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Evaluation of Recycled Portland Cement Concrete Pavements for Base Course and Gravel Cushion Material

Study SD05-07
Final Report

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DISCLAIMER

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16. Abstract

Recyclable materials from construction and demolition operations were once disposed of in landfills. However, available landfill space continues to diminish. There is a need to use recyclable materials as recycled aggregate as a supplement to natural aggregates in order to conserve natural resources and to keep these products out of landfills.

Recycled portland cement concrete has been successfully used throughout the world in pavement construction. These materials have been used in unbound base layers as well as replacement aggregates in both portland cement concrete and hot mix asphalt. The South Dakota Department of Transportation wishes to investigate the potential of using recycled concrete aggregate produced from rigid pavements. Therefore, the objectives of this project are: 1) Determine if recycled portland cement concrete pavements should be used as a base course and/or gravel cushion; 2) Develop materials guidelines and specifications for construction pavements using recycled concrete aggregates; and 3) Develop laboratory and field material testing requirements for recycled concrete.

Based upon the work conducted in this study, it was concluded the recycled portland cement concrete pavements are available as an option for the construction of gravel cushion and aggregate base course layers. Recommendations were provided for material guidelines and construction of pavement layers using recycled concrete aggregates.

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INTRODUCTION

Recycled materials from construction and demolition operations were once disposed of in landfill sites. Concrete, for example, accounts for up to 67 percent, by weight, of construction and demolition waste in the US. There is a need to use recycled aggregate as a supplement to natural aggregates in order to conserve natural resources and keep concrete out of landfills. To accomplish this, several U.S. agencies have begun using recycled portland cement concrete (PCC) materials in highway construction. Recycled concrete aggregate (RCA) is nothing more than PCC crushed into aggregate-sized particles. These particles consist of the original aggregate particles and the adhered mortar. At least 36 states now use RCA in highway construction applications. A plausible use of recycled concrete materials within the highway construction industry is to utilize these materials in unbound granular layers. The use of recycled materials for unbound pavement layers has been successful around the world.

In order to specify the use of recycled materials for unbound pavement layers, it is important to understand what the function of these layers is within the pavement section. Depending on whether the pavement structure is flexible or rigid, the function of the unbound layer is different. For rigid pavements, the function of the unbound layer is to prevent pumping, protect against frost action, provide a construction platform, drainage of water, prevent volume change in the subgrade, and/or increase structural capacity. To prevent pumping, a base course must be either free draining or resistant to the effects of water. To increase structural capacity, the base course must be able to resist deformation due to loading. The role of the unbound layer for flexible pavements is different in that the primary function is to increase structural capacity.

In South Dakota, unbound granular layers under rigid pavements, or gravel cushions, are placed to serve as a construction platform. Typical thicknesses for the gravel cushions are 5 to 6 inches. These layers are not specifically designed and constructed for drainage purposes. Preferably, these layers are constructed to be impermeable.

Unbound granular layers under flexible pavements, or aggregate base courses, in South Dakota are designed and constructed to increase structural capacity. Typical thicknesses for aggregate base courses under flexible pavements are 12 to 14 inches. Similar to the gravel cushion layers, the unbound base layers are designed and constructed to be relatively impermeable.

Within South Dakota, the material and construction requirements for gravel cushions and aggregate base courses are provided in Sections 882 and 260, respectively, of the 2004 Standard Specifications for Roads and Bridges. Currently, the material requirements for granular bases in Section 882 do not allow the use of recycled concrete aggregate. The South Dakota Department of Transportation (SDDOT) wishes to investigate the potential of using recycled concrete aggregate produced from Department owned rigid pavements for utilization in DOT construction projects. Therefore, research is needed to determine if recycled concrete aggregates produced from demolished PCC pavements can be used in South Dakota. Of particular concern about recycled concrete aggregates is the long-term durability of these materials in a pavement layer.

OBJECTIVES

The objectives of this research included the following:

1) Determine if recycled portland cement concrete pavements should be used as a base course or gravel cushion.
2) Develop materials guidelines and specifications for construction of pavements using recycled concrete for base course or gravel cushion.
3) Develop laboratory and field material testing requirements for recycled concrete.

RESEARCH APPROACH

The research approach entailed three distinct phases of work. One phase involved conducting a literature review to determine the current state-of-art for using recycled concrete aggregates in unbound granular pavement layers. The second phase of work entailed contacting other state highway agencies to gather information on current specification, standards and practices dealing with the use of RCA in unbound granular pavement areas. The final phase of work was to conduct a comprehensive laboratory study on six sources of RCA obtained from South Dakota.

FINDINGS

The literature review and survey of states clearly indicated that recycled concrete aggregates (RCA) are a viable option in the construction of pavement structures. RCA materials have been used within PCC and hot mix asphalt as well as fill material in highway embankments. However, probably the largest use of RCA in pavement construction has been in the placement of unbound layers under both rigid and flexible pavements.

Based upon the literature review, there are two general characteristics that are related to the performance of unbound granular layers: stability and durability. Stability can be defined as the ability of the unbound granular layer to withstand the repetitive actions of traffic. Terms such as shear strength and stiffness are generally used to describe stability. Durability can be defined as the ability of the unbound granular layer to perform over an extended period of time. Characteristics related to durability include the ability to resist the actions of freezing and thawing, degradation, low density, etc. Other issues related to durability that might be specific to RCA are sulfate attack and alkali-silica reactivity (ASR). Because RCA is derived from the crushing of portland cement concrete, some agencies have expressed concern about both sulfate attack and ASR. Both of these potential destructive mechanisms are considered related to durability. Another issue that has been raised in the literature, and was specifically noted by SDDOT in the problem description for this project, is possible leachate from the RCA layer. Whenever dealing with any pavement layer, another issue that must be discussed is construction. The following sections discuss information derived from this research study for each of these topics.

Potential Leachate

The primary leachate problem described in the literature was the formation of calcite, or tufa, precipitates. The issue with the precipitates is that pavement drainage systems can become partially clogged and filter fabrics used in the drainage system can lose permittivity. Because unbound granular layers are constructed to be relatively impermeable, leachate will likely not be an issue. Another concern about leaching described in the literature was the existence of heavy metals in some RCA sources. However, the literature suggests that these hazardous materials are generated from the demolition of buildings and other structures. Because the current intent of SDDOT is to reclaim materials from PCC pavements, there should not be hazardous materials within the RCA.

Another potential problem with the use of RCA layers is that water passing through a RCA layer can become highly alkaline. The literature reports instances of metal culvert and rodent guard corrosion due to the highly alkaline effluent from pavement drainage systems that contain RCA materials. Vegetation kill has also been noted near some drainage system outlets. The literature indicates that pH levels in these instances can peak between 11 and 12 shortly after construction and level off near pH values of 9 over time. Again, because the current intent of SDDOT is to construct unbound layers that have low permeabilities, the increase in alkalinity reported in the literature is not considered a problem as water will not likely pass through the layer.

In summary, based upon the literature review and the specifications and construction practices in South Dakota, the placement of RCA materials under rigid or flexible pavement should pose no leachate or precipitate problems. The noted alkalinity problems should also not be a concern. If the SDDOT decides in the future to utilize building demolition as a reclaimed material, research should be conducted to evaluate whether any hazardous materials are contained with the RCA materials. Likewise, until the SDDOT decides to include RCA materials into pavement drainage systems, there should be no concerns with leachate or increased alkalinity of pore fluids.

Durability of RCA Materials

Durability is defined as the ability of a material to perform over an extended period of time. With respect to RCA used in an unbound granular layer, there are a number of issues that are related to durability. The literature and some state agencies have expressed a concern with the potential for sulfate attack and alkali silica reactivity (ASR) within RCA layers. As with virgin aggregate used in granular layers, the ability of individual particles to withstand the forces of freezing/thawing and wetting/drying is also a concern with RCA materials. Also, degradation of particles during transport, processing, placement and compaction is a concern. Degradation that occurs within any of these steps will change the gradation of the granular materials, potentially leading to durability problems.

Two chemical reactions that could potentially be problematic in the use of RCA are sulfate attack and ASR. Both of these reactions result in the expansion of the PCC contained within RCA. The Technical Panel indicated that ASR is a problem in some areas of South Dakota. With rigid pavements (from which the RCA will be produced in South Dakota), it is suspected that active ASR reactions will usually have ceased prior to the removal of the rigid pavement layer, especially if the pavement has reached its design life. Upon being processed into RCA, the cement and aggregate will become exposed. Because the particles are not confined in the RCA layer, any future degradation caused by the ASR is not expected to affect the RCA layer. In fact, no literature was found that noted occurrences of ASR affecting an unbound RCA layer.

Sulfate attack does appear to be an issue for unbound RCA layers, especially relatively thick layers. A reference was found where sulfate attack caused problems in an unbound layer that ranged from 2 to 5 ft in thickness. South Dakota does have soils (and most likely ground and surface water) containing sulfate ions. Therefore, sulfate attack is a concern at the anticipated layer thickness under flexible pavements (12 to 14 inches). This is especially true because the original materials within the PCC used to manufacture the RCA may not be known. There was difficulty determining materials used to manufacture the PCC utilized to create the RCA used in this project.

In order to minimize any potential effects of sulfate attack, testing for sulfates within subgrade soils and nearby surface water may be warranted. Both ASTM C1580, Standard Test Method for Water Soluble Sulfate in Soil, and ASTM D516, Standard Test Method for Sulfate Ion in Water, can be used to test soils and surface water. If water soluble sulfates in soils are greater than 0.10 percent by mass or sulfate in water is greater than 150 parts per million, RCA is likely not warranted. These values are based upon ACI and Mississippi DOT definitions for sulfate exposure. The values stated above for sulfate exposure are conservative because the lone RCA sample supplied by the SDDOT for this project in which the original materials were identified included a Type I cement. If the materials within the PCC pavement used to create the RCA are known and includes Type II cement, then the RCA can be placed in an area with moderate sulfate exposure.

A number of laboratory tests were conducted as part of this study to evaluate the durability of RCA materials. Unfortunately (but fortunately for SDDOT), the existing pavement sections within South Dakota that include RCA have performed. Therefore, the opportunity to conduct durability tests on RCA materials that have not performed was not available. (Inferences made on the results of the durability tests had to be made based upon the literature, experience and practicality.)

Tests conducted on the various RCA samples included in this study were Atterberg limits, sodium sulfate soundness, the New York Freeze/Thaw test, Los Angeles Abrasion and Impact, Micro-Deval and a combination of the New York Freeze/Thaw and Micro-Deval tests. Analyses of the test data showed some strong relationships between some of the durability tests. A strength of these relationships is that the various tests showed positive relationships, signifying that both tests within the relationship indicated reduced durability with increasing test results. The sodium sulfate soundness, Los Angeles Abrasion and Impact and Atterberg limits were shown to provide good indications of durability. If results of sodium sulfate soundness testing appear excessively high, then an alternative test method would be the freeze/thaw test provided in the Final Report.

Stability of RCA

Tests conducted to evaluate stability included the repeated load shear, resilient modulus, and CBR tests. Results from the analyses indicated three characteristics were important for the stability of RCA materials: gradation, angularity of particles and cleanliness. The literature indicated that the gradation for RCA materials does not have to be different than typical aggregates when the intended purpose is as an unbound granular pavement layer. AASHTO M319 also states that RCA materials should meet applicable agency gradation requirements. Therefore, gradations contained within Section 882 of the SDDOT Standard Specification for gravel cushion and aggregate base course are acceptable when using RCA materials.

Based upon the test results and analyses conducted for this study, the crushing of reclaimed PCC pavements resulted in sufficiently angular particles to provide a stable unbound granular layer as long as undesirable natural, dirty or round aggregates are not added. Results from the Atterberg Limits will likely identify when dirty materials are added to the RCA.

Construction Issues

During the course of this study, there was one issue that arose that could have an impact on construction activities. This one issue had to do with the high water absorption values. Recall during the standard Proctor testing that results were erratic. However, once the RCA materials were allowed to soak overnight, testing results became much more reasonable. Similar issues could arise during construction.

Section 260.3 of the SDDOT Standard Specifications states that either road mix or plant mix methods can be used to prepare the granular materials for placement. No matter which method is used to prepare the RCA materials, there could be varying amounts of time between when the water is added to the RCA materials and compaction is accomplished. Therefore, compaction of the RCA materials could be variable. In an effort to remedy this potential variability, good construction practices would be to maintain the RCA materials at or near a saturated surface dry (SSD) condition.

CONCLUSIONS

Based upon the research conducted, the following conclusions were drawn:

- Recycled portland cement concrete pavements are a viable option for use in gravel cushion and aggregate base course construction.
- Because the SDDOT specifies and constructs gravel cushion and aggregate base course layers to be relatively impermeable, leachates or precipitates should pose no problems.
- Alkali-Silica reactivity is not considered a potential problem in gravel cushion or aggregate base course layers; however, it is unclear if some new deicing materials could affect the potential for alkali-silica reactivity problems in the future.
- There is a concern about sulfate attack in thick layers of gravel cushion or aggregate base course. The critical thickness is not known.
- Results from the Micro-Deval test were not found to be related to durability as defined by the lack of strong relationships with other durability tests.
- The sodium sulfate soundness test had a strong relationship with results from the Los Angeles Abrasion and Impact test and the combined New York Freeze/Thaw and Micro-Deval test. Results of the sodium sulfate test are considered an indicator of durability.
- There is a potential that the sulfates contained in the sodium sulfate solution during soundness testing can attack the cement mortar within the recycled concrete aggregate

resulting in artificially higher loss values. In these instances, the New York Freeze/Thaw test can be used as a surrogate test for the sodium sulfate soundness test.

- The Los Angeles Abrasion and Impact test had a strong relationship with the sodium sulfate soundness and New York Freeze/Thaw test. Results from the Los Angeles Abrasion and Impact test are considered related to durability.
- Results from the Atterberg limit testing, namely the liquid limit and plasticity index, identified potentially harmful fine materials added to RCA materials. Results of Atterberg limit testing is considered related to durability.
- Strong and stable gravel cushion and aggregate base course layers can be attributed to the gradation, angularity and cleanliness of the RCA materials. Current gradation requirements contained within SDDOT specifications for gravel cushion and aggregate base course are applicable.
- Recycled portland cement concrete pavements have a relatively high level of water absorption. This relatively high level of water absorption could potentially make the proper compaction of gravel cushion and aggregate base course layers variable.

RECOMMENDATIONS

Number	Recommendation	Reason/Benefit of Recommendation
1	Recycled portland cement concrete pavements should be allowed within gravel cushion and aggregate base course layers.	Results from this study as well as the experiences of other agencies suggest that recycled portland cement concrete pavements are an acceptable alternative for granular pavement layers. The recycled concrete aggregates should meet the requirements of the Revised Sections 260 and 882 of the South Dakota Standard Specifications presented in Appendices C and D of this report.
2	Only recycled portland cement concrete pavements owned by the Department should be allowed on new Department projects.	A number of references within the literature reported variability in the properties of recycled concrete aggregates when produced from construction/demolition debris. Research results derived from this study were based upon the testing of recycled rigid pavements and, therefore, are not applicable to construction/demolition debris.

3	Recycled concrete aggregates crushed from Department owned pavements can be blended with conventional aggregates.	The literature states that recycled concrete aggregates can be blended with conventional aggregates; however, the recycled concrete aggregates should still meet all applicable requirements for gravel cushion or aggregate base course.
4	The cleanliness of recycled concrete aggregates should be specified. It is recommended that the Department maintain the requirements of a maximum liquid limit of 25 and maximum plasticity index of 6.	One of the six recycled concrete aggregate samples included within this study contained natural, dirty and rounded fine materials. This recycled concrete aggregate had low shear strength and was deemed undesirable. Results of the Atterberg limits identified this poor performer.
5	In order to minimize any potential effects of sulfate attack on recycled concrete aggregate layers, the Department should test nearby subgrade soils and surface water for sulfates. ASTM C1580, Standard Test Method for Water Soluble Sulfate in Soil, and ASTM D516, Standard Test Method for Sulfate Ion in Water, should be used. Requirements within Table 2 should be followed.	The literature suggested that sulfate attack may be applicable to relatively thick unbound layers of recycled concrete aggregates used as fill material. No definitive information was found that limited the thickness of recycled concrete aggregate layers with respect to potential sulfate attack problems. Within the single reference identifying potential sulfate problems, the fill thicknesses ranged from 2 to 5 ft.
6	The sodium sulfate soundness test should be used to evaluate the durability of potential recycled concrete aggregates for gravel cushion and aggregate base course. A maximum value of 15 percent is recommended.	Section 882 of the Departments Standard Specifications does not currently include a test to specify the durability of aggregates for granular bases. The sodium sulfate soundness test was identified as related to durability during this study.
7	The “Resistance of Coarse Aggregates to Degradation by Freeze/Thaw” test contained in Appendix B of the Final Report should be utilized if the results of the sodium sulfate soundness test is greater than 30 percent. A maximum value of 15 percent for this freeze/thaw test is recommended.	The literature suggests that some recycled concrete aggregates perform poorly during the sodium sulfate soundness test. This poor performance is related to the sulfates contained within the sodium sulfate solution.

8	The Los Angeles Abrasion test is recommended to evaluate the toughness and durability of recycled concrete aggregates. A maximum percent loss of 40 percent is recommended.	The Los Angeles Abrasion test showed a strong relationship with the sodium sulfate soundness and freeze/thaw tests. Based upon the results of this study and the literature, the Los Angeles Abrasion test is warranted within the Department's standard specifications.
9	No changes are recommended to the current gradation requirements for gravel cushion or aggregate base course.	The literature suggests that gradation requirements for recycled concrete aggregates should be similar to that of conventional aggregates. No data collected within this study suggests otherwise.
10	Recycled concrete aggregate stockpiles should be maintained at a moisture content representative of a saturated surface-dry condition.	The recycled concrete aggregate samples included within this study were highly absorptive. Water absorption values for all six of the samples were above 5 percent. Problems with conducting Standard Proctor testing suggested that the recycled concrete aggregates need to be maintained at a moisture content near saturated surface-dry conditions or compaction of these materials may be highly variable.

CHAPTER 1 INTRODUCTION

1.1 Problem Statement

There are several factors that are driving forces to encourage an agency to consider using recycled materials (1) which include:

- Increasing shortage of natural aggregates
- high cost of landfill disposal
- commitment to environment
- conservation of resources
- local availability
- political pressure
- environmental safety

Recycled materials from construction and demolition operations were once disposed of in landfill sites. Concrete, for example, accounts for up to 67 percent, by weight, of construction and demolition waste in the U.S. Yet only about 5 percent is currently recycled (2). However, the availability of landfills for this purpose has rapidly diminished. In 1981 there were 50,000 landfills available in the United States for disposal of waste products. Today there are only 5,000 landfills available for waste product disposal (3). As landfill space becomes more critical, so do the regulations governing their operations. In some cases tipping fees for waste disposal have increased to the point that other alternatives must be found.

From an environmental perspective it is also essential that these materials be recycled where possible. The potential exhaustion of natural resources is not acceptable and has caused government and industry leaders to reconsider attitudes and actions concerning recycling. In addition, the permitting process for opening new aggregate quarries has become a burdensome task for suppliers due to increased environmental regulations. Due to the need to conserve our natural resources and preserve the environment, several agencies now provide incentives to those who utilize recycled materials.

There is a need to use recycled aggregate as a supplement to natural aggregates in order to conserve natural resources and keep concrete out of landfills (4). To accomplish this, several U.S. agencies have begun using recycled portland cement concrete (PCC) materials. Recycled concrete aggregate (RCA) is nothing more than PCC crushed into aggregate-sized particles. These particles consist of the original aggregate particles and the adhered mortar (5). At least 36 states now use RCA in highway construction applications. A plausible use of recycled concrete materials within the highway construction industry is to utilize these materials in unbound base course or gravel cushion applications (6). A number of European countries have requirements that recycled aggregates be utilized. The United Kingdom has put forth an initiative to include 25 percent recycled aggregates in construction (7). The use of recycled materials for unbound pavement layers has been successful around the world.

In order to specify the use of recycled materials for unbound pavement layers, it is important to understand what the function of these layers is within the pavement section. Depending on whether the pavement structure is flexible or rigid, the function of the unbound layer is different. For rigid pavements, the function of the unbound layer is to prevent pumping, protect against frost action, provide a construction platform, drainage of water, prevent volume change of the subgrade, and/or increase structural capacity. To prevent pumping, a base course must be either free draining or resistant to the effects of water. To increase structural capacity, the base course must be able to resist deformation due to loading. The role of the unbound layer for flexible pavements is different in that the primary function is to increase structural capacity.

In South Dakota, unbound granular layers, or gravel cushions, under rigid pavements are placed to serve as a construction platform. Typical thicknesses for the gravel cushions are 5 to 6 inches. These layers are not specifically designed and constructed for drainage purposes. Preferably, these layers are constructed to be impermeable.

Unbound base layers under flexible pavements, or aggregate base courses, in South Dakota are designed and constructed to increase structural capacity. Typical thicknesses for aggregate base courses under flexible pavements are 12 to 14 inches. Similar to the gravel cushion layers, the unbound base layers are designed and constructed to be relatively impermeable.

Within South Dakota, the material and construction requirements for gravel cushions and base courses are provided in Sections 882 and 260, respectively, of the 2004 Standard Specifications for Roads and Bridges. Currently, the material requirements for granular bases in Section 882 do not allow the use of recycled concrete aggregate. The South Dakota Department of Transportation (SDDOT) wishes to investigate the potential of using recycled concrete aggregate produced from Department owned rigid pavements for utilization in DOT construction projects. Therefore, research is needed to determine if recycled concrete aggregates produced from demolished portland cement concrete pavements can be used in South Dakota. Of particular concern about recycled concrete aggregates is the long-term durability of these materials in a pavement layer.

1.2 Objectives

The objectives of this research included the following:

1) Determine if recycled portland cement concrete pavements should be used as a base course or gravel cushion.
2) Develop materials guidelines and specifications for construction of pavements using recycled concrete for base course or gravel cushion.
3) Develop laboratory and field material testing requirements for recycled concrete.

CHAPTER 2 RESEARCH PLAN

2.1 Introduction

The revised work plan identified eleven tasks required to accomplish the objectives of this research project. The following sections briefly describe the approach to accomplish the research objectives. Figure 1 presents a flow diagram illustrating how the eleven tasks were conducted.

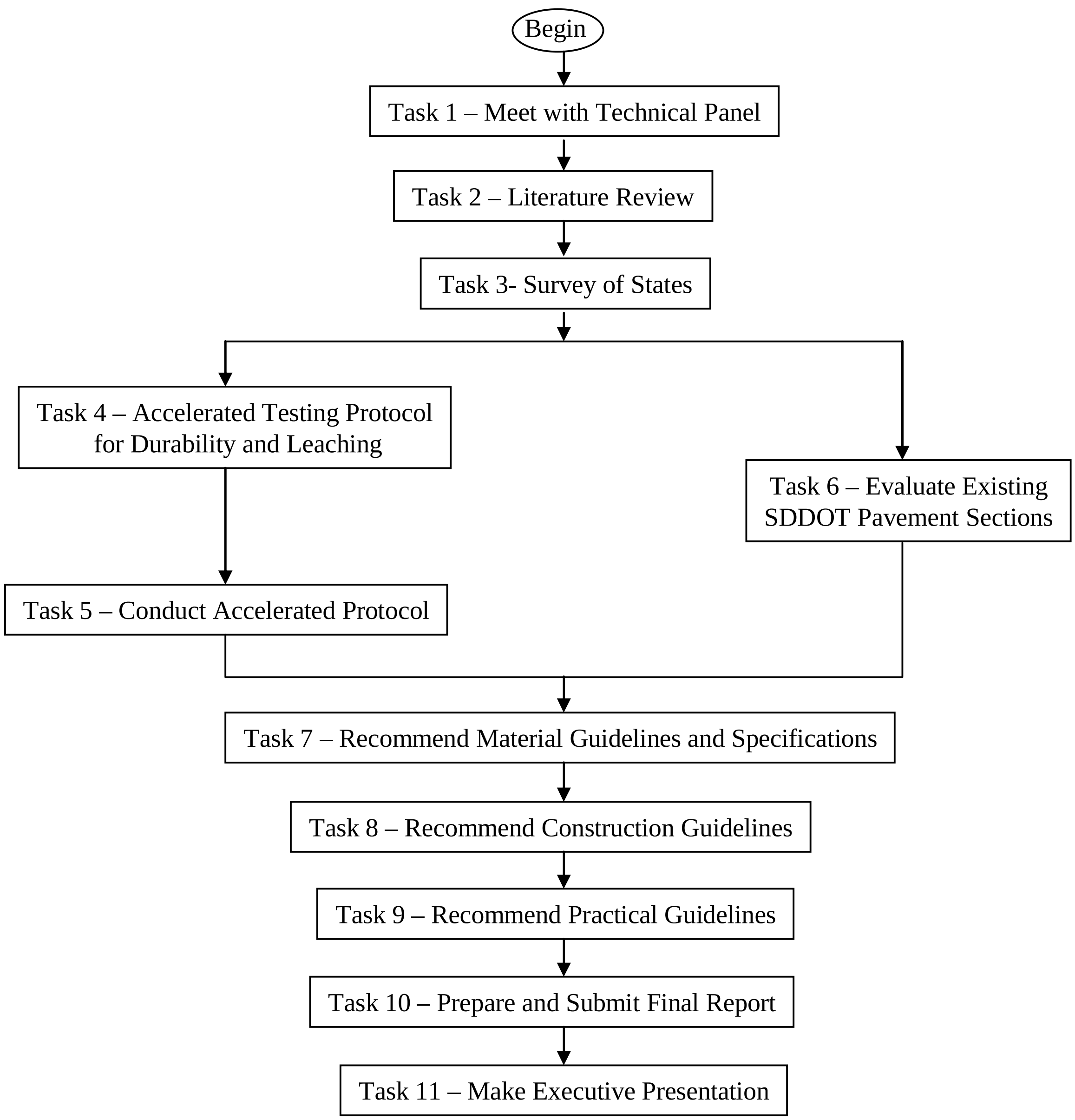


Figure 1: Flow Diagram Illustrating Research Approach

2.2 Task 1 – Meet with Project's Technical Panel to Review Project Scope and Work Plan

Prior to initiating the research project, it was necessary for the researchers to meet with the project Technical Panel. This meeting was held June 15, 2005. The meeting was used to allow the researchers and the project technical panel to discuss the project scope and work plan. During the meeting, the research team presented background information developed during preparation of the proposal and the proposed research approach. Minutes of the meeting are provided in Appendix A of this report. In addition to the formal meeting, the researchers met with various SDDOT personnel to develop background information pertinent to this project.

2.3 Task 2 – Review Current Literature, Including Other State's Experiences, Regarding Use of Recycled Concrete as a Base Course or Gravel Cushion.

Task 2 involved reviewing available literature on the use of RCA in pavement systems. Chapter 3 of this report presents the results of Task 2. The literature included published papers as well as reports and articles on the use of RCA. The literature review combined with the Task 3 survey was conducted to answer the following questions:

1) What is the current state of knowledge and art for the use of recycled concrete aggregate as an unbound pavement layer under rigid and flexible pavements? What physical and/or chemical properties of recycled concrete can affect the performance of these materials in pavement structures?

2) What test procedures, or quality standards, are being used to determine the acceptability of recycled concrete aggregate materials? How do these quality standards fit with current South Dakota DOT procedures?

3) What issues or concerns with the use of recycled concrete aggregate as unbound pavement layers can be identified that should be addressed in conducting this research?

2.4 Task 3 – Interview Other States to Evaluate Their Experiences Using Recycled Concrete to Include Laboratory and Field Tests, Pavement Performance, Training, Costs, etc.

During Task 3, the research team contacted a number of state Departments of Transportation from around the US. During these interviews/surveys, information was gathered on the use of RCA as an unbound pavement layer. Specifically, information was gathered on current specifications, standards and practices dealing with the use of RCA for both gravel cushions underlying rigid pavements and unbound granular bases underlying flexible pavements. Also of importance during the surveys was to identify situations or conditions in which RCA materials cannot be used as unbound pavement layers. Results of Tasks 3 are provided in Chapter 4 of this report.

