreases in the DCP-CBR values were observed within the subgrade layer. In other words, the top layer provided relatively higher DCP-CBR values than the subgrade.

As seen in Figure 6.6, the 50% RAP section had a very stiff top layer, with DCP-CBR values up to 10,000%.
Tests could not be completed on 07/09/2017 (pre-construction) because the penetrometer was not able to pass through the very stiff top layer. Therefore, the thickness of the top layer could not be determined before construction. However, relatively softer road conditions were observed during other field trips (on 09/14/2017 [post-construction] and 08/03/2018), and it was determined that there was a 12 in. thick very stiff top layer.

As seen in Figure 6.7, unlike for the 50% RAP section, two tests could be completed before construction on the 70% RAP section.

![Figure 6.7 Depth versus cumulative blows (left) and depth versus DCP-CBR (right) plots for the 70% RAP section](image)

Then, two more field trips that included DCP testing were completed after construction (on 09/14/2017 [post-construction] and 08/03/2018). Before construction, it was observed that the very stiff top layer’s thickness was about 5 in. (shown as Stiff Layer 1 in Figure 6.7), with DCP-CBR values between 100% and 10,000%. However, after construction, the thickness of the very stiff top layer was observed to be around 7 in. (shown as Stiff Layer 2 in Figure 6.7). As stated above, the thickness of the surface layers was planned as 3 in. Therefore, the effect of constructing the surface layer was detected by DCP testing. It was also concluded that the 70% RAP surface layer also provided high DCP-CBR values.

As seen in Figure 6.8, like for the 70% RAP section, two tests could be completed before construction on the 80% RAP section.
Figure 6.8 Depth versus cumulative blows (left) and depth versus DCP-CBR (right) plots for the 80% RAP section

After construction, two more DCP tests were performed, on 09/14/2017 (post-construction) and 08/03/2018. Before construction, the thickness of the very stiff top layer was observed to be about 4 in. (shown as Stiff Layer 1 in Figure 6.8), with DCP-CBR values around 1,000%. However, it was observed in the tests performed after construction that the thickness of the very stiff top layer was about 7 in. (shown as Stiff Layer 2 in Figure 6.8). Similar to the 70% RAP section, the change in the surface layer's thickness due to construction was detected by DCP testing. In addition, it was concluded that the 80% RAP surface layer provided high DCP-CBR values.

6.3.2 Lightweight Deflectometer (LWD) Test

The LWD (ASTM E2583) is a device that measures the surface deflection caused by a falling weight; it estimates the elastic modulus. The LWD test is used to rapidly determine the elastic moduli of soils. It uses Boussinesq’s solution for the theory of elasticity to estimate the composite elastic modulus. The equation shown below is used for the calculation of elastic modulus.

Determination of elastic modulus (Vennapusa and White 2009):

$$E_{LWD} = \frac{(1 - \nu^2) \sigma_0 \alpha f}{d_0}$$

where,

- $E_{LWD}$ = Elastic modulus (MPa)
- $\nu$ = Poisson's ratio (assumed as 0.40)
- $\sigma_0$ = Applied stress
\[ \alpha = \text{Plate radius (150 mm [Ø = 300 mm])} \]

\[ f = \text{Shape factor (assumed as 2)} \]

\[ d_0 = \text{Measured average deflection under the loading plate (mm)} \]

The falling weight and drop height were 10 kg and 0.72 m, respectively.

The LWD test results for each section and a summary of the results are provided in Figure 6.9 and Figure 6.10, respectively.

*Figure 6.9 LWD test results for the control (top left), 50% RAP (top right), 70% RAP (bottom left), and 80% RAP (bottom right) sections*
The 50% RAP section provided higher median modulus values compared to other RAP sections (Figure 6.10). Although the 50% RAP section showed a greater modulus variation in the tests performed on 09/14/2017 (post-construction), it yielded a median modulus value similar to that observed in the control section. While the range of the modulus values from the tests performed on 08/03/2018 in the 50% RAP section was similar to that of the control section, the 50% RAP section provided a lower median modulus value. Considerably lower median modulus values were observed in the RAP sections in the tests performed on 08/03/2018 compared to the tests performed on 09/14/2017 (post-construction). This may indicate a performance degradation in the surface layers due to RAP degradation.

6.3.3 Dustometer Test

The dustometer developed at CSU was used to determine the amounts of dust generated by the test sections. Only one run was performed on each test section on 09/14/2017 (post-construction) and on 08/14/2018. Test results are provided in Figure 6.11.
For the measurements taken on 09/14/2017 (post-construction), all of the RAP sections exhibited lower amounts of dust compared to the control section. The lowest amount of dust was collected from the 50% RAP section. According to the tests performed on 08/14/2018, the 70% RAP section provided the lowest amount of dust. The 50% RAP section also provided a lower amount of dust compared to the control section. However, the 80% RAP section provided the highest amount of dust among all of the sections.

### 6.3.4 Scrape Test

Scrape tests were performed on 10/31/2017 and 08/03/2018 following a procedure similar to the one described above. Test results for each section are provided in Figure 6.12, and a summary of the test results for all sections is provided in Figure 6.13.
Figure 6.12 Section-by-section scrape test results

Figure 6.13 Summary of scrape test results
In the tests performed on 10/31/2017, while more surface materials were collected from the 50% RAP section compared to the control section, the 70% and 80% RAP sections showed the lowest amounts of floating surface materials. However, a different trend was observed for the tests that were performed on 08/03/2018. On that day, the 50% RAP section showed results that were similar to those observed on 10/31/2017, in that a higher amount of free surface material was collected on the 50% RAP section than on the control section. The difference was that considerably higher amounts of floating surface materials were collected from the 70% and 80% RAP sections compared to the control section on 08/03/2018. This may indicate that the RAP lost its binding properties and allowed the surface materials to become loose due to a lack of bonding. Lastly, the 70% RAP section showed the lowest amount of floating surface material among all of the RAP sections on both days.

