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CEMENT STABILIZATION OF AGGREGATE BASE MATERIAL BLENDED WITH RECLAIMED ASPHALT PAVEMENT

by

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A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Ashley Vannoy Brown

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Ashley Vannoy Brown in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

CEMENT STABILIZATION OF AGGREGATE BASE MATERIAL BLENDED WITH RECLAIMED ASPHALT PAVEMENT

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Department of Civil and Environmental Engineering

Master of Science

The purpose of this research was to investigate the effects of reclaimed asphalt pavement (RAP) content and cement content on the strength and durability of recycled aggregate base materials. Specifically, the unconfined compressive strength (UCS) and final dielectric value in the Tube Suction Test (TST) were measured in a full-factorial experimental design including five RAP contents, five cement contents, and three replicate specimens of each possible treatment. Specimen mixtures consisted of 0, 25, 50, 75, or 100 percent RAP and 0.0, 0.5, 1.0, 1.5, or 2.0 percent Type I/II Portland cement. Both the RAP and base materials were sampled from the I-84 pavement reconstruction project performed in Weber Canyon near Morgan, Utah, during the summers of 2004 and 2005. The laboratory testing procedures consisted of material characterizations, specimen preparation, and subjection of the specimens to strength and durability testing, and the data were evaluated using analysis of variance (ANOVA) testing.

Both the RAP and base materials included in this research were determined to be non-plastic, and the AASHTO and Unified soil classifications for the RAP material were determined to be A-1-a and SM (well-graded sand with gravel), respectively, and for the base material they were A-1-a and SW-SM (well-graded sand with silt and gravel), respectively. The optimum moisture contents (OMCs) for the blended materials were between 5.6 and 6.6 percent, and maximum dry density (MDD) values were between 129.7 and 135.5 lb/ft^3. In both cases, decreasing values were associated with increasing RAP contents.

The results of the ANOVA performed on the UCS data indicate that UCS decreases from 425 to 208 psi as RAP content increases from 0 to 100 percent and increases from 63 to 564 psi as cement content increases from 0.0 to 2.0 percent. Similarly, the final dielectric value decreases from 14.9 to 6.1 as RAP content increases from 0 to 100 percent and decreases from 14.0 to 5.8 as cement content increases from 0.0 to 2.0 percent.

With design criteria requiring 7-day UCS values between 300 and 400 psi and final dielectric values less than 10 in the TST, the results of this research suggest that milling plans should be utilized to achieve RAP contents in the range of 50 to 75 percent, and a cement content of 1.0 percent should be specified for this material. Cement contents less than 1.0 percent are not sufficient to stabilize the material, and greater cement contents may cause cracking. Because control of the actual cement content in the field depends on the contractor’s equipment and skill, inspection protocols should be implemented during construction to ensure high-quality work.

Additional recommendations are associated with the construction process. The specimens prepared in this research were compacted to relative densities of 100 percent using modified Proctor energy. Therefore, field compaction levels must approach these density values if the same material properties are to be achieved. In addition, all specimens tested in this study were cured at 100 percent relative humidity. Following compaction in the field, cement-treated layers should be moistened frequently during the first few days after construction or promptly sealed with a prime coat or wearing surface to ensure that the cement continues to hydrate. Variability in RAP and cement contents should also be minimized to achieve consistent material properties.

ACKNOWLEDGMENTS

I wish to give my sincere gratitude to Dr. Spencer Guthrie for his guidance, honest example, and friendship. I would also like to thank Dr. Dennis Eggett of the Brigham Young University (BYU) Center for Collaborative Research and Statistical Consulting for his assistance in this research. Appreciation is given to the Utah Department of Transportation for funding this project. In addition, I am extremely thankful to the following BYU students who have assisted me throughout the course of this research: Ben Reese, Rebecca Crane, Stephen Frost, and Brandon Blankenagel. Most importantly, I would like to extend my love to my wife and family for their support and patience as I completed this phase of my academic career.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Because the building of new roadways within the continental United States has been largely completed (*1*), rehabilitation and reconstruction of existing pavements have necessarily become the primary tasks of the highway construction industry. Several methods are currently being used to rejuvenate fatigued flexible pavement structures, including, for example, placement of surface treatments or asphalt overlays, complete excavation and replacement, and full-depth reclamation (FDR) with and without chemical stabilization. This research focused on the utilization of FDR in conjunction with Portland cement stabilization.

FDR is the in-situ pulverization of the asphalt surface layer and a portion of the underlying base course. Cement stabilization is not always used in conjunction with FDR but should be considered when the strength or durability of the existing materials is poor. When cement stabilization is specified, cement and water are added after the initial pulverization, and the material is thoroughly mixed and recompacted to create a new, cement-stabilized base layer. FDR with cement stabilization is especially appropriate when resurfacing is not sufficient for rehabilitation, the existing distresses extend into the base and subgrade layers, 15 to 20 percent of the surface area necessitates full-depth patching, or the existing pavement is inadequate for projected traffic levels (*2*).

FDR is notably cost-efficient, as recycling costs are 25 to 50 percent less, on average, than full removal and replacement (*3*). FDR is also becoming more appealing because of the decreasing availability of high-quality aggregates; in effect, the use of FDR extends the life of valuable virgin aggregate resources (*4*). This method is also environmentally friendly because it utilizes material that may otherwise be discarded in other types of pavement reconstruction.

While numerous agencies have adopted the practice of FDR, only a limited number of research studies have been performed to characterize the strength and durability of recycled layers (*5*, *6*). In one project, the effects of reclaimed asphalt pavement (RAP) and cement content on the compaction characteristics and strength of recycled materials in Oman were evaluated (*5*); the authors of that work suggested minimum cement contents required to stabilize recycled materials typical of those in Oman. In another study, the results of research on the compaction characteristics, resilient modulus, and rutting of recycled materials indicated that emulsions, lime, or cement may be added to improve material properties (*6*).

Given the relative lack of information on FDR in the literature, the Utah Department of Transportation (UDOT) commissioned a research project at Brigham Young University (BYU) to investigate design and construction issues associated with FDR. Earlier work on the project addressed the effects of two sources of RAP on the moisture susceptibility, stiffness, and strength of two different Utah base materials (*7*). The current research extends the previous work by evaluating the effects of cement stabilization on the strength and moisture susceptibility of recycled materials. Specifically, the purpose of this research was to determine optimum cement contents necessary for stabilizing recycled materials comprised of varying RAP contents.

1.2 SCOPE

The scope of this laboratory research is limited to one source of base material and one source of RAP. Therefore, materials characterized by particle-size distributions or other properties different than those of the materials investigated in this study may yield different test results and should be tested accordingly. The materials for this research were provided by UDOT and were sampled from the Interstate 84 (I-84) FDR project performed in Weber Canyon near Morgan, Utah, during the summers of 2004 and 2005. Type I/II Portland cement was used in accordance with UDOT specifications. Five RAP contents and five cement contents were evaluated in this research in a full-factorial experimental design to examine the effects of different combinations of RAP and cement. Response variables included unconfined compressive strength (UCS) and final dielectric value in the tube suction test (TST). The UCS test was used to measure material strength after a 7-day cure, and the TST was used to assess material durability.

1.3 OUTLINE OF REPORT

This report consists of five chapters. Chapter 1 presents the problem statement and scope of the research, and Chapter 2 provides a review of construction and design issues associated with FDR and cement stabilization. Chapter 3 details the procedures that were used in the laboratory experimentation, and Chapter 4 discusses the results of the experimentation. Chapter 5 offers conclusions and recommendations based on the results of the study.

CHAPTER 2

FULL-DEPTH RECLAMATION WITH CEMENT STABILIZATION

2.1 OVERVIEW

Given the necessity of recycling to preserve natural resources, Prokopy states, "Thousands of miles of streets and roads in the U.S. are deteriorating, and pavement engineers and contractors are taking up the mantle to repair them, many in the form of full depth reclamation with cement" (*8*, p. 25). The following sections describe design and construction issues associated with this technique.

