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Effects of Reclaimed Asphalt Pavement on Mechanical Properties of Base Materials

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EFFECTS OF RECLAIMED ASPHALT PAVEMENT ON MECHANICAL PROPERTIES OF BASE MATERIALS

by

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GRADUATE COMMITTEE APPROVAL

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ABSTRACT

EFFECTS OF RECLAIMED ASPHALT PAVEMENT ON MECHANICAL PROPERTIES OF BASE MATERIALS

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Master of Science

Reuse of reclaimed asphalt pavement (RAP) in the full-depth recycling (FDR) process is a cost-effective and environmentally responsible method of asphalt pavement reconstruction. Although FDR has been used for several years in some locations, the effect of RAP on the mechanical properties of recycled base materials has not been well documented. The purpose of this research was to investigate the influence of RAP on the mechanical properties of recycled base materials typical of northern Utah.

Two sources of RAP, two sources of base, and RAP contents of 0, 25, 50, 75, and 100 percent were utilized in a full-factorial experimental design with three replicates of each unique combination. Testing procedures consisted of material classifications, compaction tests, and evaluations of strength, stiffness, and moisture susceptibility of each material blend. The California bearing ratio (CBR) test was used to measure strength, the free-free resonant column test was used to measure stiffness, and the tube suction test (TST) was used to measure moisture susceptibility. Once all the testing was completed, a fixed effects analysis of variance (ANOVA) was performed on each of the test results, or dependent variables. The independent variables were RAP content, RAP

type, and base type, together with all their interactions. Results of the ANOVA were used to quantify the effects of RAP on the mechanical properties of the base materials.

The data indicate that CBR values decrease as RAP content increases, with the greatest percentage reduction occurring with the addition of 25 percent RAP. For stiffness testing at the optimum moisture content determined for each blend, the general trend was a decrease in stiffness from 0 percent RAP to 25 percent RAP, followed by a steady increase in stiffness as the RAP content was increased from 25 to 100 percent. Following a 72-hr drying period at 140ºF, however, the general trend reversed; an increase in stiffness occurred as the RAP content was increased from 0 to 25 percent, and a steady decrease in stiffness was observed for RAP contents above 25 percent. The TST data suggest that additions of 25 and 50 percent RAP actually increase the moisture susceptibility of the recycled material compared to the neat base, although the blended material tested in this study was classified as non-moisture-susceptible when the RAP content was 75 percent or higher.

Because of the marked impact of RAP content on the mechanical properties of recycled base materials, engineers should accurately determine asphalt layer thicknesses prior to pavement reconstruction and carefully determine the optimum blending depth for each project. While asphalt milling or base overlays may be required in some locations to avoid excessively high RAP contents, reduced blending depths may be warranted in other areas to prevent the use of low RAP contents. In summary, while the use of RAP in the FDR process is environmentally responsible and offers potentially significant cost savings, thicker pavement base layers, base stabilization, or both may be required in many instances to ensure adequate long-term pavement performance.

ACKNOWLEDGMENTS

The author wishes to express heartfelt gratitude to Dr. Spencer Guthrie for continually leading, guiding, and showing a great deal of patience as this thesis was completed. Appreciation is given to Dr. Mitsuru Saito and Dr. Norman Jones for their willingness to serve as committee members, to Dr. Dennis Eggett for his help with the statistical analysis, and to Mike Colety of Kimley-Horn and Associates, Inc. for his understanding throughout the thesis-writing process. The author also wishes to thank John Hema, who will always be regarded as a great friend, and Ben Griggs, who assisted with this project.

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Most importantly, the author would like to extend great love and appreciation to his wife, Kelly, for helping him to be more than he ever thought he could be, as well as to his children, Dallin and Devanne, who provide motivation to work hard.

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CHAPTER 1
INTRODUCTION

1.1 PROBLEM STATEMENT

In the United States, many miles of asphalt pavement are in need of repair. As deteriorated pavements are replaced, millions of tons of used asphalt are generated. Asphalt reclamation techniques have been developed to reduce the amount of waste caused by removal of aged asphalt. Reuse of the reclaimed asphalt pavement (RAP) in the process of full-depth recycling (FDR) is one such approach. FDR consists of in-situ pulverization of the layer of asphalt together with a portion of the underlying base to create a new base layer.