6.3.5 International Roughness Index (IRI) Test

For the IRI test, the Roadroid mobile phone application was used on 10/31/2017 and 08/14/2018. A single pass was made on each section (Figure 6.14), and the estimated IRI (eIRI) and calculated IRI (cIRI) were obtained.

![Figure 6.14 Overview of IRI data collected on 10/31/2017 (top) and 08/14/2018 (bottom)](image)

eIRI values are based on a peak and root mean square vibration analysis, in which a correlation is made with Swedish laser measurements on paved roads. The speed should be 20 to 100 km/h. cIRI values are based on quarter-car simulation, and a narrower speed range (e.g., 60 to 80 km/h) is considered (Forslöf and Jones 2015). Both the eIRI and cIRI values of each section on the two testing days are shown in Figure 6.15 and Figure 6.16, respectively. The eIRI values are generally higher in comparison to the cIRI values on both days. For the tests performed on 10/31/2018, the lowest IRI values were seen in the control section. However, for the tests performed on 08/14/2018, the 70% and 80% RAP sections showed comparatively lower IRI values.
Figure 6.15 eIRI and cIRI results for each section on 10/31/2017

Figure 6.16 eIRI and cIRI results for each section on 08/14/2018

6.3.6 Visual Distress Identification

In the control section, no distress was observed on 09/14/2017 (post-construction); however, four potholes were observed throughout the section on 10/31/2017 (Figure 6.17). On 08/03/2018, no distress was observed.
In the 50% RAP section, potholes (Figure 6.18 and Figure 6.19) and transverse and longitudinal cracks (Figure 6.20 and Figure 6.21) were observed. Figure 6.18 and Figure 6.20 are from the observation performed on 09/14/2017 (post-construction), and Figure 6.19 and Figure 6.21 are from the observation performed on 10/31/2017. On 08/03/2018, no distress was observed.
Figure 6.19 Potholes observed in the 50% RAP section on 10/31/2017

Haluk Sinan Coban, Iowa State University

Figure 6.20 Transverse and longitudinal cracks observed in the 50% RAP section on 09/14/2017

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In the 70% RAP section, transverse and longitudinal cracks and alligator cracks were observed on 09/14/2017 (post-construction) (Figure 6.22 and Figure 6.23). On 08/03/2018, no distress was detected.
In the 80% RAP section, alligator cracks were observed on 09/14/2017 (post-construction). On 10/31/2017 (post-construction), transverse cracks and alligator cracks were observed (Figure 6.24). On 08/03/2018, no distress was observed.

Haluk Sinan Coban, Iowa State University

Figure 6.23 Transverse (left) and alligator (right) cracks observed in the 70% RAP section on 10/31/2017
6.4 SUPPLEMENTARY LABORATORY TESTING

6.4.1 Gradation

6.4.1.1 Control Section

Samples were collected from a depth of around 3 in. below the road surface. From 07/27/2017 to 09/14/2017 (post-construction), the gravel and sand contents decreased, and the silt and clay content increased. However, similar gradations were observed between 09/14/2017 (post-construction) and 08/03/2018 (Figure 6.25).
Immediately after construction on 07/27/2017, an increase in the gravel content and a decrease in the sand, silt, and clay contents due to construction were observed. As time progressed from 07/27/2017 to 08/03/2018, the silt and clay contents increased and the gravel content decreased. In addition, a slight increase in the sand content was observed (Figure 6.26).
Immediately after construction on 07/27/2017, an increase in the gravel content and a decrease in the sand, silt, and clay contents were observed. As time progressed from 07/27/2017 to 08/03/2018, the silt and clay contents increased and the gravel and sand contents decreased (Figure 6.27).
6.4.1.4 80% RAP Section

Immediately after construction on 07/27/2017, an increase in the gravel content and a decrease in the sand, silt, and clay contents were observed. As time progressed from 07/27/2017 to 08/03/2018, the silt and clay contents increased and the gravel and sand contents decreased (Figure 6.28).

![Figure 6.28 Gradations of surface layer material in the 80% RAP section at various times](image)

6.4.2 Asphalt Binder Content Determination

AASHTO T 308-16, Standard Method of Test for Determining the Asphalt Binder Content of Hot-Mix Asphalt (HMA) by the Ignition Method, was followed to determine the asphalt binder contents of the test sections. Ignition tests were conducted on the materials collected from the scrape test (Figure 6.29).
A summary of the results is shown in Error! Not a valid bookmark self-reference.. As seen in Error! Not a valid bookmark self-reference., the calculated RAP contents were lower than the estimated RAP contents. The difference was attributed to the lack of free particles containing asphalt binder on the surface.