2.2 DESIGN

The design of a cement-treated, recycled material mainly involves determination of the optimum cement content for the material given the variability in RAP content inherent in the project and the type of underlying base material that will be blended with the RAP. Because asphalt layer thickness usually varies along a roadway, pulverization of the asphalt and underlying base to a constant depth inevitably yields different RAP contents at different locations along the pavement; materials having different RAP contents may require different cement contents. In addition, aggregate base materials having different mineralogical compositions and gradations will require different cement contents, or, like sulfate-bearing materials, they may not be suitable for stabilization with cement due to delayed ettringite formation, for example (*9*). Therefore, in laboratory testing, representative samples of materials should be evaluated at RAP contents typical of actual field conditions, and both strength and durability should be assessed for each unique material composition to ensure satisfactory field performance.

While sufficient amounts of cement should be specified to provide adequate structural support for the pavement surface layer and to ensure adequate resistance of the cement-treated material to environmental degradation, the addition of excessive amounts of cement can cause cracking of the affected layer; overly stabilized layers may exhibit shrinkage cracking due to self-dessication of the material as the cement hydrates, but they may also experience structural cracking under heavy trafficking as a result of being too stiff, or brittle (*10, 11*). That is, while the addition of some cement may dramatically improve material properties, the addition of too much cement can lead to premature pavement cracking and roughness. Therefore, design activities should be centered on determining the optimum cement content with respect to both strength and durability. Recent research suggests that the UCS test and the TST can be used for this purpose (*12*).

Because it is inexpensive and easily executed, the UCS test is commonly used by many departments of transportation to determine the amount of cement required to stabilize a material (*13*). The Portland Cement Association (PCA) suggests a target UCS of between 300 and 400 psi after 7 days of curing (*3*). Cement contents below those required to achieve these UCS values may not offer sufficient structural capacity, while higher cement contents may cause cracking as described previously.

Regarding durability, the TST has been proposed as an improved method of assessing the resistance to moisture ingress and freeze-thaw cycling of cement-treated materials compared to American Society for Testing and Materials (ASTM) D 559 or ASTM D 560 (*14*), which both involve approximately one month of cyclic wetting and drying or freezing and thawing. The TST was initially developed by the Finnish National Road Administration and the Texas Transportation Institute to investigate the moisture susceptibility of granular bases (*3*), but it has been increasingly used for designing stabilized materials (*12*).

Moisture-susceptibility rankings determined in the TST are based on dielectric theory together with the principles of suction and permeability. Compacted specimens are dried and subjected to a 10-day capillary soak and daily surface dielectric measurements (*15*). The dielectric value is a measure of the amount of unbound water that exists near the specimen surface. The presence of unbound water can "lead to rapid loss of base strength particularly in freeze-thaw environments" (*14*, p. 29). For materials with high suction and sufficient permeability, substantial amounts of unbound water rise within the aggregate matrix, leading to higher dielectric values at the surface. Non-moisture-susceptible materials, on the other hand, maintain a steep moisture gradient throughout the test, with little moisture reaching the surface, and have lower dielectric values at the end of the TST.

The classification of the durability, or moisture susceptibility, of a material is based on the final average dielectric value measured in the TST. Materials with final dielectric values less than 10 are considered to be non-moisture-susceptible, while materials with final dielectric values between 10 and 16 are considered to be marginally moisture-susceptible. Materials having dielectric values greater than 16 are said to be highly moisture susceptible (*16*). Therefore, in the design of cement-treated materials, sufficient cement should be added to achieve final dielectric values less than 10 in the TST.

2.3 CONSTRUCTION

As explained previously, FDR is the process of pulverizing and blending the asphalt layer with a predetermined thickness of the underlying base course. A reclaimer is usually used to pulverize the asphalt and base layers, and the blended material may then be subjected to preliminary compaction and grading. When desired road elevations cannot be achieved with the existing material, additional RAP or base material can be added from another source or removed as needed. If specified, cement is then spread, usually in powder form, over the entire pulverized area and mixed to the required depth in a second pass of the reclaimer as shown in Figure 2.1. Mixing water is typically supplied directly to the mixing chamber of the reclaimer by a water truck. After the cement-treated material has been mixed, it is compacted and graded in preparation for application of a prime coat, if specified, and a wearing course. If a prime coat is not placed, the layer should be moistened frequently during the first few days after construction to ensure that the cement continues to hydrate.

FIGURE 2.1 Reclaimer mixing cement-treated base material.

2.4 SUMMARY

FDR is the process of pulverizing and blending the asphalt layer with a predetermined thickness of the underlying base course. Specific laboratory procedures are available for determining the optimum cement content for recycled base materials. Laboratory testing should confirm that the materials have negligible sulfate concentrations, and sufficient cement should be added to achieve target 7-day UCS values of between 300 and 400 psi and a dielectric value less than 10 in the TST. Representative samples of materials should be evaluated in the laboratory at RAP contents typical of actual field conditions to ensure satisfactory field performance. If designed and constructed properly, the addition of cement will improve the strength and durability of the recycled material.

CHAPTER 3

LABORATORY PROCEDURES

3.1 OVERVIEW

The purpose of this research was to investigate the effects of RAP content and cement content on the strength and durability of recycled aggregate base materials. Specifically, the UCS and final dielectric value in the TST were measured in a full-factorial experimental design including five RAP contents, five cement contents, and three replicate specimens of each possible treatment. Specimen mixtures consisted of 0, 25, 50, 75, or 100 percent RAP and 0.0, 0.5, 1.0, 1.5, or 2.0 percent Type I/II Portland cement. Both the RAP and base materials were sampled from the I-84 pavement reconstruction project performed in Weber Canyon near Morgan, Utah, during the summers of 2004 and 2005.

The laboratory testing procedures consisted of material characterizations, specimen preparation, and subjection of the specimens to strength and durability testing. The following sections describe these test procedures, as well as the statistical techniques utilized to analyze the test results.

3.2 MATERIALS CHARACTERIZATION

A variety of tests were employed to characterize both the RAP and base materials, including dry and washed sieve analyses, specific gravity analyses, and liquid and plastic limits tests. Once the data were obtained from these tests, each material was classified using the American Association of State Highway and Transportation Officials (AASHTO) and Unified soil classification systems.

For the dry sieve analyses, a large tray shaker was used to separate all of the sampled materials over the 3/4-in., 1/2-in., 3/8-in., No. 4, No. 8, No. 16, No. 30, No. 50, and No. 100 sieves. Materials finer than the No. 100 sieve were separated across the No.

200 sieve using a 12-in-diameter sieve shaker. The sieving procedures followed the guidelines established in ASTM D 422 (Standard Test Method for Particle-Size Analysis of Soils). Because all of the bulk samples were sieved in their entirety, an accurate representation of the particle-size distribution of each material sample could be established. Furthermore, separation of the materials across the specified sieve sizes enabled ready fabrication of replicate specimens with the same gradations.

Smaller samples produced to match the overall material gradations were then used for completion of the other material characterizations. Washed sieve analyses were performed according to ASTM C 117 (Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing), and apparent specific gravity and absorption tests were conducted according to ASTM D 854 (Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer). Atterberg limits were determined according to ASTM D 4318 (Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils). If the material under evaluation did not have a blow count exceeding 25 following liquid limit testing at water contents significantly higher than the original water content, the testing was stopped, and the material was labeled as non-plastic.

For this research, both the AASHTO and the Unified soil classification systems were used to classify the different materials. The classifications were based on the results of the washed sieve analyses and Atterberg limits tests performed on each material. The standards used for the classifications were AASHTO M-145 (Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes) and ASTM D 2487 (Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System)).