When a pavement base layer can no longer adequately support the traffic loadings for which it was designed, structural damage to the pavement can occur. One way to alleviate this problem is to remove the asphalt within the boundaries of the problem area and replace the base material. This repair work may be required for miles of road, and, as more and more miles are in need of repair, the volume of deteriorated asphalt and base material that must be discarded can become excessive. The FDR technique has the potential for reducing the quantity of such waste materials, as the old asphalt is reused in the reconstructed pavement.

Although the FDR process has been used for several years in some locations, the effect of RAP on the mechanical properties of base materials has not been well documented. Many professionals within the pavement industry believe that 50 percent is an optimum RAP content for use in the FDR process and that the addition of RAP enhances the structural value of the recycled layer. However, one published study indicates that, as the amount of RAP increases, the strength of the base layer actually decreases (*1*). The authors of that work suggest that the maximum RAP content should be limited to 60 percent in recycled base materials similar to those they tested. However, given that both the quantity and source of RAP can affect the mechanical properties of recycled base materials, further testing is needed.

Particle angularity is another characteristic that should be investigated in conjunction with the FDR technique. The particles that comprise a base material can be classified as angular, subangular, rounded, or subrounded (*2*). Although the specific effects of particle angularity on the mechanical properties of recycled base materials have not been investigated, angular particles generally exhibit greater inter-particle friction than rounded particles, which can improve the bearing capacity of the base layer.

The purpose of this study was to quantify the influence of RAP on the mechanical properties of recycled base materials typical of northern Utah. For this research, two different base materials and two different RAP materials were used. Subrounded and angular aggregate base materials were tested, as well as RAP from two different locations produced using full-size and portable asphalt recycling machines. RAP contents of 0, 25, 50, 75, and 100 percent were utilized in a full-factorial experimental design with three replicates of each unique combination. With five RAP contents, two types of RAP, and two types of base, the experimental program included a total of 20 combinations.

Testing procedures consisted of classifying each of the four individual materials and determining the optimum moisture content (OMC) and maximum dry density (MDD) associated with each of the 20 combinations. Testing was then conducted to investigate the strength, stiffness, and moisture susceptibility of each material blend. The California bearing ratio (CBR) test was used to measure strength, the free-free resonant column test was used to measure stiffness, and the tube suction test (TST) was used to measure moisture susceptibility. Once all the testing was completed, a fixed effects analysis of variance (ANOVA) was performed on each of the test results, or dependent variables. The independent variables were RAP content, RAP type, and base type, together with all their interactions. The ANOVA was performed to assess the significance of RAP on the mechanical properties of the base materials.

1.2 OUTLINE OF REPORT

This report contains five chapters. Chapter 1 presents the objectives and scope of the research, and Chapter 2 discusses the FDR process. The experimental methodology utilized in the research is described in Chapter 3. Chapter 4 provides the test results, which include statistical analyses of the collected data, and Chapter 5 gives a summary of research findings and recommendations for further research.

CHAPTER 2
FULL-DEPTH RECLAMATION

2.1 OVERVIEW

An estimated 50 million tons of asphalt are milled annually in the United States (*3*). In response to the high amounts of waste associated with asphalt milling, engineers have developed recycling techniques in an effort to be more environmentally responsible (*4*). New techniques incorporating the use of RAP are continually being explored due to the high volumes of RAP that are produced during roadway rehabilitation and reconstruction projects.

A major incentive for incorporating RAP into new roadways is the cost savings that can result. One of the most expensive aspects of replacing old asphalt with new asphalt is transporting the materials to and from the construction site. As higher volumes of old asphalt are reused, both the materials transportation costs and the waste contribution to the environment are reduced (*5*). Indeed, the FDR process has the potential to greatly decrease, if not eliminate altogether, the volume of material that might otherwise be transported to a landfill. Another potential cost benefit of FDR is the reduction in the amount of new granular base materials necessary to replace the base material that has failed.