Table 6.1 Calculated asphalt binder and RAP contents

<table>
<thead>
<tr>
<th></th>
<th>Asphalt Binder (%)</th>
<th>Estimated RAP Content (%)</th>
<th>Calculated RAP Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Section</td>
<td>0.2</td>
<td>0</td>
<td>3.6</td>
</tr>
<tr>
<td>50% Class 5 - 50% RAP</td>
<td>1.1</td>
<td>50</td>
<td>21.7</td>
</tr>
<tr>
<td>30% Class 5 - 70% RAP</td>
<td>1.4</td>
<td>70</td>
<td>26.9</td>
</tr>
<tr>
<td>20% Class 5 - 80% RAP</td>
<td>1.6</td>
<td>80</td>
<td>31.5</td>
</tr>
<tr>
<td>100% RAP</td>
<td>5.2</td>
<td>100</td>
<td>100.0</td>
</tr>
</tbody>
</table>
6.5 SUMMARY

Blends of Class 5 crushed limestone aggregate and RAP materials were prepared at 50%, 70%, and 80% RAP contents to construct aggregate surface layers for three test sections on CR 44 in Goodhue County, MN. A control section was also constructed using only Class 5 aggregate surface material. An evaluation of the constructed road sections to determine an optimum RAP content that provides the greatest benefit was accomplished by performing DCP, LWD, dustometer, scrape, and IRI tests.

For the DCP tests, very stiff top layers with DCP-CBR values greater than 100% were observed in each test section. For the 70% RAP and 80% RAP sections, increases in the thicknesses of the stiff top layers were observed after construction. Pre-construction DCP tests could not be completed in the 50% RAP section; therefore, no information about the change in the thickness of the stiff surface layer could be obtained from that test section.

According to the LWD test results, the 50% RAP section showed higher elastic moduli compared to the other RAP sections. The lowest elastic moduli were observed in the 70% RAP section. After construction, lower elastic modulus values were observed in all of the RAP sections over time. It was speculated that the reduction in the layer stiffnesses of the RAP sections over time might be the result of possible degradation of the RAP material.

According to the dustometer data, around two months after construction the 50% RAP section produced the lowest amount of dust among all of the test sections. In addition, it was observed that the amount of collected dust increased as the RAP content increased. However, around one year after construction, the 70% RAP section produced the lowest amount of dust. One common result between the two dustometer tests performed on two different dates was that the 80% RAP test section generated the highest amount of dust among all of the RAP test sections.

According to the scrape test data, around three months after the construction the lowest amount of free-floating surface material was collected from the 70% RAP test section. In addition, it was observed that more floating surface material was collected from the 50% RAP section compared to the control section. This suggests that using higher RAP contents (to some extent) in the surface layer may have provided better binding between the aggregates and RAP materials. However, over time an increase in the amount of free-floating surface material was observed in the 70% and 80% RAP test sections; a similar amount of free-floating surface material was observed in the 50% RAP section. This suggests that the high-percentage RAP materials may have lost their binding properties over time, which caused an increase in the amount of free-floating surface material.

According to the IRI tests, the lowest IRI values were observed on the control section around three months after construction. However, around one year after construction the 70% RAP and 80% RAP test sections showed lower IRI values, which suggests that the higher RAP contents may have improved the binding between the aggregates and RAP materials, which resulted in a smoother road surface.

Several distresses were observed approximately two months after construction. However, no significant failures were observed around one year after construction.
Various trends were observed based on various in situ tests. Some of the trends that were observed as the RAP percentage increased are normally associated with better performance. Others are traditionally associated with poorer performance. Overall, it appears that it is possible to provide an acceptable surface for an unpaved road using RAP material. However, it does not appear that a particular RAP percentage provided what would be traditionally understood as the best performance according to all of the field and laboratory tests that were conducted. Therefore, it is difficult to identify an optimum percentage of RAP to mix with virgin aggregate to provide the best performance.
CHAPTER 7: GENERAL SUMMARY

In the State of Minnesota, about 50% (66,000 miles) of roads are gravel or crushed rock roads. These roads have great importance because they connect rural areas, which benefits the state’s economy by facilitating high-volume agricultural and other economically important activities and provides transportation lifelines to rural residences and workers. Several issues, such as loss of strength and generation of fugitive dust, have been reported as major problems on these roads, and considerable effort must be expended to maintain these roads. Good-quality aggregates and road surface layers are required to mitigate these problems. However, in the State of Minnesota many good-quality virgin aggregate sources have been depleted, which has increased the costs for constructing and maintaining gravel and crushed rock roads.

Studies have shown that RAP materials are a promising alternative that could reduce the use of virgin aggregates for gravel and crushed rock roads. Several benefits of using RAP as a base, subbase, or surface aggregate were reported for this project. Unused RAP materials are sometimes stockpiled for a considerable amount of time before an appropriate use is found; therefore, stockpiles grow in size unless other uses for the RAP materials are found. In some cases, the material might be contaminated, so it cannot be used for hot mix asphalt. In other cases, the material might not be in a location where it can be transported to a hot mix asphalt plant economically. Therefore, local transportation agencies in the State of Minnesota have been encouraged to consider the use of RAP for gravel and crushed rock roads.

The objective of this project was to provide a better understanding of how the use of various virgin aggregate and RAP mixtures for road surface layers affects the performance of gravel roads and, with further analysis, determine the optimal RAP content for Minnesota gravel roads. To satisfy this objective, this project included a literature review, preliminary laboratory testing, economic and feasibility analysis, and two field studies. The project’s major tasks are listed below, and brief information is provided for each:

1. Literature review
   Several studies related to the use of RAP materials in various road applications were reviewed and summarized. The literature review was supplemented with an internet survey that solicited information about use of RAP materials in the State of Minnesota and the preferred RAP contents in RAP-virgin aggregate mixtures.