3.3 SPECIMEN PREPARATION

After the materials had been sieved and the particle-size distributions of the bulk samples had been determined, samples were prepared for evaluation of the optimum moisture content (OMC) and maximum dry density (MDD) associated with each material blend. The samples were prepared so that the gradations of the RAP and base materials matched the gradations of the bulk samples. The moistened samples were allowed to soak for 24 hours prior to compaction, which was performed using the modified Proctor procedure to create 4-in.-diameter specimens with a target height of 4.58 in. Described in ASTM D 1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3))) Method B, the modified Proctor procedure requires compaction of specimens in five lifts of 25 blows per lift with a 10-lb hammer dropped from a height of 18 in. Figure 3.1 shows the compaction apparatus used in this research.

In order to minimize the occurrence of voids around exterior specimen surfaces, a metal blade was used to spade along the inside of the mold before compaction of each lift to allow fines to fill cavities between coarse aggregates and the mold wall (*13*). In addition, after each lift was compacted, the surface was scarified to create an interlocking

FIGURE 3.1 Compaction apparatus.

interface between lifts (*17*). Following compaction of the last lift, an additional five blows were applied to the specimen surface with a finishing tool to flatten and level the surface. The finishing tool is depicted in Figure 3.2. Specimens were prepared in this manner for determining the OMC and MDD for all five RAP-base ratios at a cement content of 0.0 percent. For preparation of cement-treated specimens, the amount of water added to each sample was increased by 1 percentage point above OMC for every 4 percent cement added to the mixture. In addition, for samples to be treated with cement, materials retained on the No. 4 sieve were weighed out separately from the materials finer than the No. 4 sieve, and the coarse fractions were soaked in water as shown in Figure 3.3 for 24 hours prior to compaction.

FIGURE 3.2 Finishing tool.

The fine fractions were stored in a dry condition during the coarse aggregate soaking period, after which they were intimately mixed with the designated amount of cement. Both the weight of mixing water and cement needed for each sample were computed as a percentage of the dry weight of the RAP-base mixture. Once the fines were mixed with the cement, the excess water in the coarse aggregate was poured off to obtain the adjusted OMC, and the fines were then thoroughly mixed with the moistened coarse aggregate. Compaction followed immediately afterwards.

For evaluation in both the UCS test and the TST, specimens containing 0, 25, 50, 75, or 100 percent RAP and 0.0, 0.5, 1.0, 1.5, or 2.0 percent cement were evaluated in a full-factorial experiment with three replicates of each unique treatment. Thus, 150 specimens were prepared, with 75 specimens for each test. Additional information regarding the preparation and testing of specimens for strength and durability is provided in the following sections.

FIGURE 3.3 Soaking of coarse aggregate.

3.4 UNCONFINED COMPRESSIVE STRENGTH TEST

The specimens prepared for UCS testing were compacted in a steel mold as shown in Figure 3.4. Following compaction, the UCS specimens were then extruded from the mold as illustrated in Figure 3.5. After extrusion, all specimens were placed in a fog room, where they were subjected to 100 percent relative humidity for a 7-day curing period. As required by PCA guidelines (*17*), the specimens were then subjected to a 4-hour soak under water just before capping and compression testing in accordance with ASTM D 1633 (Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders). The specimens were soaked in plastic buckets as displayed in Figure 3.6.

After the 4-hour soak, the specimens were capped with a high-strength gypsum compound as illustrated in Figure 3.7. The caps provided a flat, level surface on both specimen ends that equally distributed the compressive load over the cross-sectional area of each specimen. Immediately after being capped, the specimens were subjected to UCS testing at a constant strain rate of 0.05 in./min; a UCS test in progress is shown in Figure 3.8. The maximum load sustained by each specimen was then divided by the cross-sectional area of the specimen to obtain the compressive strength.

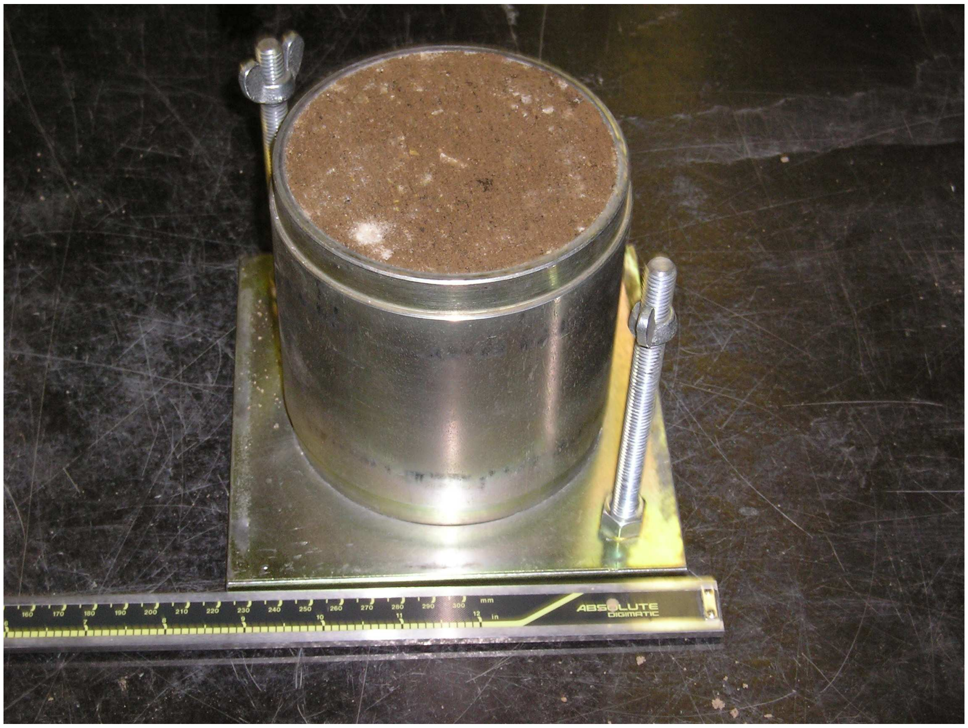

FIGURE 3.4 Compacted UCS specimen in steel mold.

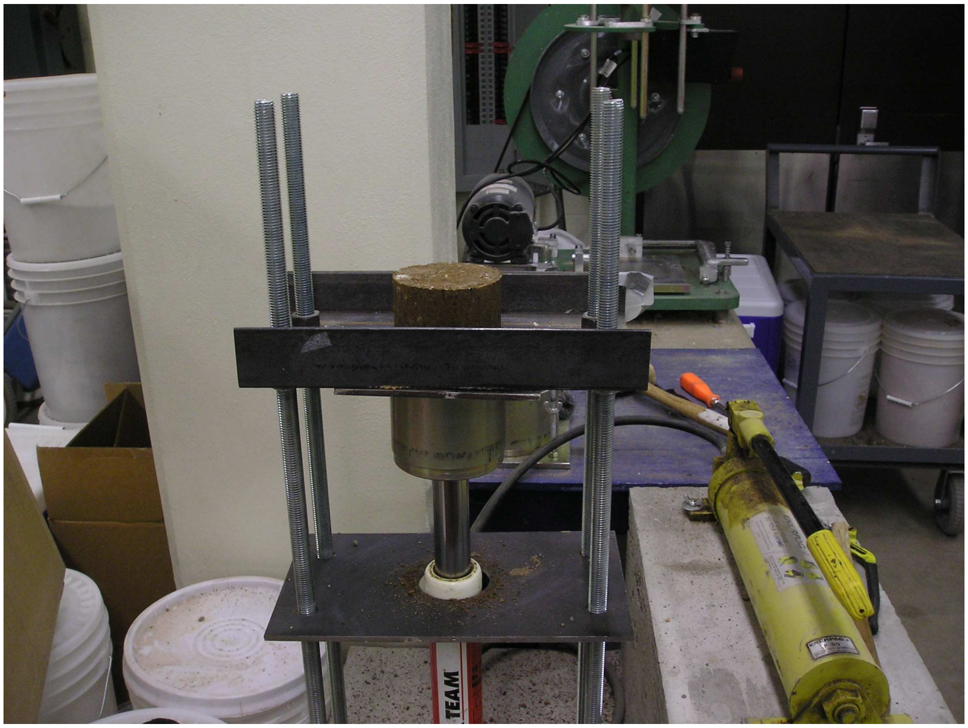

FIGURE 3.5 Extrusion of UCS specimen.