Because the FDR process involves in-situ pulverization of the damaged asphalt with the existing aggregate base material, it is an economically attractive recycling method. Furthermore, FDR can be used to address both functional and structural pavement failures. The following sections describe specific types of pavement distress that may be repaired using FDR, provide details about the FDR process, and present materials design issues.

2.2 PAVEMENT DISTRESS TYPES

Table 2.1 lists typical pavement distress types associated with asphalt pavements, along with the type of damage. Functional failure typically results from pavement surface problems, such as excessive roughness or inadequate skid resistance, while pavement distresses caused by structural failure are typically associated with strength or stiffness inadequacies within the underlying base layer of the roadway. Except when swell occurs in the subgrade soil, FDR may be used to address all of the listed distresses to various degrees. However, the use of FDR is normally reserved for reconstruction of pavements that have structurally failed under traffic loading.

Traffic-induced structural distress within a flexible pavement typically begins with longitudinal cracking as shown in Figure 2.1. With repeated traffic loading, the longitudinal cracking density within the wheel paths increases and begins to follow the pattern associated with alligator cracking, which is illustrated in Figure 2.2. If not repaired, alligator cracking inevitably leads to potholing as depicted in Figure 2.3. Block cracking, shown in Figure 2.4, is also a form of structural distress that may be appropriately addressed using FDR. Block cracking results mainly from repeated stresses

TABLE 2.1 Distress Types for Asphalt Pavements (*6*)

Distress Type	Structural	Functional
Alligator or Fatigue Cracking	X	
Bleeding		X
Block Cracking	X	
Corrugation		X
Depression		X
Joint Reflection Cracking	X	
Lane/Shoulder Drop-off or Heave		X
Lane/Shoulder Separation		X
Longitudinal or Transverse Cracking	X	
Patch Deterioration	X	X
Polished Aggregate		X
Potholes	X	X
Pumping and Water Bleeding	X	X
Raveling and Weathering		X
Rutting		X
Slippage Cracking	X	
Swell	X	X

and strains due to daily temperature cycling, but traffic loads can increase the cracking severity.

The type and severity of the distresses present on a given pavement should be considered to determine whether the problem is due to the asphalt or the underlying layers and to evaluate the potential efficacy of FDR as a reconstruction method. Because pavement distresses due to structural failure often necessitate improvement of the underlying base or subbase layers of the roadway, the use of FDR is an increasingly common method of pavement reconstruction. The use of FDR as a repair method for structural pavement distress is described in the next section.

FIGURE 2.1 Longitudinal cracking.

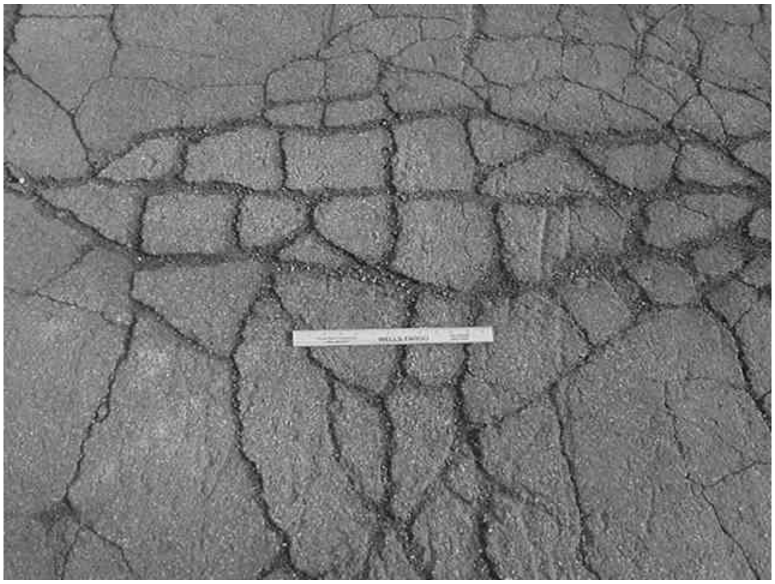

FIGURE 2.2 Alligator cracking.

FIGURE 2.3 Potholing.