2. Preliminary laboratory testing
   Several laboratory tests were performed on various RAP materials, one virgin aggregate, and mixtures of RAP materials and virgin aggregate to determine index properties of the materials and the engineering properties of their mixtures.
3. Economic and feasibility analysis

Example cost estimate calculations were made for the maintenance of a hypothetical one-mile-long gravel or crushed rock road surface. Two different analyses, one for the use of virgin aggregates alone and one for the use of virgin aggregates with RAP material, were performed.

4. Primary field study

Six test sections were constructed with different surface aggregates in Goodhue and Carlton Counties. Virgin RAP-aggregate blends having 15% to 60% RAP contents were used as surface aggregates on the six test sections. Virgin aggregate material was also used alone as surface aggregate on a control section. Cross-sectional surveys, PASER evaluations, and scrape, LWD, DCP, IRI, and dustometer tests were performed to evaluate the field performance of the test sections. The field study was supplemented with gradation, CBR, and asphalt binder content laboratory tests.

5. Secondary field study

Three different RAP-Class 5 aggregate blends containing 50%, 70%, and 80% RAP contents were used to construct three additional test sections in Goodhue County. Another control section was also constructed using only Class 5 aggregate surface material. DCP, LWD, dustometer, scrape, and IRI tests were performed to evaluate the field performance of the additional test sections. Visual distress observations were also performed. The field study was supplemented with gradation and asphalt binder content laboratory tests.

After completing the research tasks listed above, the following general conclusions were drawn:

1. According to the laboratory UC test results, using 20% MPLS RAP#1, 50% MPLS RAP#2, and 50% Jackson RAP in mixes separately provided the highest strength values. In addition, using 30% of each RAP material yielded the second highest strength values in all of the mixes. It was concluded that 30% would be the optimum RAP content if a maximum laboratory UC strength is desirable.

2. Cylindrical specimens, composed of virgin aggregate and RAP mixtures, prepared for UC testing did not hold their shapes easily due to their material properties (lacking binding materials and cohesion). CBR testing was found to be more suitable because the specimens were confined in molds during testing.

3. For both MPLS RAP mixes, the CBR values decreased as the RAP content increased to 40% and then exhibited a modest increase when 50% RAP was used. MPLS RAP#2 provided higher CBR values than MPLS RAP#1 because MPLS RAP#2 had finer particles providing better bonding. Using finer RAP in the mixes yielded higher CBR values and provided better binding capability with the soil aggregates.

4. The estimated costs for maintaining two basic road sections with and without RAP were similar, but the costs were slightly higher when a mixture of RAP and gravel or crushed rock was used. Small savings in maintenance and re-graveling or re-rocking costs could make the use of the RAP mixture more economical than the use of the original surfacing material. A 1.5% increase in costs was found when 50% RAP was used instead of 100% virgin aggregates. However, if the ways that using RAP might improve road performance are considered (e.g., a reduction in fugitive dust), the need for re-
graveling or re-rocking might be reduced. In such cases, some savings might be obtained. The higher cost of an alternative surface mixture might be justified if fugitive dust emissions are reduced and a better road surface is provided for road users and neighbors.

5. In the primary field study, the scrape test results showed that using RAP with aggregates generally reduced the amounts of floating material present on the granular surfaces of the road sections (except for the 30% RAP section in Carlton County). However, varying RAP contents did not provide a specific trend in terms of floating material reduction.

6. According to the PASER results for the Goodhue County test section, using surfacing materials with RAP contents greater than 40% improved dust control and reduced the amount of loose aggregate. However, the RAP sections in Carlton County were rated to have more rutting and washboarding. In this case, it appears that the addition of RAP can exacerbate rutting and washboarding if the material it is mixed with is poorly graded sand and if the base is soft.

7. In the primary field study, a reduction in elastic modulus values was observed as RAP content increased. One exception was observed in the 60% RAP section in Goodhue County, where higher modulus values were observed in the 60% RAP section compared to the 40% RAP section. In addition, it was observed in Carlton County that modulus values increased in all test sections over time.

8. In the primary field study, in Goodhue County the 15% RAP section had the highest DCP-CBR values and the 60% RAP section had the lowest values. However, in Carlton County the highest DCP-CBR values were observed in the 30% RAP section and the lowest DCP-CBR values were observed in the 50% RAP section. Test sections with lower RAP contents provided higher DCP-CBR values.

9. In the primary field study, the amount of floating aggregate appeared to decrease modestly as the percentage of RAP in the mix increased. Measurements indicated that the amount of dust generated decreased as the percentage of RAP in a road surface mixture increased.

10. In the primary field study, the laboratory CBR values decreased as the RAP content increased for the Goodhue County test section materials. However, for Carlton County the laboratory CBR values were higher for the 30% RAP-aggregate compared to the control section built with aggregate only. The road surfacing aggregate used in the 30% RAP-aggregate section was classified as a poorly graded sand. Adding RAP actually improved the stability of the aggregate by adding large particles to the poorly graded sand. Based on the experience from the Carlton County test sections, it was found that RAP can be used to improve the gradation of materials that lack large particle sizes if the RAP includes a sufficient amount of large particles.

11. In the secondary field study, very stiff surface layers showing DCP-CBR values greater than 100% were observed in each test section. For the 70% RAP and 80% RAP sections, increases in the thicknesses of the stiff surface layers were observed after construction. Because pre-construction DCP tests could not be completed in the 50% RAP section, no information about the change in the thickness of the stiff surface layer could be obtained from that section.