FIGURE 3.6 Soaking of UCS specimens.

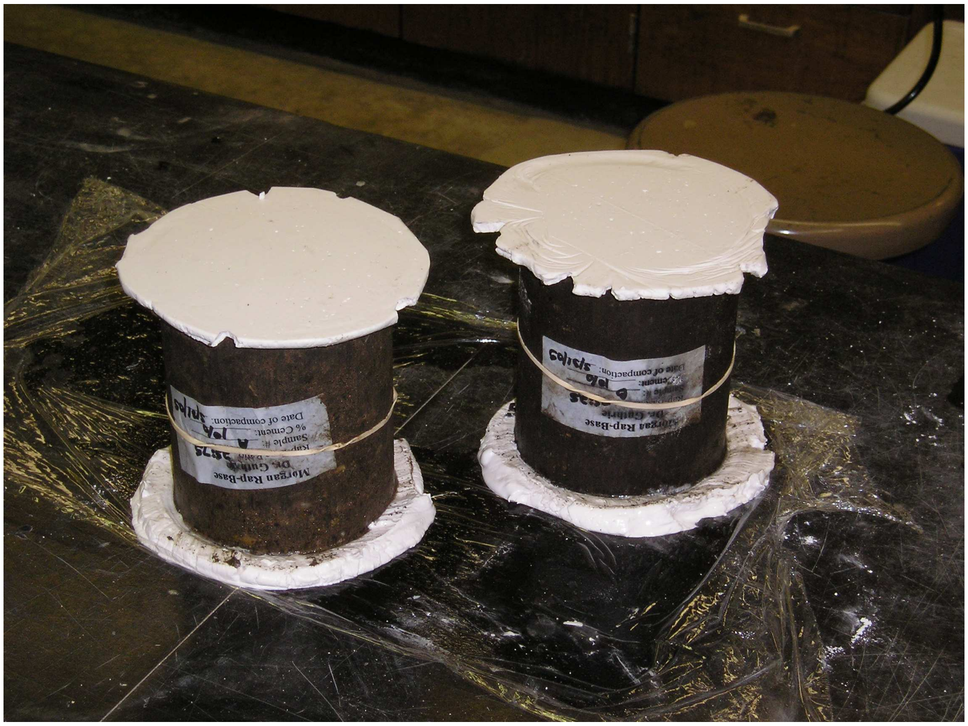

FIGURE 3.7 Capped UCS specimens.

FIGURE 3.8 UCS testing.

3.5 TUBE SUCTION TEST

The TST was performed in accordance with Texas Department of Transportation (TxDOT) Test Method Tex-144-E (Tube Suction Test), except that each specimen was compacted to a target height of 4.58 in. inside a 4-in-diameter plastic mold trimmed to a height of approximately 5.5 in. During compaction, a steel sleeve was placed around the plastic mold to prevent buckling of the mold walls. To facilitate capillary soaking of the specimens, the bottom of each mold was pre-drilled with four 1/16-in.-diameter holes, with one hole in each quadrant about 1 in. from the center of the mold. In addition, a series of 1/16-in.-diameter holes were drilled at 0.5-in. intervals in a line around the side of the mold about 0.25 in. from the bottom.

After the specimen weights and heights were measured immediately following compaction, the specimens were placed in a fog room for a 7-day curing period, after which they were dried in an oven at 140°F for 72 hours. At the conclusion of the drying period, the weight and initial dielectric values of each specimen were measured, and the specimens were placed in a 0.5-in.-deep water bath inside a closed ice chest to maintain a constant temperature and to minimize evaporation of the bath water during the soaking. The weights and dielectric values of the specimens were then measured daily for 10 days; the final measurements were performed 240 hours after the initial measurements.

The surface dielectric probe shown in Figure 3.9 was utilized to measure the dielectric values of the specimen surfaces. The probe was equipped with a 4.5-lb weight that provided consistent vertical probe pressure for all of the measurements. On each day, five measurements were taken around the perimeter of each specimen surface, and one measurement was taken in the center. The highest and lowest values recorded for each specimen each day were discarded, and the remaining four were averaged to report as the test result for that day. Directly following the final measurements, the specimens were placed in a 230°F oven for 24 hours for complete drying and subsequent determination of specimen moisture contents and dry densities.

FIGURE 3.9 Dielectric surface probe.

3.6 STATISTICAL ANALYSES

The results of the testing were evaluated using analysis of variance (ANOVA) (*18*). This method allows for simultaneous comparisons of multiple populations means while controlling the probability of a Type I error. A Type I error is committed upon rejection of a true null hypothesis in favor of a false alternative, where the null hypothesis is the postulation that the population means are equal and the alternative is the conjecture that the means are different. The probability of occurrence for a Type I error is denoted by the symbol α, which is selected by the researcher as the tolerable level of error for the given experiment. The value of α is compared to the level of significance, or *p*-value, computed from the sample data in the ANOVA, where the *p*-value represents the probability of observing a sample outcome more contradictory to the null hypothesis than the observed sample result. When the *p*-value is less than or equal to α, the null hypothesis can be rejected, leading to acceptance of the alternative hypothesis. However, when the *p*-value is greater than α, one must conclude that insufficient evidence exists to reject the null hypothesis. In this study, analyses were conducted using the standard α value of 0.05. At this α level, only a 5 percent chance existed for falsely claiming that differences between any treatments were different. ANOVA testing was used to investigate both the main effects and significant interactions associated with each response variable in this research.

3.7 SUMMARY

A full-factorial experimental design was utilized in this laboratory research to investigate the effects of RAP content and cement content on the strength and durability of recycled aggregate base materials sampled from the I-84 reconstruction project in Weber Canyon near Morgan, Utah. Specimen mixtures consisted of 0, 25, 50, 75, or 100 percent RAP and 0.0, 0.5, 1.0, 1.5, or 2.0 percent Type I/II Portland cement, and three replicate specimens of each unique treatment were prepared following ASTM D 1557 Method B. The laboratory procedures consisted of dry and washed sieve analyses, specific gravity analyses, liquid and plastic limits tests, preparation of moisture-density curves, UCS testing, and durability testing in the TST following TxDOT Test Method Tex-144-E. Factors such as composition, gradation, moisture, compaction effort, and curing conditions were all carefully controlled during the experimentation, and ANOVA testing was utilized to analyze the research results.

CHAPTER 4
RESULTS

4.1 OVERVIEW

The results of the testing, including materials characterization, UCS testing, and TST evaluations, are presented first in the following sections. The collected data and statistical analyses are then discussed.

4.2 MATERIALS CHARACTERIZATION

Materials characterizations included dry and washed sieve analyses, specific gravity analyses, and liquid and plastic limits tests. Table 4.1 presents the washed particle-size distributions for both the RAP and base materials, which are depicted visually in Figure 4.1. Table 4.2 reports the specific gravity and absorption values for the RAP and base materials. Because both materials were determined to be non-plastic, the Atterberg limits could not be determined. Based on these data, the AASHTO and Unified soil classifications for the RAP material were determined to be A-1-a and SM (well-graded sand with gravel), respectively, and for the base material they were A-1-a and SW-SM (well-graded sand with silt and gravel), respectively.

The OMC and MDD values associated with each RAP-base blend are presented in Table 4.3, which illustrates the negative relationships that exist between RAP content and both OMC and MDD. Regarding OMC, less water is needed to achieve optimum particle lubrication at higher RAP contents because less water is absorbed by particles coated with asphalt cement. The reason that MDD decreases with increasing RAP contents is because RAP has a lower specific gravity than neat stone; the specific gravity of asphalt cement is about 1.02. These relationships are illustrated graphically in Figures 4.2 and 4.3.