2.5 Task 4 – Propose Accelerated Testing Protocol to Determine Freeze-Thaw and Leaching Performance

During the Task 1 meeting with the Technical panel, the SDDOT stated that the durability of RCA was the major concern for the Department. In the past, the SDDOT had been reluctant to use RCA because of these concerns. Therefore, the researchers identified a number of tests that would evaluate the durability of RCA materials.

Based upon the literature review and survey of states conducted in Tasks 2 and 3, respectively, a number of tests were identified to evaluate durability. The most common tests to evaluate durability of granular pavement layers were freeze/thaw tests. Two freeze/thaw tests were identified and utilized during the project: sodium sulfate soundness and the New York Freeze/Thaw test. Another category of test that can be related to durability is toughness/abrasion tests. Two test methods were selected to evaluate the toughness/abrasion characteristics of the RCA materials: Los Angeles Abrasion and Impact and the Micro-Deval test. The Micro-Deval test was selected because it includes the introduction of water within the test method and; therefore; may be a better predictor of durability.

To further evaluate the durability of the RCA materials, the New York Freeze/Thaw test and Micro-Deval test were combined. Initially, the New York Freeze/Thaw test was conducted on the materials, then the Micro-Deval test was performed. This testing methodology was selected because it was considered a harsh test to evaluate durability as the combination of the two methods included both freeze/thaw cycles and wet abrasion.

The final test selected for durability was the resilient modulus test. During conversations with SDDOT personnel, there were concerns that the exposed PCC mortars may re-cement. If this occurred, flexible pavements may act as full depth asphalt pavements which, according to the Department, have not performed well within South Dakota. Therefore, a portion of the RCA materials were selected to evaluate the potential for the exposed PCC mortars to re-cement. As part of the characterization of the RCA materials, resilient modulus testing was conducted. In order to evaluate the potential for re-cementing, samples were prepared and stored in a temperature and humidity controlled room for 128 days. As per ASTM C511, Standard Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes, the samples were stored in a moist room maintained at 73.4 ± 3.6°F (23.0 ± 2.0° C) with a relative humidity of not less than 95 percent. At varying intervals, samples were removed from the moist room and the resilient modulus determined. If re-cementing occurred, the resilient modulus (or stiffness) should increase.

As stated above, only a portion of the RCA materials were tested in this manner. Selection of the RCA materials for this testing was based upon gradation, Los Angeles Abrasion and Impact loss and the percent flat and elongated particles. Specific to the gradation was the percentage of material passing the No. 200 (0.075mm) sieve (fines). Materials with higher fines content potentially have more exposed mortar which would increase the possibility of re-cementing. The Los Angeles Abrasion loss and percent flat and elongated particles were utilized in the selection process for a similar reason. Higher percentages of loss or flat and elongated particles indicate a higher potential for RCA particle breakdown when compacting the test samples. Breakdown of the RCA particles would potentially expose unhydrated cement within the mortar resulting in a higher potential for re-cementing.

2.6 Task 5 – Conduct Accelerated Durability Testing

Once the testing protocol for evaluating the durability of RCA was developed, testing was conducted.

2.7 Task 6 – Evaluate Existing SDDOT Pavement Sections

The intention of Task 6 was to evaluate existing SDDOT pavement sections in which RCA materials had been used. During the Task 1 Technical Panel meeting, SDDOT indicated that there are very few projects in which RCA has been used. All of the projects that had utilized RCA were performing satisfactorily. Because the pavements were performing as intended, SDDOT did not desire to conduct any destructive testing to evaluate the performance of the RCA materials. Therefore, with the concurrence of the Technical Panel, Task 6 involved obtaining RCA materials from South Dakota and conducting tests to characterize their suitability for use as granular pavement layers.

The SDDOT identified six RCA materials currently being crushed within South Dakota for use in this study. Each of the six RCA materials were subjected to a series of classification tests that included: Los Angeles Abrasion, Micro-Deval, sodium sulfate soundness, particle size analysis, coarse aggregate angularity, particle shape, and specific gravity and absorption. These same six RCA materials were also included within the Tasks 4 and 5 durability evaluations.

In addition to the classification tests used to characterize the different RCA materials, three tests were used to evaluate the mechanical properties of the materials including resilient modulus, shear strength and the California Bearing Ratio. The shear strength was measured using a procedure recommended at the conclusion of National Cooperative Highway Research Program Project 4-23, Performance Related Tests of Aggregates for use in Unbound Pavement Layers (*8*).

2.8 Tasks 7 through 11 - Deliverables

Tasks 7 through 11 represent the deliverables for this project. Results from Tasks 1 through 6 were utilized to develop recommendations on the use of RCA materials as gravel cushion or aggregate base course layers as well as material requirements.

CHAPTER 3 LITERATURE REVIEW

3.1 Introduction

The available literature on recycled concrete aggregate (RCA) can be divided into three general areas: use and limitations of recycled materials, current tests and potential performance-related tests, and specifications. The following sections present the results of the literature review for these three categories.

3.2 Use and Limitations of Recycled Concrete Materials

Portland cement concrete (PCC) is becoming a burdensome waste in many areas. Goldstein (9) states that more concrete is consumed per year than any other substance except water. He reports that the equivalent of one ton of concrete is produced for each person on Earth every year. When concrete reaches the end of its lifespan, it must be disposed of properly. Concrete accounts for up to 67 percent, by weight, of construction and demolition waste. Yet, in 1995 only about 5 percent was being recycled (10).

The Federal Highway Administration (FHWA) indicates that approximately 2 billion tons of natural aggregate are produced each year in the US (11). Aggregate production will likely increase to over 2.5 billion tons per year by 2020. This needed volume of aggregate has raised concerns about the availability of natural aggregates in the coming years.

In 2001, NCHRP Project 4-21, "Appropriate Use of Waste and Recycled Materials in the Transportation Industry," provided a database (12) that showed at least 36 states used reclaimed concrete material in highway construction applications. At least 11 states allowed its general use mainly as an aggregate in granular base or subbase applications. An August 2002 survey distributed by the Federal Highway Administration (FHWA) via electronic mail indicated that the transition toward recycling of concrete is now widespread. That survey showed that only 9 states do not currently recycle concrete as indicated in Figure 2. However, some of these states may have little or no concrete pavements available for recycling.

Three states, Alabama, Delaware, and Georgia did not respond to the FHWA survey, but phone contact with each of the three states indicated that recycled concrete was allowed in certain roadway applications. The same FHWA survey showed that only 11 states (Maryland and Oregon were included with the previous nine) did not permit recycled concrete to be used in aggregate base courses. A few of the 11 states indicated previous problems with alkali silica reactivity (ASR) in some of their concrete products and have, therefore, been cautious about recycling those materials into other roadway materials.

Chesner et al (13) reported on the use of 19 waste and by-product materials reused in the highway construction industry. The report lists properties of these materials, how they are being used, and limitations that may be considered for their use. Recycled concrete aggregate is used in PCC pavement, granular base, and embankment fill. The quality of recycled materials often varies depending on source and may need to be blended with conventional aggregates in order to meet typical strength requirements.

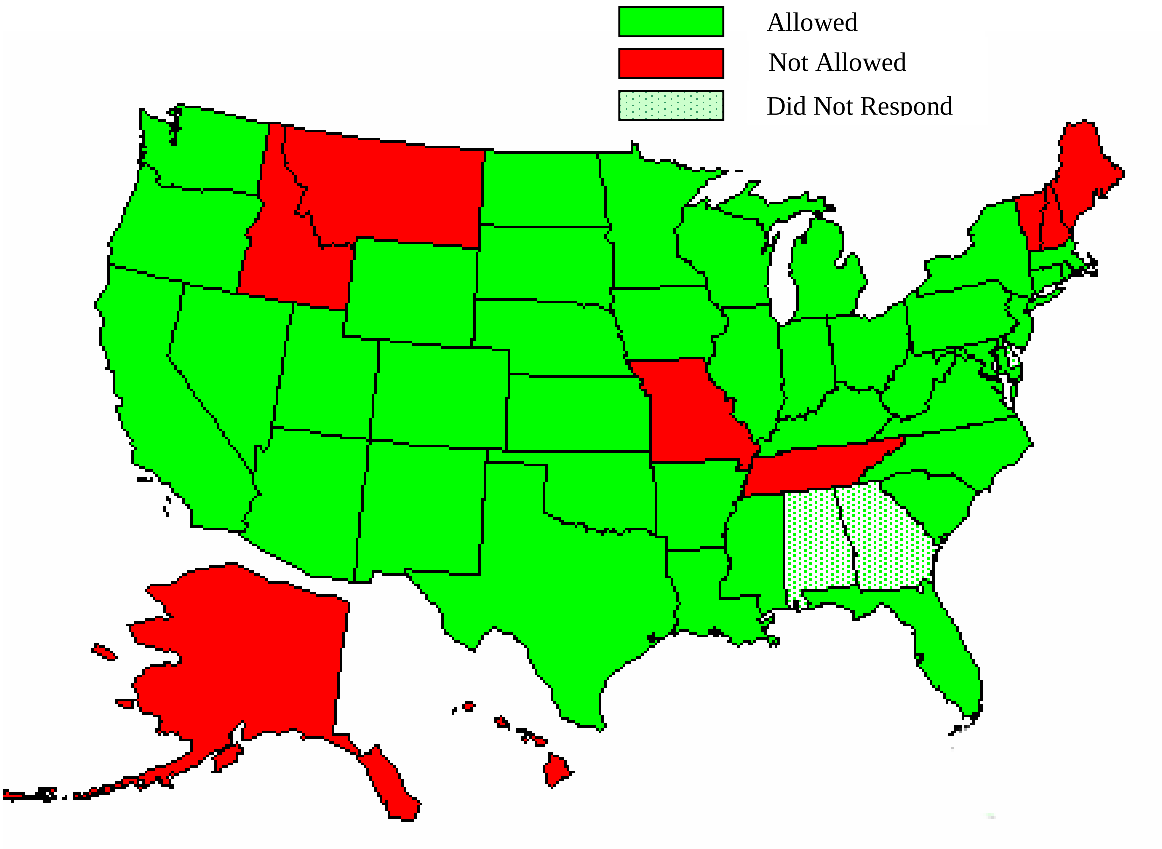


Figure 2: Responses to FHWA Survey Regarding Recycling of Concrete

Work by Bennert et al (14) with New Jersey materials showed that recycled asphalt pavement (RAP) material was much more likely to have higher permanent strain than dense-graded aggregate base course (DGABC) unless it was blended with natural aggregate. In that research, 25 percent RAP performed almost identically to the 100 percent DGABC. As the percent RAP was increased, the permanent strain also increased and at 100 percent RAP the permanent strain accelerated quickly under repeated load conditions as shown in Figure 3. However, the same research showed that the use of 100 percent RCA may actually result in base courses that have less permanent strain under repeated loading than DGABC with conventional aggregate.

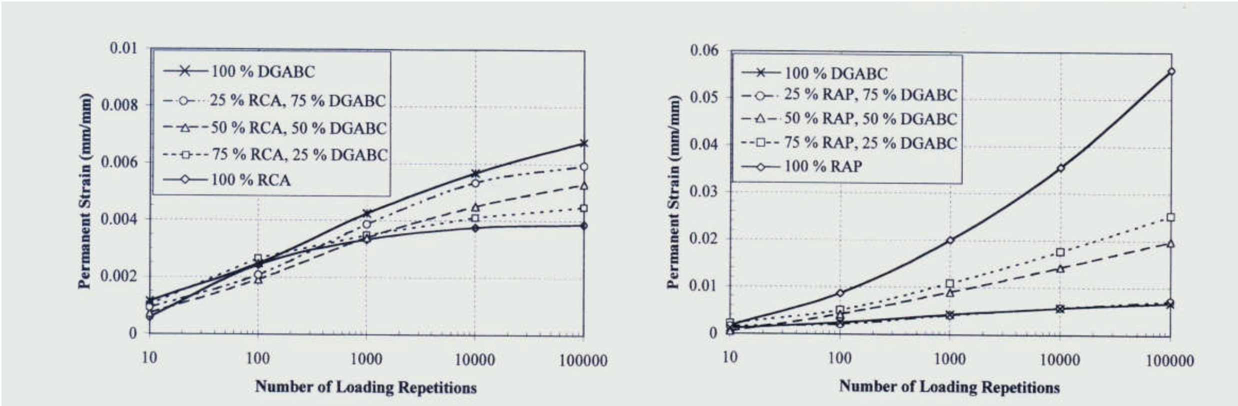


Figure 3: Permanent Strain Results for RCA and RAP Blended Samples (14)

Unlike RAP, RCA material may perform quite well without the need for blending with conventional aggregates. Petrarca (15) investigated the use of RCA on some local projects in New York between 1977 and 1982. Concrete used for recycling in Petrarca's study was crushed from sidewalks, driveways, curbs, and pavements. More than 100 tests were conducted and it was determined that crushed concrete consistently met all requirements for excellent long-term performance as dense-graded aggregate base or subbase. However, the quality of aggregates with sources used to produce RCA will depend on the original intended use of the PCC (12). For example, precast concrete typically uses smaller aggregate size and requires PCC with higher compressive strength than other concrete structures or pavements. Also factors such as air entrainment may affect the suitability of RCA for highway construction uses.

Petrarca (15) also found that crushing and screening operations had a considerable effect on the stability of RCA granular base materials. For example, when an additional crusher was added to plant operations to increase the quality of crushed particles, California Bearing Ratio's (CBR) values increased by 17 percent and density increased by 1.5 lb/ft^3.

There are some concerns with the use of RCA materials in certain pavement layers. Snyder and Bruinsma (16) reported on five field studies and five laboratory studies to evaluate the use of RCA materials in unbound layers underneath pavements. Field studies reported by Snyder and Bruinsma (16) included evaluations of existing pavement drainage systems for pavements utilizing RCA base materials and monitoring of various test sections containing RCA materials and natural aggregates. Based on the field studies, RCA materials within drainage base layers have the potential to precipitate calcium carbonate materials (called calcite). The calcium carbonate precipitates are created from calcium hydroxide ions present in exposed cement paste, water, and atmospheric carbon dioxide (17). These precipitates can significantly reduce the permittivity of drainage filter fabrics used within pavement drainage systems. However, permittivity can also be reduced by insoluble residue that is not related to the use of RCA materials.

Effluent from drainage layers containing RCA materials are generally very alkaline. Snyder and Bruinsnma (16) reported pH levels as high as 11 to 12 from some of the field sections and from the laboratory studies. However, laboratory work indicated that the pH levels reached a peak shortly after water was introduced and decreased over time. Reports of vegetations kills near drain outlets were noted. However, Snyder and Bruinsma indicated that insects and frogs were living in the effluent.

The laboratory studies described by Snyder and Bruinsma (16) indicated that the amount of calcium carbonate precipitate was proportional to the amount of RCA materials passing the No. 4 (4.75mm) sieve. Washing RCA during processing practically eliminates the formation of the calcium carbonate precipitates.

There may also be other environmental concerns with the use of RCA. Constituents in the effluent from one RCA stockpile study that are considered hazardous were arsenic, chromium, aluminum, and vanadium (16). These elements were present in quantities that exceed drinking water standards. However, it is not clear if drinking water standards should apply to the pavement base discharge since it will be diluted many times over within a short distance from the point of discharge (16). It should also be stated that the RCA used in this study was created from building demolition and not pavements. High chloride contents in RCA may present problems in areas of the country where de-icing salts are used in winter maintenance operations (13).

The potential for alkali-aggregate or alkali-silica reactivity (AAR or ASR) that may cause expansion and cracking has also limited the use of RCA in some applications. Concrete that has deteriorated as a result of alkali-aggregate reactions (AAR) may raise some concern about its suitably for reuse. This is clearly the case if the recycled material is to be reused in new PCC. For use in unbound base courses, the primary issue would seem to be one of individual particle degradation, and in this sense would affect unbound base performance in a manner similar to that of freeze-thaw susceptible or moisture-sensitive aggregate particles. Because aggregate particles in unbound aggregate bases are not confined as they are in PCC, the degradation is not expected to cause an overall expansion of the structural material. Rather, it might cause particle breakdown leading to reduced shear strength.

There are two distinct reactions affecting rocks included in AAR. In both cases, the physical response is triggered by chemical reactions involving highly alkaline pore solutions in the concrete and components in the aggregates. The reactions are classified by the specific aggregate type or component involved in the reaction: the breakdown of dolomite in the case of alkali-carbonate reaction (ACR); and dissolution of silica or siliceous components in alkali-silica reaction (ASR) (18). In both cases, the physical response is the development of internal stress within the aggregate particle that can lead to fracturing and expansion of the concrete.

Of the two reactions, ASR is far more prevalent because of the wide variety of rocks that are susceptible. In ASR, highly alkaline pore solution attacks the siliceous components of the aggregates producing an alkali-silica gel. The gel reaction product is hygroscopic and can swell when provided moisture; with swelling potential dependent on its chemistry (19). Although reactive constituents occur in both coarse and fine aggregates, durability problems are more often associated with coarse aggregate particles (20).

The ACR affects a small suite of rock with a very specific set of characteristics: roughly equal amounts of calcite and dolomite, with a significant amount (5-35 percent) of insoluble residue. The rocks exhibit a typical texture of dolomite rhombs floating in a fine-grained matrix of calcite and acid-insoluble minerals (18). The alkaline pore solution attacks the dolomite crystals, releasing magnesium that combines with hydroxyl to form brucite with an increase in volume. The volumetric increase causes fracturing of the aggregate particle leading to increased access of fluid to the interior of the particle.

In the case of massive concrete elements, expansions resulting from AAR can continue for extended periods of time. With pavements and other thin elements, it is suspected that active AAR reactions will usually have ceased prior to removal of the concrete because of chemical factors that lower the alkalinity of the pore solution and, in the case of ASR, transform the gel from a swelling to non-swelling state. In such cases it seems unlikely the reuse of the material in an unbound base course would reactivate damaging AAR; but, the damaged particles could have an effect on performance that should be picked-up by other tests that evaluate the integrity and resistance to mechanical breakdown of the particles.

In certain situations, concrete may be removed while the AAR is still active. Stockpiling of crushed concrete would likely serve to diminish the potential for further AAR deterioration. This is suspected since alkalis could leach from the paste and exposed paste surfaces and ASR gel would begin to carbonate, thus shifting the chemical balance away from that needed to promote expansion. Thus, the most likely scenario for AAR to affect the performance of an unbound aggregate base exists in situations where the removed concrete was actively undergoing AAR, and the crushed material was quickly reused in the base course. However, this potential period for expansion of particles in a base course would likely be short, since the same processes of leaching and carbonation could proceed in the unbound pavement layer.

There have been published occurrences of sulfate attack in RCA materials. Prior to discussing these published occurrences, a brief description of the mechanisms of sulfate attack is provided. There are a number of chemical compounds common to portland cement (Table 1). Of particular importance to sulfate attack are tricalcium aluminate (C_3A) and gypsum (C_SH_2). During hydration, the C_3A reacts with sulfate ions that are produced from the dissolution of gypsum (21, 22). The by-product of the reaction between C_3A and gypsum is ettringite. Ettringite is a stable compound as long as there is an ample supply of sulfate ions. When sufficient sulfate ions are not available, the ettringite is converted to monosulfoaluminate.

Sulfate attack only occurs after the concrete has hardened. When the monosulfoaluminates come into contact with a new source of sulfate ions (from soils with high sulfate contents, groundwater, seawater, etc.), the monosulfoaluminates are converted back into ettringite (21). The conversion of monosulfoaluminate to ettringite is accompanied by a large increase in volume (above 200 percent) (22). This increase in volume can lead to massive expansion forces and subsequent cracking within a hardened concrete.

Table 1: Typical Composition of Ordinary Portland Cement (21)

Chemical Name	Chemical Formula	Shorthand Notation	Weight Percent
Tricalcium silicate	$3CaO\ SiO_2$	C_3S	50
Dicalcium silicate	$2CaO\ SiO_2$	C_2S	25
Tricalcium aluminate	$3CaO\ Al_2O_3$	C_3A	12
Tetracalcium aluminoferrite	$4CaO\ Al_2O_3\ Fe_2O_3$	C_4AF	8
Calcium sulfate dehydrate (gypsum)	$CaSO_4\ 2H_2O$	CSH_2	3.5

The American Concrete Institute (ACI) has published requirements for the cements used in concrete exposed to sulfate-containing materials (23). These requirements are based upon limiting the amount of C_3A to reduce the potential of sulfate attack. Table 2 presents the ACI requirements. This table indicates ranges of sulfate exposure based upon the percentage of sulfates within soils and ground/surface water. The four categories include negligible exposure, moderate exposure, severe exposure and very severe exposure. These requirements were developed for building codes; however, at least one state DOT has adopted similar requirements for transportation construction (24). The Mississippi Department of Transportation has adopted similar requirements to the ACI requirements (Table 3).

Table 2: Requirements for Concrete Exposed to Sulfate-Containing Solutions (24)

Sulfate Exposure	Water soluble sulfate (SO4) in soil, percent by weight	Sulfate (SO4) in water, ppm	Cement Type
Negligible	$0.00 \leq SO_4 < 0.10$	$0 \leq SO_4 \leq 150$	
Moderate	$0.10 \leq SO_4 < 0.20$	$150 \leq SO_4 < 1500$	II, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)
Severe	$0.20 \leq SO_4 \leq 2.00$	$1500 \leq SO_4 \leq 10,000$	V
Very Severe	$SO_4 > 2.00$	$SO_4 > 10,000$	V plus pozzolan

Table 3: Cementitious Materials for Soluble Sulfate Conditions (23)

Sulfate Exposure	Water-soluble sulfate (SO4) in soil, % by mass	Sulfate (SO4) in water, ppm	Cementitious material required
Moderate & Seawater	0.10 – 0.20	150 – 1500	Type II cement or Type I cement with 25% Class F, FA or 50% GGBFS replacement
Severe	0.20 – 2.00	1500 – 10,000	Type II cement with 25% Class F, FA

Rollings and Rollings (22) presented the results of a forensic investigation at Holloman Air Force Base (AFB) in New Mexico. Site conditions near the construction project included a high water table and local soils (typically silty sands and sandy silts) with relatively high sulfate contents. The project in question consisted of a portland cement concrete parking ramp, access taxiway, aircraft shelter, maintenance hanger and associated asphalt road and parking lot, concrete sidewalks and landscaped areas.

The authors also indicated that standard construction practices at Holloman AFB include a minimum of 2 ft thick nonexpansive fill and that a Type V sulfate resistant cement be used in all concrete that will be near or on the ground. Because of grades and fill requirements for the project, approximately 2 to 5 ft of fill material was needed for the project. The contractor offered and the government accepted the use of some recycled concrete aggregate that was being removed from another AFB as fill materials. The concrete had shown no existing durability problems prior to excavation.

Rollings and Rollings (22) indicate that isolated heaving of some of the constructed structures began shortly after construction. Heaving became progressively worse over time. Samples of RCA removed from the sections showed an abundance of ettringite and thaumasite (similar to ettringite except carbonate and silica is substituted for the alumina). Therefore, sulfate attack of RCA base layers is a concern especially for layers that are relatively thick.

3.3 Desirable Properties, Current Tests, and Potential Performance-Related Tests

This section describes the desirable properties of granular materials to be used in unbound base layers. The term "granular" is used here because some of the described tests have been used for natural aggregates but not RCA. Current tests used to characterize granular materials are discussed and, finally, potential performance related tests are described.

3.3.1 Desirable Properties of Granular Materials for use in Unbound Layers

Unbound aggregate base layers are commonly utilized within pavement structures. An unbound base course can be defined as a layer of graded aggregate materials that lies immediately below the wearing surface of a pavement, whether the wearing surface is a hot mix asphalt structure or a portland cement concrete pavement structure. Depending upon whether the pavement system is rigid or flexible, the intended function of an unbound aggregate base layer is different. For rigid pavements, the unbound aggregate base layer is used to: (1) prevent pumping; (2) protect against frost action; (3) drain water; (4) prevent volume change in the subgrade; (5) increase structural capacity; and/or (6) expedite construction (25). With respect to flexible pavements, unbound aggregate base layers are intended to increase structural capacity by providing stiffness and resistance to fatigue (25).

Saeed et al (8) detailed desirable performance related characteristics of unbound granular layers to resist typical distresses common to both rigid and flexible pavements. Tables 4 and 5 describe the common distresses related to granular base layers for rigid and flexible pavements, respectively. For rigid pavements, Saeed et al (8) indicated distresses that can be attributable to unbound granular layers are cracking, pumping/faulting and frost heave. Cracking in rigid pavements includes longitudinal cracks, fatigue cracking, and corner breaks. Longitudinal cracks develop parallel to the pavement centerline, generally within the wheel path. These longitudinal cracks are caused by loads (stresses) applied to the pavement that are higher than the flexural strength of the portland cement concrete. Fatigue cracking in rigid pavements typically occurs due to repeated loads on the pavement but may also be caused by thermal gradients or moisture variations within the portland cement concrete. Corner breaks are also structural breaks within the concrete near the corners of pavement panels. As related to underlying granular layers, theses structural cracks that develop within rigid pavements can be caused by inadequate support. Inadequate support provided by the granular layer can be caused by low stiffness/shear strength, pumping of base/subgrade fines, inadequate density (consolidation of base materials), high moisture content, degradation of base materials and/or inadequate particle angularity and surface texture.

Table 4: Rigid Pavement Distresses and Contributing Factors of Unbound Layers (excerpt from 8)

DISTRESS	BASE FAILURE MANIFESTATION	CONTRIBUTING FACTORS
Cracking	Inadequate support can increase tensile stresses within the slab under repeated wheel loads and result in longitudinal cracking; cracking initiates at the bottom of the slab and propagates to the surface and migrates along the slab; when a crack develops, increased load is placed on the base resulting in deformation within the base; the crack introduces moisture to the base resulting in further loss of support and, thereby, further deformation. Corner breaks (and associated faulting) may be caused by lack of base support from erosion or pumping of the base material; freeze-thaw damage of the base may also contribute to loss of support.	Low base stiffness and shear strength Pumping of base/subgrade fines Low density in base Improper gradation High fines content High moisture level Lack of adequate particle angularity and surface texture Degradation under repeated loads or freeze-thaw cycling
Pumping/Faulting	Pumping involves the formation of a slurry of fines from a saturated base, which is ejected through joints or cracks in the pavement under the action of repetitive wheel loads.	Poor drainability (low permeability) Free water in base Low base stiffness and shear strength High fines content Degradation under repeated loads
Frost Heave	Ice lenses are created within the base/subbase during freezing temperatures as moisture is pulled from below by capillary action. During spring thaw, large quantities of water are released from the frozen zone.	Freezing temperatures Capillary source of water Permeability of material high enough to allow free moisture movement to the freezing zone.

Pumping involves fines being removed from the base and being transported by water to the surface of a rigid pavement at the location of a joint or crack (25). The action of ejecting the fines/water mix is caused by the action of repeated wheel loads. This action of removing fines results in eroding the base materials near the joint leading to inadequate support. Severe pumping can then lead to faulting at the joint. As related to the underlying granular layers, pumping/faulting can be caused by poor drainage within the granular layer, free water within the granular layer, low stiffness/shear strength, high fines contents and/or degradation of the granular layer under repeated loads.

Frost heave causes uneven displacement of portland cement concrete slabs resulting in a rough riding surface. The heave is caused by the formation of ice lenses within the pavement structure. Another aspect is that of thaw weakening when the ice lenses melt. The moisture created from the thawing of the ice lenses can cause the base to lose stiffness which can result in pumping, faulting and corner breaks.