12. In the secondary field study, the 50% RAP section showed higher elastic moduli compared to the other RAP sections. The lowest elastic moduli were observed in the 70% RAP section. After construction, lower elastic moduli were observed in all of the RAP sections over time. This observation might suggest that the RAP surface was degrading (possibly due to loss of bonding among the particles), which may have caused the performance degradation.
13. In the secondary field study, approximately two months after construction the 50% RAP section produced the lowest amount of fugitive dust among all of the test sections. In addition, it was observed that the amount of dust collected increased as the RAP content increased. However, around one year after construction the 70% RAP section produced the lowest amount of fugitive dust. One common result between the two dustometer tests performed on different dates was that the 80% RAP test section generated the highest amount of dust among all of the RAP sections.

14. According to the scrape test data, approximately three months after construction the lowest amount of free surface material that was collected among all of the test sections was from the 70% RAP section. In addition, it was observed that comparatively more surface material was collected from the 50% RAP section compared to the control section. This suggests that using higher RAP contents (to some extent) in the surface layer provided better binding between the aggregate particles and RAP materials. However, over time an increase in the amount of free surface material was observed in the 70% and 80% RAP sections while similar amounts of free surface material were observed in the 50% RAP section, which suggests that the materials with higher RAP contents may have lost their binding properties over time, which might have caused an increase in the amount of free surface material.

15. In the secondary field study, the lowest IRI values were observed in the control section three months after construction. However, around one year after the construction the 70% and 80% RAP sections showed lower IRI values, which suggests that the higher RAP contents in these sections improved the binding between the aggregate particles and RAP materials; this binding likely contributed to a smoother road surface.

Overall, the results of this investigation provide insights into the effect of using RAP material for the surface layers of unpaved gravel and crushed rock roads. Given all of the test results summarized above, it was concluded that the optimal RAP content for gravel roads changes according to the properties of the materials used (both the RAP and virgin aggregates) and the testing method. In light of the effects of the subgrade layer properties on the overall performance of pavements, along with the effects of weather conditions and various other related parameters, it was also concluded that obtaining an optimum RAP content is site-dependent.
REFERENCES


APPENDIX A
INTERNET SURVEY RESULTS
<table>
<thead>
<tr>
<th>Name of Person (County Information)</th>
<th>Has your jurisdiction added RAP to unpaved driving surfaces?</th>
<th>If yes, how did you use it?</th>
<th>What percentage of RAP was used, if know?</th>
<th>Compared to surfaces where RAP was used, did performance improve?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karin Grandia (Itasca County)</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Darrell Pettis (Le Sueur County)</td>
<td>Yes</td>
<td>On surface course</td>
<td>50 to 100%</td>
<td>Yes, the amount of dust was reduced. However, in about 1 to 2 years, the RAP broke down was just as much dust.</td>
</tr>
<tr>
<td>Aaron VanMoer (Lyon County)</td>
<td>No</td>
<td></td>
<td></td>
<td>We have only reclaimed asphalt with an underlying gravel base. The resulting mixture sets up extremely hard and non-porous. Have never left this surface more than 1 year before coving with the new bituminous mat. Would be curious how well it performs as an aggregate surface layer. One thing for sure is that it is very dusty when dry and sticks to vehicles something terrible. Hard to clean off.</td>
</tr>
<tr>
<td>Larry Haukos (Traverse County)</td>
<td>Yes</td>
<td>Repair soft spots</td>
<td>100%</td>
<td>RAP works extremely well for repair of soft spots (frost boils).</td>
</tr>
<tr>
<td>Name of Person (County Information)</td>
<td>Has your jurisdiction added RAP to unpaved driving surfaces?</td>
<td>If yes, how did you use it?</td>
<td>What percentage of RAP was used, if known?</td>
<td>Compared to surfaces where RAP was used, did performance improve?</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>-------------------------------------------------------------</td>
<td>-----------------------------</td>
<td>------------------------------------------</td>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>Chris Byrd (Benton County)</td>
<td>Yes</td>
<td>Shoulders 100%</td>
<td>On shoulders, it performed really well. In some cases remained stable at near 1:1 slope</td>
<td></td>
</tr>
<tr>
<td>Joe Triplett (Chisago County)</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jonathan Large (Mahnomen County)</td>
<td>Yes</td>
<td>On surface course 100%</td>
<td>The RAP was used in an area (150') that is annually overtopped by water runoff, have not had an event since it was incorporated into the short stretch but seems to be performing fine.</td>
<td></td>
</tr>
<tr>
<td>John Welle (Aitkin County)</td>
<td>Yes</td>
<td>On surface course</td>
<td>Yes.</td>
<td></td>
</tr>
<tr>
<td>Steve Kubista (Chippewa County)</td>
<td>Yes</td>
<td>On surface course</td>
<td>Used 100% RAP with added emulsion as surface treatment. I do not know if we have seen an increase in performance, but it is needed to help with the shortage of aggregate sources in our area.</td>
<td></td>
</tr>
<tr>
<td>David Overbo (Clay County)</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Name of Person (County Information)</td>
<td>Has your jurisdiction added RAP to unpaved driving surfaces?</td>
<td>If yes, how did you use it?</td>
<td>What percentage of RAP was used, if known?</td>
<td>Compared to surfaces where RAP was used, did performance improve?</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>-----------------------------</td>
<td>------------------------------------------</td>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>Stephen Schnieder (Nobles County)</td>
<td>Yes</td>
<td>On surface course</td>
<td>Not sure of the rate</td>
<td>Yes, there was less dust which was the purpose of placing the RAP material and mixing it with the gravel. The RAP material was placed along residences only, not the entire length of the roadway.</td>
</tr>
<tr>
<td>Randy Groves (Murray County)</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gregory Isakson (Goodhue County)</td>
<td>Yes</td>
<td>Shoulders</td>
<td>67% RAP and 33% virgin sand</td>
<td>Only been in service for a couple weeks but it appears that it will perform very well</td>
</tr>
<tr>
<td>Dan Sauve (Clearwater County)</td>
<td>Yes</td>
<td>I have used it on all of the above</td>
<td>About a 50/50</td>
<td>Yes works very well for subgrade repairs and as a shoulderering material.</td>
</tr>
<tr>
<td>William Rabenberg (Redwood County)</td>
<td>No</td>
<td>Shoulders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Name of Person (County Information)</td>
<td>Has your jurisdiction added RAP to unpaved driving surfaces?</td>
<td>If yes, how did you use it?</td>
<td>What percentage of RAP was used, if known?</td>
<td>Compared to surfaces where RAP was used, did performance improve?</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>-------------------------------------------------</td>
<td>---------------------------------</td>
<td>-----------------------------------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>James Grube (Hennepin County)</td>
<td>Yes</td>
<td>On surface course</td>
<td>100% millings from a mill and overlay project</td>
<td>Hennepin County only has 2 gravel roads and they have been covered with millings for about 8 years now. Prior to adding the millings, the roads needed re-grading at least once a week. Once covered with millings they held up for at least a year before hot mix patching was needed and then eventually spot overlays were required. Currently, they are basically millings with large areas of the asphalt surface.</td>
</tr>
<tr>
<td>Jeff Marlowe (Renville County)</td>
<td>No</td>
<td></td>
<td></td>
<td>Although we have not used this method, I would be interested in the results of the study. There are several roads in Renville County where dust is a safety concern.</td>
</tr>
<tr>
<td>Name of Person (County Information)</td>
<td>Has your jurisdiction added RAP to unpaved driving surfaces?</td>
<td>If yes, how did you use it?</td>
<td>What percentage of RAP was used, if known?</td>
<td>Compared to surfaces where RAP was used, did performance improve?</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>----------------------------</td>
<td>------------------------------------------</td>
<td>---------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| James Foldesi (St. Louis County)   | Yes                                                           | On surface course          | 50%                                      | CSAH 70 - Near Babbit was recently reconstructed and realigned away from the Northshore Mining expansion. 2" of millings from the existing bituminous surface and 2" of new Class 5 aggregate were mix with a reclaimer and stabilized with CaCl2 via direct injection. After construction, MnDOT detoured MN TH 1 traffic onto the road. The Forest Service segment was maintained by MnDOT and required blading every other day. The St. Louis County segment required blading once every 4-5 weeks. The detoured traffic was 1500 ADT +/-.
   The road has held up well to the heavy mining operation loads and the employees.
   It requires a motor grader about every 6-8 weeks until freeze up. |
APPENDIX B
INTERMEDIATE REPORT OF LABORATORY AND FIELD TESTS ON
GOODHUE COUNTY TEST SECTIONS USING WASTE SHINGLES
INTRODUCTION