TABLE 4.1 Particle-Size Distributions

Sieve Size	Percent Passing (%)	
	RAP	Base
3/4 in.	95.4	98.2
1/2 in.	90.0	90.5
3/8 in.	83.0	82.0
No. 4	59.8	58.0
No. 8	38.2	43.9
No. 16	21.3	34.5
No. 30	12.1	23.6
No. 50	6.7	14.5
No. 100	2.3	10.8
No. 200	0.5	7.9

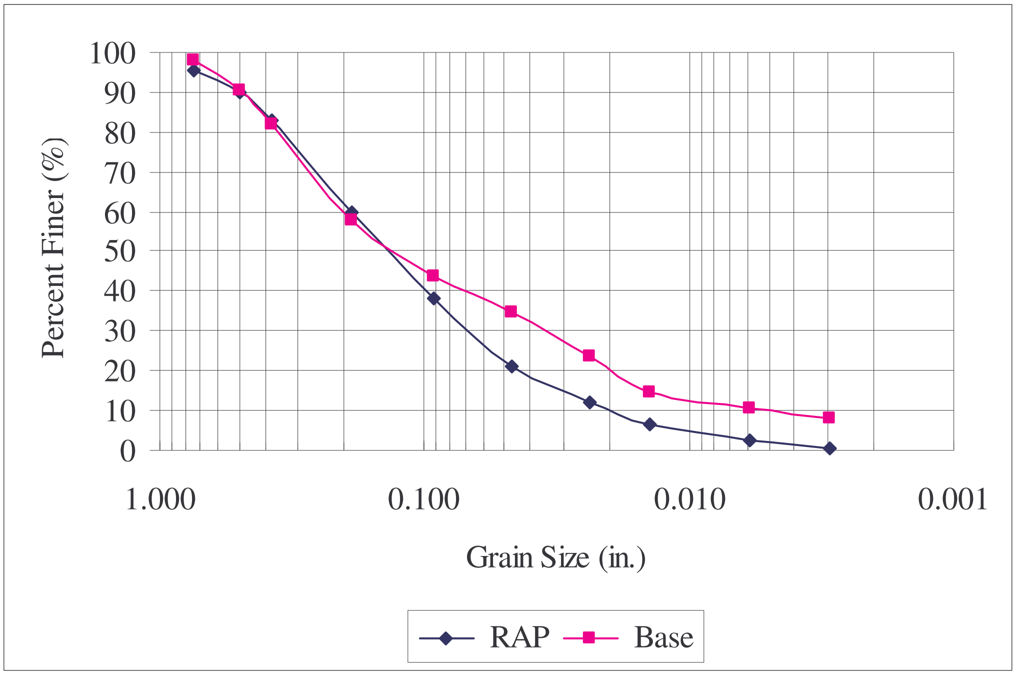

FIGURE 4.1 Particle-size distributions.

TABLE 4.2 Material Properties

Test Type	RAP	Base
Specific Gravity	2.47	2.64
Absorption (%)	4.22	5.27

TABLE 4.3 Moisture-Density Data

RAP Content (%)	Base Content (%)	OMC (%)	MDD (lb/ft^3)
0	100	6.6	135.5
25	75	6.4	132.9
50	50	6.1	132.0
75	25	5.6	131.8
100	0	5.6	129.7

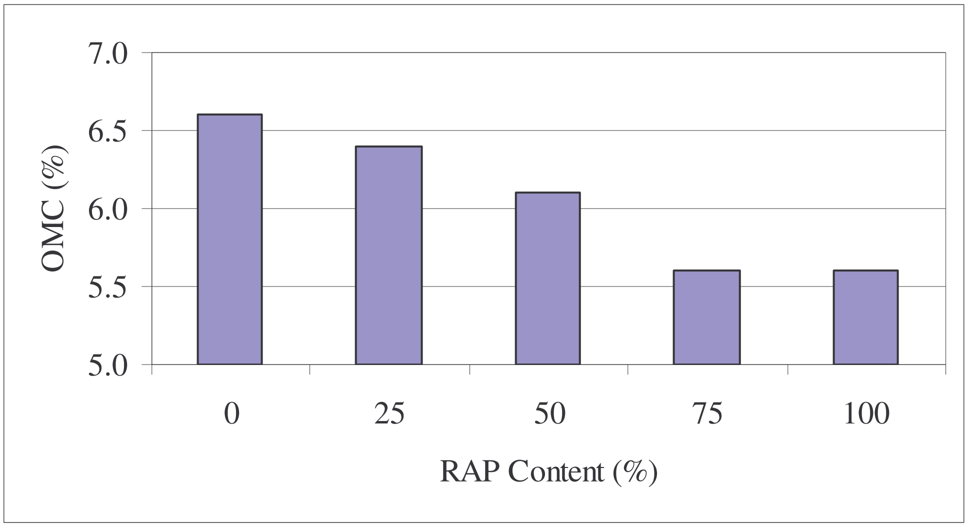

FIGURE 4.2 Effect of RAP content on OMC.

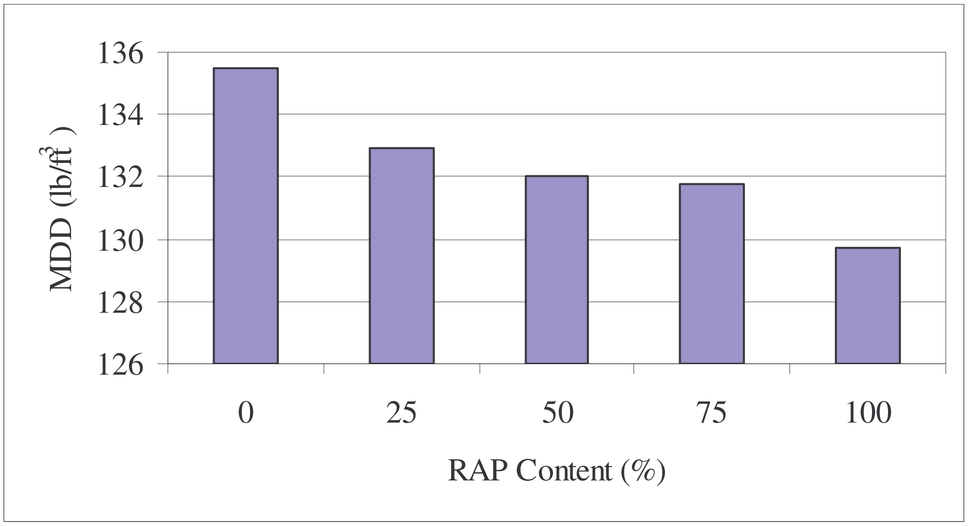

FIGURE 4.3 Effect of RAP content on MDD.

4.3 UNCONFINED COMPRESSIVE STRENGTH

As explained in Chapter 2, UCS is an important design property; sufficient cement should be added to obtain a target UCS of between 300 and 400 psi. The results of the UCS testing conducted in this research are displayed in Table 4.4. An ANOVA was performed on the data to investigate the significance of each factor on the measured UCS values. Being less than the standard error rate of 0.05, the *p*-values shown in Table 4.5 indicate that RAP content, cement content, and the interaction between RAP content and cement content were all significant.

The main effects of RAP content and cement content are presented in Table 4.6, which shows that increasing RAP contents lead to lower UCS values while increasing cement contents lead to higher UCS values. For example, increasing the RAP content to 25, 50, 75, and 100 percent in this research led to corresponding reductions in UCS values of 10, 23, 35, and 51 percent, respectively, compared to 0 percent RAP. Conversely, increasing the cement content to 0.5, 1.0, 1.5, and 2.0 percent led to increases in UCS values of 154, 467, 654, and 795 percent, respectively, compared to 0 percent cement.