Table 5: Flexible Pavement Distresses and Contributing Factors of Unbound Layers (excerpt from 8)

DISTRESS	BASE FAILURE MANIFESTATION	CONTRIBUTING FACTORS
Fatigue Cracking	Lack of base stiffness causes high deflection/strain in the asphalt concrete surface under repeated wheel loads, resulting in fatigue cracking of the asphalt concrete surface. Alligator cracking only occurs in areas where repeated wheel loads are applied. The same result can also be caused by inadequate thickness of the base. Changes in base properties with time can render the base inadequate to support loads	Low modulus base Improper gradation High fines content High moisture level Lack of adequate particle angularity and surface texture Degradation under repeated loads or freeze-thaw cycling
Rutting	Inadequate shear strength in the base allows lateral displacement of particles with applications of wheel loads and results in a decrease in the base layer thickness in the wheel path. Rutting may also result from consolidations of the base due to inadequate initial density. Changes in base properties with time due to poor durability or frost effects can result in rutting.	Low shear strength Low density of base material Improper gradation High fines content High moisture level Lack of adequate particle angularity and surface texture Degradation under repeated loads or freeze-thaw cycling
Depressions	Inadequate initial compaction or nonuniform material conditions result in additional localized reduction in volume with load applications.	Low density of base material
Frost Heave	Ice lenses are created within the base/subbase during freezing temperature as moisture is pulled from below by capillary action. During spring thaw, large quantities of water are released from the frozen zone, which can include all unbound materials.	Freezing temperatures Capillary source of water Permeability of material high enough to allow free moisture movement to the freezing zone.

Saeed et al (8) also detailed desirable performance related characteristics of unbound granular layers to resist distresses common to flexible pavements (Table 5). For flexible pavements, fatigue cracking, rutting, depressions and frost heaving are related to the properties of granular base layers. Fatigue cracking is the result of repeated loads on a flexible pavement. Fatigue cracking can be caused by the loss of stiffness in the granular base. Loss of base stiffness will result in large tensile strains developing at the bottom of the hot mix asphalt layer. After repeated wheel loads, the large tensile strains at the bottom of the hot mix asphalt layer will cause cracks to develop that propagate to the surface of the hot mix asphalt layer in the form of fatigue cracks. Properties of the granular base layer related to fatigue cracking include: low modulus materials, improper gradation, high fines content, high moisture level, lack of particle angularity and surface texture and degradation of the granular base materials (8).

Rutting in flexible pavements related to unbound granular layers can be caused by densification of the layer or by loss of shear strength in any of the flexible pavement layers. Densification within pavement layers is caused by insufficient density at the time of construction. Inadequate shear strength within the granular base layer allows lateral displacement of particles which results in a decreased thickness of the base layer within the wheel path. The overlying hot mix asphalt, being flexible, will depress leading to permanent deformation within the wheel path. Properties of the granular layer related to rutting include: shear strength, in-place density, stability, lack of particle angularity and surface texture and/or degradation of the material under repetitive loads or freeze-thaw cycles.

Depressions are somewhat similar to rutting in that they are a downward movement of the pavement surface; however, unlike rutting depressions occur in a localized area. Depressions can be caused by localized areas of low density or by the localized degradation of granular base materials.

Distresses caused by frost heave in flexible pavements are manifested similarly to those for rigid pavements. The heave is caused by the creation of ice lenses. Spring thaw of the ice lenses can also lead to the loss of stability within the granular base layer.

3.3.2 Current Tests

The Federal Highway Administration (13) has published important properties for aggregates used in unbound granular layers. These properties would also be important for RCA materials utilized in unbound pavement layers. Properties identified include gradation, particle shape, stability, permeability, abrasion resistance and resilient modulus. Table 6 presents the linkage between these aggregate properties and pavement performance.

Gradation influences stability, drainage and susceptibility to frost heave. Well-graded aggregates will tend to provide best stability. An aggregate that contains no fines (minus No. 200 sized materials) can develop internal shear strength, but is often difficult to handle during construction (25). Aggregates that contain a large percentage of fines will not develop sufficient internal shear strength because the aggregate particles will essentially float within the fines (25). Aggregates with high fines content are also frost susceptible.

Table 6: Linkage Between Aggregate Properties and Performance (8)

Pavement Type	Performance Parameter	Related Aggregate Property	Test Parameters That May Relate To Performance
Flexible	Fatigue Cracking	Stiffness	Resilient modulus, Poission's ratio, gradation, fines content, particle angularity and surface texture, frost susceptibility, degradation of particles
	Rutting, Corrugations	Shear Strength	Failure stress, angle of internal friction, cohesion, gradation, fines content, particle geometrics (texture, shape, angularity), moisture effects
	Fatigue Cracking, Rutting, Corrugations	Toughness	Particle strength, particle degradation, particle size, gradation, high fines
		Durability	Particle deterioration, strength loss
		Frost Susceptibility	Permeability, gradation, percent minus 0.02 mm size, fines type
		Permeability	Gradation, fines content
Rigid	Cracking, Pumping, Faulting	Shear Strength	Failure stress, angle of internal friction, cohesion, gradation, fines content, particle geometrics (texture, shape, angularity), moisture effects
		Stiffness	Resilient modulus, Poission's ratio
		Toughness	Particle strength, particle degradation, particle size, gradation
		Durability	Particle deterioration, strength loss
	Cracking, Pumping, Faulting, Roughness	Permeability	Gradation, fines content
		Frost Susceptibility	Permeability, gradation, percent minus 0.02mm size, fines type

The use of angular aggregates having surface texture and the proper shape are needed to provide a stable unbound granular layer that has the needed shear strength. Desirable aggregate particles for use in unbound granular layers include a high level of angularity, rough surface texture and cubical particles (13). Angular, cubical particles having a high level of surface texture will result in a stable base that has sufficient shear strength to resist lateral displacement (deformation). Aggregates that are thin or elongated are prone to segregation and breakdown during construction.

Granular base layers must have sufficient stability, especially in flexible pavements. Large, angular, cubical and durable aggregates that have a dense grading are needed to provide stability over the design life of a pavement. As stated previously, loss of stability can lead to numerous distresses within both rigid and flexible pavements. The term stability can be considered the combination of shear strength and stiffness.

Permeability within a granular base is important to assist in preventing frost heave. A granular base layer must be free draining to reduce the potential for ice lenses developing in the layer. Also, moisture that does infiltrate into the layer must not become trapped leading to loss of stability.

The presence of plastic fines within an unbound granular layer can significantly reduce the load carrying capacity of the granular layer. Plastic fines are highly susceptible to moisture changes and increases in moisture can cause a significant reduction in shear strength.

Degradation of particles within an unbound granular layer can result in a loss of stability. Hard durable aggregates that are abrasion resistant are needed to ensure that a pavement will reach its intended design life.

The final important property identified by the FHWA includes the resilient modulus. The resilient modulus test can assist in providing design coefficients for inclusion of granular layers within a pavement system. Resilient modulus defines the relationship between stress and strain for a material and; therefore, is related to the stiffness of the material.

There are various test methods that can be used to characterize these important characteristics of granular materials for use under rigid and flexible pavements. Table 7 presents these various tests along with AASHTO and/or ASTM test methods to measure these important properties of granular base materials.

Table 7: Granular Aggregate Test Procedures (excerpt from 13)

Property	Test Method	Reference
Gradation	Sizes of Aggregate for Road and Bridge Construction	ASTM D448/AASHTO M43
	Sieve Analysis of Fine and Coarse Aggregate	ASTM C136/AASHTO T27
Particle Shape	Flat and Elongated Particles in Coarse Aggregate	ASTM D4791
	Uncompacted Voids Content of Fine Aggregate (As influenced by Particle Shape, Surface Texture, and Grading	AASHTO T304
	Index of Aggregate Particle Shape and Texture	ASTM D3398
Base Stability	California Bearing Ratio	ASTM D1883/AASHTO T193
	Moisture-Density Relations of Soils Using a 5.5 lb (2.5 kg) Rammer and a 12-in. (305mm) Drop	ASTM D698/AASHTO T99
	Moisture-Density Relations of Soils Using a 10-lb (4.54 kg) Rammer and an 18-in. (457 mm) Drop	AASHTO T180
Permeability	Permeability of Granular Soils (Constant Head)	ASTM D2434/AASHTO T215
Plasticity	Determining the Plastic Limit and Plasticity Index of Soils	ASTM D4318/AASHTO T90
	Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test	ASTM 2419/AASHTOT176
Abrasion Resistance	Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C535
	Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C131/AASHTO T96
Resilient Modulus	Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils - SHRP Protocol P46	AASHTO T307

3.3.3 Potential Performance Related Tests

Within Section 3.3.1, the desirable properties of granular base materials were described. Predominantly, granular base materials need to provide stiffness (stability) for support of overlying layers (whether flexible or rigid) and be durable. In order to provide the needed stiffness, the granular base materials should be hard, angular and have adequate surface texture and the proper gradation. Potential performance related tests to evaluate properties related to stiffness could include:

Coarse aggregate angularity (fractured face count)
Coarse aggregate angularity (uncompacted voids)
Fine aggregate angularity
Flat and Elongated Test
Flat or Elongated Test
Los Angeles Abrasion and Impact
Micro-Deval Abrasion
California Bearing Ratio
Shear Strength
Resilient Modulus

Durability is generally defined for granular base layers using sulfate soundness tests, whether it be sodium or magnesium. Variations of the sulfate soundness tests which perform actual freezing have also been used to evaluate the performance of granular base materials. The following sections describe potential performance related tests for unbound granular layer materials.

3.3.3.1 Coarse Aggregate Angularity

Angular coarse aggregates are needed within unbound granular layers to ensure a stable layer that has the needed stiffness to resist deformation due to repetitive loads. There are two primary tests available for evaluating the angularity of coarse aggregates: the fractured face test and the coarse aggregate flow test (or sometimes called uncompacted voids in coarse aggregate test).

The fractured face test is conducted in accordance with ASTM D5821-01, Determining the Percentage of Fractured Particles in Coarse Aggregate. To run this test, a representative sample having a specified mass, depending on the nominal maximum aggregate size, is washed and dried to a constant mass. Individual aggregate particles are then visually inspected to determine whether a particle has a fractured face. A fractured face is defined as an angular, rough or broken surface of an aggregate particle created by crushing, by other artificial means or by nature. A face is considered a "fractured face" only if it has a projected area at least as large as one quarter (25 percent) of the maximum projected area of the particle. Once visually inspected, each aggregate particle is placed within one of two categories: 1) fractured particles and 2) particles without a fractured face. It is also, possible to further differentiate the fractured particles as to whether each particle has a single fractured face or two or more fractured faces.

The Uncompacted Voids in Coarse Aggregate (AASHTO TP-56) method is identical to the fine aggregate angularity test (AASHTO T304) used in the Superpave mix design system, except the equipment size has been increased to accommodate the larger aggregates. The uncompacted voids tests is an indirect measure of particle shape, angularity and particle surface texture. These three aggregate characteristics affect the packing characteristics of an aggregate sample. The test is conducted by allowing a sample of coarse aggregate to flow through an orifice of a funnel into a calibrated cylinder. The uncompacted void content is calculated as the air void content between the loosely compacted aggregates. Needed for this calculation are the bulk specific gravity of the coarse aggregate and the volume of the calibrated cylinder. Similar to AASHTO T304, three Methods are included for the coarse aggregate flow test. Method A specifies a known gradation, Method B specifies that the test be run on three individual size fractions and Method C specifies the test is run on the "as-received" gradation.

During NCHRP 4-23, Performance Related Tests of Aggregates for Use in Unbound Pavement Layers, Saeed et al (8) recommended the uncompacted voids in coarse aggregate (Method A) as a performance related property. This test was recommended because it could provide a good overall indicator of the potential to resist permanent deformation as it is related to particle shape, angularity and surface texture.

3.3.3.2 Fine Aggregate Angularity

The angularity, shape and texture of fine aggregates is generally evaluated using the fine aggregate flow test (AASHTO T304). This test is based upon the National Aggregate Association Flow Test that was developed to evaluate the effect of fine aggregates on the finishability of portland cement concrete. The fine aggregate flow test is the predecessor of the coarse aggregate flow test described previously.

The test method for uncompacted voids in fine aggregate determines the loose uncompacted void content of fine aggregate by allowing the fine aggregate to flow through an orifice located at the bottom of a specified funnel and fall freely into a calibrated funnel. The uncompacted void content of the fine aggregate is calculated using the mass of aggregate within the calibrated cylinder, bulk specific gravity of the fine aggregate and volume of the calibrated cylinder.

There are three methods for running AASHTO T304. Method A specifies a known gradation, Method B specifies the testing of three size fractions and Method C entails testing the "as-received" materials.

Similar to the coarse aggregate flow test, Saeed et al (8) recommended the use of the fine aggregate flow test for unbound pavement layers (Method A). This test was identified as being related to performance. The combination of the fine aggregate and coarse aggregate flow tests should characterize the combined effect of particle shape, angularity and texture for unbound granular layer materials.

3.3.3.3 Coarse Aggregate Particle Shape

The shape of coarse aggregate particles in generally evaluated in accordance with ASTM D4791, Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate. Flat and/or elongated particles can break under compaction, thus changing the characteristics of the unbound granular layer materials. A large percentage of flat and/or elongated particles can also affect the workability of the granular materials during construction. The ASTM D4791 method begins by reducing a sample to a minimum test sample mass that is based upon the nominal maximum aggregate size of the material's gradation. For size fractions with at least 10 percent retained, 100 particles are split out for testing. Each particle is then measured to determine length and width. Generally, this is conducted with a proportional caliper in which the length (maximum dimension) is used to set the caliper. Then, the thickness of the particle is compared to the desired ratio by determining if the particle will pass between the other end of the caliper and a fixed post. Flat and elongated particles are placed in one pile and the particles that are not flat and elongated are placed in a separate pile. The percentage of flat and elongated particles, by mass, are then calculated based upon a weighted average for the sample's gradation.

An alternative aggregate property is to measure flat or elongated aggregate particles. The same proportional caliper is used to measure flat or elongated particles as is used to measure flat and elongated particles. Flat particles are determined by setting the larger opening of the caliper to the particles width. The particle is considered flat if the thickness of the particle can be placed within the smaller opening. Elongated particles are determined by setting the larger opening of the caliper to the length. The particle is considered elongated if the width of the particle can be placed within the smaller opening. This test is slightly more time consuming than the flat and elongated test because each particle is measured for both flatness and elongation. However, the flat or elongated test has been recommended over the flat and elongated test for hot mix asphalt aggregates (26).

3.3.3.4 Aggregate Toughness and Abrasion

Aggregates must be resistant to breakdown and abrasion to withstand stockpiling, shipping, placement and compaction. Aggregate breakdown and abrasion changes the gradation of the granular materials which can significantly affect the performance of an unbound granular layer. Within the U.S., the most common method of evaluating the toughness of coarse aggregates is the Los Angeles Abrasion and Impact test (AASHTO T96). The Los Angeles Abrasion and Impact test method entails an aggregate sample being placed inside a large rotating steel drum containing a specific number of spherical steel charges. As the steel drum rotates, the aggregate sample and steel charges are picked up by flights within the drum until they drop a height of approximately 27 inches on the opposite side of the drum. This action subjects the aggregate sample to abrasive forces through the contact of aggregate particles on both other aggregate particles and the steel spheres and impact forces as the aggregates and steel charges are dropped from the flights. The steel drum is rotated at a constant speed of 30 to 33 rpm and is rotated for 500 revolutions.

The Micro-Deval test was developed in France during the 1960's and was based on the Deval test developed in the early 1900's (27). The Micro-Deval test provides a measure of abrasion resistance and durability of mineral aggregates through the actions of abrasion between aggregate particles and between aggregate particles and steel spheres in the presence of water. A standardized test method for the Micro-Deval test is provided in AASHTO T327, Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus. This test method entails abrading the aggregate sample within a small diameter drum with steel charges in the presence of water. The steel charges are smaller in diameter than those used in the Los Angeles Abrasion and Impact test (3/8 in. compared to 2 in.). Test samples are soaked in 2 liters of water for a minimum of one hour prior to testing. Both the aggregates and water are introduced into the drum for testing. The drum is rotated at 100 ±5 rpm for two hours. Unlike the drum used for the Los Angeles Abrasion and Impact test, there are no flights within the drum. At the conclusion of the test, the aggregate sample is dried to constant mass and, similar to the Los Angeles and Impact test, the mass loss determined.

3.3.3.5 Strength Tests

As stated numerous times within this report, strength, or stability, is a needed characteristic for all unbound pavement layers. The most common test to evaluate the strength of highway materials is the California Bearing Ratio (CBR) Test. This test has been used for many years to provide an indication of the structural capacity provided by a granular pavement layer. The CBR test was developed by the California Highway Department in 1929 for use in an empirical flexible pavement design procedure (28). Results from the CBR test provide an index of strength. The test involves pushing a 3 sq. in. piston into a sample at a specified rate of 0.05 in/min. The unit load is recorded at each 0.1 in. of penetration up to a total deformation of 0.5 in. Deformations at 0.1 and 0.2 in. are then compared with loads needed to cause equal deformation into a standard, well-graded crushed stone containing ¾ in. maximum sized particles. The CBR test is run in accordance with AASHTO T193.

Saeed et al (8) identified shear strength of the granular materials as the single most important property that governs unbound layer performance. In order to measure shear strength, Saeed et al (8) recommended the triaxial shear test. This test was recommended because: 1) the test is universally accepted for measuring shear strength; 2) most state DOTs have the capability to run the test; 3) the test method can allow testing at different stress states; 4) the test method includes repetitive loadings similar to the actions of traffic; 5) the test provides an indication of both resilient and permanent strains; and 6) the test method can allow for varying moisture content. A method of test was provided by Saeed et al (8) at the conclusion of NCHRP Project 4-23. The method is very similar to triaxial shear tests conducted on soils in that a sample is confined and a deviator stress is applied. However, the method recommended by Saeed et al (8) differs in that the method recommends a cyclic loading following a haversine waveform.

3.3.3.6 Fundamental Properties

A fundamental property that can be determined for granular materials is the resilient modulus. The resilient modulus is useful in characterizing the stiffness of a granular material and provides the amount of recoverable strain due to a specific stress state. Similar to the shear strength test described above, the resilient modulus test is a triaxial test in that a confining stress is used to confine the sample and a deviator stress is applied to cause deformation. Unlike the shear strength test, the sample is not loaded to failure. Rather, relatively small strains are induced in order to determine the magnitude of recoverable strain for various stress states. Defined, the resilient modulus is the ratio of a deviator stress to the amount of recoverable strain (28). Resilient modulus is a required input for all granular and fine-grained pavement layers within the new Mechanistic-Empirical Pavement Design Guide.

3.3.3.7 Durability Tests

The most common tests to evaluate the durability, especially freeze/thaw, of granular base materials are the sodium and magnesium sulfate tests. These tests have also been shown related to degradation due to the actions of wetting and drying. Sulfate soundness tests are conducted in accordance with AASHTO T104, Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate. The test is conducted by preparing a sample per specification depending upon if the material is a coarse or fine aggregate. Samples are then soaked in a saturated solution of either sodium or magnesium sulfate for 16 to 18 hours. The samples are then drained and oven dried to a constant mass. Typically, samples are subjected to five cycles of wetting and drying. After the final cycle, the sample is rinsed to remove the sulfate solution and dried back to constant mass. The weighted averaged of aggregate loss is then determined. There is some concern in the literature that these tests may not be applicable for RCA materials. It is hypothesized that the sulfate ions can attack the cement mortar surrounding aggregate particles which can lead to severe mass loss in samples (13).

Another method to evaluate the freeze/thaw characteristics of granular materials was developed by Senior and Rogers (27). This method is similar to the sulfate soundness test in that the test evaluates durability; however, the method is slightly different in that samples are subjected to actual freezing temperature instead of the simulated freezing in the sulfate soundness test. Individual size fractions retained on the 0.530 in., 3/8 in. and No. 4 sieves (13.2, 9.5 and 4.75mm) are placed in separate 1 liter jars. The samples are soaked in a 3 percent sodium chloride (NaCl) solution for 24 hours. After soaking, the samples are drained and sealed prior to being placed in a freezer for 16 hours. Freezing is following by thawing at room temperature for 8 hours. The freezing and thawing defines one cycle of conditioning. Conditioning is repeated for a total of five cycles. A weighted average of mass loss is then determined based upon the samples gradation.

The New York State Department of Transportation has adopted a test similar to the method proposed by Senior and Rogers (27). This test method is documented in Test Method NY 703-09, Standard Test Method for Resistance of Coarse Aggregates to Freezing and Thawing. The primary difference between the New York method and the Senior and Rogers (27) method is that the New York method requires 25 freeze/thaw cycles.

Both the Los Angeles Abrasion and Impact and Micro-Deval tests have been used as indicators of durability. In fact, a reasonable correlation has been developed between the magnesium sulfate soundness test and the Micro-Deval test (26, 27)

A study conducted by the Ohio Department of Transportation used a concrete freeze/thaw machine manufactured by ScienTemp to compare the durability of RCA to a gravel and limestone aggregate (29). Each aggregate sample (3 RCA sources and a single source of limestone and gravel) were prepared by fractionating the samples on the 1 in., ¾ in., No. 4 and No. 30 (25mm, 19mm, 4.75mm and 0.60mm) sieves. Each fraction was then covered with ½ in. (12.5mm) of water and subjected to 54 freeze/thaw cycles. After the freeze/thaw condition, the percent loss was determined for each fraction. This process continued to determine the cumulative percent loss after a total of 100 and 160 freeze/thaw cycles had been accumulated. Based upon the results of this testing, Mulligan (29) concluded that the RCA materials were not as durable as the natural (virgin) aggregates. This was based upon an increased amount of aggregate loss observed for the RCA materials. This observation was generally true for each fraction size evaluated.

3.4 Materials Specifications for Recycled Concrete

Chesner (30) has prepared a white paper and specification for the use of RCA in unbound pavement layers. This reference provides an excellent overview of the specification developed for using RCA in unbound layers (which was adopted as AASHTO M 319-02, Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course) by providing narrative discussions on each section of the specification.

Within the Chesner specification are several "Notes" that are related to the construction and performance of RCA in unbound granular layers. The first Note discusses the compaction of RCA materials in the field. Chesner indicates that the proper compaction of these materials "… is critical to the performance…" of the granular layer. The author also indicated that the water absorption characteristics of RCA materials is generally higher than typical aggregates and, therefore, RCA mateirals will likely have a higher optimum moisture content. Chesner (29) also indicates that the control of compaction in the field can be difficult. This is primarily caused by variations in specific gravity of the RCA materials. An appendix presented within the specification presents an alternative method (alternative to Proctor and field density testing) of controlling layer density. This method basically entails rolling the granular layer until refusal.

Another note within the specification (30) indicates that engineers should be aware that pore water within and passing through RCA layers may be highly alkaline in nature. Water emerging from a RCA layer may have a pH of approximately 11 to 12 which indicates that it may be corrosive to metal culverts and rodent guards on drainage system outlets.

The specification (30) also notes that the use of RCA should be minimized, when possible, over a geotextile drainage layer, gravel drain fields, drain field piping or soil lined stormwater retention/detention facilities. Soluble minerals can precipitate and be transported from the RCA materials and deposited within drainage systems. The precipitants are sometimes referred to as tufa-like or portlandite deposits.

Chesner (30) indicates that layers of RCA materials can be expected to gain strength over time. The gain in strength is due to re-cementing of the RCA fines. The note indicates that if the RCA materials are to be utilized in a drainage layer, the fine portion of the RCA should be removed to reduce the potential for re-cementation and resultant loss in permeability.

The fifth Note states that RCA materials will typically yield high sulfate soundness loss values in the lab. Chesner (30) indicates this can happen with "… conventional sulfate soundness …" which suggests that high loss values may occur with either sodium or magnesium sulfate soundness solutions.

The final Note contained within the specification recommended by Chesner (30) indicates that engineers should be cautioned to ensure that RCA materials are not contaminated with extraneous solid waste or hazardous materials. The White Paper indicates that there is more potential for solid waste or hazardous materials when the RCA materials are obtained from building demolition.

A typical material that is contained within recycled portland cement concrete pavements is hot mix asphalt. Rigid pavements are routinely overlaid with hot mix asphalt. Even when milling the hot mix asphalt layer off a portland cement concrete pavement, hot mix asphalt materials will still likely be included when recycling the rigid pavement. The Minnesota DOT allows up to 3 percent asphalt binder within a RCA sample, by weight (11). With this specification, milling the asphalt layer may not always be necessary, thus, reducing construction time and cost. Other states limit the amount of recycled asphalt pavement to values as low as 2 percent (31).

The White Paper provided by Chesner (30) discusses gradation requirements and proportioning within the specification. The authors state that there is no evidence that the gradation requirements for RCA should be any different than virgin aggregates used for granular aggregates. The authors recommend the requirements set forth in AASHTO M147, Materials for Aggregate an Soil-Aggregate Subbase, Base and Surface Courses, and ASTM D 2940, Graded Aggregate Materials for Bases or Subbases for Highways and Airports, or the specifying agency for gradation requirements. Other materials, e.g. natural aggregates, can be successfully combined with RCA in order to meet gradation requirements.

Physical properties within the specification includes a general description of RCA as materials consisting of crushed concrete and natural aggregate that has been derived from the crushing of portland cement concrete that are hard, durable fragments of stone, gravel, slag, crushed concrete and/or sand. Requirements for RCA are included for the amount of plastic soils using Atterberg liquid limits, plasticity index and sand equivalency, Los Angeles Abrasion and soundness.

The specification also states that RCA materials should not have more than 5 percent hot mix asphalt or masonry materials.

CHAPTER 4 SURVEY OF STATES

4.1 Survey of States - Summary

Seven states were interviewed about their use of recycled concrete aggregates (RCA) as a base course under flexible pavements or as a cushion material under rigid pavements. These states include Alabama, Maine, New York, North Carolina, North Dakota, Texas, and Wisconsin. Responses range from 'have not used, but allow' to 'used and very pleased'. Every state that has used RCA has indicated that they were satisfied with the performance of RCA and had no pavement failures that could be attributed to the RCA. Reaction was that the material was good to very good with no difference in the use of RCA from that of regular (virgin) aggregate.

In most cases, specification requirements were derived from their regular aggregate specifications or required the material to meet the same specifications as for their regular aggregates. Neither Alabama nor Maine had used RCA under pavements with any significance. However, Maine does presently have under way a warranty project where the contractor is using RCA. Alabama allows its use, but to date contractors do not generally use RCA due to the availability of virgin aggregate. Alabama feels that the use of RCA is market driven.

Texas (Houston District) and New York have had the most experience with RCA of those states surveyed. Though no significant problems have been encountered, New York stated they had to watch the gradation as too fine a gradation would cause sensitivity to water/moisture. On the other hand, Texas felt that a high fine content was necessary to keep the influx of water from entering. In this regard New York has no end-result specification when it comes to density, though Texas requires a specified density using a Proctor. Texas further requires a certain percent of cement to be added through a pug mill as they feel this is necessary to hold it together and prevent water from entering.

How RCA is used is dependent on the state and what they want to accomplish with the material. Some states want the material to drain and move water from beneath the pavement, while others are more concerned about keeping water out altogether. As in New York's case, they feel increased fines cause problems with drainage. When a drainage layer is placed on the subbase, New York always uses edge drains.

With the exception of New York, none of the other states surveyed seemed too concerned about freeze-thaw. New York runs a freeze-thaw test. Other states, particularly southern tier states, do not have a test requirement for freeze-thaw or they require the same tests as that for virgin aggregates.

As evidenced by the Houston District of Texas, when a density requirement is specified, edge drains are not used. Therefore there is limited application on interstate highways of RCA in the Houston District. Most all states require edge drains on interstate highways, and therefore specify a RCA gradation that will drain with compaction to refusal instead of a density requirement. The use of a fabric with edge drains is again state preference.

From a specifications standpoint of the states surveyed, the specifications called for is dependent on how the RCA material is used; however, all states surveyed did have a gradation specification. This varied from Maine requiring the RCA to strictly meet AASHTO M 319 in all aspects to states' individual preference. (NOTE: Since Maine follows M 319 their requirements will not be discussed further here.) The primary specification requirements are addressed individually in the following paragraphs.