FIGURE 2.4 Block cracking.

2.3 FULL-DEPTH RECYCLING

FDR can be performed using either full-size reclaimers or portable asphalt recycling machines illustrated in Figures 2.5 and 2.6, respectively. Both types of equipment pulverize the asphalt using a rotating drum fitted with metal teeth; Figure 2.7 shows the typical configuration of the teeth on a full-size reclaimer. The amount of base material with which the RAP is mixed is controlled by setting the cutting depth to the desired value. While a pulverization depth of 8 in. has been used in Utah, depths exceeding 12 in. have been used for highway reconstruction in other states.

When the asphalt layer is too thick to achieve the desired thickness of the final recycled base layer at the target RAP content, milling and hauling away of the upper portion of the asphalt layer may be required prior to FDR. In addition, in areas where elevation constraints such as curb and gutter exist, a portion of the recycled material will usually need to be hauled away because the volume of the recycled materials generally exceeds the volume of the in-situ materials prior to pulverization.

Water can be introduced directly into the pulverization chamber during mixing to extend the life of the cutting bits and to bring the water content of the base material close to OMC. The OMC is the moisture condition at which the greatest dry density can be achieved for a given level of compaction; as the dry density of a material increases, so does its strength. Issues associated with material strength are addressed in the next section.

FIGURE 2.5 Full-size reclaimer.

FIGURE 2.6 Portable asphalt recycling machine.

FIGURE 2.7 Metal teeth on rotating drum.

2.4 MATERIALS DESIGN ISSUES

An important aspect pertaining to the use of FDR is the effect of RAP content on the base layer strength. Because the thickness of asphalt layers can vary with distance down the road, the effective RAP content introduced to the base material may also vary considerably within a given construction segment. Therefore, the sensitivity of the base layer properties to RAP content becomes important information in the pavement design process.

Although a commonly cited benefit of combining RAP with a failed base material is an increase in layer strength, Figure 2.8 shows that increases in RAP content yield reductions in strength as measured in the CBR test (*1*). However, because the effect of RAP content on strength can be influenced by other factors, such as the amount and composition of asphalt cement in the RAP, the angularity of the base aggregate, and the gradation of the recycled blend (*2, 7, 8*), further research is needed to quantify the effect of RAP on the mechanical properties of base materials.

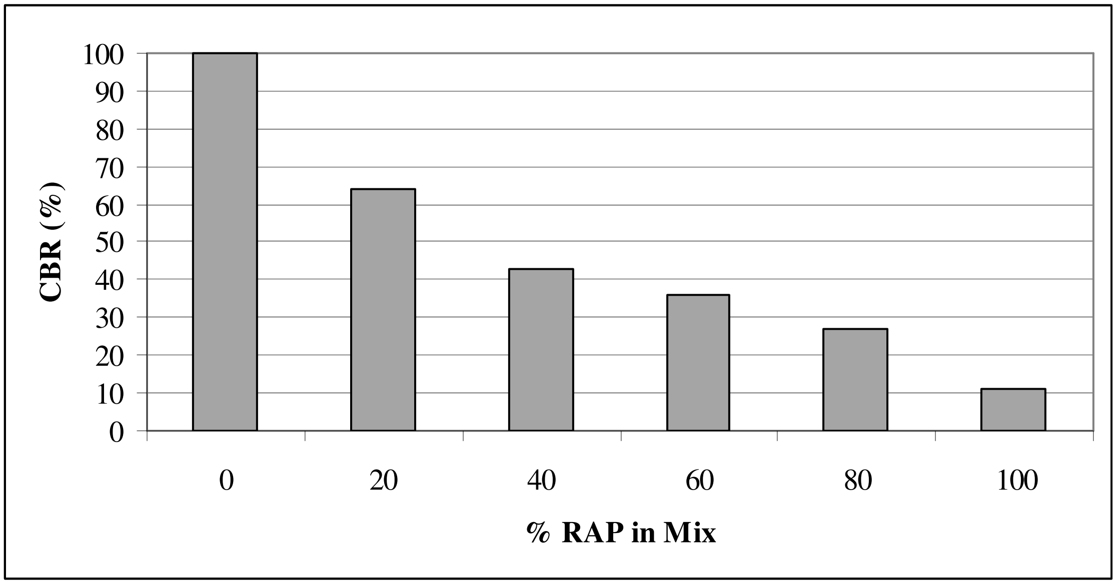

FIGURE 2.8 Effect of RAP content on aggregate strength (*1*).