The interaction between RAP content and cement content is displayed in Figure 4.4, which shows that the effect of RAP content depends on the value of cement content. For example, at cement contents of 1.0, 1.5, and 2.0 percent, increasing RAP contents from 0 to 100 percent cause monotonic reductions in UCS. However, at cement contents of 0.0 and 0.5 percent, increasing RAP contents from 0 to 25 or 50 percent are associated with greater UCS values.

At cement contents of 1.0, 1.5, and 2.0 percent, decreasing UCS values with increasing RAP content probably occur because the asphalt cement coating the RAP prohibits the formation of bonds between the cement paste and the aggregate surfaces. That is, with increasing RAP content, more of the aggregate surface area in a given specimen is coated with asphalt cement and therefore less able to develop strong bonds with the cement paste. At cement contents of 0.0 and 0.5 percent, the differences in UCS between specimens having different RAP contents is less pronounced because little or no cement is available to stabilize the material.

TABLE 4.4 Unconfined Compressive Strength Data

Cement Content (%)	Specimen	RAP Content (%)				
		0	25	50	75	100
		Unconfined Compressive Strength (psi)				
0.0	1	67	93	80	93	42
	2	57	78	86	78	45
	3	57	94	78	94	46
0.5	1	88	142	191	142	118
	2	164	174	189	174	123
	3	138	176	219	176	117
1.0	1	381	353	360	353	241
	2	480	464	382	464	261
	3	467	462	353	462	226
1.5	1	668	546	473	546	252
	2	676	588	488	588	314
	3	624	583	466	583	313
2.0	1	886	759	505	759	306
	2	839	653	554	653	360
	3	777	576	501	576	353

TABLE 4.5 Significance Levels for Unconfined Compressive Strength

Factor	*p* -value
RAP Content	<0.0001
Cement Content	<0.0001
RAP Content*Cement Content	<0.0001

TABLE 4.6 Main Effects on Unconfined Compressive Strength

Response Variable	RAP Content (%)					Cement Content (%)				
	0	25	50	75	100	0.0	0.5	1.0	1.5	2.0
UCS (psi)	425	383	328	276	208	63	160	357	475	564

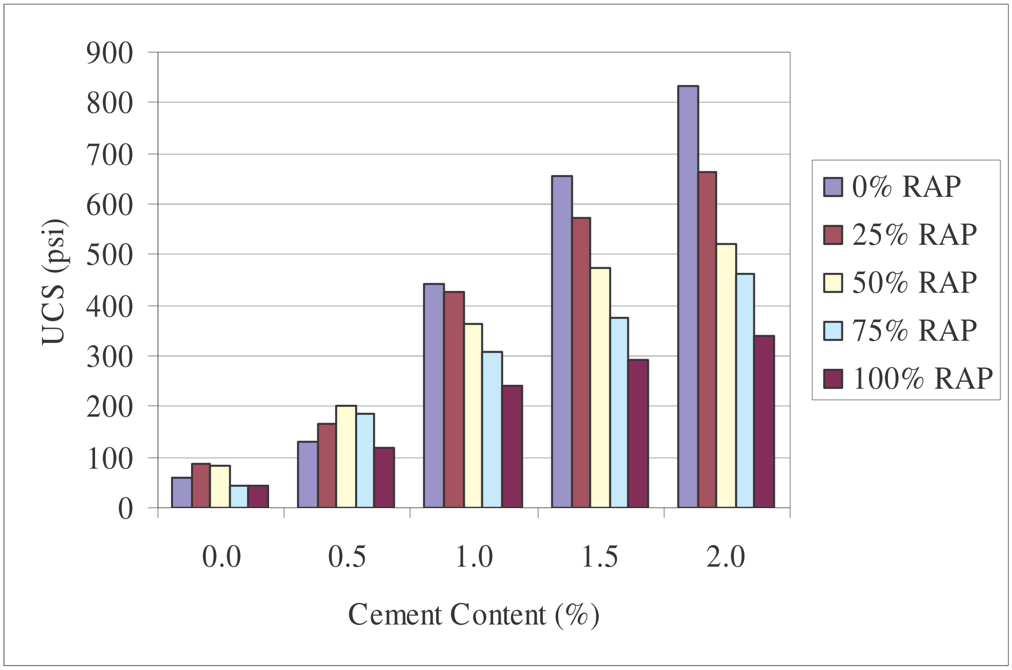

FIGURE 4.4 Interaction between RAP content and cement content for UCS.

4.4 TUBE SUCTION TEST

The TST was utilized to determine the moisture susceptibility of each of the material blends. Dielectric value and dry density were the response variables associated with this testing.

4.4.1 Dielectric Value

Table 4.7 presents the final average dielectric values for all of the specimens evaluated in the TST. An ANOVA was performed on the data to investigate the significance of each factor on the measured dielectric values. Comparable to the UCS results, all of the *p*-values were less than the standard error rate of 0.05 as shown in Table 4.8. Therefore, RAP content, cement content, and the interaction between RAP content and cement content were all significant.

The main effects of RAP content and cement content are presented in Table 4.9, which shows that increasing RAP contents and cement contents generally lead to lower dielectric values in the TST. For example, increasing the RAP content to 25, 50, 75, and 100 percent in this research led to reductions of 20, 48, 64, and 59 percent, respectively, in final dielectric values compared to 0 percent RAP. Increasing the cement content to 0.5, 1.0, 1.5, and 2.0 percent led to corresponding reductions in dielectric values of 22, 37, 51, and 59 percent, respectively, compared to 0 percent cement.

The interaction between RAP content and cement content is displayed in Figure 4.5, which shows that the effect of RAP content again depends on the value of cement content. For example, at a cement content of 0.0 percent, increasing RAP contents from 0 to 50 percent cause increases in dielectric value compared to 0 percent RAP; further additions of RAP to 75 and 100 percent cause decreases in dielectric value compared to 50 percent RAP. However, at cement contents of 0.5, 1.0, 1.5, and 2.0 percent, increasing RAP contents from 0 to 50 percent cause decreases in dielectric value compared to 0 percent RAP, and further additions of RAP to 75 and 100 percent cause increases in dielectric value compared to 50 percent RAP except at 2.0 percent cement.

At RAP contents of 25, 50, 75, and 100 percent, decreasing dielectric values with increasing cement contents probably occur because the formation of cementitious products in the aggregate matrix reduces permeability and therefore restricts water flow to the specimen surface during the TST. However, at 0 percent RAP, increasing the cement content to 0.5 and 1.0 percent leads to increases in dielectric value compared to 0.0 percent cement. In these cases, perhaps the presence of cement effectively increases the suction of the specimen but is inadequate to markedly reduce the permeability of the specimen matrix. If true, higher capillary rise would lead to greater moisture contents at the specimen surface and therefore higher dielectric values compared to untreated specimens. At 0 percent RAP, specimens treated with 1.5 and 2.0 percent cement exhibit decreases in dielectric value compared to 0.0 percent cement as would be expected.

Similar to increasing cement content to 0.5 and 1.0 percent at 0 percent RAP, increasing RAP content to 25 and 50 percent at 0.0 percent cement leads to higher dielectric values than those associated with 0 percent RAP. Increases in dielectric value compared to 0 percent RAP may be caused by increases in permeability that more readily allow water to be transmitted through the specimen matrix. Increasing the cement content, however, counteracts the proposed effect of RAP on permeability so that the dielectric values associated with all RAP contents decline below 10 as the cement content approaches 2.0 percent. With a reduction in permeability, all of the specimens treated with 2.0 percent cement exhibited lower dielectric values than untreated specimens even though the magnitude of suction may be higher in the cement-treated specimens.