4.2 Gradation

New York has material set up as four types. The gradation basically calls for 100 percent passing the 2 in. (50mm) sieve. The requirements on the No. 40 and No. 200 (0.425 and 0.075mm) sieves are the same for all types and is 5-40 percent passing the No. 40 and 0-10 percent passing the No. 200 sieve. In North Dakota all material must pass the 1 ½ in. (37.5mm) sieve with 0-12 percent passing the No. 200 sieve. In the case of both of these states, a specified in-place density is not required in the field, but rather they require rolling to refusal. North Dakota has no other requirements on RCA other than gradation. New York indicated that they have a concern with the crushed RCA being too fine and have to watch this closely as the high fines material is sensitive to water/moisture. On the other hand, Wisconsin stated that they did not have an issue with the minus No. 200 material with the specifications setting the minus No. 200 limit.

To the other extreme, Texas, in the Houston District, does not have a minus No. 200 sieve requirement. Gradation is dependent on the Grade specified. For their Grade 1 RCA, all material must pass a 1 ¾ in. (45mm) sieve with 15-30 percent passing the No. 40 sieve. North Carolina calls for 4-12 percent passing the No. 200 sieve. Both Texas and North Carolina have a specified density requirement as they want a tight base in which water is not readily able to enter. Both states try to only place RCA above the subgrade water table. Both states pointed out that there was a need for the contractor to add as much as 2 to 3 percent more water than for other aggregates in order to meet density requirements. Both Texas and North Carolina stated that there was a steep learning curve for contractors due to problems setting up the material and the additional handling that is required. RCA materials need more water and the contractor has to take it easy in putting water in as the RCA will not absorb water very fast. In Texas, the RCA requires more effort with a motor grader blade to get to grade and the contractor is required to slush roll (add water to top at end of compaction/finishing process). This is primarily due to the cement added in Texas. North Carolina does not use RCA around drain pipes, but they do require pipe to be wrapped with a fabric with coarse sand placed around the pipe and fabric.

4.3 Physical Properties

The physical property requirements of states for RCA are once again dependent on how the material is used, but more dependent on state preference. For instance, the Los Angeles Abrasion test is not required in either Texas or New York. However, Alabama, North Carolina, and Wisconsin do require the LA Abrasion test. Specification limits range from 40 percent loss to as high as 60 percent. Wisconsin waives the LA Abrasion requirement when the concrete is from a DOT project.

Liquid limit and plasticity index requirements likewise vary from state to state. Though they do not have a liquid limit requirement, New York sets the plasticity index of the material passing the No. 40 sieve at 5 or less. Texas has a liquid limit requirement of 35 percent maximum and a plasticity index of 10 maximum for their Grade 1 material. These values change to 40 percent maximum and 12 maximum for their Grades 2 and 3 materials. When RCA is from concrete pavement off a North Carolina DOT project, they raise the liquid limit maximum to 35 from 30.

Soundness testing is not required in Wisconsin, but Alabama requires soundness testing because it is a requirement of virgin aggregates. Alabama has a maximum loss of 15 percent and 10 percent when magnesium sulfate or sodium sulfate is used, respectively. North Carolina waives their sodium sulfate soundness tests when the RCA is from concrete pavement off a NCDOT project. Wisconsin has waived completely all freeze-thaw tests as the sodium sulfate breaks down the "paste" that is still attached to the aggregate after crushing. New York has developed a freeze-thaw test using magnesium sulfate, but they stated that the test was not entirely representative. Their Types 1, 2 and 4 materials (types vary only in gradation requirements) are accepted on the basis of Magnesium Sulfate Soundness Loss after four cycles of 20 percent or less. (NOTE: Appendix C of AASHTO M 319 makes reference to a sodium chloride brine solution used in New York. New York does not use sodium with crushed concrete aggregates when they are used in unbound applications.)

4.4 Deleterious Substances

New York specifications state that at least 95 percent, by weight, of RCA be free from organic and other deleterious material, but may contain up to 5 percent by weight asphalt and/or brick. North Carolina does not specify where the concrete comes from and has no specific requirement on deleterious material, though they perform a visual inspection. A small amount of deleterious material is not an issue with North Carolina, but if a large amount is present, then material is not used. Texas places a maximum limit of 1.5 percent on deleterious materials, whereas Wisconsin sets the limit at less than 10 percent hot mix asphalt (HMA) in the RCA with other deleterious material requirements being the same as for their basic aggregate.

Some states, like Alabama and North Carolina, have a QC/QA program in place for aggregates. Alabama holds the contractor who is crushing concrete to the same requirements as other producers of aggregates. In North Carolina, RCA generally is crushed on project and used. NCDOT inspects the Contractor's crushing operations and pulls samples at the site for testing. If the crushing takes place off project, then NCDOT treats the RCA as a regular aggregate under their QC/QA aggregate program. None of the states interviewed stated they put a restriction on where the concrete came (source approval), as the driving forces for RCA use is primarily to support recycling efforts and economics. However, NCDOT stated that they did look at source approval for large volume projects requiring the contractor/producer to have a QC/QA plan with a certified technician and certified lab on site to meet their aggregate QC/QA program requirements. Though the source of the concrete is not specified or regulated, New York approves stockpiles of RCA prior to use. New York stated that one of their biggest problems was the requirement of stockpiling as suppliers do not like to crush and have to stockpile large quantities. This is particularly the case in the New York City area where stockpiling space is limited. Likewise, North Carolina requires a stockpile of 300 tons minimum for either off site or on site operations. Where concrete comes from different sources, New York has a concern about hazardous materials either already in the concrete or being added by contractors in order to dispose of them.

CHAPTER 5 MATERIALS AND TEST METHODS

5.1 Introduction

This chapter provides information on the RCA materials utilized during the research effort along with descriptions of each laboratory test used during the project.

5.2 Materials

A total of six RCA materials were obtained from South Dakota for use in this project. All six of the RCA materials were identified by SDDOT and provided to the researchers. Little information was available about each of the materials. Mr. Daris Ormesher of the SDDOT attempted to identify specifics about the PCC used to crush into the RCA materials; however, this information was not available. The only specifics available for all six of the RCA materials are the pavement from which the PCC was obtained. Following are the identifiers provided for the six RCA materials included within the research.

Sample Number	Identifier
1	I-29
2	City of Mitchell
3	Riverside Road Exit, I-90
4	Whitewood, I-90
5	Yankton, US 81
6	Rapid City, 5th Street

5.3 Test Methods

The following sections describe each of the tests conducted on the RCA materials.

5.3.1 Particle Size Analysis (AASHTO T27)

All states set gradation limits for materials that are to be used as base course layers and gravel cushions under pavements. The gradation of a material is an indicator of other properties such as permeability, frost susceptibility, and shear strength. This routine test consists of shaking a sample of known mass through a stack of sieves in descending sizes. The standard procedure of this method is outlined in AASHTO T27, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.

5.3.2 Atterberg Limits (AASHTO T89 & T90)

The plasticity of the minus No. 40 (0.425mm) sieve size material was evaluated using Atterberg Limits. Plastic limits are used to identify the moisture content at which a material begins to exhibit plastic behavior. The liquid limit is used to define when the material behaves as a viscous liquid. The numerical difference between the two limits is called the Plasticity Index

(PI) which indicates the magnitude of the range of moisture contents a material will remain in a plastic state. This test is used by many DOT's as another means to measure the cleanliness of a granular material.

5.3.3 Moisture/Density Relationship; Standard Proctor (AASHTO T99)

Field compaction of granular layers is very important to the life of any overlying pavement structure, be it flexible or rigid. Proper compaction of a given material increases the shear strength and stiffness and decreases the permeability. Laboratory compaction typically is used to establish a relationship between moisture content and dry density, which is then used to determine an estimated optimum moisture content and maximum dry density. To do this, a representative sample is compacted into a mold, of known volume, through a range of moisture contents and the resulting calculated dry densities are plotted versus the moisture contents. This graph is used to estimate the maximum density and corresponding moisture content. Based upon current SDDOT practices, the researchers chose to follow the procedure set forth by AASHTO T99, Moisture-Density Relations of Soils Using a 2.5-kg Rammer and a 305-mm Drop, to define optimum moisture and maximum dry density for the RCA materials. This test is typically termed the "Standard Proctor Test."

5.3.4 Flat and/or Elongated Particles (ASTM D4791)

The shape characteristics of coarse RCA particles (retained on the No. 4 (4.75mm) sieve) were evaluated using ASTM D4791, Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate. The percentages determined from this procedure helps make inferences about the amount of breakdown that may occur during compaction of the material. Breakdown of particles during field work changes the overall gradation of the aggregate, which may affect performance. The test method proportionally quantifies an aggregate's dimensions in order to define its shape. Representative samples of RCA were measured with a proportional caliper using three ratios of 5:1, 3:1, and 2:1. Length is defined as the maximum dimension of the particle and width is the largest dimension perpendicular to the length. Thickness is defined as being the dimension perpendicular to both the width and length. Particles were classified into two groups: Flat <u>and</u> Elongated and Flat <u>or</u> Elongated. Particles are classified as Flat and Elongated if the ratio of length to thickness is larger than the ratio being used to measure. Flat or Elongated particles are those that fail the definitions of flat or elongated.

5.3.5 Uncompacted Void Content of Coarse Aggregate (AASHTO TP56)

In addition to the particle size distribution and particle shape, the shear strength of granular materials is greatly influenced by the angularity of the particles. In order to evaluate the angularity characteristics of the coarse RCA materials, AASHTO TP56, Uncompacted Void Content of Coarse Aggregate (As Influenced by Particle Shape, Surface Texture and Grading), was conducted. This test method entails allowing a graded sample of coarse aggregate to fall freely from a specified height into a calibrated cylinder. Using the bulk specific gravity of the materials, the percentage of air voids between the particles within the calibrated cylinder is determined. Results from this test are expressed as the percent voids between the particles.

5.3.6 Specific Gravity and Absorption (AASHTO T85/T84)

Specific gravity is the ratio of the weight of a given volume of material to the weight of a similar volume of water. Or stated another way in terms of an aggregate, specific gravity is a numerical value showing the number of times heavier an aggregate particle is when it is compared to an equal volume of water. Most naturally occurring aggregates have a specific gravity of 2.6 to 2.7, although values as low as 2.4 or as high as 3.0 have been encountered. Specific gravity of an aggregate is not an indication of the quality of the aggregate itself; however, it can be an indication of potential problems and is needed for computations involving volume and mass. Another property derived from the specific gravity test is water absorption. Absorption has been used as an indicator of aggregate durability as related to freezing and thawing. High absorption has been used as a sign of unsound aggregates. AASHTO test methods T 84, Specific Gravity and Absorption of Fine Aggregates, and T85, Specific Gravity and Absorption of Coarse Aggregates, were used to determine the specific gravity and absorption of the fine and coarse grained particles of RCA, respectively.

5.3.7 Uncompacted Void Content of Fine Aggregate (AASHTO T304)

Uncompacted Void Content of fine aggregate or fine aggregate angularity (FAA) is an index that is a function of particle shape, angularity, and surface texture; which could provide an indicator of the potential for resisting permanent deformation. This test is performed by filling a 100mL cylindrical measure by allowing the fine aggregate to freely flow through a funnel from a fixed height into the measure. The aggregate is struck off the top of the measure and the mass is determined. The uncompacted void content is calculated based on the absolute volume of the fine aggregate and the volume of the measure and expressed as the percent air voids.

5.3.8 Sand Equivalency Test (AASHTO T176)

The Sand Equivalency Test is used to determine the amount of clay-sized fines that are present in the sand size portion of coarse aggregates. This gives an indication to the susceptibility of the aggregate to moisture change. Testing was performed on all six samples of RCA in accordance to AASHTO T176 by submerging the minus No. 4 (4.75mm) sieve size material in a graduated cylinder filled with working calcium chloride solution. The sample was shaken to disperse the clay-sized particles into solution and the sedimentation process was observed. The cylinder was allowed to sit undisturbed for 20 minutes after which the top of the clay suspension cloud was measured. After the clay reading was taken, the weighted foot assembly and sand indicator was lowed onto the sand at the bottom of the cylinder in order to determine the sand reading. The sand/clay ratio was determined from the clay and sand readings that were obtained.

5.3.9 Los Angles Abrasion and Impact (AASHTO T96)

The Los Angles Abrasion and Impact Test simulates the amount of breakdown that an aggregate may experience during processing, handling, and placement. This is important because as the aggregate degrades the gradation changes, which as stated earlier is an indicator of several other aggregate properties. Testing was conducted according to AASHTO T96, Los Angles Abrasion and Impact by placing a sample graded according to the nominal maximum aggregate size in a rotating steel drum with steel spheres. After 500 revolutions the sample was washed over a sieve coarser than the No.12 sieve and the retained material dried to determine the percentage of loss.

5.3.10 Micro-Deval Abrasion Loss for Coarse Aggregates (AASHTO T 327)

Micro-Deval abrasion loss is used to determine abrasion loss with minimal to no impact, unlike the LA Abrasion and Impact Test. Also, this test can be used as an indicator of the soundness of coarse particles. All six samples were tested in accordance with AASHTO T 327. Two replicate samples of each material were graded based on the nominal maximum aggregate size. The composite sample was then placed in a stainless steel jar along with 5000g of steel charge and 2 liters of water and allowed to soak for at least 1 hour. The jar was then rotated at 100 ± 5 rpm for 2 hours or 105 minutes allowing the aggregate particles to abrade with the steel charges. After the specified time, the sample was removed from the jar and washed over a No. 4 and No. 16 (4.75mm and 1.18mm) sieve. The retained material was then dried back to a constant mass and the percent weight loss was determined to the nearest tenth.

5.3.11 Sodium Sulfate Soundness of Aggregates (AASHTO T104)

Soundness testing gives insight to the amount of degradation that an aggregate may experience caused by environmental factors, particularly freeze/thaw. The RCA was tested in accordance to AASHTO T104, which calls for a graded sample to be immersed into a sodium sulfate solution for 15 hours followed by 8 hours of oven drying. During the drying process the dissolved salts crystallize within the permeable pores of the aggregate particles causing expansive forces similar to the expansion of water when freezing. The samples were subjected to 5 cycles of soaking and drying before being washed thoroughly over a No. 8 (2.36mm) sieve. The material retained was then dried to a constant mass and the percent loss calculated.

5.3.12 New York Style Freeze/Thaw for Aggregates

A variation of the New York freeze/thaw procedure subjected the aggregate samples to 5 freeze/thaw cycles while submerged in a 3 percent solution of NaCl. The New York method for this test calls for 20 freeze/thaw cycles; however, work by Senior and Rogers (27) in Ontario indicate 5 cycles is sufficient. Each sample was prepared in the same manner and gradation as that used for the Micro-Deval test procedure previously described. Once two replicate composite samples were prepared for each material they were allowed to soak in the NaCl solution for 24 hours. After the 24 hour soak period the samples were placed in a temperature controlled environmental chamber at 5°F (-15° C) and allowed to freeze for approximately 17 hours. A temperature probe was placed at the approximate center of mass of one of the samples to monitor core temperature. The following day the samples were allowed to thaw at 73°F (23° C) for at least 7 hours and then the process was repeated. Once the 5 cycles were completed the amount of mass loss due to freeze/thaw was found by washing the samples over the No. 4 and No. 16 sieves. The material larger than the No. 16 sieve was dried back to a constant mass and the percent mass loss was determined to the nearest tenth.

5.3.13 California Bearing Ratio (AASHTO T193)

The California Bearing Ratio (CBR) has been a widely accepted test procedure for determining a soil or soil-aggregate mixture's strength for use in pavement design calculations. This procedure measures the resistance exhibited by a laboratory compacted sample when it is subjected to strain controlled load. The measured resistance is expressed as a percent of that of a solid limestone rock, which is given the value of 100. Samples can be tested after a saturation period (this produces a worst case situation for mixtures containing clays) or they can be tested unsoaked to yield a maximum value under favorable conditions. The RCA samples in this study were tested after the prescribed soaking period.

5.3.14 Repeated Load Triaxial Test for Shear Strength of Aggregates

The Repeated Load Triaxial Test is a performance test for aggregates that was proposed by the NCHRP Project 4-23 staff at Applied Research Associates, Inc (*8*). This test procedure consists of subjecting laboratory compacted samples 6 in. (150mm) in diameter by 12 in. (300mm) tall to an increasing haversine load waveform until failure. The samples were compacted at optimum moisture content in 6 equal lifts to 95 percent of Standard Proctor (AASHTO T99) with vibratory compaction. Initially the specimens were confined with a 15 psi (103kPa) pressure and loaded with a 10 psi (69kPa) deviator for 1,000 repetitions, after which the deviator increased to 20 psi (138kPa) for another 1,000 load repetitions. After the first two stages the deviator stress was increased in increments of 10 psi and 5 psi until the specimen failed (5 psi was used the closer the sample got to its failure load). Specimen failure was defined by reaching a strain equal to 5 percent of the initial specimen height. A plot of load versus strain was developed from the data to determine the load before failure and the load at failure.

5.3.15 Determining the Resilient Modulus of Soils and Aggregate Materials (NCHRP 1-28A)

Stiffness is a characteristic used as an aid in pavement structural design, as well as an indicator to material performance within the pavement system. Even though modulus values can be determined from the repeated load triaxial test, it was decided to conduct resilient modulus testing of each sample following the method recommended by NCHRP Project 1-28A. This procedure simulates the stresses at various depths within a pavement structure caused by passing wheel loads by using a triaxial pressure chamber and a servo-controlled hydraulic actuator, as shown in Figure 4. The amount of recoverable axial deformation that was exhibited by the specimens was measured using internal platen to platen displacement transducers. The specimens used in this test are fashioned in the same manner as those used in the Repeated Load Shear Test. Specimens were subjected to a 1,000 repetition preconditioning stage prior to testing. After the preconditioning stage the sample was tested under a combination of varying confining pressures and cyclic stresses ranging from 1.5 psi (10kPa) to 140 psi (965kPa) in a 30 sequence test. Each sequence consisted of a single confining stress and cyclic stress of 100 load repetitions. The amount of axial deformation and the corresponding loads were measured during the last 6 load cycles of each sequence.

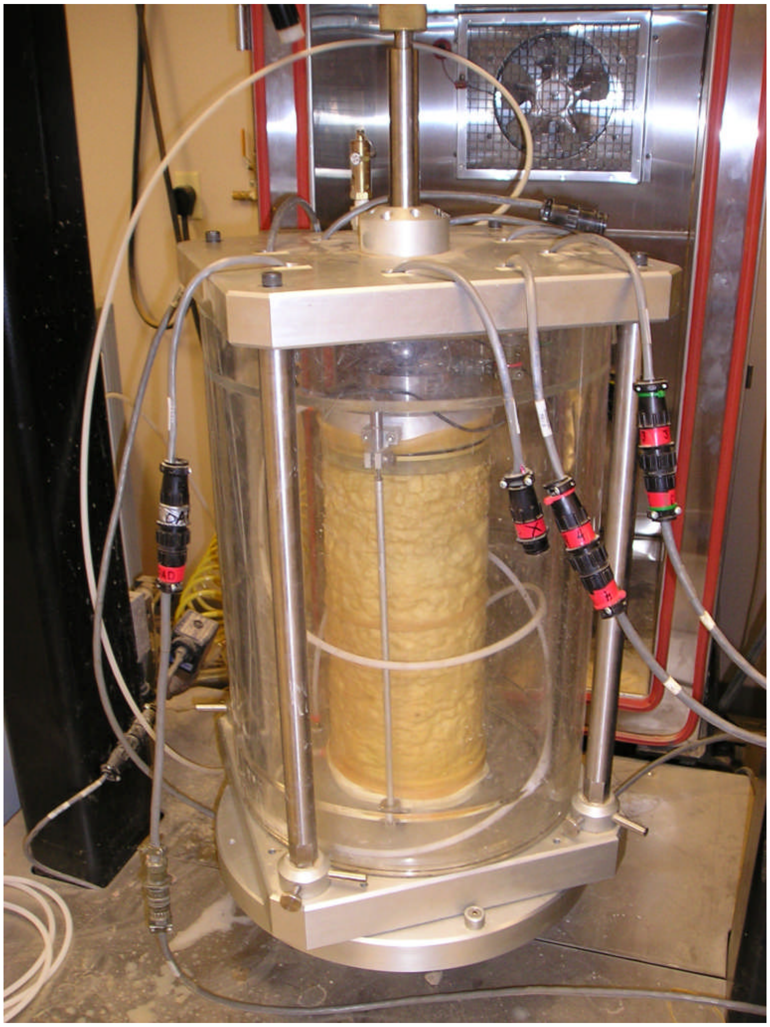


Figure 4: Resilient Modulus Testing Apparatus

CHAPTER 6   TEST RESULTS AND ANALYSIS

6.1 Introduction

This section presents the results and analyses obtained from the testing performed on each of the RCA samples. After presenting the test results, analyses of the data are provided to accomplish the project objectives.

6.2 Test Results

The following sections present results of all testing conducted on the six RCA materials obtained for this research. Results are presented for classification testing, mechanical property testing and durability testing.

6.2.1 Classification Tests

As stated in Chapter 2, a number of tests were identified as classification tests for RCA materials. These tests included particle size analysis, coarse aggregate angularity, particle shape, Atterberg limits, sand equivalency, sodium sulfate soundness, specific gravity and absorption, Los Angeles Abrasion loss, and Micro-Deval loss. The following paragraphs present results of these classification tests.

Table 8 provides the results of particle size analysis testing conducted on the six RCA materials. Also included in Table 8 is the fineness modulus (FM) calculated for each gradation. The FM was calculated by first determining the cumulative percent retained on each of the sieves. These values were then summed and divided by 100 to provide the FM.

Generally, the RCA materials had a maximum aggregate size of 1 in. (25 mm). Based upon the gradation results, Sample 6 was the coarsest RCA material and Sample 5 was the finest. Results on the ½ in. (12.5 mm) sieve ranged from a high of 97.4 percent for Sample 1 to a low of 67.4 percent for Sample 6. On the No. 4 (4.75 mm) sieve, results ranged from a high of 63.4 percent for Sample 5 to a low of 34.9 percent for Sample 6. Fines content (material passing No. 200 sieve) for the different RCA samples ranged from 1.5 to 11.4 percent with Sample 5 having the highest fines content and Sample 6 having the lowest.

Table 8: Results of Particle Size Analysis Testing

Percentage by Dry Weight Passing Sieve						
Sieve \ Sample #	No. 1 (I-29)	No. 2 (City of Mitchell)	No. 3 (Riverside Rd Exit)	No. 4 (White-wood)	No. 5 (Yankton)	No. 6 (Rapid City)
1 in.	100	100	100	100	99.4	93.5
¾ in.	100	97.8	90.9	93.8	95.3	86.4
½ in.	97.4	85.0	74.0	72.8	85.5	67.4
No. 4	51.2	48.9	48.1	36.6	63.4	34.9
No. 8	32.1	35.3	38.4	25.2	49.3	23.4
No. 40	13.0	15.7	19.7	12.0	24.5	7.1
No. 100	7.4	7.6	10.2	7.0	15.3	2.9
No. 200	5.4	5.3	6.9	4.7	11.4	1.5
Fineness Modulus	2.989	3.097	3.187	3.526	2.673	3.844

Gradation results are also illustrated in Figures 5 and 6 where they are compared to the current SDDOT criteria for gravel cushion and aggregate base course, respectively. None of the RCA materials explicitly meet the requirements for a gravel cushion. However, Samples 2 and 5 do have gradations that closely match requirements for a Gravel Cushion. Samples 1, 2, 3, and 5 all meet the gradation requirements for Aggregate Base Course. Samples 4 and 6 do not have gradations that closely resemble either a gravel cushion or aggregate base course. Both of these gradations are too coarse.

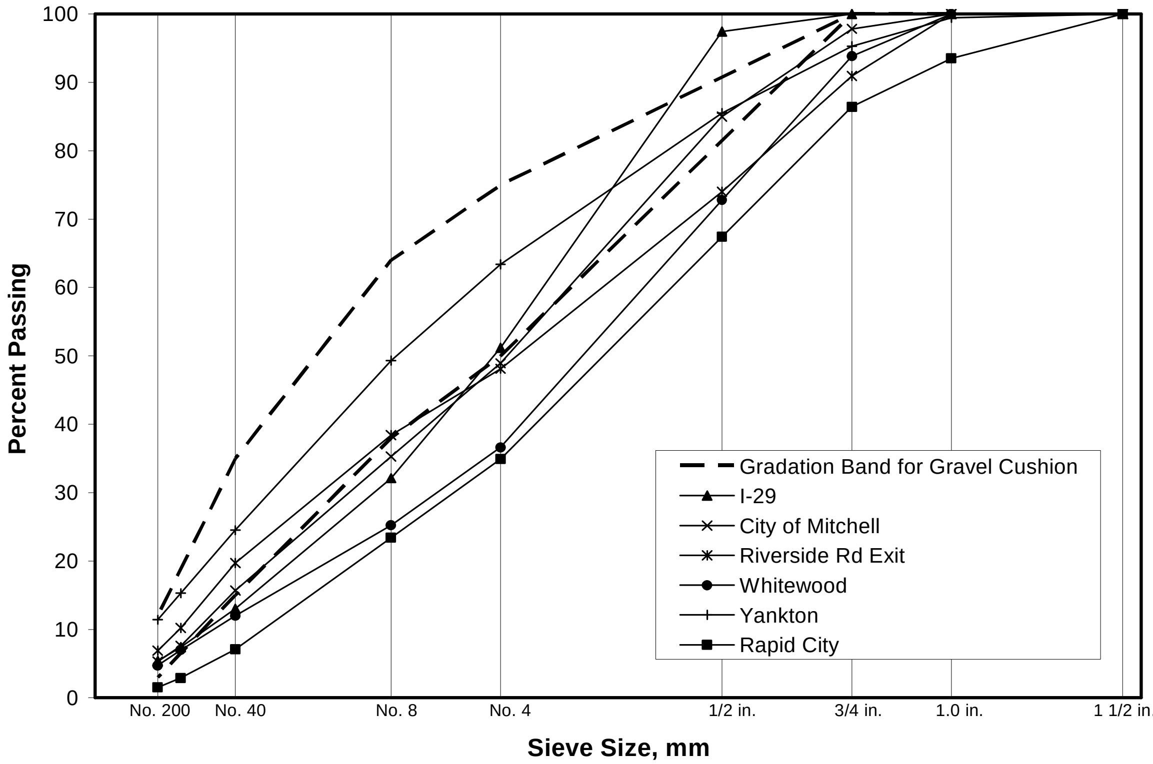


Figure 5: Gradation Results for the Six RCA Materials Compared to Gravel Cushion Requirements

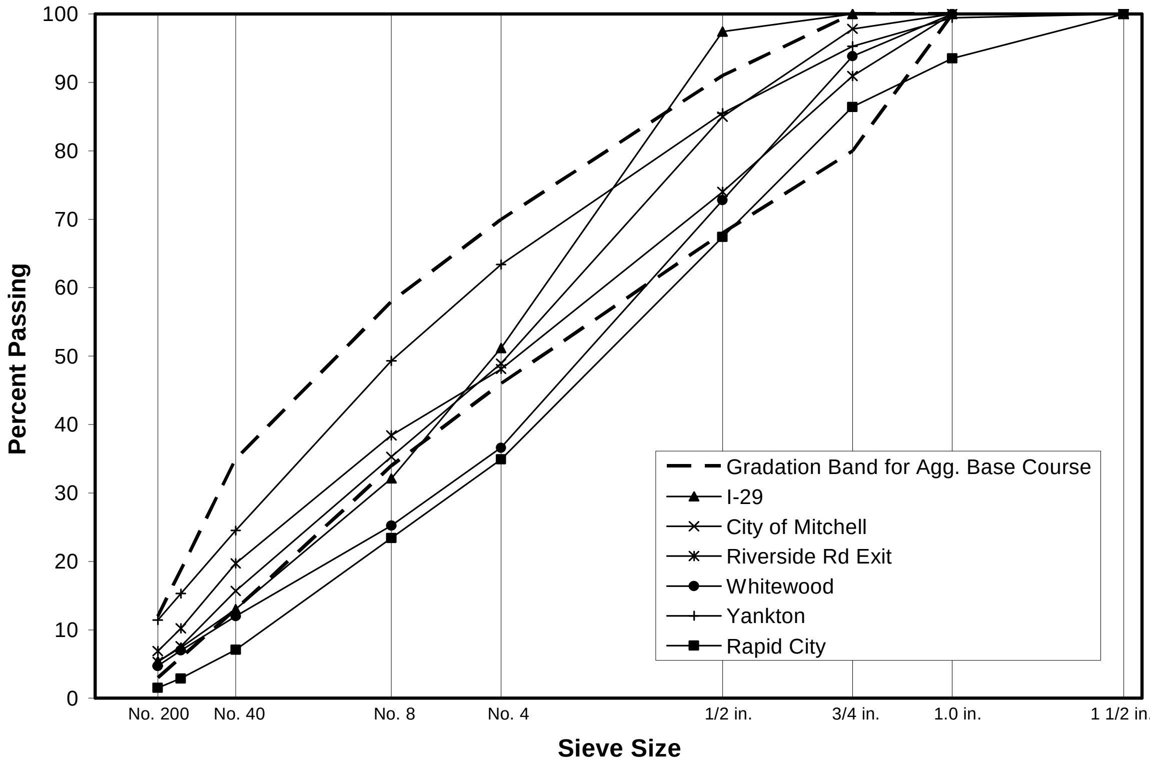


Figure 6: Gradation Results for the Six RCA Samples Compared to Aggregate Base Requirements

Table 9 presents the results of the Atterberg limit testing conducted on the minus No. 40 (0.425 mm) sized material from each of the RCA samples. Results are provided within Table 9 for liquid limit, plastic limit and plasticity index. Of the six samples, five were non-plastic. The only RCA material having plastic fines was Sample 5. For this material, the liquid limit was 31, plastic limit was 20 and plasticity index was 11. According to section 882.2 of the SDDOT Standard Specification, Gravel Cushion and Aggregate Base Course must have a liquid limit less than 25 and plasticity index less than 6. Therefore, Sample 5 would not meet the requirements for either a Gravel Cushion or Aggregate Base Course.