The original chemical composition of the asphalt cement in the RAP is likely to be a function of the climate in which the pavement was constructed, and its properties at the time of reclamation will depend on the degree to which aging occurred during the service life of the pavement. The amount and viscosity of the asphalt cement in the RAP can also influence the bonding that may occur between aggregate particles following compaction, where higher quantities of asphalt cement with lower viscosities can lead to greater asphalt cement deformation between and around individual aggregate particles during summertime heating and under traffic loading. Upon cooling, the aggregates become more firmly bonded together.

Regarding particle shape, increasing angularity generally yields greater inter-particle friction and therefore offers greater resistance to deformation under load (*7*). Because dense gradations are characterized by higher inter-particle friction than aggregate structures having higher amounts of void space, well-graded aggregates exhibit greater strength than that typical of poorly graded aggregates. Therefore, specifying balanced proportions of diverse particle sizes for a crushed stone material is a common approach for maximizing the strength of aggregate layers.

When the resulting strength or durability of recycled materials is inadequate for the expected traffic loads and environmental conditions, however, base stabilization may be appropriate. Stabilization agents may be classified into three categories: mechanical, chemical, and bituminous (*9*). Mechanical stabilization involves the addition of granular materials to the existing material in an effort to increase the base layer strength. Chemical stabilizers include materials such as Portland cement, fly ash, and hydrated lime (*5, 9, 10*). Foamed asphalt and asphalt emulsions are examples of typical bituminous stabilizers. The majority of these stabilization agents can be easily added in conjunction with FDR and may still be more cost-effective than transporting new granular base material to the construction site.

While detailed information about the efficacy of different types of stabilizers for improving material properties has been published (*3, 5, 10, 11, 12, 13*), the literature is largely absent of experimental data documenting the effects of RAP on the mechanical properties of recycled base material. Not only is the effect of RAP content not well established, but the effects of RAP type and base type on the properties of recycled layers also need further investigation.

2.5 SUMMARY

FDR is a relatively new technique for incorporating the use of RAP in roadway reconstruction projects and can be used to repair both functional and structural distresses in asphalt pavements. A major incentive for incorporating RAP into a new roadway is the cost savings that can result. One of the most expensive aspects of replacing old asphalt with new asphalt is transporting the materials to and from the construction site. As higher volumes of old asphalt are reused, construction costs have the potential to drop significantly.

FDR is an especially effective method for addressing structural distresses caused by inadequate base or subbase layers and can easily be performed in conjunction with base stabilization. Although a commonly cited benefit of combining RAP with a failed base material is an increase in layer strength, one study shows that increases in RAP content yield reductions in strength. However, because the effect of RAP content on strength can be influenced by other factors, such as the amount and composition of the asphalt cement in the RAP, the angularity of the base aggregate, and the gradation of the recycled blend (*2, 7, 8*), further research is needed to quantify the effect of RAP on the mechanical properties of base materials.

CHAPTER 3
PROCEDURES

3.1 OVERVIEW

The purpose of this research was to investigate the effects of RAP content, RAP type, and base type on the mechanical properties of recycled base materials. Specifically, the strength, stiffness, and moisture susceptibility of laboratory specimens were measured in a full-factorial experimental design (*14*). Five different RAP contents, two different RAP types, and two different base types were included in the study, and three replicate specimens of each possible combination were tested. Specimen mixtures consisted of 0, 25, 50, 75, or 100 percent RAP.

One of the RAP materials (R1) was donated by the Utah Department of Transportation (UDOT) in conjunction with reconstruction of Interstate 84 (I-84) in Weber Canyon; it was milled from the surface of the previously undisturbed asphalt layer specifically for use in this project. The second RAP material (R2) was obtained from a local company that specializes in the manufacturing of asphalt pulverizing equipment. That material was obtained from a parking lot pavement in Pleasant Grove, Utah, using a portable asphalt recycling machine mounted to a loader.