TABLE 4.7 Dielectric Value Data

Cement Content (%)	Specimen	RAP Content (%)				
		0	25	50	75	100
		Dielectric Values				
0.0	1	19.8	24.5	20.5	6.4	6.8
	2	14.3	22.1	19.6	6.8	6.1
	3	15.0	23.1	13.1	5.6	5.6
0.5	1	18.1	17.8	5.1	6.3	8.6
	2	17.3	17.9	6.4	6.7	6.6
	3	18.9	15.9	4.3	6.2	6.7
1.0	1	24.7	7.2	5.1	5.2	5.6
	2	21.0	7.2	4.4	5.7	6.2
	3	16.7	6.0	5.0	4.9	6.5
1.5	1	7.6	6.3	4.2	5.4	5.1
	2	17.6	7.0	5.8	5.5	4.6
	3	10.9	6.7	5.3	5.2	6.2
2.0	1	7.0	5.7	6.1	4.5	5.9
	2	6.9	5.4	6.0	4.2	5.5
	3	8.2	5.7	6.3	5.0	5.3

TABLE 4.8 Significance Levels for Dielectric Value

Factor	*p* -value
RAP Content	<0.0001
Cement Content	<0.0001
RAP Content*Cement Content	<0.0001

TABLE 4.9 Main Effects on Dielectric Value

Response Variable	RAP Content (%)					Cement Content (%)				
	0	25	50	75	100	0.0	0.5	1.0	1.5	2.0
Dielectric Value	14.9	11.9	7.8	5.6	6.1	14.0	10.9	8.8	6.9	5.8

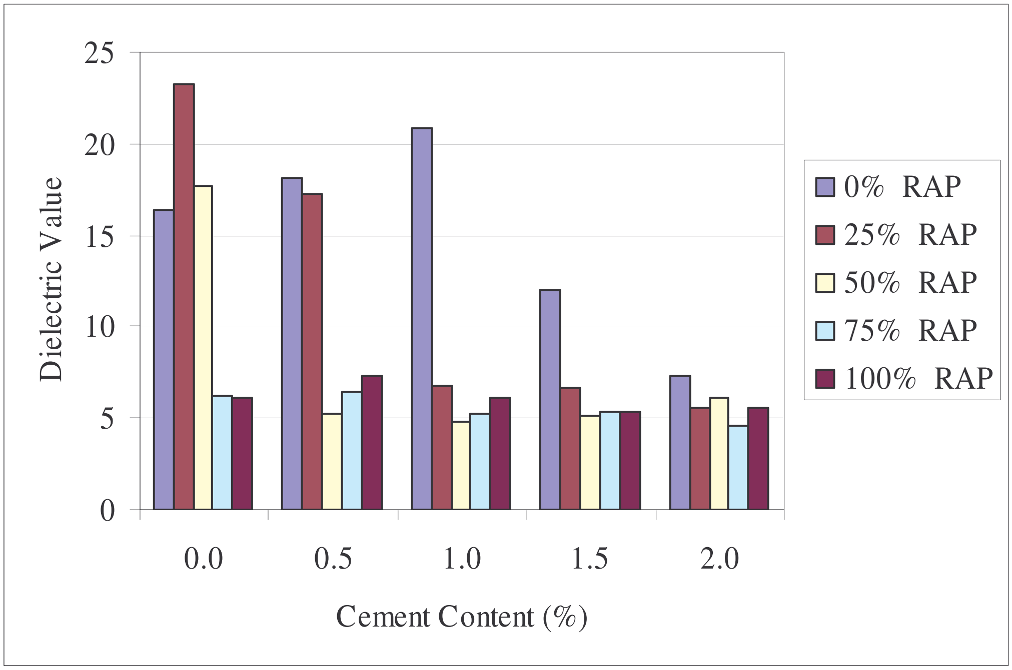

FIGURE 4.5 Interaction between RAP content and cement content for dielectric value.

4.4.2 Dry Density

As described in Chapter 3, all of the TST specimens were oven-dried after the capillary soak to facilitate calculation of dry densities, which are displayed in Table 4.10. An ANOVA was performed on the data to investigate the significance of each factor on the dry densities. Unlike previous results, not all of the *p*-values were less than the standard error rate of 0.05 as shown in Table 4.11. In this case, only RAP content and the interaction between RAP content and cement content were significant.

The main effects of RAP content and cement content are presented in Table 4.12, which shows that increasing RAP contents generally correspond to decreasing dry densities. Specifically, increasing the RAP content to 25, 50, 75, and 100 percent in this research led to corresponding reductions in dry densities of 0.5, 0.4, 0.0, and 0.1 percent, respectively, compared to 0 percent RAP. Increasing the cement content to 0.5, 1.0, 1.5, and 2.0 percent led to corresponding increases in dry density of 0.3, 2.2, 0.9, and 1.7 percent, respectively, compared to 0 percent cement, but this effect was not significant according to Table 4.11. The interaction between RAP content and cement content is displayed in Figure 4.6.

TABLE 4.10 Dry Density Data

Cement Content (%)	Specimen	RAP Content (%)				
		0	25	50	75	100
		Dry Density (lb/ft^3)				
0.0	1	134.5	133.8	128.6	129.5	130.3
	2	132.0	135.5	127.5	131.0	130.0
	3	134.1	135.2	128.9	130.3	130.4
0.5	1	134.3	131.0	130.6	131.3	130.4
	2	134.3	133.2	128.8	131.8	132.2
	3	131.1	133.4	131.7	130.7	131.2
1.0	1	133.4	132.3	134.2	132.1	130.8
	2	135.2	131.5	131.1	131.5	131.4
	3	134.3	131.8	130.6	132.1	125.1
1.5	1	133.9	133.4	131.2	131.1	130.6
	2	132.2	132.8	133.6	133.2	130.6
	3	133.4	133.1	132.4	133.5	131.8
2.0	1	132.9	132.5	134.1	131.0	131.0
	2	133.2	132.7	133.3	128.9	131.2
	3	133.8	133.9	133.9	129.7	132.4

TABLE 4.11 Significance Levels for Dry Density

Factor	*p* -value
RAP Content	<0.0001
Cement Content	0.3427
RAP Content*Cement Content	0.0073

TABLE 4.12 Main Effects on Dry Density

Response Variable	RAP Content (%)					Cement Content (%)				
	0	25	50	75	100	0.0	0.5	1.0	1.5	2.0
Dry Density (lb/ft^3)	133.5	133.1	130.6	132.3	131.2	132.4	131.7	131.8	132.5	132.3

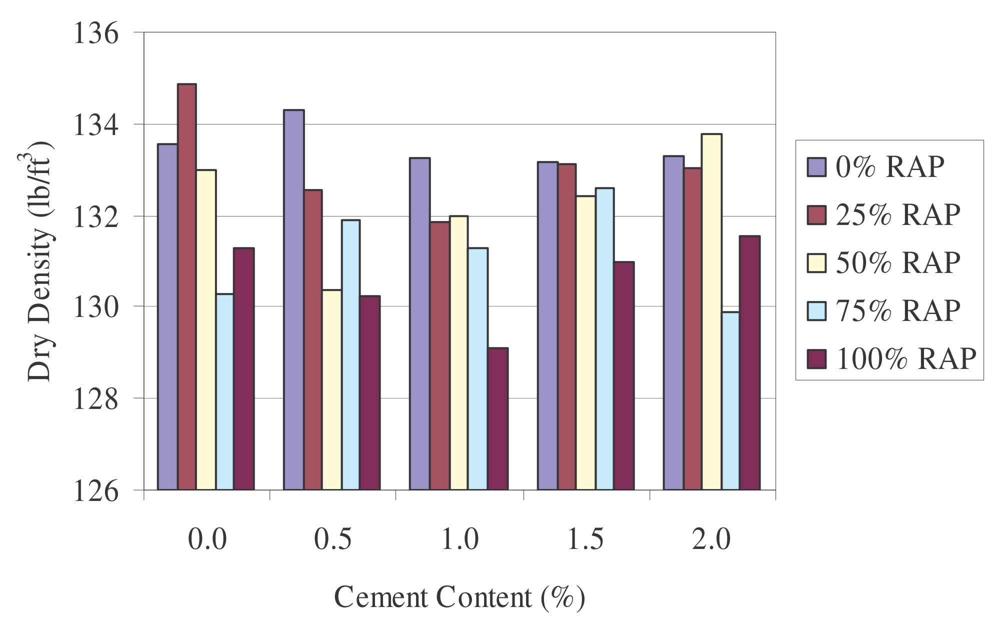

FIGURE 4.6 Interaction between RAP content and cement content for dry density.