Table 9: Results of Atterberg Limit Testing

Sample # / Property	No. 1 (I-29)	No. 2 (City of Mitchell)	No. 3 (Riverside Rd Exit)	No. 4 (White-wood)	No. 5 (Yankton)	No. 6 (Rapid City)
Liquid Limit	---	---	---	---	31	---
Plastic Limit	---	---	---	---	20	---
Plasticity Index	NP	NP	NP	NP	11	NP

As stated previously, both the flat and elongated and the flat or elongated characteristics of the RCA materials were determined in order to evaluate particle shape. Results of this testing are presented in Table 10. Results from testing at a ratio of 5:1 showed little difference between the different RCA materials for either measure of particle shape. The widest range of test results occurred when using the flat and elongated definition and the 2:1 ratio ranging from 29.1 percent to 63.7 percent. The data suggests that Sample 3 had the least cubicle particles and that samples 1 and 2 were the most cubicle.

Table 10: Results of RCA Particle Shape Testing

Property \ Sample #	Ratio	No. 1 (I-29)	No. 2 (City of Mitchell)	No. 3 (Riverside Rd Exit)	No. 4 (White-wood)	No. 5 (Yankton)	No. 6 (Rapid City)
Flat and Elongated, %	5:1	0.1	0.7	0.6	0.0	0.0	0.0
	3:1	2.2	5.2	11.9	6.8	9.0	14.3
	2:1	29.9	29.1	63.7	37.9	61.4	46.0
Flat or Elongated, %	5:1	0.0	0.4	0.0	0.0	0.0	0.0
	3:1	0.3	1.5	4.9	0.3	0.4	0.0
	2:1	4.7	7.7	15.8	6.7	12.0	11.8

Results of specific gravity and absorption testing on the coarse and fine fractions of the RCA materials are presented in Table 11. Also included within Table 11 is the average specific gravity for the different RCA stockpiles which was determined volumetrically based upon the specific gravities of the coarse and fine fractions. For the combined stockpile, the apparent specific gravities of the different six RCA materials were generally similar with values ranging from 2.564 to 2.655. Bulk specific gravity values were also somewhat similar with values ranging from 2.198 to 2.295. Absorption values were all relatively high with all of the RCA materials exhibiting absorptions of 5 percent or higher. This level of absorption is much higher than most naturally occurring aggregates and is likely caused by air entrainment of the PCC materials.

Table 11: Results of Specific Gravity and Absorption Testing

Fraction \ Sample #	Property	No. 1 (I-29)	No. 2 (City of Mitchell)	No. 3 (Riverside Rd Exit)	No. 4 (White-wood)	No. 5 (Yankton)	No. 6 (Rapid City)
Coarse Particles	Apparent	2.668	2.587	2.599	2.581	2.607	2.572
	Bulk	2.314	2.233	2.255	2.204	2.299	2.331
	Absorption, %	5.7	6.1	5.9	6.6	5.1	4.0
Fine Particles	Apparent	2.641	2.539	2.610	2.620	2.633	2.606
	Bulk	2.257	2.193	2.201	2.190	2.194	2.258
	Absorption, %	6.5	6.2	7.1	7.5	7.6	5.9
Total Stockpile	Apparent	2.655	2.564	2.604	2.595	2.620	2.589
	Bulk	2.286	2.213	2.229	2.199	2.247	2.295
	Absorption, %	6.1	6.2	6.5	7.0	6.4	5.0

The uncompacted void content of coarse aggregate test was conducted to provide an indication of the angularity characteristics of the RCA materials. Results from this testing showed that all six RCA materials had similar uncompacted void content as results ranged from 47 to 50 percent. These results indicate angular coarse particles in the six RCA materials.

In order to evaluate the angularity characteristics of the fine aggregates, the uncompacted voids test was conducted on the fine fraction of each stockpile. Results for the different uncompacted voids tests resulted in similar values for five of the six samples. Samples 1 and 2 had uncompacted voids test results of 47 percent while Samples 3, 4 and 6 had 48 percent uncompacted voids. Sample 5 had the lowest uncompacted voids content with a value of 42 percent. Uncompacted void contents for fine aggregates that are above 45 are generally considered a sufficiently angular material.

Similar to the uncompacted voids content of the fine aggregates, the sand equivalency results were somewhat similar for five of the six RCA samples. Table 12 presents the results of sand equivalency testing. As shown in the table, Samples 1, 2, 3, 4, and 6 had somewhat similar sand equivalencies with values ranging from 70 to 89. Sample 5 had a much lower sand equivalency value at 46 percent.

Table 12: Results of Sand Equivalency Testing

Sample # / Property	No. 1 (I-29)	No. 2 (City of Mitchell)	No. 3 (Riverside Rd Exit)	No. 4 (White-wood)	No. 5 (Yankton)	No. 6 (Rapid City)
Sand Equivalency	78	74	70	81	46	89

Two tests were included to evaluate toughness and abrasion resistance, the Los Angeles Abrasion and Impact and Micro-Deval. As stated previously, these two tests are also considered to be related to durability of granular materials. Table 13 presents results of toughness and abrasion testing. Percent mass loss by the Los Angeles Abrasion and Impact test ranged from a low of 26 percent for Sample 4 to a high of 41 percent for Sample 5. Micro-Deval loss values were all relatively similar and ranged from a low of 15 percent for Sample 4 to a high of 19 percent for Sample 2. Section 882.2 of the SDDOT Standard Specifications states that for Gravel Cushion and Aggregate Base Course, the Los Angeles Abrasion Loss must be less than 40 percent. Therefore, Sample 5 would not meet this criteria.

Table 13: Results of Toughness and Abrasion Testing

Sample # / Property	No. 1 (I-29)	No. 2 (City of Mitchell)	No. 3 (Riverside Rd Exit)	No. 4 (White-wood)	No. 5 (Yankton)	No. 6 (Rapid City)
Los Angeles Abrasion, % Loss	28.4	30.2	34.7	25.8	40.7	39.0
Micro-Deval, % Loss	16.9	18.8	19.4	15.2	18.2	16.8

6.2.2 Mechanical Property Tests

Three tests were conducted to evaluate the mechanical properties of the RCA materials: resilient modulus, repeated load shear strength, and California Bearing Ratio. However, prior to conducting these mechanical tests, a reference laboratory density had to be developed in order to compact test specimens. According to SDDOT specifications, the standard Proctor is used to determine the maximum dry density and optimum moisture content for granular materials. Samples for mechanical property testing were compacted and tested at 95 percent of maximum dry density using optimum moisture content based upon the Task 1 panel meeting (Appendix A). The following paragraphs describe the standard Proctor and mechanical property test results.

Results of the standard Proctor tests are presented in Table 14 as the maximum dry density and optimum moisture content. Some problems were encountered while trying to conduct the standard Proctor tests, especially for Sample 6. Initially, the standard Proctor data was irregular making it difficult to identify an appropriate relationship between dry density and moisture content. An example of the erratic data for Sample 6 is illustrated in Figure 7. Shown on this figure are the original "points" from the Proctor data depicted by shaded circles. As can be seen from this figure, the data was very erratic. Results as shown in Figure 7 made it difficult for selecting the maximum dry density and optimum moisture content. Because of the erratic nature of the data, further investigation of the materials and testing process was conducted.

Table 14: Results of Standard Proctor Testing

Sample # / Property	No. 1 (I-29)	No. 2 (City of Mitchell)	No. 3 (Riverside Rd Exit)	No. 4 (White-wood)	No. 5 (Yankton)	No. 6 (Rapid City)
Max. Dry Density, lb/ft^3	109.3	114.3	114.4	112.7	120.5	115.9
Optimum Moisture Content, %	11.8	12.4	13.6	13.5	11.9	10.2

Results from the classification testing described above were first evaluated. Of this data, the relatively high absorption data was considered a potential cause of the erratic data. Typical procedures for running a standard Proctor test includes preparing four samples at varying moisture contents. After preparing the four test specimens, laboratory compaction begins. Because of this process, there is a longer period of time between sample preparation and compaction for some samples. The hypothesis for the erratic data was that due to the varying times between sample preparation and compaction and the relatively high absorption values some samples absorbed more water than others leaving less free water for compaction. To test this hypothesis, samples were prepared and allowed to stand overnight prior to compaction. This process would allow water to be absorbed into the RCA particles.

Figure 7 also shows Proctor results for Sample 6 after allowing the samples to stand overnight. As shown on this figure, results after standing overnight produced a discernable relationship between dry density and moisture content. Therefore, standard Proctors for all materials were rerun while allowing the samples to stand overnight. Results shown in Table 14 reflect Proctor results after allowing samples to stand overnight.

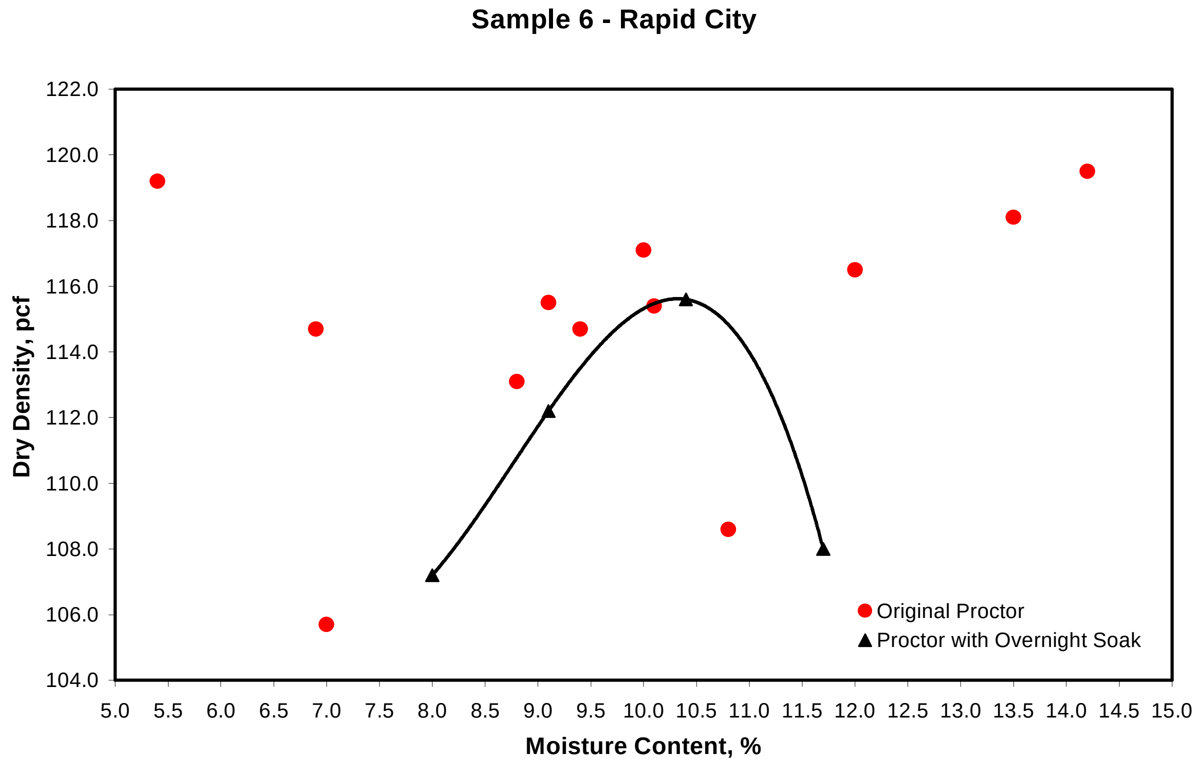


Figure 7: Standard Proctor Results for RCA Sample 6

Resilient modulus test results are presented in Table 15. All samples were compacted to 95 percent of the maximum dry density and at optimum moisture content shown in Table 14 determined from the standard Proctor tests. Results provided in Table 15 are the average resilient modulus of three replicate samples at a confining stress of 5 psi (34 kPa) and deviator stress of 15 psi (103 kPa). Also included within Table 15 are regression coefficients for the "universal" constitutive equation for fitting resilient modulus data. This information is provided because the 2002 Mechanistic-Empirical Pavement Design Guide utilizes these regression coefficients. Equation 1 presents the universal constitutive equation for fitting resilient modulus data. Table 15 includes the regression coefficients k_1, k_2, and k_3.

$$Mr = k_1 P_a \left[\frac{\theta}{P_a}\right]^{k_2} \left[\frac{\tau_{oct}}{P_a}\right]^{k_3}$$ **Equation 1**

Where,

Mr = resilient modulus
θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$
σ_1 = major principal stress

σ_2 = intermediate principal stress = σ_3 for tests on cylindrical samples
σ_3 = minor principal stress (confining pressure)
τ_{oct} = octahedral shear stress

$$= \frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2}$$

Pa = normalizing stress (atmospheric pressure)
k_1, k_2, k_3 = regression constants (obtained from fitting data to equation)

Table 15: Results of Resilient Modulus Testing

Sample # / Property	No. 1 (I-29)	No. 2 (City of Mitchell)	No. 3 (Riverside Rd Exit)	No. 4 (White-wood)	No. 5 (Yankton)	No. 6 (Rapid City)
Resilient Modulus, psi *	16,838	20,919	20,824	18,844	17,863	19,533
k_1	790.2	999.9	944.9	841.5	843.8	907.2
k_2	0.833	0.945	0.984	0.907	0.778	0.830
k_3	-0.569	-0.813	-0.745	-0.575	-0.478	-0.534

* 1 psi = 6.895 kPa

As shown in Table 15, resilient modulus values did not vary greatly between the six RCA materials. Resilient modulus values ranged from a low of 16,838 psi to a high of 20,919 psi.

The next mechanical property test conducted on each of the six RCA materials was the repeated load triaxial test for shear strength. For this test, failure was defined as the deviator stress causing 5 percent strain in the samples. Results of the repeated load testing are illustrated in Figure 8. Each line within this figure represents the average of three tests. As shown in Figure 8, there was a wide range of performance for the six RCA materials. Of the six materials, Sample 4 had the highest shear strength and Sample 5 had the lowest. In fact, Sample 4 had about twice the shear strength as Sample 5.

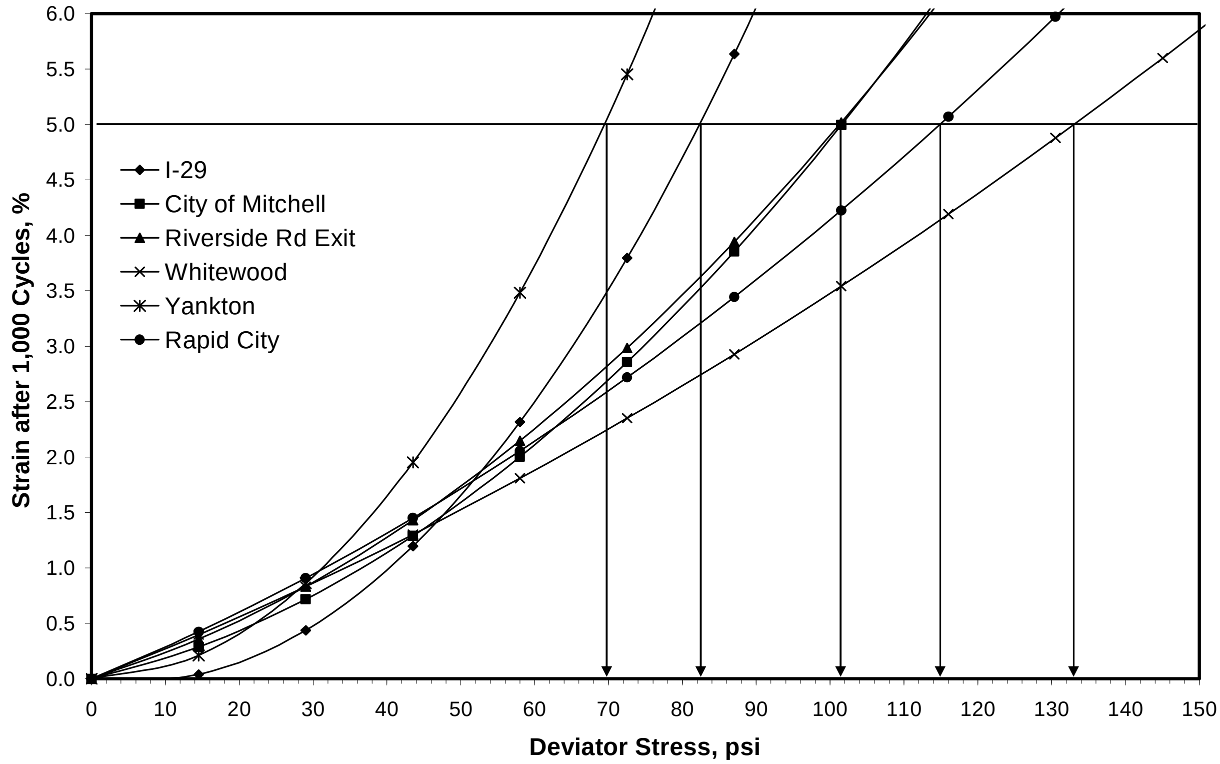


Figure 8: Results of Repeated Load Triaxial Strength Testing

The final mechanical property test conducted was the California Bearing Ratio (CBR) test. Results from the CBR tests are presented in Table 16. CBR values ranged from a low of 12 to a high of 47. Though these values are lower than what is typically reported for granular materials, they are not lower than anticipated. Recall that the samples were compacted to 95 percent of the maximum dry density using a standard Proctor effort. Being that the samples were compacted to a lower density than maximum dry density and the standard Proctor hammer was used instead of the modified compactive effort, CBR values would be expected to be lower. Of the six samples, only the results from Sample 2 are considered low.

Table 16: Results of California Bearing Ratio Testing

Property \ Sample #	No. 1 (I-29)	No. 2 (City of Mitchell)	No. 3 (Riverside Rd Exit)	No. 4 (White-wood)	No. 5 (Yankton)	No. 6 (Rapid City)
CBR	27	12	26	37	23	47

6.2.3 Durability Tests

A number of tests were conducted to evaluate the durability of the RCA materials. Durability tests included sodium sulfate soundness, freeze/thaw testing, combination of freeze/thaw testing and the Micro-Deval, and an evaluation of the re-cementing potential for the RCA fines.

Additionally, the Los Angeles Abrasion and Impact and Micro-Deval tests presented earlier are also considered related to durability.

Results for the sodium sulfate soundness, New York Freeze/Thaw, and combination of New York Freeze/Thaw and Micro-Deval tests are presented in Table 17. Sodium sulfate soundness results ranged from a low of 9 percent loss for Sample 1 to a high of 36 percent loss for Sample 6. Results from the New York freeze/thaw test ranged from a low of 7 percent to a high of 17 percent loss. Results from the combined New York freeze/thaw and Micro-Deval testing were generally similar. Five of the six RCA materials had test results between 23 and 27 percent loss. Sample 6 had a loss after this combined testing of 33 percent.

Table 17: Results of Sulfate and Freeze/Thaw Testing

Property \ Sample #	No. 1 (I-29)	No. 2 (City of Mitchell)	No. 3 (Riverside Rd Exit)	No. 4 (White-wood)	No. 5 (Yankton)	No. 6 (Rapid City)
Sodium Sulfate Soundness, % loss	9	15	13	11	22	36
NY Freeze/Thaw Test, % loss	7	10	12	5	17	14
Micro-Deval + NY F/T, % loss	25	27	24	24	23	33

The final testing that was conducted to evaluate the durability of the RCA materials was to conduct resilient modulus testing on samples that had been stored in a temperature and humidity controlled room. This testing was conducted to evaluate the potential for RCA materials re-cementing in the field. Only Samples 1, 3 and 6 were subjected to this testing. Results of tests conducted on these three materials are provided in Table 18.

Table 18: Results of Resilient Modulus Testing With Time

Days Stored \ Sample #	No. 1 (I-29)	No. 3 (Riverside Rd Exit)	No. 6 (Rapid City)
0	16,838 psi	20,824 psi	19,533 psi
7	21,601 psi	20,663 psi	20,354 psi
28	19,068 psi	24,806 psi	17,665 psi
128	*	21,234 psi	*

* Samples fell apart prior to testing.
1 psi = 6.895 kPa

6.3 Analysis of Test Results

The overall objective of this project was to evaluate whether recycled portland cement concrete pavements provide a viable option as a granular layer under rigid pavements (gravel cushion) and/or flexible pavements (aggregate base course). As such, two characteristics of the materials are important to performance: stability and durability. The following sections present analyses conducted to accomplish the project objectives.

6.3.1 *Stability of RCA Materials*

Three tests were conducted to evaluate the stability of the RCA materials: repeated load triaxial test for shear strength, resilient modulus and CBR. For each of these measures of stability (or strength), results from the classification tests were used to try and predict stability (or in other words determine which classification tests may be related to stability). Classification tests that are shown related to the stability of RCA materials should be included within specifications and guidelines governing the use of RCA materials. Classification tests included within the analyses included the following:

- Particle size distribution
- Percent flat and elongated particles at 5:1, 3:1 and 2:1
- Percent flat or elongated particles at 5:1, 3:1 and 2:1
- Percent uncompacted voids in coarse aggregate
- Percent uncompacted voids in fine aggregate
- Sand Equivalency
- Los Angeles Abrasion and Impact, percent loss
- Micro-Deval, percent loss
- Standard Proctor results

A classification test that was conducted during this study that is not included within the above list is Atterberg limits and plasticity index. Results from this testing were not included because five of the six RCA materials were non-plastic and, therefore, did not have test results for plasticity index.

Instead of including the percent passing for each individual sieve included within the particle size distribution, a fineness modulus was calculated for each material. The fineness modulus (FM) is an index of the fineness of an aggregate. High FM values indicate coarser materials.

Initial analysis of the repeated load shear test data involved conducting an analysis of variance (ANOVA) to determine if the results for the six RCA materials were significantly different. An ANOVA could be performed because three replicate tests were conducted for each material. For the purposes of this study, it was important to determine if significant differences occurred in the performance data in order to evaluate whether any of the classification tests would identify the differences. Results of the ANOVA for the repeated load shear test data are shown in Table 19. This table shows that there were significant differences in the shear test results at a 5 percent level of significance.

Table 19: Results of ANOVA on Repeated Load Shear Test Data

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio	Probability Level
RCA Sample	5	169,622.7	33,924.5	33.05	0.000
Error	12	12,317.3	1,026.4		
Total	17	181,940			

Because of the significant differences in the repeated load shear data, a Duncan's Multiple Range Test (DMRT) was conducted. The DMRT is useful in comparing means that are found significantly different by ranking the means to show which are significantly different. Results of the DMRT for the shear strength data are presented in Table 20. Samples with the same letters are not significantly different. Based upon the DMRT, RCA samples 1 and 5 had similar shear strengths and were different (lower) than the other four RCA samples. Samples 2, 3 and 6 also had similar shear strength and were different than the other three materials. Finally, Sample 4 had the highest shear strength and was different than the other five RCA samples.

Table 20: Results of Duncan's Multiple Range Test for Repeated Load Shear Test Data

RCA Sample	Mean Shear Strength, psi	Duncan's Ranking*
5 (Yankton)	70	A
1 (I-29)	82	A
2 (City of Mitchell)	102	B
3 (Riverside Rd Exit)	102	B
6 (Rapid City)	115	B
4 (Whitewood)	133	C

* RCA samples with the same letter are not significantly different.

The next analysis technique involved conducting simple linear regressions between each of the classification tests and the results of the repeated load shear test. This technique was conducted to determine whether there was a significant relationship between the classification tests and shear strength.

Table 21 presents the results of the simple linear regressions between each of the classification tests and the repeated load triaxial shear strength test results. Information contained within Table 21 includes the coefficient of determination (R^2) for the linear relationship between the classification tests and shear strength; the F-ratio determined from an analysis of variance to evaluate the significance of each regression; the significance of the relationship; and whether the relationship is considered significant at a 5 percent level of significance. As shown in Table 21 only one classification test had a significant relationship with shear strength at the 5 percent significance level: fineness modulus. Two other classification tests were, however, significant at a 10 percent level of significance. Both the uncompacted void content in fine aggregate and sand equivalency were significant at a 10 percent level of significance.

Table 21: Results of Linear Regressions for Shear Strength Data

Classification Test	R^2	F-ratio	Prob. Level	Significant at 5 Percent?
Fineness Modulus	0.728	11.512	0.028	Yes
Flat and Elongated, 3:1	0.075	0.326	0.599	No
Flat and Elongated, 2:1	0.061	0.259	0.638	No
Flat or Elongated, 3:1	0.000	0.000	0.985	No
Flat or Elongated, 2:1	0.006	0.024	0.884	No
Uncompacted Voids in Coarse Agg.	0.000	0.000	0.982	No
Uncompacted Voids in Fine Agg.	0.583	5.388	0.081	No
Sand Equivalency	0.540	4.713	0.096	No
Los Angeles Abrasion	0.182	0.892	0.398	No
Micro-Deval	0.276	1.525	0.285	No
Maximum Dry Density	0.083	0.363	0.579	No
Optimum Moisture Content	0.044	0.183	0.691	No

Figure 9 illustrates the relationship between shear strength and fineness modulus. Also included in this figure are the regression statistics. Based upon this figure, shear strength increased as the fineness modulus increased. This relationship indicates that as the gradation becomes coarser, the shear strength increased for the RCA materials. Samples 1 and 5 had the two lowest FMs and also the two lowest shear strengths. Samples 4 and 6 had the two highest FMs and highest shear strengths, similar to the DMRT rankings shown in Table 20.