In order to better characterize the effects of asphalt binder on the properties of gravel roads, this brief report was prepared partially based on a final report describing test sections constructed using waste shingles in Goodhue County for a previous Minnesota Local Road Research Board project (Wood et al. 2014). These test sections were stabilized using post-consumer tear-off scrap shingles (TOSS). Additional field observations and laboratory and field tests were undertaken to further investigate the properties of each section. An attempt was made to find correlations among the various properties of these sections and to understand the implications of these correlations for the optimal recycled asphalt pavement (RAP) project.

Two field visits to the Goodhue County test sections were made on 7/31/2014 and 8/9/2014. Figure B1 shows a schematic plan of the three test sections in Goodhue County. Figure B2 shows a satellite image of the test sections.

Figure B1 Plan of Goodhue County shingles sections

Figure B2 Satellite image of Goodhue County shingles sections
FIELD OBSERVATIONS

On 7/31/2014, field observations were conducted. Pictures were taken from various perspectives to provide an overview of the road sections (Figures B3 to B8).

Figure B3 TOSS LS CL6 2013 section facing west

Figure B4 TOSS LS CL6 2013 section facing east
Figure B5 TOSS LS CL6 2013 section facing west from 205th Avenue

Figure B6 Close-up shot of TOSS LS CL6 2013 section
Figure B7 Close-up shot of TOSS LS CL6 2013 section facing east

Figure B8 TOSS LS CL6 2012 section facing east
LABORATORY AND FIELD TESTS

Sieve Analysis

Considering the amount of fine particles below the #200 sieve, ASTM C117-13 and ASTM C136-06 were used as protocols for sieve analysis. From Figure B9, it can be inferred that TOSS CL6 2012 had a relatively larger amount of fine and sand content compared to the other two sections.

![Comparative Gradation of All Three Sections](image)

**Figure B9 Comparative gradation of all three sections**

The control section had a higher proportion of gravel and coarser sand, along with a correspondingly lower proportion of fines. TOSS CL6 2013 had a relatively higher proportion of coarse sand and gravel in comparison to the control section. It should be noted that although TOSS CL6 2012 had a relatively high proportion of fines in the road surfacing material, the surface was still tightly bound and emitted comparatively less dust.