One of the base materials (B1) was also obtained from the I-84 project. That aggregate was recovered from the field after more than 30 years in service and was characterized by subrounded particles typical of river gravel. The second base material (B2) was a crushed limestone product donated by a local supplier of road base material.

The laboratory testing procedures consisted of materials characterizations, compaction of the individual test specimens, and subjection of the specimens to strength, stiffness, and moisture-susceptibility tests. Strength was measured in terms of CBR, stiffness was measured using a free-free resonant column, and moisture susceptibility was assessed in the TST. The following sections describe the test procedures.

3.2 MATERIALS CHARACTERIZATIONS

A variety of tests were necessary to facilitate classification of each of the neat 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.

The first step in classifying the different test materials was to perform a dry sieve analysis on each individual material. 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 American Society of Testing and Materials (ASTM) D 422. Because all of the bulk samples were sieved in their entirety, an accurate representation of the particle-size distribution of each material 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 other soil characterization testing. Washed sieve analyses were performed according to ASTM C 117, and apparent specific gravity and absorption tests were determined according to the ASTM D 854. Atterberg limits were determined according to ASTM D 4318, and the plasticity index was then computed using Equation 3.1:

$$PI = LL - PL \tag{3.1}$$

where PI = plasticity index, %

LL = liquid limit, %

PL = plastic limit, %

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 (NP).

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 guide used for the AASHTO classification system was AASHTO M-145, while ASTM D 2487 was used for the Unified soil classification.

3.3 COMPACTION

Following the classification of the RAP and base materials, testing of the materials in a compacted state was performed. The modified Proctor compaction effort described in Method C of ASTM D 1557 was utilized. This procedure requires a 10-lb hammer and an 18-in. drop height and is appropriate when more than 20 percent by mass of the material being compacted is retained on the 3/8-in. sieve and less than 30 percent by mass of the material is retained on the 3/4-in. sieve. This method calls for 56 blows per layer and a total of five layers per specimen using a 6-in.-diameter mold; the target specimen height is 4.6 in. Figure 3.1 shows the device used to compact the specimens created for this research.

To determine the OMC and MDD of each material blend, compaction was performed at a minimum of four different moisture contents ranging between about 5 and 8 percent. The specified amount of water was mixed into the aggregate and allowed to soak for at least 24 hours before compaction; as shown in Figure 3.2, each sample was sealed inside a plastic bag so that the water within the aggregate could not evaporate. Figure 3.3 shows a finished specimen in the compaction mold. The height and weight of each compacted specimen were measured, and then the moisture content was determined by oven drying at 230ºF for 24 hours. Moisture-density curves were then prepared for each material, from which the OMC and MDD values were visually determined.

FIGURE 3.1 Mechanized compaction device.

FIGURE 3.2 Soaking of aggregate samples.

FIGURE 3.3 Compacted specimen in mold.

Following determination of OMC and MDD values for each aggregate blend, numerous specimens were compacted for evaluation of strength, stiffness, and moisture susceptibility. As described previously, the specified amount of water was mixed into the aggregate blend, which was allowed to soak for at least 24 hours prior to compaction. The modified Proctor compaction procedure was again utilized.

The test specimens were compacted in 6-in.-diameter plastic molds specially prepared for this project. A metal sleeve was placed around each specimen during the compaction process to prevent buckling of the plastic side walls. The target height of the specimens was again 4.6 in., which provided about 0.9 in. of overhead space between the surface of the specimen and the top of the mold, which was approximately 5.5 in. in height. Compaction of the specimens in the molds provided protection against damage during handling and enabled placement of four metal screws into the bottom surface of each specimen for use in free-free resonant column testing. Figure 3.4 shows the installation of the screws in the bottom of a mold. The aggregate samples were compacted inside the molds after installation of the screws, which ensured good mechanical coupling between the aggregate matrix and the bottom of the container. Also, to facilitate capillary soaking required in the TST, 1/16-in.-diameter holes were