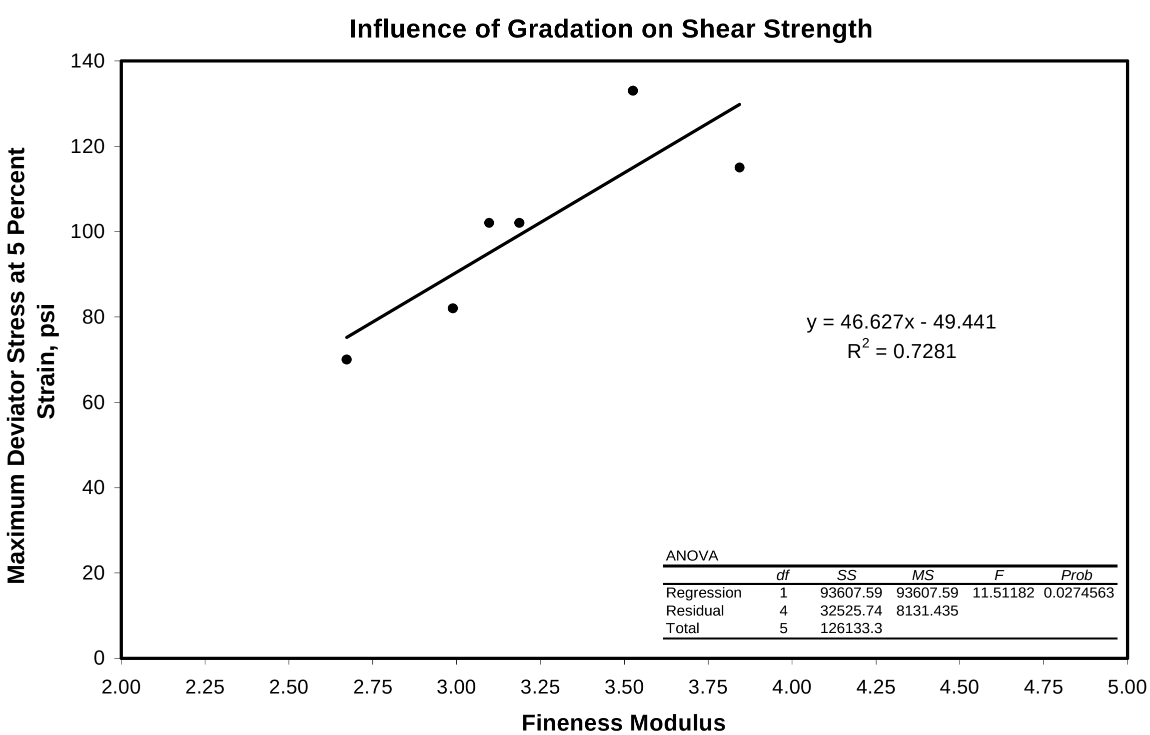


Figure 9: Relationship between Fineness Modulus and Shear Strength

Figure 10 illustrates the relationship between shear strength and the uncompacted void content of fine aggregates. The uncompacted void content in fine aggregate test provides an index property that is a function of the fine aggregate particle shape, angularity and surface texture. Higher values of this test are desirable. Based upon Figure 10, RCA materials having fine aggregates with more angularity (higher uncompacted void contents) had more shear strength. Sample 5 had the lowest uncompacted void content and also had the lowest shear strength, similar to the DMRT rankings. However, the uncompacted void content for the fine aggregates were similar for Samples 1, 2, 3, 4 and 6. Sample 4 did have the highest uncompacted void content (along with Samples 3 and 6) and the highest shear strength (as shown in Table 20).

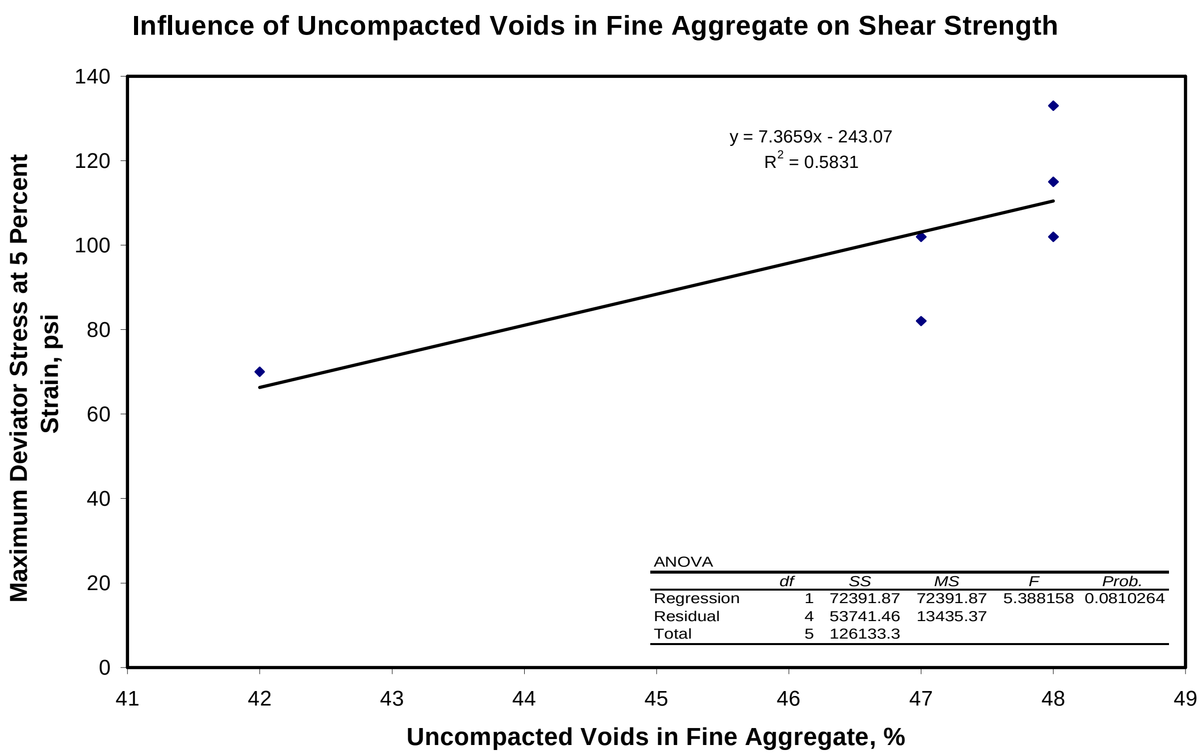


Figure 10: Relationship between Uncompacted Void Content of Fine Aggregate and Shear Strength

The final classification test that showed a relationship with shear strength was sand equivalency. Figure 11 illustrates this relationship and shows that shear strength increased with increasing values of sand equivalency. Shear strength of granular materials is generally considered to be related to the gradation and angularity of the aggregate particles, as shown in Figures 9 and 10. Therefore, since sand equivalency is considered a measure of the cleanliness of the aggregate materials, this relationship was somewhat surprising. However, when considering the relationships of shear strength with gradation (fineness modulus) and uncompacted void content in fine aggregates, the relationship between sand equivalency and shear strength shown in Figure 11 can be explained. Sample 5 had the lowest sand equivalency and uncompacted void content in fine aggregate. Table 8 also showed that Sample 5 had the highest percentage of fines (material passing the No. 200 sieve). Visually, Sample 5 appeared to have soil mixed with the RCA. The color of Sample 5 was a brown instead of a white color like the other five RCA samples. The low sand equivalency, low uncompacted void content in fine aggregate and high fines content suggest that some type of natural, dirty and rounded fine material had been added to Sample 5. This is also indicated by the high plasticity index (Table 9). The natural, dirty and rounded fine material is likely the cause of the lower shear strength and is, therefore, considered undesirable.

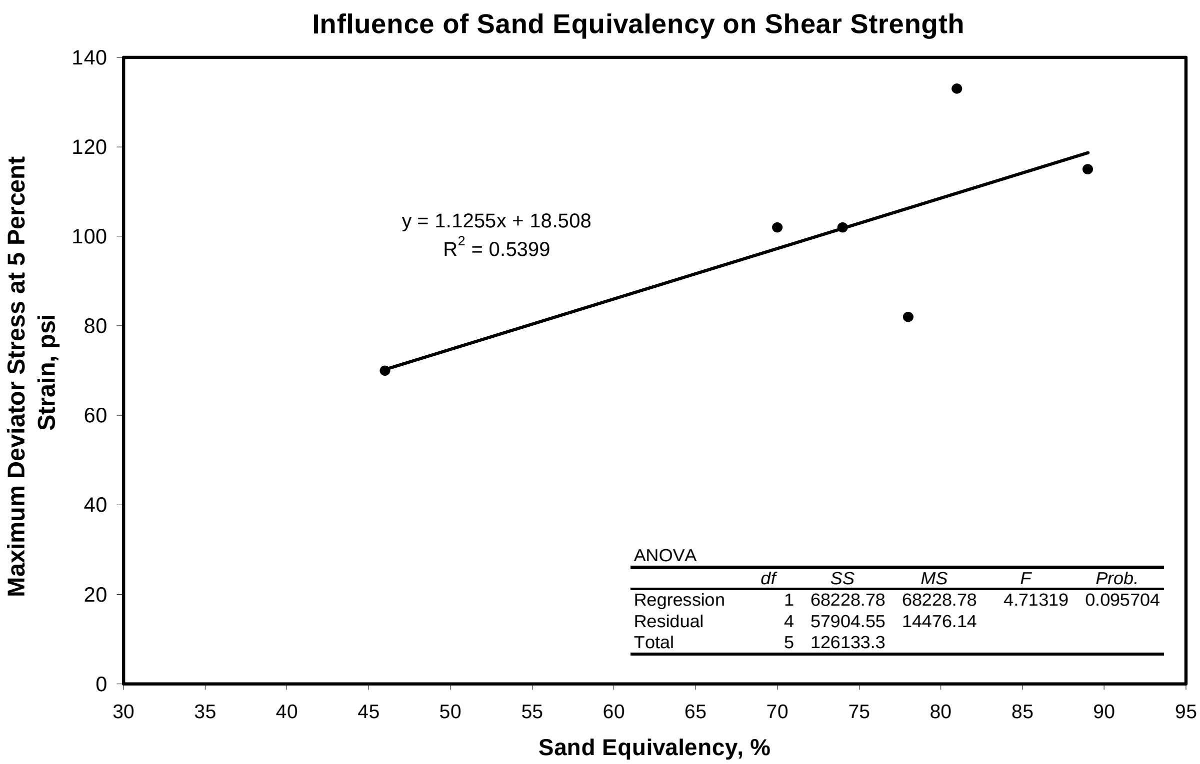


Figure 11: Relationship between Sand Equivalency and Shear Strength

The next performance measure related to stability was the resilient modulus test. Similar to the repeated load shear test data, the first analysis technique was to conduct a ANOVA to determine whether significant differences occurred in the resilient modulus data for the six RCA materials. Results of the ANOVA are presented in Table 22. This table shows that there were significant differences in resilient modulus test results for the six materials.

Table 22: Results of ANOVA in Resilient Modulus Test Data

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio	Probability Level
RCA Sample	5	39,508,580	7,901,715	3.99	0.023
Error	12	23,742,540	1,978,545		
Total	17	63,251,110			

Because of the effect of RCA material on the resilient modulus results, a DMRT was again performed to determine which RCA samples were different. Results of the DMRT are shown in Table 23. This table shows that Samples 1, 5, 4 and 6 had similar test results and that Samples 5, 4, 6, 3, and 2 also had similar test results. In essence, the DMRT showed that Sample 1 had a significantly lower resilient modulus than Samples 2 and 3.

Table 23: Results of Duncan's Multiple Range Test for Resilient Modulus Data

RCA Sample	Mean Resilient Modulus, psi	Duncan's Ranking*
1 (I-29)	16,838	A
5 (Yankton)	17,863	AB
4 (Whitewood)	18,844	AB
6 (Rapid City)	19,533	AB
3 (Riverside Rd Exit)	20,824	B
2 (City of Mitchell)	20,919	B

*RCA samples with the same letter are not significantly different.

The next analysis technique was to conduct simple linear regressions between the results of the classification tests and resilient modulus. Table 24 presents the results of the simple linear regressions. This table shows that none of the classification tests had a reasonable relationship with resilient modulus. The lack of reasonable relationships is not surprising considering the DMRT ranking shown in Table 23. Practically, there was very little difference in the resilient modulus test results.

Table 24: Results of Linear Regressions for Resilient Modulus Data

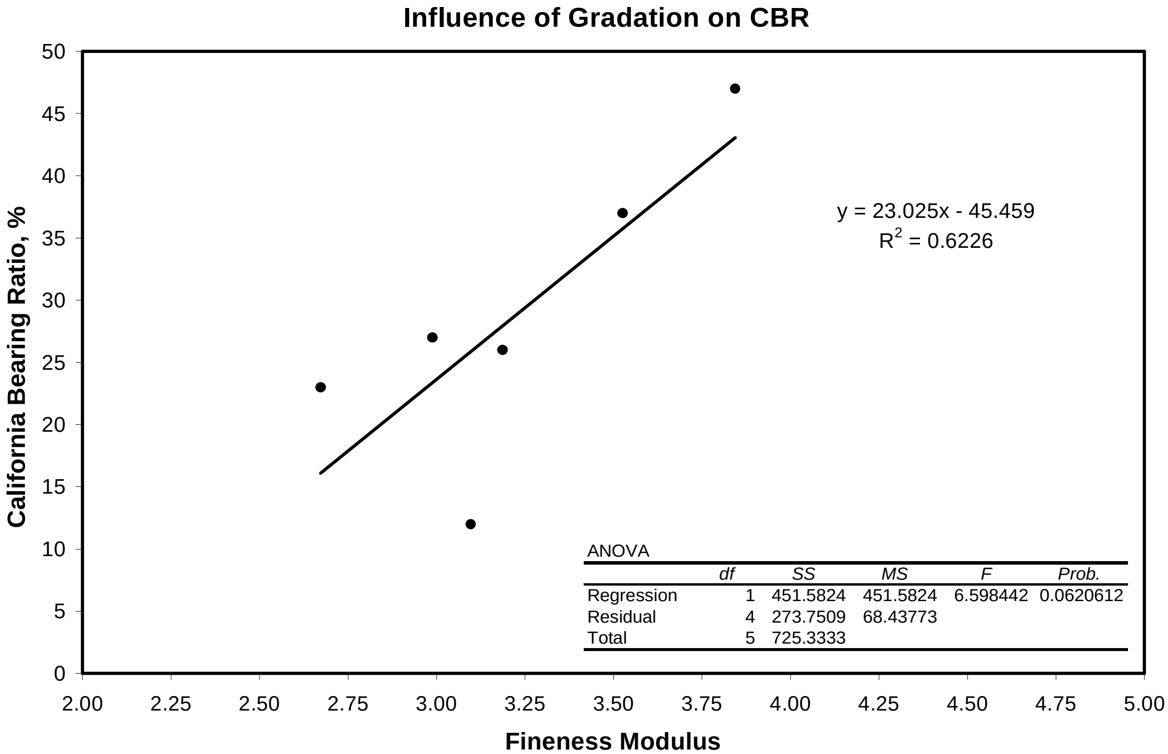
Classification Test	R^2	F-ratio	Prob. Level	Significant at 5 Percent?
Fineness Modulus	0.110	0.494	0.521	No
Flat and Elongated, 3:1	0.210	1.062	0.361	No
Flat and Elongated, 2:1	0.025	0.103	0.764	No
Flat or Elongated, 3:1	0.405	2.721	0.174	No
Flat or Elongated, 2:1	0.259	1.395	0.303	No
Uncompacted Voids in Coarse Agg.	0.032	0.131	0.736	No
Uncompacted Voids in Fine Agg.	0.185	0.909	0.395	No
Sand Equivalency	0.039	0.163	0.707	No
Los Angeles Abrasion	0.004	0.017	0.903	No
Micro-Deval	0.262	1.416	0.300	No
Maximum Dry Density	0.026	0.108	0.759	No
Optimum Moisture Content	0.078	0.336	0.593	No

The final measure of stability used in this study was the CBR test. An ANOVA could not be perfomed for the CBR data because only a single replicate test was performed for each RCA material. Therefore, only simple linear regressions were conducted. Table 25 presents the results of the simple linear regressions conducted to relate the classification tests and CBR. None of the classification tests had a significant relationship with the CBR results at a 5 percent level of significance level; however, two classification tests had a significant relationship at a 10 percent level of significance: fineness modulus and uncompacted void content of coarse aggregates.

Table 25: Results of Linear Regression for California Bearing Ratio Data

Classification Test	R^2	F-ratio	Prob. Level	Significant at 5 Percent?
Fineness Modulus	0.623	6.598	0.062	No
Flat and Elongated, 3:1	0.297	1.693	0.263	No
Flat and Elongated, 2:1	0.014	0.055	0.826	No
Flat or Elongated, 3:1	0.116	0.525	0.509	No
Flat or Elongated, 2:1	0.011	0.044	0.844	No
Uncompacted Voids in Coarse Agg.	0.540	4.618	0.098	No
Uncompacted Voids in Fine Agg.	0.138	0.641	0.468	No
Sand Equivalency	0.313	1.822	0.249	No
Los Angeles Abrasion	0.024	0.100	0.768	No
Micro-Deval	0.441	3.149	0.151	No
Maximum Dry Density	0.003	0.010	0.925	No
Optimum Moisture Content	0.162	0.773	0.429	No

Figure 12 illustrates the relationship between fineness modulus and CBR. Similar to the repeated load shear test data, an increase in the fineness modulus resulted in an increase in strength (shown as an increase in CBR). This relationship suggests that coarser gradations provide more strength. The results of the analyses conducted to relate fineness modulus to shear strength and CBR (Figures 9 and 12) both suggest the importance of gradation on the stability of RCA materials.



	df	SS	MS	F	Prob.
Regression	1	451.5824	451.5824	6.598442	0.0620612
Residual	4	273.7509	68.43773		
Total	5	725.3333			

Figure 12: Relationship between Fineness Modulus and California Bearing Ratio

Figure 13 presents the relationship between the uncompacted void content of coarse aggregates and CBR. The trend of this relationship is that more angular coarse aggregates improve the stability of RCA materials. Figures 10 and 13 illustrate the importance of angular coarse and fine aggregates for stable RCA layers.

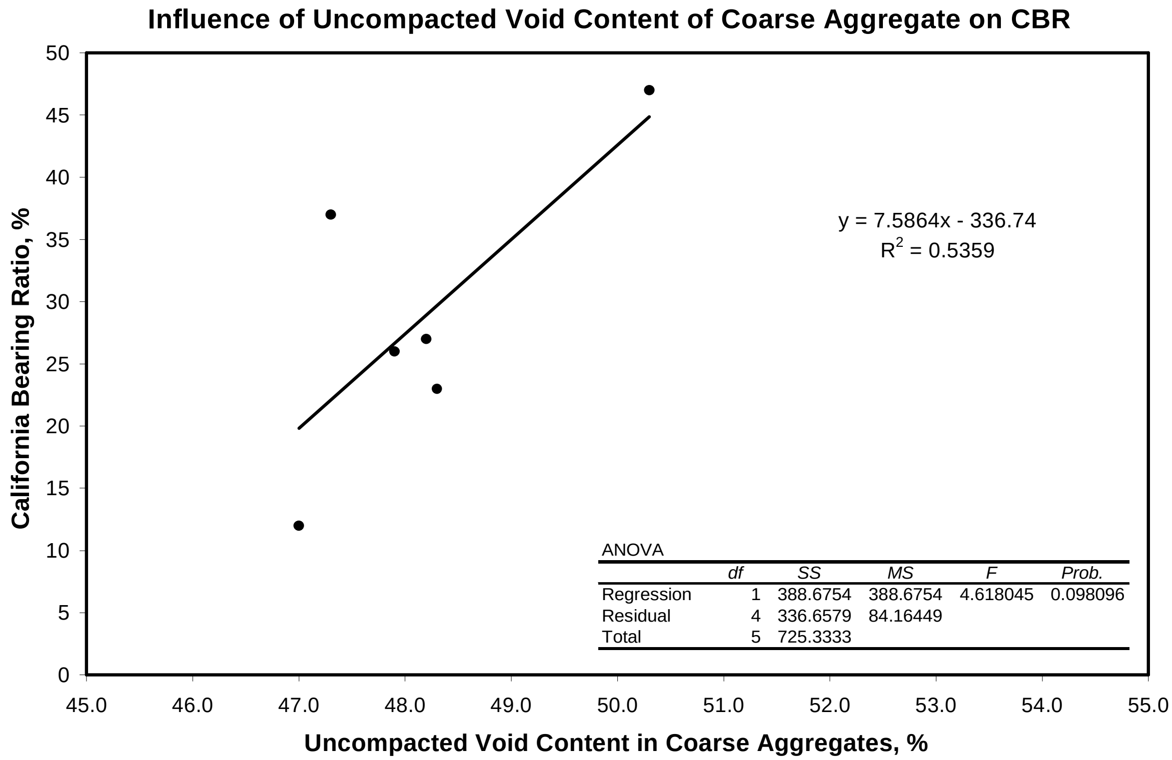


Figure 13: Relationship between Uncompacted Void Content of Coarse Aggregates and California Bearing Ratio

6.3.2 Durability of RCA Materials

As stated numerous times within this report, a major concern of the SDDOT with the use of RCA materials as granular layers under rigid and flexible pavements was durability. Six different tests were conducted specifically to evaluate the durability of the RCA materials: Atterberg limits, sodium sulfate soundness, the New York Freeze/Thaw test, Los Angeles Abrasion, Micro-Deval, and combination of New York Freeze/Thaw and Micro-Deval tests. Since all of these test methods were included because they provide an indication of durability, the initial analysis of the data was to develop a correlation matrix between the test results. Atterberg limits could not be included within this analysis because five of the six RCA materials were non-plastic (Table 9) and, therefore, did not have a quantitative measure of durability.

Correlation matrices are an easy method of illustrating the relationships between a series of independent variables. To conduct this analysis the Pearson Product-Moment method was employed. Table 26 presents the correlation matrix for the durability data. The top values within each cell represent the correlation coefficient (R) and the bottom values represent the significance levels (P). High R values represent stronger correlations between the two variables while lower P values represent greater significance of the relationship. Of the various comparisons, the strongest relationship was between results from the Los Angeles Abrasion and New York Freeze/Thaw test. The R value for this relationship was 0.982. The Los Angeles

Abrasion test also had a strong relationship with results from the sodium sulfate soundness test (R=0.762). The only other relationship that showed a strong correlation was sodium sulfate soundness and the combination of the New York Freeze/Thaw and Micro-Deval test.

Table 26: Correlation Matrix for Durability Test Results

	New York Freeze/Thaw	Micro-Deval + NY F/T	Sodium Sulfate Soundness	Los Angeles Abrasion	Micro-Deval
New York Freeze/Thaw	1.000	0.130 (0.806)	0.662 (0.152)	0.982 (0.001)	0.536 (0.272)
Micro-Deval + NY F/T		1.000	0.768 (0.074)	0.270 (0.604)	-0.169 (0.749)
Sodium Sulfate Soundness			1.000	0.762 (0.078)	-0.032 (0.951)
Los Angeles Abrasion				1.000	0.434 (0.389)
Micro-Deval					1.000

Figure 14 illustrates the relationship between the Los Angeles Abrasion test results and the New York Freeze/Thaw test results. Also included within this figure are the regression statistics. Based upon the regression statistics, the relationship between the Los Angeles Abrasion and New York Freeze/Thaw test results is significant at a 5 percent level of significance. The slope of the relationship indicates that the two methods are providing a similar indication for the durability of RCA materials. As the Los Angeles Abrasion percent loss increased, the percent loss after the five freeze/thaw cycles also increased.

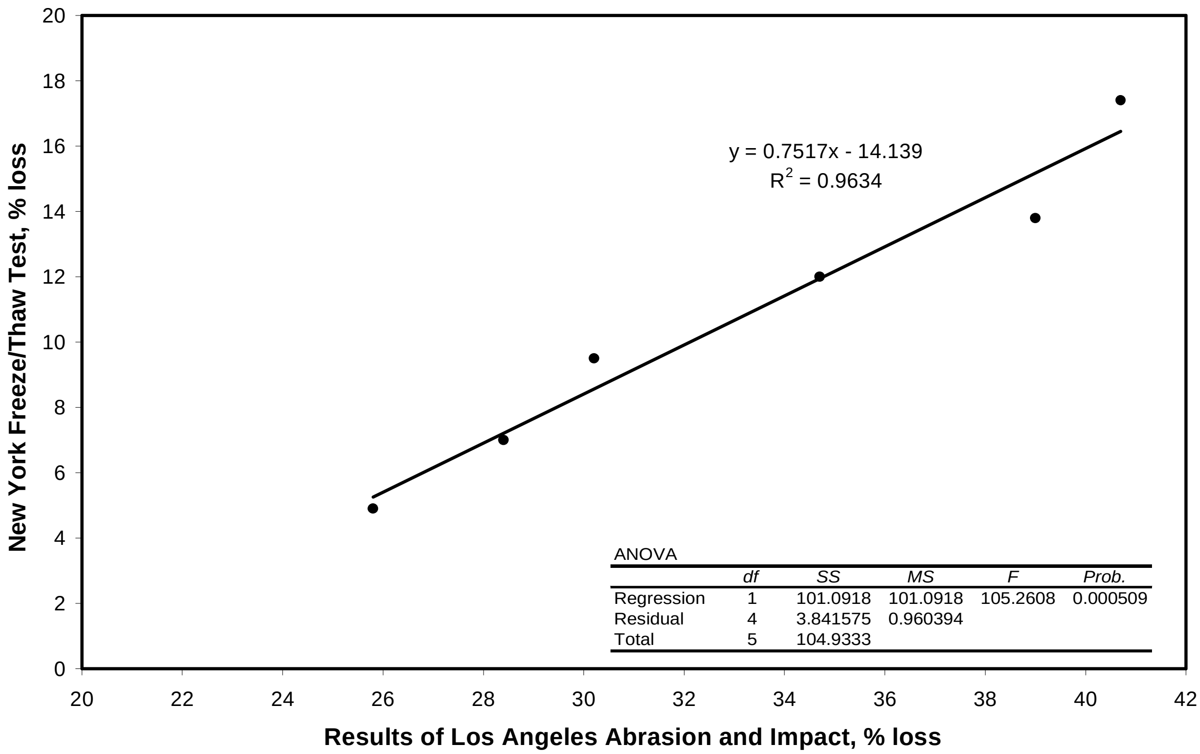


Figure 14: Relationship between Los Angeles Abrasion and New York Freeze/Thaw Tests

Figure 15 presents the relationship between Los Angeles Abrasion percent loss and the sodium sulfate soundness percent loss. As the percent loss in the Los Angeles Abrasion test increased, the sodium sulfate soundness percent loss also increased. Figures 14 and 15 suggest that the Los Angeles Abrasion test has a strong relationship with both the sodium sulfate soundness and New York Freeze/Thaw tests. These relationships are interesting because both the sodium sulfate soundness and New York Freeze/Thaw tests are used in the laboratory to simulate the actions of freezing and thawing in the field. The Los Angeles Abrasion test is simply an abrasion and impact test; however, the strong relationships shown in Figures 14 and 15 suggest that the Los Angeles Abrasion test could be included within a specification as an indicator of the susceptibility of RCA materials to freeze/thaw.