Standard laboratory procedures were followed, as depicted in Figure B10.
In order to calculate the stiffnesses of the test sections, test protocol ASTM E2583-07 was executed using a lightweight deflectometer (LWD). Four data points were considered across each cross-section covering shoulders and wheel paths. In Figure B11, it can be clearly seen that section TOSS CL6 2012 had the highest stiffness and was comparatively stiffer than the control section.

Overall, observations indicated increased stiffness subsequent to TOSS stabilization.

The procedure in ASTM D2216-10 was followed to determine the moisture contents of the surfaces of the test sections. Samples were taken from both the top and bottom surfaces of the test sections. The purpose was to determine the relationship between moisture content and fugitive dust emissions in the
surface of the road. Table B1 shows that the control section had a considerably drier top compared to its bottom.

Table B1 Moisture content for all sections

<table>
<thead>
<tr>
<th></th>
<th>Control Section</th>
<th>TOSS CL6 2013</th>
<th>TOSS CL6 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top</td>
<td>Bottom</td>
<td>Top</td>
</tr>
<tr>
<td>Pan Weight (g)</td>
<td>778.4</td>
<td>697.4</td>
<td>736.6</td>
</tr>
<tr>
<td>Material Weight (g)</td>
<td>2209.6</td>
<td>2098.9</td>
<td>2333.9</td>
</tr>
<tr>
<td>Total Weight (g)</td>
<td>2988</td>
<td>2796.3</td>
<td>3070.5</td>
</tr>
<tr>
<td>Total Weight After Drying (g)</td>
<td>2982.7</td>
<td>2766.9</td>
<td>3030.8</td>
</tr>
<tr>
<td>Moisture Content (%)</td>
<td>0.24</td>
<td>1.42</td>
<td>1.73</td>
</tr>
</tbody>
</table>

Meanwhile, the TOSS-stabilized sections showed fairly equal moisture content on the top as well as on the bottom. Notably, TOSS CL6 2012 had the highest moisture content.

**Binder Content**

Ignition tests were conducted to find the binder content of the materials in the test sections and to determine whether the binder content had any effect on the other properties of the material. The standard procedures in ASTM D6307-10 were followed to provide the results (Table B2).
### Table B2 Binder content for TOSS-stabilized sections

<table>
<thead>
<tr>
<th></th>
<th>TOSS CL6 2013</th>
<th>TOSS CL6 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of the Pan (g)</td>
<td>1138.3</td>
<td>1138.3</td>
</tr>
<tr>
<td>Weight of the Sample (g)</td>
<td>3434.8</td>
<td>2084.1</td>
</tr>
<tr>
<td>Total Weight (g)</td>
<td>4573.1</td>
<td>3222.4</td>
</tr>
<tr>
<td>Total Weight After Ignition (g)</td>
<td>3332</td>
<td>2961.8</td>
</tr>
<tr>
<td>Weight of Sample After Ignition (g)</td>
<td>2193.7</td>
<td>1823.5</td>
</tr>
<tr>
<td>Percentage Asphalt Content (%)</td>
<td>36.133</td>
<td>12.504</td>
</tr>
</tbody>
</table>

The results indicate that the TOSS CL6 2013 section had a relatively higher asphalt content in comparison to the TOSS CL6 2012 section. It was clearly visible in the field that the TOSS CL6 2013 section had a higher asphalt content; in Figure B12 it can be seen that the material could be removed in clumps from the surface of the TOSS CL6 2013 section.

![Figure B12 TOSS LS CL6 2013 section with shingle clumps](image_url)
There may be a relationship between the fineness of the TOSS and asphalt content that may explain clump formation; it is recommended that this possibility be further investigated. It would also be desirable to find an optimal binder content after comparing the asphalt content with other properties.

**Scrape Test**

A scrape test was conducted on the test sections using a standard garden hoe modified with two plates welded to the sides. The test was conducted by a single person applying normal horizontal force to pull the hoe across the cross-section of the road. All of the loose surface material that was dragged along due to this action was collected and weighed. This test allowed the amounts of floating material on the surfaces of the test sections to be compared. Further testing could be conducted to provide more reliable values. Table B3 shows how TOSS stabilization reduced the amount of floating material on the road surfaces.

**Table B3 Scrape test results for all sections**

<table>
<thead>
<tr>
<th>Wt. of loose material on top (lb)</th>
<th>Control Section</th>
<th>TOSS CL6 2013</th>
<th>TOSS CL6 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>18</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>23</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>49</td>
<td>54</td>
<td></td>
</tr>
</tbody>
</table>

| Total Weight (lb) | 160 | 90  | 107 |

It can also be seen that the TOSS CL6 2012 section had comparatively less floating material than the TOSS CL6 2013 section. It was visually observed that the TOSS CL6 2013 section had a considerable amount of floating material on the shoulders. Figure B13 shows the control section after the scrape test was performed.
CONCLUSION

A summary of the test results is provided in Table B4. Because there was no established relationship between asphalt content and the performance of TOSS-stabilized crushed rock, it could not be concluded that better performance was expected with higher asphalt content. Also, the parameter by which dust reduction was compared among the test sections is unlikely to be appropriate because the dust emission data were collected at a different time from when the other data were collected. However, it is evident that the TOSS CL6 2012 section performed relatively well after 298 days, in that dust was reduced by 34%.