4.5 SUMMARY

Test procedures included dry and washed sieve analyses, specific gravity analyses, liquid and plastic limits tests, UCS testing, and TST evaluations for both the RAP and base materials included in this research. The AASHTO and Unified soil classifications for the RAP material were determined to be A-1-a and SM (well-graded sand with gravel), respectively, and for the base material they were A-1-a and SW-SM (well-graded sand with silt and gravel), respectively. The OMCs for the blended materials were between 5.6 and 6.6 percent, and MDD values were between 129.7 and 135.5 lb/ft^3. In both cases, decreasing values were associated with increasing RAP contents.

The results of the ANOVA performed on the UCS data indicate that the UCS decreases from 425 to 208 psi as RAP content increases from 0 to 100 percent and increases from 63 to 564 psi as cement content increases from 0.0 to 2.0 percent. The results of the ANOVA also indicate that the effects of RAP and cement on UCS are interdependent, probably because the cement paste is less able to develop strong bonds between aggregate particles coated with asphalt cement.

The results of the ANOVA performed on the TST data indicate that the final dielectric value decreases from 14.9 to 6.1 as RAP content increases from 0 to 100 percent and decreases from 14.0 to 5.8 as cement content increases from 0.0 to 2.0 percent. The results of the ANOVA again indicate that the effects of RAP and cement are interdependent; in this case, the interaction is apparently sensitive to the relative effects of each factor on the suction and permeability of the blended materials.

The results of the ANOVA performed on the dry density data indicate that increasing RAP contents generally correspond to decreasing dry densities; however, the effect was not monotonic. The effect of cement content on dry density was not significant.

Based on the criteria for design given in Chapter 2, Table 4.13 summarizes the strength and durability of each material blend. Materials having UCS values between 300 and 400 psi and final dielectric values less than 10 in the TST were classified as "acceptable." Those with dielectric values greater than 10 were classified as "moisture susceptible," and those with UCS values greater or less than the specified range were classified as "too strong" or "too weak," respectively. The table shows that none of the blends with 0 or 25 percent RAP meet the specified criteria, and only at 1.0 percent cement does the blend with 50 percent RAP achieving "acceptable" status. For blends with 75 percent RAP, cement contents of both 1.0 and 1.5 percent are suitable, while a cement content of 2.0 percent is required for 100 percent RAP. Therefore, one may conclude that blends with 75 percent RAP appear to be the least sensitive to variation in cement content, while blends with 1.0 percent cement seem to be the least sensitive to variation in RAP content. Milling plans should therefore be utilized to achieve RAP contents in the range of 50 to 75 percent, and a cement content of 1.0 percent should be specified for this material. Because control of the actual cement content in the field depends on the contractor's equipment and skill, inspection protocols should be implemented during construction to ensure high-quality work.

TABLE 4.13 Mix Design Classification

Cement Content (%)	RAP Content (%)				
	0	25	50	75	100
0.0	W, M	W, M	W, M	W	W
0.5	W, M	W, M	W	W	W
1.0	S, M	S	A	A	W
1.5	S, M	S	S	A	W
2.0	S	S	S	S	A

A = Acceptable
M = Moisture Susceptible
S = Too Strong
W = Too Weak

CHAPTER 5

CONCLUSION

5.1 SUMMARY

UDOT commissioned a research project at BYU to investigate design and construction issues associated with FDR. Earlier work on the project addressed the effects of two sources of RAP on the moisture susceptibility, stiffness, and strength of two different Utah base materials (*7*). The current research extends the previous work by evaluating the effects of cement stabilization on the strength and moisture susceptibility of recycled materials. Specifically, the purpose of this research was to determine optimum cement contents necessary for stabilizing recycled materials comprised of varying RAP contents.

The scope of this laboratory research was limited to one source of base material and one source of RAP. The materials were provided by UDOT and were sampled from the I-84 FDR project performed in Weber Canyon near Morgan, Utah, during the summers of 2004 and 2005. Five RAP contents and five cement contents were used in this research in a full-factorial experimental design to examine the effects of different combinations of RAP and cement, and three replicates specimens of each possible treatment were tested. Specimen mixtures consisted of 0, 25, 50, 75, or 100 percent RAP and 0.0, 0.5, 1.0, 1.5, or 2.0 percent Type I/II Portland cement. Response variables included UCS and final dielectric value in the TST. The UCS test was used to measure material strength after a 7-day cure, and the TST was used to assess material durability. In addition, dry and washed sieve analyses, specific gravity analyses, and liquid and plastic limits tests were performed on both the RAP and base materials. The results of the testing were evaluated using ANOVA testing; in the ANOVA, the main effects and significant interactions associated with each response variable were investigated.

5.2 FINDINGS

Both the RAP and base materials included in this research were determined to be non-plastic, and the AASHTO and Unified soil classifications for the RAP material were determined to be A-1-a and SM (well-graded sand with gravel), respectively, and for the base material they were A-1-a and SW-SM (well-graded sand with silt and gravel), respectively. The OMCs for the blended materials were between 5.6 and 6.6, and MDD values were between 129.7 and 135.5 lb/ft^3. In both cases, decreasing values were associated with increasing RAP contents.

The results of the ANOVA performed on the UCS data indicate that the UCS decreases from 425 to 208 psi as RAP content increases from 0 to 100 percent and increases from 63 to 564 psi as cement content increases from 0.0 to 2.0 percent. The results of the ANOVA also indicate that the effects of RAP and cement on UCS are interdependent, probably because the cement paste is less able to develop strong bonds between aggregate particles coated with asphalt cement.

The results of the ANOVA performed on the TST data indicated that the final dielectric value decreases from 14.9 to 6.1 as RAP content increases from 0 to 100 percent and decreases from 14.0 to 5.8 as cement content increases from 0.0 to 2.0 percent. The results of the ANOVA again indicate that the effects of RAP and cement are interdependent; in this case, the interaction is apparently sensitive to the relative effects of each factor on the suction and permeability of the blended materials.

The results of the ANOVA performed on the dry density data indicate that increasing RAP contents generally correspond to decreasing dry densities; however, the effect was not monotonic. The effect of cement content on dry density was not significant.

The data show that none of the blends with 0 or 25 percent RAP meet the design criteria presented in Chapter 2, and only at 1.0 percent cement does the blend with 50 percent RAP achieving “acceptable” status. For blends with 75 percent RAP, cement contents of both 1.0 and 1.5 percent are suitable, while a cement content of 2.0 percent is required for 100 percent RAP. Therefore, one may conclude that blends with 75 percent RAP appear to be the least sensitive to variation in cement content, while blends with 1.0 percent cement seem to be the least sensitive to variation in RAP content.

5.3 RECOMMENDATIONS

The results of this research suggest that milling plans should be utilized to achieve RAP contents in the range of 50 to 75 percent, and a cement content of 1.0 percent should be specified for this material. Cement contents less than 1.0 percent are not sufficient to stabilize the material, and greater cement contents may cause cracking. Because control of the actual cement content in the field depends on the contractor's equipment and skill, inspection protocols should be implemented during construction to ensure high-quality work.

Additional recommendations are associated with the construction process. The specimens prepared in this research were compacted to relative densities of 100 percent using modified Proctor energy. Therefore, field compaction levels must approach these density values if the same material properties are to be achieved. In addition, all specimens tested in this study were cured at 100 percent relative humidity. Following compaction in the field, cement-treated layers should be moistened frequently during the first few days after construction or promptly sealed with a prime coat or wearing surface to ensure that the cement continues to hydrate. Variability in RAP and cement contents should also be minimized to achieve consistent material properties during the construction process.

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