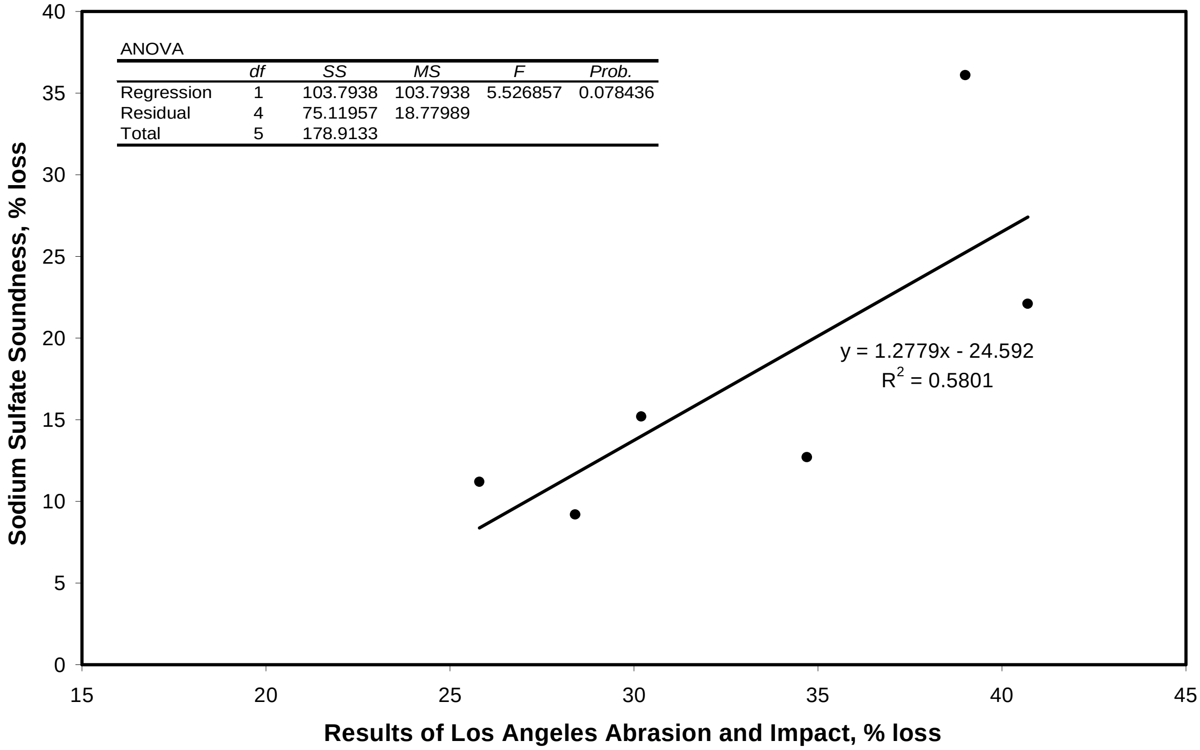


Figure 15: Relationship between Los Angeles Abrasion and Sodium Sulfate Soundness

The other strong relationship shown in Table 26 was between sodium sulfate soundness and the New York Freeze/Thaw test combined with the Micro-Deval. This relationship is illustrated in Figure 16. As would be expected, since both tests evaluate the susceptibility of granular materials to the actions of freezing and thawing, sodium sulfate soundness percent loss values increased as the combined New York Freeze/Thaw and Micro-Deval percent loss increased. Figures 14 through 16 suggest that the Los Angeles Abrasion, sodium sulfate soundness, New York Freeze/Thaw and combined New York Freeze/Thaw and Micro-Deval tests are all providing a similar indication of durability for the RCA materials included in this study.

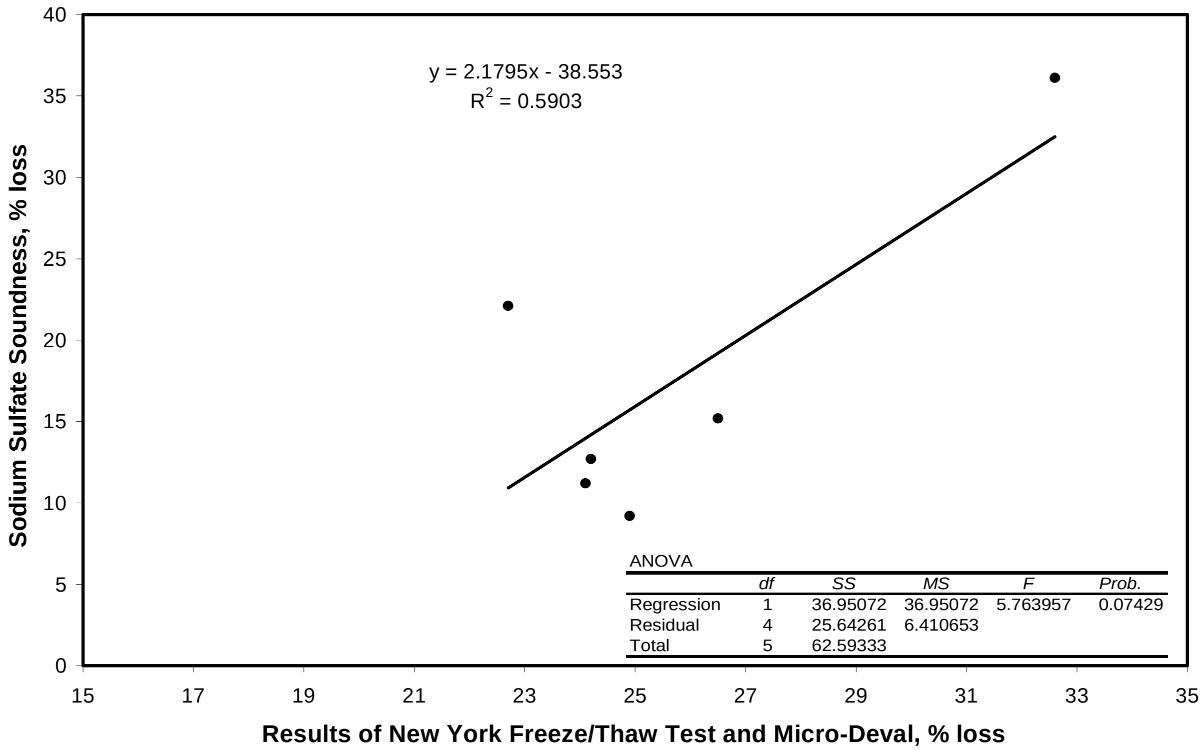


Figure 16: Relationship between Sodium Sulfate Soundness and New York Freeze/Thaw Tests

The final testing conducted to evaluate the long term performance of RCA materials as a granular layer was to cure compacted RCA samples in a temperature and humidity controlled moist room for an extended period of time. This testing was conducted on three selected RCA materials to specifically determine whether the RCA samples might re-cement over time. Results of this testing were presented in Table 18 and are illustrated in Figure 17. This figure shows that the resilient modulus did not increase over the time that the samples were stored in the temperature and humidity controlled room. The relationships shown in Figure 17 indicate that the fines and exposed mortar within the RCA samples did not re-cement. Re-cementing of the fines and exposed mortar would have resulted in an increase in the resilient modulus values because the RCA materials would have become stiffer due to the re-cementing. In fact, two of the three samples stored for 128 days fell apart while trying to load the samples for testing. Though the data from these two samples at 128 days would have been beneficial in answering the question about re-cementing of the fines, the fact that the samples fell apart provides a qualitative indication that re-cementing did not occur. Based upon the RCA samples tested in this study, re-cementing of RCA fines while in-place should not be a concern.

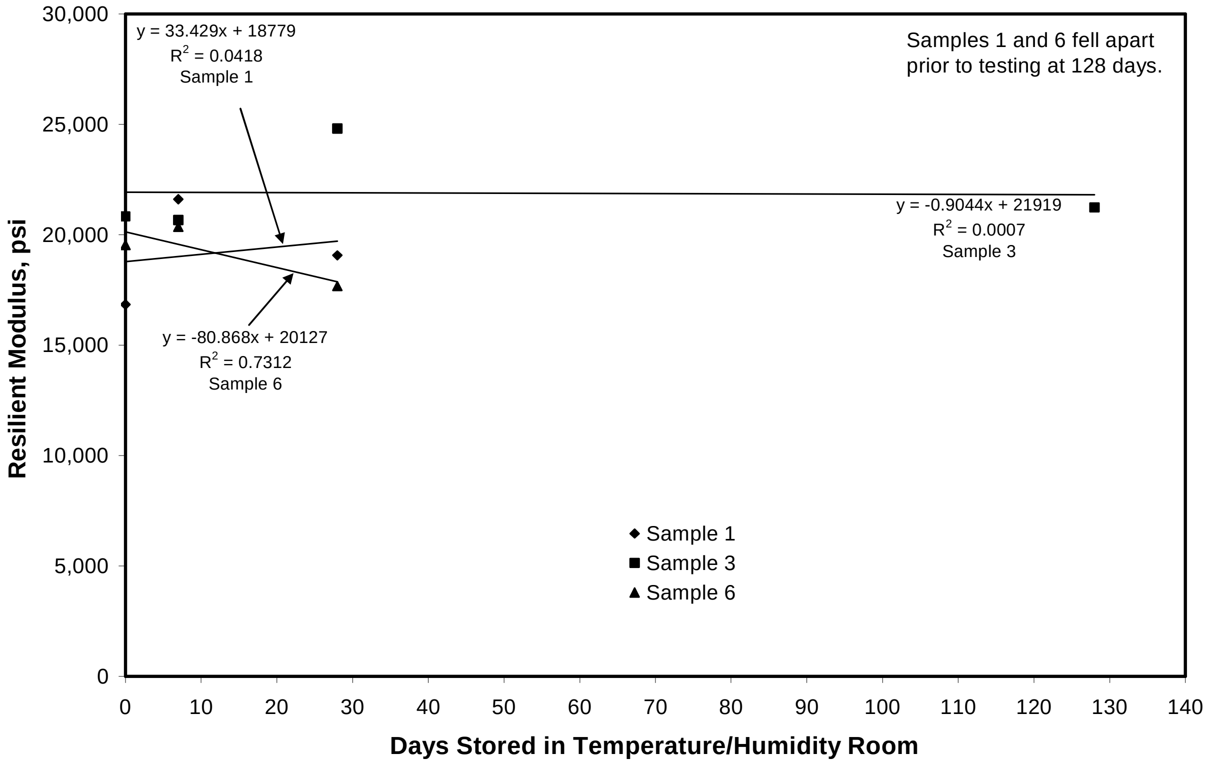


Figure 17: Resilient Modulus Results with Time

CHAPTER 7 SUMMARY/DISCUSSION

7.1 Introduction

The literature review (Task 2) and survey of states (Task 3) clearly indicated that recycled concrete aggregates (RCA) is a viable option in pavement construction. Though not specifically mentioned in the literature review, RCA materials have been used within PCC and hot mix asphalt as well as fill material in embankments. However, probably the largest use of RCA in pavement construction has been in the placement of unbound layers under both rigid and flexible pavements.

Based upon the literature review, there are two general characteristics that are related to the performance of unbound granular layers: stability and durability. Stability can be defined as the ability of the unbound granular layer to withstand the repetitive actions of traffic. Terms such as shear strength and stiffness are generally used to describe stability. Durability can be defined as the ability of the unbound granular layer to perform over an extended period of time. Characteristics related to durability include the ability to resist the actions of freezing and thawing, degradation, low density, etc. Other issues related to durability that might be specific to RCA are sulfate attack and alkali- silica reactivity (ASR). Because RCA is derived from the crushing of portland cement concrete, some agencies have expressed concern about both sulfate attack and ASR. Both of these potential destructive mechanisms are considered related to durability. Another issue that has been raised in the literature, and was specifically noted by SDDOT in the problem description for this project, is possible leachate from the RCA layer. Whenever dealing with any pavement layer, another issue that must be discussed is construction. Therefore, this chapter will provide a summary of the information and/or data accumulated within this study on four general topics: leachate, durability, stability and construction. The following sections discuss each of these topics.

7.2 Potential of Leachate

During discussions with SDDOT personnel and the Technical Panel, the intention for use of RCA materials is to construct unbound granular layers under rigid and flexible pavements. For rigid pavements, the RCA materials will be used to construct a gravel cushion with the primary role of providing a strong and stable construction platform. For flexible pavements, the RCA materials will be used to construct a traditional unbound base layer that adds structural capacity to the pavement system. Both applications are specified and constructed to be strong and stable with minimal permeability (slangly termed “tight”).

Because of the desire of the RCA layers in South Dakota is for these layers to be relatively impermeable, the leachate problems described in the literature will likely not be an issue. The primary leachate problem described in the literature was the formation of calcite, or tufa, precipitates. The issue with the precipitates is that pavement drainage systems can become partially clogged and filter fabrics used in the drainage system can lose permittivity. Another concern about leaching described in the literature was the existence of heavy metals in some RCA sources. However, the literature suggests that these hazardous materials are generated from the demolition of buildings and other structures. Because the current intent of SDDOT is to reclaim materials from PCC pavements, there should not be hazardous materials within the RCA.

Another potential problem with the use of RCA layers is that water passing through a RCA layer can become highly alkaline. The literature reports instances of metal culvert and rodent guard corrosion due to the highly alkaline effluent from pavement drainage systems that contained RCA materials. Vegetation kill has also been noted near drainage system outlets. The literature indicates that pH levels in these instances can peak between 11 and 12 shortly after construction and level off near pH values of 9 over time. Again, because the current intent of SDDOT is to construct unbound layers that have low permeabilities, the increase in alkalinity reported in the literatures is not considered a problem as water will not likely pass through the layer.

In summary, based upon the literature review and the specifications and construction practices in South Dakota, the placement of RCA materials under rigid or flexible pavement should pose no leachate or precipitate problems. The noted alkalinity problems should also not be a concern. If the SDDOT decides in the future to utilize building demolition as a reclaimed material, research should be conducted to evaluate whether any hazardous materials are contained with the RCA materials. Likewise, until the SDDOT decides to include RCA materials into pavement drainage systems, there should be no concerns with leachate or increased alkalinity of pore fluids.

7.3 Durability of RCA Materials

As stated above, durability is defined as the ability for a material to perform over an extended period of time. With respect to RCA used in an unbound granular layer, there are a number of issues that are related to durability. The literature and some state agencies have expressed a concern with the potential for sulfate attack and ASR within RCA layers. As with virgin aggregate used in granular layers, the ability of individual particles to withstand the forces of freezing/thawing and wetting/drying is also a concern with RCA materials. Also, degradation of particles during transport, processing, placement and compaction is a concern. Degradation that occurs within any of these steps will change the gradation of the granular materials, potentially leading to durability problems.

The two chemical reactions that could potentially be problematic in the use of RCA are sulfate attack and ASR. Both of these reactions result in the expansion of the PCC combined within RCA. During the Task 1 Technical Panel meeting, the panel indicated that ASR is a problem in some areas of South Dakota. With rigid pavement (from which the RCA will be produced in South Dakota), it is suspected that active ASR reactions will usually have ceased prior to the removal of the rigid pavement layer, especially if the pavement has reached its design life. Upon being processed into RCA, the cement and aggregate will become exposed. Because the particles are not confined in the RCA layer, any future degradation caused by the ASR is not expected to affect the RCA layer. In fact, no literature was found that noted occurrences of ASR affecting the unbound RCA layer. It should be pointed out, however, that recent research and experiences have indicated that some new deicing materials, namely potassium acetate, potassium formate, sodium acetate and sodium formate, have been shown to increase the potential for ASR in rigid pavements (32). It is unclear whether the use of these deicing materials could affect the performance of RCA layers within rigid or flexible pavement structures. Investigation of the affect of these new deicing materials on the performance of RCA layers was outside the scope of this project; however, this issue should be considered.

Sulfate attack does appear to be an issue for unbound RCA layers, especially relatively thick layers. As noted in the literature review, a reference was found where sulfate attack caused problems in an unbound layer that ranged from 2 to 5 ft in thickness. Based upon the Task 1 Technical Panel meeting, South Dakota does have soils (and most likely ground and surface water) containing sulfate ions. Therefore, sulfate attack is a concern at the anticipated layer thickness under flexible pavement (12 to 14 inches). This is especially true because the original materials within the PCC used to manufacture the RCA may not be known. There was difficulty determining materials used to manufacture the RCA used in this project.

In order to minimize any potential effects of sulfate attack, testing for sulfates within subgrade soils and nearby surface water may be warranted. Both ASTM C1580, Standard Test Method for Water Soluble Sulfate in Soil, and ASTM D516, Standard Test Method for Sulfate Ion in Water, can be used to test soils and surface water. If water soluble sulfates in soils are greater than 0.10 percent by mass or sulfate in water is greater than 150 parts per million, RCA is likely not warranted. These values are based upon ACI and Mississippi DOT definitions for sulfate exposure presented in Tables 2 and 3. The values stated above for sulfate exposure are conservative because the lone RCA sample supplied by the SDDOT for this project in which the original materials were identified included a Type I cement. If the materials within the PCC pavement used to create the RCA are known and includes Type II cement, then the RCA can be placed in an area with moderate sulfate exposure (as defined in Tables 2 and 3).

A number of laboratory tests were conducted as part of this study to evaluate the durability of RCA materials. Unfortunately (but fortunately for SDDOT), the existing pavement sections within South Dakota that include RCA have performed. Therefore, the opportunity to conduct durability tests on RCA materials that have not performed was not available. (Inferences made on the results of the durability tests had to be made based upon the literature, experience and practicality.)

Tests conducted on the various RCA samples included in this study were Atterberg limits, sodium sulfate soundness, the New York Freeze/Thaw test, Los Angeles Abrasion and Impact, Micro-Deval and a combination of the New York Freeze/Thaw and Micro-Deval tests. Analyses of the test data within section 6.3.2 showed some strong relationships between some of the durability tests. A strength of these relationships is that the various tests showed positive relationships, signifying that both tests within the relationship indicated reduced durability with increasing test results. The only test of the five included in the correlation matrix (Table 26) that did not have a significant relationship with any of the other tests was the Micro-Deval. Therefore, the Micro-Deval is not considered for possible inclusion within a specification.

Of the different laboratory tests conducted to evaluate durability, Atterberg limits, sodium sulfate soundness, New York Freeze/Thaw test and Los Angeles Abrasion and Impact are considered as having the most potential for inclusion within a specification. Of these tests, the literature indicated that the sodium sulfate soundness test may not be applicable. Within AASHTO M319, Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course, there is a note that states some RCA materials will yield high soundness loss values when subjected to either the sodium or magnesium sulfate soundness test. However, RCA materials tested for this project generally had reasonable results when tested for sodium sulfate soundness. Currently, sodium sulfate soundness is not required for unbound granular layer materials by SDDOT or within AASHTO M147, Materials for Aggregate and Soil Aggregate Subbase, Base and Surface Courses. Therefore, typical specification values are not available for aggregates used in unbound layers. Aggregates used in portland cement concrete and hot mix asphalt within South Dakota are required to have a sodium sulfate soundness percent loss of 12 or 15 percent depending upon the material and Class. Of the six RCA samples tested in this project, four had sodium sulfate soundness loss values of 15 or less. The remaining two RCA samples (Samples 5 and 6) also had the highest loss values when tested according to the New York Freeze/Thaw test and Los Angeles Abrasion and Impact test (Figure 18). This suggests the sodium sulfate soundness that may be warranted in a specification.

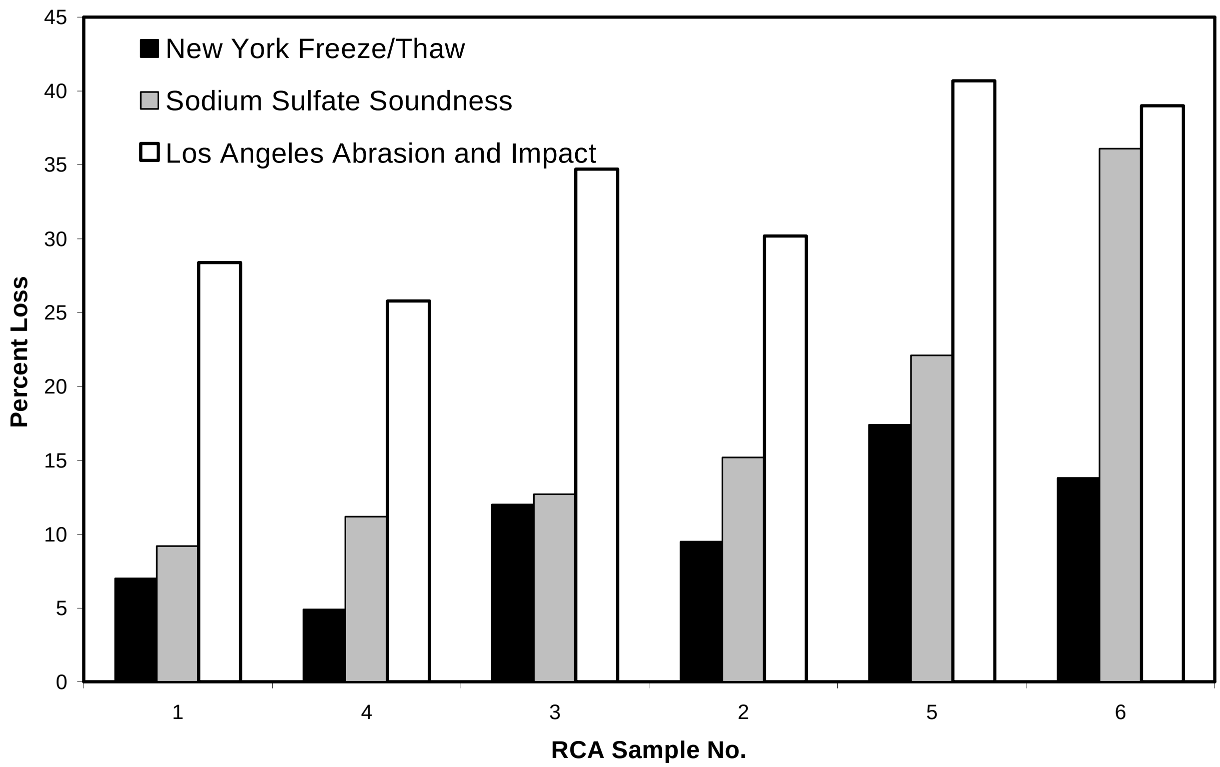


Figure 18: Comparison of Results from Selected Durability Tests

According to AASHTO M319, when excessively high sodium sulfate soundness values are encountered for RCA materials, the New York Freeze/Thaw test is an acceptable alternative. When using the New York Freeze/Thaw test, a maximum allowable loss of 20 percent is recommended. As shown in Table 17 and Figure 18, none of the RCA materials exceeded 20 percent loss. However, similar to the sodium sulfate soundness and Los Angeles Abrasion testing, Samples 5 and 6 yielded the highest loss vales for the New York Freeze/Thaw testing. Results for these two samples were 17 and 14 percent loss, respectively. Therefore, it is unclear if this test should be included within a specification. However, if sodium sulfate soundness results for an RCA sample appear to be excessive, then the New York Freeze/Thaw test could be conducted to validate the soundness testing. In such instances, New York Freeze/Thaw test results greater than 15 percent would indicate an RCA sample with a potential for durability problems. The critical value of 15 percent was selected based upon Figure 14, which illustrates the relationship between Los Angeles Abrasion loss and the New York Freeze/Thaw loss. Current SDDOT requirements (Section 882) require a maximum Los Angeles Abrasion loss of 40 percent. Based upon the relationship depicted in Figure 14, this would relate to about 15 percent loss in the New York Freeze/Thaw test. For this reason, a standard method of test has been developed in SDDOT test method format for the freeze-thaw test and is provided in Appendix B.

As discussed in section 6.3.2, the Los Angeles Abrasion and Impact test had a strong relationship with both sodium sulfate soundness and New York Freeze/Thaw test results. This suggests that the results of the Los Angeles Abrasion and Impact test are related to RCA durability. As mentioned above, the SDDOT Standard Specifications currently includes a requirement of a maximum of 40 percent loss for gravel cushion and aggregate base course materials. AASHTO M319 recommends a maximum loss of 50 percent for unbound granular materials. Based upon the Los Angeles Abrasion and Impact test results from this study and the strong relationship with sodium sulfate soundness and New York Freeze/Thaw results, a maximum mass loss of 40 percent appears reasonable. The test results and strong relationships with other durability test results suggest that the Los Angeles Abrasion and Impact test is warranted in an RCA specification.

The final test conducted to evaluate durability was Atterberg Limits. Five of the six RCA samples were non-plastic based upon these tests. Sample 5 had a plasticity index of 11 percent. Results from the sand equivalency classification testing also showed that Sample 5 was the least clean RCA sample. The sand equivalency value for Sample 5 was 46 while the remaining samples had sand equivalency greater than 70 percent. Results from the shear testing showed that Sample 5 had the lowest shear strength (Table 20). Due to the low shear strength and agreement with the sand equivalency, Atterberg limits and plasticity index are warranted within an RCA specification. Section 882 of the SDDOT Standard Specifications and AASHTO M319 both have requirements for liquid limit and plasticity index. A maximum liquid limit of 25 percent a plasticity index of 6 is included with Section 882. Based upon the results from this study, these values appear appropriate.

In summary durability of the RCA materials within a rigid or flexible pavement structure was of major concern for the SDDOT. Alkali-silica reactivity does not appear to be an issue with RCA materials; however, sulfate attack does appear to be an issue. Testing of subgrade soils and nearby surface water for sulfates should be strongly considered prior to placing RCA granular layers in South Dakota. The sodium sulfate soundness, Los Angeles Abrasion and Impact and Atterberg limits also provide good indications of durability. If results of sodium sulfate soundness testing appear excessively high, then an alternative test method would be the freeze/thaw test provided in Appendix B. Table 27 presents values of each test appropriate for specification limits.

Table 27: Durability Related Tests and Specification Limits

Test	Property	Maximum Test Result
Atterberg Limits	Liquid Limit	25
	Plasticity Limit	6
Los Angeles Abrasion and Impact	% Loss	40
Sodium Sulfate Soundness	% Loss	15
Freeze/Thaw*	% Loss	15

∗ Freeze/Thaw testing is required only if an RCA material meets Atterberg Limit and Los Angeles Abrasion requirements and results of soundness testing are significantly higher than 30 percent.

7.4 Stability of RCA

Analysis of the stability data accumulated within this study was discussed in section 6.3.1 of this report. Tests conducted to evaluate stability included the repeated load shear, resilient modulus, and CBR tests. Results from the analyses indicated three characteristics were important for the stability of RCA materials: gradation, angularity of particles and cleanliness. The literature indicated that the gradation for RCA materials does not have to be different than from typical aggregates when the intended purpose is as an unbound granular pavement layer. AASHTO M319 also states that RCA materials should meet applicable agency gradation requirements. Therefore, gradations contained within Section 882 of the SDDOT Standard Specification for gravel cushion and aggregate base course are acceptable when using RCA materials.

All of the RCA samples utilized within the study were 100 percent crushed. The only occurrence of uncrushed particles was when uncrushed aggregates from the PCC were exposed. However, these uncrushed aggregate particles still contained cement mortar around the particle which provided angularity to the particle. This is shown by the similarities in the uncompacted voids in coarse aggregate test results. Results from this test ranged from 47 to 50 percent, which is a relatively small range. By comparison, during a recently completed NCHRP project, White et al (33) recommended a minimum uncompacted void content in coarse aggregate of 45 percent for aggregates used in hot mix asphalt designed for heavy duty traffic. Therefore, all of the RCA samples included within this study are considered sufficiently angular.

From an angularity standpoint, the only issue identified was the uncompacted void content of fine aggregate for Sample 5. Figure 10 illustrated that a strong relationship between shear strength and the uncompacted void content in fine aggregates. Sample 5 had the lowest shear strength and the lowest uncompacted void content in fine aggregate. Recall that Sample 5 had a brownish color which was different than the other five RCA samples and that it was hypothesized that natural, dirty, rounded fine material had been added to the RCA. In addition to the uncompacted void content in fine aggregate, results from the Atterberg limit and sand equivalency tests also identified Sample 5 as a potential problem. Since Atterberg limits are currently included within the Standard Specifications for granular base materials, the uncompacted void content of five aggregates is not warranted.

In summary, three properties were shown related to the stability of unbound pavement layers comprised of RCA: gradation, particle angularity and cleanliness. Gradations contained within section 882 of the SDDOT Standard Specifications for gravel cushion and aggregate base course should be applicable when RCA materials are used. The crushing of reclaimed portland cement concrete pavements results in sufficiently angular particles to provide a stable unbound granular layer as long as undesirable natural, dirty or round aggregates are not added.

7.5 Construction Issues

During the course of this study, there was one issue that arose that could have an impact on construction activities. This one issue had to do with the high water absorption values. Recall during the standard Proctor testing that results were erratic. However, once the RCA materials were allowed to soak overnight, testing results became much more reasonable. Similar issues could arise during construction.