Figure B13 Control section after scrape test
Table B4 Comparison of the material properties of the test sections

<table>
<thead>
<tr>
<th>Properties</th>
<th>Control Section</th>
<th>TOSS CL6 2013</th>
<th>TOSS CL6 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve Analysis</td>
<td>Fine – 11%</td>
<td>Fine – 8.6 %</td>
<td>Fine – 14%</td>
</tr>
<tr>
<td>IRI Indexes</td>
<td>1.8</td>
<td>1.7</td>
<td>1.5</td>
</tr>
<tr>
<td>Stiffness (MPa)</td>
<td>54.94</td>
<td>61.56</td>
<td>84.87</td>
</tr>
<tr>
<td>Moisture (%)</td>
<td>1.42</td>
<td>1.72</td>
<td>2.08</td>
</tr>
<tr>
<td>Binder Content (%)</td>
<td>-</td>
<td>36.13</td>
<td>12.50</td>
</tr>
<tr>
<td>Floating Material (lb)</td>
<td>160</td>
<td>90</td>
<td>107</td>
</tr>
<tr>
<td>Dust Reduction (%) (Wood et al. 2014)</td>
<td>-</td>
<td>61 (After 14 days)</td>
<td>34 (After 298 days)</td>
</tr>
</tbody>
</table>

REFERENCES


APPENDIX C
MODIFIED PAVEMENT SURFACE EVALUATION AND RATING SYSTEM (PASER) CHART
<table>
<thead>
<tr>
<th>Rating</th>
<th>Very Good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Very Poor</th>
<th>Failed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Negligible use</td>
<td>Rate -1&quot; deep; rates over -10% of roadway</td>
<td>Rate 1&quot; to 3&quot; deep; rates over 15% to 35% of roadway</td>
<td>Rate 3&quot; to 6&quot; deep; rates over 40% of roadway; drivers tend to drive between the rates not through them</td>
<td>Rate 6&quot; to 12&quot; deep;</td>
<td>Rate over 12&quot; deep;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Washboarding</th>
<th>Very Good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Very Poor</th>
<th>Failed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Negligible corrugations</td>
<td>Corrugations generally -1&quot; deep; less than 10% of roadway with significant corrugations, little loss of vehicle control</td>
<td>Corrugations generally 1&quot;-2&quot; deep; 10%-25% of roadway with significant corrugations, more safety is significantly compromised as vehicle loses control</td>
<td>Corrugations generally 2&quot;-3&quot; deep; over 25% of roadway with significant corrugations. Major safety loss as drivers are tempted to drive faster, eliminating the need to stop the corrugations</td>
<td>Very Poor; Similar to &quot;Poor&quot; but deeper and more extensive corrugations</td>
<td>Failed; Similar to &quot;Very Poor&quot; but deeper and more extensive corrugations</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Potholes</th>
<th>Very Good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Very Poor</th>
<th>Failed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Negligible potholes</td>
<td>Some small potholes; most &lt;1&quot; deep and 1&quot; in diameter</td>
<td>Up to 3&quot; deep though not &gt;2&quot;, &lt;2&quot; in diameter</td>
<td>Many potholes, up to 6&quot; deep and 3&quot; in diameter</td>
<td>Up to 6&quot; deep and &gt;4&quot; in diameter</td>
<td>Impassable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loose Aggregates</th>
<th>Very Good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Very Poor</th>
<th>Failed</th>
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</thead>
<tbody>
<tr>
<td>Description</td>
<td>Negligible loose aggregate; Negligible risk of stripped roadbed</td>
<td>Loose aggregate is beams &lt;1&quot; deep; Loose aggregate is &lt;1/4&quot; thick</td>
<td>Loose aggregate is beams &lt;2&quot; deep; Loose aggregate is &lt;1.5&quot; thick</td>
<td>Loose aggregate is beams 2&quot;-4&quot; deep;</td>
<td>Very Poor; Loose aggregate in beams &gt;4&quot; deep;</td>
<td>Failed; Sand and dust</td>
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<table>
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<tr>
<th>Dust</th>
<th>None</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Not Rated</th>
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<tr>
<td>Description</td>
<td>Negligible dust; No visibility obstruction; No dust; No visibility obstruction due to material; Dust not assessed</td>
<td>Minor dust; No visibility obstruction; Dust not assessed</td>
<td>Significant dust; Obstructs visibility; Dust not assessed</td>
<td>Heavy dust; Major visibility obstruction; Dust not assessed due to material; Dust not assessed</td>
<td>Due to the material is the roadway surface; Dust not assessed</td>
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<table>
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<th>Crown</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Note</th>
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<tr>
<td>Description</td>
<td>Cross slope &lt;3%; Good</td>
<td>Cross slope &gt;3%; Fair</td>
<td>Cross slope &lt;1%; Poor</td>
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<table>
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<tr>
<th>Roadside Drainage</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
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<td>Description</td>
<td>Roadway above</td>
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<td>Roadway or below</td>
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<tr>
<td></td>
<td>surrounding terrain; Good</td>
<td>grade of</td>
<td>grade of</td>
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<tr>
<td></td>
<td>Ditches and culverts</td>
<td>surrounding terrain; Poor or no</td>
<td>surrounding terrain; Poor or no</td>
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<tr>
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<td></td>
<td>Ditches</td>
<td>Ditches</td>
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Note: | | | | | | | | | |
APPENDIX D
SOIL PROPERTIES OBTAINED FROM WEB SOIL SURVEY
<table>
<thead>
<tr>
<th>Material Code</th>
<th>Soil Name</th>
<th>Depth (in.)</th>
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<th>Liquid Limit (L-R-H)</th>
<th>Plasticity Index (L-R-H)</th>
<th>USCS</th>
<th>AASHTO</th>
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<td>M506B</td>
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