Section 260.3 of the SDDOT Standard Specifications states that either road mix or plant mix methods can be used to prepare the granular materials for placement. No matter which method is used to prepare the RCA materials, there could be varying amounts of time between when the water is added to the RCA materials and compaction is accomplished. Therefore, compaction of the RCA materials could be variable. In an effort to remedy this potential variability, good construction practices would be to maintain the RCA materials at or near a saturated surface dry (SSD) condition.

CHAPTER 8 CONCLUSION AND RECOMMENDATIONS

8.1 Introduction

As presented in Chapter 1 of this report the objectives of this research included the following:

1. Determine if recycled portland cement concrete pavements should be used as a base course or gravel cushion.
2. Develop materials guidelines and specifications for construction of pavements using recycled concrete for base course or gravel cushion.
3. Develop laboratory and field material testing requirements for recycled pavements.

The following sections present conclusion and recommendations based upon the research conducted to accomplish the project objectives.

8.2 Conclusion

Based upon the research conducted, the following conclusions are drawn:

- Recycled portland cement concrete pavements are a viable option for use in gravel cushion and aggregate base course construction.
- Because the SDDOT specifies and constructs gravel cushion and aggregate base course layers to be relatively impermeable, leachates or precipitates should pose no problems.
- Alkali-Silica reactivity is not considered a potential problem in gravel cushion or aggregate base course layers; however, it is unclear if some new deicing materials could affect the potential for alkali-silica reactivity problems in the future.
- There is a concern about sulfate attack in thick layers of gravel cushion or aggregate base course. The critical thickness is not known.
- Results from the Micro-Deval test were not found to be related to durability as defined by the lack of strong relationships with other durability tests.
- The sodium sulfate soundness test had a strong relationship with results from the Los Angeles Abrasion and Impact test and the combined New York Freeze/Thaw and Micro-Deval test. Results of the sodium sulfate test are considered an indicator of durability.
- There is a potential that the sulfates contained in the sodium sulfate solution during soundness testing can attack the cement mortar within the recycled concrete aggregate resulting in artificially higher loss values. In these instances, the New York Freeze/Thaw test can be used as a surrogate test for the sodium sulfate soundness test.
- The Los Angeles Abrasion and Impact test had a strong relationship with the sodium sulfate soundness and New York Freeze/Thaw test. Results from the Los Angeles Abrasion and Impact test are considered related to durability.
- Results from the Atterberg limit testing, namely the liquid limit and plasticity index, identified potentially harmful fine materials added to RCA materials. Results of Atterberg limit testing is considered related to durability.
- Strong and stable gravel cushion and aggregate base course layers can be attributed to the gradation, angularity and cleanliness of the RCA materials. Current gradation

requirements contained within SDDOT specifications for gravel cushion and aggregate base course are applicable.

- Recycled portland cement concrete pavements have a relatively high level of water absorption. This relatively high level of water absorption could potentially make the proper compaction of gravel cushion and aggregate base course layers variable.

8.3 Recommendations

Number	Recommendation	Reason/Benefit of Recommendation
1	Recycled portland cement concrete pavements should be allowed within gravel cushion and aggregate base course layers.	Results from this study as well as the experiences of other agencies suggest that recycled portland cement concrete pavements are an acceptable alternative for granular pavement layers. The recycled concrete aggregates should meet the requirements of the Revised Sections 260 and 882 of the South Dakota Standard Specifications presented in Appendices C and D of this report.
2	Only recycled portland cement concrete pavements owned by the Department should be allowed on new Department projects.	A number of references within the literature reported variability in the properties of recycled concrete aggregates when produced from construction/demolition debris. Research results derived from this study were based upon the testing of recycled rigid pavements and, therefore, are not applicable to construction/demolition debris.
3	Recycled concrete aggregates crushed from Department owned pavements can be blended with conventional aggregates.	The literature states that recycled concrete aggregates can be blended with conventional aggregates; however, the recycled concrete aggregates should still meet all applicable requirements for gravel cushion or aggregate base course.
4	The cleanliness of recycled concrete aggregates should be specified. It is recommended that the Department maintain the requirements of a maximum liquid limit of 25 and maximum plasticity index of 6.	One of the six recycled concrete aggregate samples included within this study contained natural, dirty and rounded fine materials. This recycled concrete aggregate had low shear strength and was deemed undesirable. Results of the Atterberg limits identified this poor performer.

5	In order to minimize any potential effects of sulfate attack on recycled concrete aggregate layers, the Department should test nearby subgrade soils and surface water for sulfates. ASTM C1580, Standard Test Method for Water Soluble Sulfate in Soil, and ASTM D516, Standard Test Method for Sulfate Ion in Water, should be used. Requirements within Table 2 should be followed.	The literature suggested that sulfate attack may be applicable to relatively thick unbound layers of recycled concrete aggregates used as fill material. No definitive information was found that limited the thickness of recycled concrete aggregate layers with respect to potential sulfate attack problems. Within the single reference identifying potential sulfate problems, the fill thicknesses ranged from 2 to 5 ft.
6	The sodium sulfate soundness test should be used to evaluate the durability of potential recycled concrete aggregates for gravel cushion and aggregate base course. A maximum value of 15 percent is recommended.	Section 882 of the Departments Standard Specifications does not currently include a test to specify the durability of aggregates for granular bases. The sodium sulfate soundness test was identified as related to durability during this study.
7	The "Resistance of Coarse Aggregates to Degradation by Freeze/Thaw" test contained in Appendix B should be utilized if the results of the sodium sulfate soundness test is greater than 30 percent. A maximum value of 15 percent for this freeze/thaw test is recommended.	The literature suggests that some recycled concrete aggregates perform poorly during the sodium sulfate soundness test. This poor performance is related to the sulfates contained within the sodium sulfate solution.
8	The Los Angeles Abrasion test is recommended to evaluate the toughness and durability of recycled concrete aggregates. A maximum percent loss of 40 percent is recommended.	The Los Angeles Abrasion test showed a strong relationship with the sodium sulfate soundness and freeze/thaw tests. Based upon the results of this study and the literature, the Los Angeles Abrasion test is warranted within the Department's standard specifications.
9	No changes are recommended to the current gradation requirements for gravel cushion or aggregate base course.	The literature suggests that gradation requirements for recycled concrete aggregates should be similar to that of conventional aggregates. No data collected within this study suggests otherwise.

10	Recycled concrete aggregate stockpiles should be maintained at a moisture content representative of a saturated surface-dry condition.	The recycled concrete aggregate samples included within this study were highly absorptive. Water absorption values for all six of the samples were above 5 percent. Problems with conducting Standard Proctor testing suggested that the recycled concrete aggregates need to be maintained at a moisture content near saturated surface-dry conditions or compaction of these materials may be highly variable.

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APPENDIX A

MINUTES OF TECHNICAL PANEL MEETING

On Wednesday, June 15, 2005 in compliance with Task 1 of South Dakota Research Project SD 2005-07, research team members of Burns Cooley Dennis, Inc. (BCD) met with the project technical panel in the Commission Room of the South Dakota Department of Transportation building in Pierre, South Dakota. This meeting allowed the researchers and the project technical panel to get acquainted and discuss the project scope and work plan.

The meeting began at approximately 8:15 AM with a total of eight representatives present. Those in attendance were as follows:

Dr. Allen Cooley – Burns Cooley Dennis, Inc., Principal Investigator
Jimmy Brumfield – Burns Cooley Dennis, Inc., Co-Principal Investigator
Daris Ormesher – South Dakota DOT, Research Division
Joe J. Feller – South Dakota DOT, Chief Materials & Surfacing Engineer
Thomas G. Grannes – SDDOT, Materials Engineer
Marc Hoelscher – FHWA, South Dakota Division Office
Jason Humphrey – SDDOT, Construction and Specifications Engineer
Paul Oien – South Dakota DOT, Research Division

Mr. Daris Ormesher began the meeting and called for self introductions. After self introductions, the meeting was turned over to Dr. Cooley who gave a presentation consisting of an overview of the project and the research team members. Dr. Cooley's PowerPoint presentation is attached and made a part of these minutes. The technical panel team members were encouraged to ask questions during the presentation and to present any information to the researchers that they felt was pertinent and useful in conducting the research.

Dr. Cooley began by presenting an overview of those who would be involved with this project along with background information on BCD. The presentation also involved discussion of each of the tasks outlined in the research proposal. The following highlights the discussion comments and decisions that were made during the presentation.

During discussion of leachate testing, Mr. Ormesher pointed out that there would only be a trace amount of leachate present in South Dakota's crushed concrete. From this information the research team will scale back the amount of testing to be performed to determine the contaminates that could potentially leach from recycled concrete aggregates (RCA); however, the research team felt that determining this information would be beneficial to the Department and will therefore perform some leachate testing.

It was pointed out that South Dakota does not have a specification requirement for sulfate soundness for RCA when RCA is used for gravel cushion or base course – only when used in hot mix asphalt (HMA) and concrete. Presently RCA when used for gravel cushion and base course must meet the same requirements as specified for virgin materials (i.e. gradation, soundness, abrasion, etc.). Dr. Cooley asked whether sodium or magnesium was used in the sulfate soundness tests. It was pointed out that sodium was used. Dr. Cooley stated that he would prefer that magnesium be used because it is a harsher test. **South Dakota will determine why sodium is used and not magnesium in the sulfate soundness tests.**

During discussion of Task 5, Mr. Feller pointed out that he had concerns with the use of RCA, particularly long term durability. As was discussed earlier, emphasis will be placed heavier on durability testing over leachate testing.

Tasks 5 and 6 – It was determined that at least six different samples of RCA would be obtained by the researchers. Hopefully these will come from different areas of the state and include different aggregate sources/types.

In conjunction with LA Abrasion, the researchers propose to look at the Micro-Deval Abrasion test. BCD will run shear strength tests and CBR tests on the RCA materials. The Department wanted to know about the mechanistic-empirical characterization of the RCA. BCD also planned to conduct resilient modulus on the RCA material in anticipation of the new M-E guide.

Dr. Cooley asked how SDDOT classified density requirements for unbound layers. It was pointed out that the Department used a standard proctor. Therefore, BCD will target 95% standard proctor as the standard for all strength characterization testing.

Dr. Cooley felt that it would be of great benefit if trenching of an existing project could be performed and samples obtained from under the pavement. Mr. Humphrey asked the question, "Shouldn't we see how the laboratory tests will predict or estimate performance before cutting up pavements." The researchers responded in the affirmative. The Department does not want to do destructive evaluation of their pavements if not needed and the opening up/trenching of a pavement section should be given more thought. **South Dakota will determine where RCA projects are located and then determine if there are any broken panels that could lend themselves to possible removal by maintenance forces and samples of the RCA obtained.**

The researchers asked about the Department's use of the terms gravel cushion and base course where RCA was concerned. It was pointed out that when used as a cushion it was under concrete pavement and was placed as a working platform with no structural values assigned. When used under HMA pavement, RCA is classified as a base course and is given credit in the total structural value for the pavement design. The RCA is assigned a structural number value of 0.1 per inch depth. The Department uses the 1993 AASHTO design procedure with resilient modulus along with the DARWin Program.

Discussion proceeded toward deliverables by the research team. Once again it was pointed out that durability was the issue that drove this research project. Mr. Feller had been approached by a contractor on whether the Department would allow the use of RCA. Mr. Feller said that he responded by stating that he was reluctant in allowing its use because of durability concerns. Currently RCA has been used on very few projects with allowance of use through plan notes. The researchers were to focus on those AASHTO tests or any other tests that would be good predictors of the durability of the RCA. If any new test was developed or one found that is not in AASHTO format, the researchers are to write procedures in AASHTO format.

Mr. Oien asked, "Don't we want a crushing specification and not just an AASHTO test method?" It was pointed out that this was not necessarily the case. It was pointed out that from an economical standpoint it would be better to work with those gradations that could be obtained by the contractors using their crushing equipment. Knowing that different crushing equipment can and do produce different gradations, the researchers' focus should be on the durability issues of RCA given that a possible wider gradation range for acceptable use may have to be determined. Mr. Feller pointed out that the Department would probably be able to obtain different materials crushed by different crushers, but probably not the same materials from different crushers.

The technical panel was concerned about the project deliverables. Mr. Tom Grannes asked, "Will there need to be construction specifications for the use of RCA that would be different from "normal" base materials?" At the end of laboratory testing, the researchers will evaluate the need for "special" specifications related to RCA.

Mr. Humphrey asked about how the researchers could present the gradation required from the samples they are furnished. Mr. Brumfield pointed out that most any gradation could be developed in the lab from materials furnished whether the RCA materials were crushed in the lab or obtained from contractor stockpiles. It was pointed out that the researchers could break down material in the lab and blend back to any gradation, but that the research team would prefer to receive material from the Contractor's stockpile that is representative of what can be produced and readily available in the field.

SDDOT staff pointed out that they had an ASR problem with aggregates particularly with poor quality sands along the Missouri River basin. The research team will try to determine what boundaries, if any, this may present in using RCA under pavements.

Since there are few existing projects where RCA has been used, the researchers are to place greater emphasis on laboratory testing of samples, than on field evaluation of projects. Dr. Cooley pointed out that possible project site visits along with observing contractor crushing operations could be beneficial in helping produce gradation specifications. Further, observation of in situ RCA would be beneficial in determining performance to date particularly the Sioux Falls project that has been in place since 1998.

As a follow up to this meeting, **South Dakota personnel will try to determine where RCA has been used, any on-going (next six months or less) projects utilizing RCA, and the location(s) of stockpiles of RCA.**

The meeting adjourned at approximately 10:15 AM. Dr. Cooley and Mr. Brumfield thanked the technical team members for their input and stated that the meeting would be very beneficial to them in conducting the research.

APPENDIX B

DRAFT METHOD OF TEST FOR RESISTANCE OF COARSE AGGREGATES TO DEGRADATION BY FREEZE/THAW

Resistance of Coarse Aggregates to Degradation by Freeze/Thaw

1. SCOPE

1.1 This method covers the procedure for determining the resistance of the coarse aggregate fraction of Recycled Concrete Aggregate to degradation by repeated exposure to freezing and thawing in a sodium chloride (NaCl) solution.

1.2 This procedure does not purport to address all the safety issues and problems associated with its use. It is the responsibility of the use of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

2.1 AASHTO Standards

- M 92, Wire-Cloth Sieves for Testing Purposes
- M 231, Weighing Devices Used in the Testing of Materials
- T 27, Sieve Analysis of Fine and Coarse Aggregates
- T 327, Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus.
- T 228, Specific Gravity of Semi-Solid Bituminous Materials

2.2 New York State Department of Transportation

- Standard Test Method for Resistance of Coarse Aggregates to Freezing and Thawing

2.3 ASTM

- E 11, Standard Specification for Wire Cloth and Sieves for Testing Purposes
- E 100, Standard Specification for ASTM Hydrometers

3. SUMMARY OF TEST METHOD

The Freeze/Thaw test subjects a sample of coarse aggregate to the stresses produced by the freezing action of water while in nature in a laboratory controlled procedure. The procedure uses a standard grading of material initially soaked at room temperature in a solution of 3% NaCl. After the initial soaking period the sample is then subjected to alternating periods of freezing and thawing for 5 cycles. Once the 5 cycles are finished the sample is washed over a specified group of sieves and the retained material is dried and weighed. The mass that is lost is accepted as the portion disintegrated by freezing and thawing.

4. SIGNIFICANCE AND USE

This test is a test of the soundness of coarse aggregate particles. Some aggregates are less resistant to the stresses caused by the freezing action of water and these aggregates tend to breakdown over time in environments with drastic temperature changes.

5. APPARATUS

5.1 *Freeze/Thaw Apparatus* - A room, tank, or chamber capable of reaching temperature ranges of -20^{o} C to +25^{o} C.

5.2 *Sample Containers* – The containers should semi-rigid and cylindrical in shape having dimensions of: 150mm in diameter by 300mm deep (concrete cylinder molds w/lip).

Note 1- These containers can be obtained from
M. A. Industries Inc.
Peachtree City, GA 30269

5.3 *Sieves* – Must conform to either AASTHO M 92 or ASTM E 11 having the following sizes:

19.0 mm
16.0 mm
12.5 mm
9.5 mm
6.3 mm
4.75 mm
1.18 mm

5.4 *Oven* – An oven of appropriate size capable of maintaining a uniform temperature of 110^{o} C.

5.5 *Balance* – The balance should conform to AASHTO M 231, Class G5.

5.6 *Specific Gravity Measurement* – A glass cylindrical or conical shaped vessel with a precision ground stopper. The stopper should have a centrally placed to allow excess to escape in accordance with T228. Alternatively, a hydrometer may be used that conforms to ASTM E 100 or suitable combination of glassware and balance, capable of determining the specific gravity of the solution to ±0.001.

6. SODIUM CHLORIDE SOULUTION

Prepare the 3% by mass solution of sodium chloride by combining rock salt with water. Adjust the solution with water and/or rock salt until a specific gravity of 1.020 at 23.3 ± 5º C is achieved.

7. SAMPLE PREPARATION

7.1 The test sample shall be washed and oven-dried at 110± 5° C to a constant mass and separated according to T 27. Test samples are then recombined based on the grading shown below according to the nominal maximum aggregate size (NMAS), as per T 327.

Table 1 – NMAS of 19 mm

Passing	Retained	Mass (g)
19.0 mm	16.0 mm	375
16.0 mm	12.5 mm	375
12.5 mm	9.5 mm	750

Table 2 – NMAS of less than 16.0 mm

Passing	Retained	Mass (g)
12.5 mm	9.5 mm	375
9.5 mm	6.3 mm	375
6.3 mm	No. 4	750

Table 3 – NMAS Less than 12.5 mm

Passing	Retained	Mass (g)
9.5 mm	6.3 mm	750
6.3 mm	No. 4	750

8. TEST PROCEDURE

8.1 Prepare a representative sample of 1500 ± 5g and record the mass to the nearest 1.0g as Mass “A”

8.2 Place the sample in a freeze/thaw container and add 950 ml of the 3% NaCl solution. Allow the sample to soak for 24 hours at room temperature (23.3° ± 5° C).

8.3 Immediately following step 8.2 the sample should be placed in the freeze/thaw apparatus at a temperature -15° ± 3° C for 15±1 hour.

Note 2 - The internal temperature should be measured with a temperature probe placed at the approximate center of mass of one of the many samples being tested. The internal temperature should reach -15° ± 3° C prior to removal.

8.4 After completing the freezing portion of each cycle, heat the sample until the internal temperature reaches 23° ± 5° C. The thawing segment is completed in approximately 8 to 10 hours.

8.5 Repeat steps 8.3 and 8.4 until 5 complete cycles have been conducted.

8.6 After the completion of 5 freeze/thaw cycles the sample is washed over a No. 4 and No. 16 size sieves.

8.7 Combine the material that is retained on the No. 4 and No. 16 sieves, using care not to lose any material.

8.8 Oven-dry the retained material at 110 ± 5° C to a constant mass.

8.9 Weigh the sample to the nearest 1.0g and record as Mass “B”.

9. CALCULATIONS

9.1 Calculate the freeze/thaw loss to the nearest 0.1 percent with eq. 1.

Eq. 1: Percent loss = (A-B)/A x 100

10. REPORT

10.1 *The report shall include the following:*

10.2 The maximum aggregate size of the as received aggregate sample.

10.3 The percent loss of the test sample to one decimal place.

APPENDIX C

REVISED SECTION 260

PART B GRANULAR BASES & SURFACING

PART B GRANULAR BASES & SURFACING

SECTION 260 GRANULAR BASES AND SURFACING

260.1 DESCRIPTION

This work consists of providing one or more courses of aggregate on a prepared surface.

260.2 MATERIALS

A. **Subbase, Base Course, Gravel Cushion and Gravel Surfacing** shall conform to Section 882. Granular additives (sand, rock, etc.) may be necessary to produce material of the type specified.

B. **Clay Binder,** when required for Gravel Surfacing, shall conform to Section 883.

260.3 CONSTRUCTION REQUIREMENTS

A. Subbase and Base Course: Roadway shaping shall be performed in accordance with Section 210 prior to placement of the material.

The material shall be processed by either road mix or plant mix methods. Materials processed by road mix methods shall be windrowed and equalized to the satisfaction of the Engineer prior to placement. The material in the windrow will be limited to the quantity necessary to construct a maximum of a 4 in. (100mm) compacted layer. The equipment used to spread the material shall be a blade or other suitable equipment. Granular material which is dumped on the prepared surface shall be windrowed prior to incorporating additives.

Materials processed by plant mix method shall be fed uniformly into the mixer at a predetermined rate. The plant shall be equipped with positive proportioning devices and shall thoroughly mix the materials.

When the material is laid by a spreader, it shall have been previously processed by a central plant.

Materials placed on shoulders adjacent to asphalt concrete or portland cement concrete pavement, shall be mixed with water by a central plant and placed on the shoulder by an approved spreader. The material placed shall be limited to the quantity necessary to construct a maximum of a 4 in. (100mm) compacted layer.

Each layer shall be compacted to the specified density before the next lift is placed and shall be rolled until a uniform, stable surface is obtained. Base Course shall be compacted to 97 percent of the maximum dry density. Subbase shall be compacted to 95 percent of the maximum dry density. The maximum dry density will be determined by SD 104, method 4 and SD 105 or SD 114.

When reclaimed portland cement concrete pavements are used as the granular material, the contractor should consider maintaining stockpiles at or near a moisture content equal to a saturated surface dry condition. Granular materials derived from crushing concrete pavements will have high water absorptions which may result in variable construction. Maintaining the crushed concrete pavements at or near a saturated surface dry condition may provide for a more consistent construction process.

The final rolling of the top surface of the granular material shall embed as many loose stones as possible. The finished surface shall be smooth and free from waves and the Contractor shall finish the surfacing materials to within ±0.5 percent of the typical section cross slope.

The quarter crown within any 12 foot (3.6m) transverse length (or actual lane width paved with a single paver pass) shall not exceed 0.04 feet 913m) when measured with a straight edge, stringline, or other suitable equipment.

Material used for backfilling unclassified excavation digouts, intersecting roads, and entrances shall be compacted to the satisfaction of the Engineer.

Recycled portland cement concrete pavement used as granular base materials shall not be used in areas where drainage fabric, edge drains, or other similar drainage systems are present.

B. **Gravel Cushion**: Gravel cushion shall be constructed in accordance with section 260.3 A, except specified density is not required. The Contractor shall spread the gravel evenly to the specified width. Watering shall be accomplished during the spreading operation. Rolling shall proceed simultaneously with the spreading and watering and continue in overlapping strips until a uniform, stable surface is obtained.

Pneumatic tired rollers shall have an effective roller weight of a t least 250 pounds per inch (4.5 kilograms per millimeter) of roller width or satisfactory vibratory compaction equipment. Tires shall be uniformly inflated so their air pressures will not vary by more than 5 psi. Rollers shall be operated with tire pressures and wheel loads within the manufacturer's recommended range for the size and ply of the tire being used.

Steel rollers shall furnish a minimum rolling weight of 275 pounds per inch (4.9 kilograms per millimeter) of rolling width.

Gravel surfacing placed on shoulders adjacent to asphalt concrete or portland cement concrete pavement shall be mixed with water by a central plant and placed on the shoulder by an approved spreader. The material placed shall be limited to a quantity necessary to construct a maximum of a 4 inch (100mm) compacted layer

C. **Gravel Surfacing:** Gravel Surfacing shall be constructed in accordance with Section 260.3 B.

Gravel surfacing placed on shoulders adjacent to asphalt concrete or portland cement concrete pavement shall be mixed with water by a central plant and placed on the shoulder by an approved spreader. The material placed shall be limited to a quantity necessary to construct a maximum of a 4 inch (100 mm) compacted layer.

When clay binder is required it shall be processed by a plant mix method in accordance with 260.3.A.

D. **Base Course, Salvaged; Gravel Cushion, Salvaged; Subbase, Salvaged; and Gravel Surfacing, Salvaged:** These materials shall be placed in accordance with section 260.3.A except the compaction and density requirements shall be as follows:

Compaction and density requirements shall be a minimum of 95 percent of the target density. The target density shall be established by SD 219 and compacted under the following conditions:

1. A minimum of one test strip of each lift placed shall be completed to determine the target density and optimum rolling sequence. The test strips will remain in place as part of the completed work.
2. The depth of the test strip lift shall be representative of the project.
3. When there is a significant change in mix proportions, weather conditions, or other controlling factors, the Engineer may require construction of another test strip to check target density.
4. Pneumatic and steel face roller requirements shall conform to Section 260.3.B.

260.4 METHOD OF MEASUREMENT

Subbase; Subbase, Salvaged; Base Course, Salvaged; Gravel Cushion; Gravel Cushion, Salvaged; Gravel Surfacing (including clay binder); and Gravel Surfacing, Salvaged will be measured to the nearest 0.1 ton (0.1 metric ton). Water and materials which are paid for under separate items will not be measured under these items.

260.5 BASIS OF PAYMENT

Subbase, Base Course, Gravel Cushion and Gravel Surfacing (including Clay Binder) will be paid for at the contract unit price per ton (metric ton).

If roadway shaping is required, and a bid item is not provided, payment for the granular material items will be full compensation for necessary shaping work.

APPENDIX D

REVISED SECTION 882

AGGREGATES FOR GRANULAR BASES AND SURFACING

AGGREGATES FOR GRANULAR BASES AND SURFACING

882.1 GENERAL REQUIREMENTS

The aggregates for granular bases and surfacing shall consist of sound durable particles of gravel, sand, or crushed portland cement concrete pavements from Department projects may include limited amounts of fine soil particles, but shall be free of sod, roots, vegetation, wood, paper, metal, glass and other foreign objectionable material. The physical characteristics and quality of the materials shall conform to the specifications for the particular material required by the contract.

882.2 SPECIFIC REQUIREMENTS

Granular material of which 30 percent of the particles retained on the No. 4 sieve shall contain one or more fractured faces.

Aggregates for granular bases and surfacing shall conform to the requirements of Table 1.

Requirement	**Subbase**	**Gravel Cushion**	**Aggregate Base Course**	**Limestone Ledge Rock**		**Gravel Surfacing**
				Base Course	**Gravel Cushion**	
Sieve	**Percent Passing**					
2” (50mm)	100					
1’ (25.0mm)	70-100		100	100		
3/4” (19.0mm)		100	80-100	80-100	100	100
½” (12.5mm)			68-91	68-90		
No. 4 (4.75mm)	30-70	50-75	46-70	42-70	46-70	50-78
No. 8	22-62	38-64	34-58	29-53	29-53	37-67
No. 40	10-35	15-35	13-35	10-28	10-28	13-35
No. 200	0.0-15.0	3.0-12.0	3.0-12.0	3.0-12.0	3.0-12.0	4.0-15.0
Liquid Limit, max		25	25	25	25	
Plasticity Index	0-6	0-6	0-6	0-3	0-3	4-12
L A Abrasion Loss, max.	50	40	40	40	40	40
Sodium Sulfate Soundness, max.		15	15			
Foot Notes		2, 3	1, 2, 3			
Processing Required	crushed	crushed	crushed	crushed	crushed	crushed

FOOT NOTES:

1. The fraction passing the No. 200 (75 µm) sieve shall not be greater than 2/3 of the fraction passing the No. 40 (425 µm) sieve. In no case shall the upper limit specified for the No. 200 (75 µm) sieve be exceeded.
2. Requirements include quarried ledge rock
3. Requirements for sodium sulfate soundness only apply to reclaimed portland cement concrete pavement materials used as gravel cushion or aggregate base course. If the recycled concrete aggregates meet the liquid limit, plasticity index and Los Angeles

Abrasion requirements and have a sodium sulfate soundness value greater than 30 percent, the materials should be tested in accordance with SD XXX to evaluate the resistance to freeze/thaw actions. Results of SD XXX should not exceed 15 percent.

882.3 SAMPLES AND TESTING

Sampling …………………………………………………SD201
Gradation…………………………………………………SD202
Liquid Limit and Plasticity Index…………………………...SD207
L. A. Abrasion Test………………………………………AASHTO T96
Crushed Particles…………………………………………SD 211
Soundness Test (Sodium Sulfate Solution 5 cycles)………..SD220
Coarse Aggregate Degradation by Freeze/Thaw……………SD XXX