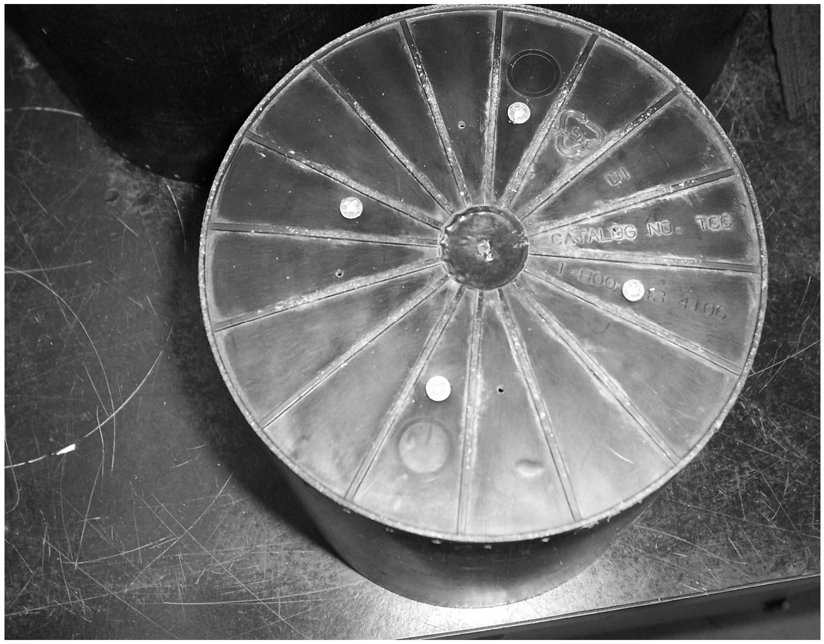

FIGURE 3.4 Placement of metal screws in bottom of mold.

pre-drilled approximately 0.25 in. above the bottom of the mold at a horizontal spacing of 0.5 in.

3.4 TESTING

Immediately following compaction, the height and weight of each specimen were measured, and the first stiffness measurement was obtained using the free-free resonant column. Individual specimens were compacted, tested sequentially, and then sealed in plastic bags as shown in Figure 3.5 to prevent water evaporation before the start of the drying period; after a batch of specimens was completed, all of the specimens were placed in the oven at the same time.

The stiffness of each specimen was determined a second time after 72 hours of drying at 140ºF, and the specimens were then subjected to a 10-day capillary soak to determine moisture susceptibility. Following the capillary soaking, the specimens were fully submerged under water for 24 hours before stiffness was measured a third time. Directly after stiffness testing, the specimens were subjected to CBR tests and oven-drying at 230ºF for 24 hours to determine moisture contents and enable calculation of specimen dry densities.

FIGURE 3.5 Specimens sealed in plastic bags prior to drying.

Therefore, stiffness was measured immediately after compaction at OMC, after a period of heating that might simulate summertime conditions, and after a period of soaking, which might simulate conditions of field saturation. The strength of the specimens was measured in the saturated condition. This testing protocol was particularly efficient, as it allowed the use of the same set of specimens for all of the testing; the only destructive test was performed last. The following sections describe the strength, stiffness, and moisture-susceptibility test procedures utilized in the study.

3.4.1 Strength

The CBR of an aggregate base material is an indication of its bearing capacity under traffic loading. The CBR value is determined as the ratio of the resistance to penetration of the tested material to the penetration resistance of a standard crushed stone (*5*). The ratio is computed at penetration depths of 0.1 in. and 0.2 in., and the larger value is reported as the CBR. Table 3.1 lists the bearing values for the standard crushed stone corresponding to penetration values ranging from 0.1 in. to 0.5 in.

TABLE 3.1 Penetration Resistance of Standard Crushed Stone (*5*)

Penetration (in.)	Pressure (psi)
0.1	1000
0.2	1500
0.3	1900
0.4	2300
0.5	2600

The CBR values for the tested materials were obtained by following a modified version of the procedures outlined in ASTM D 1883. Each soil was tested at 100 percent compaction, and no testing was performed to monitor swell during the soaking process due to the minimal clay content within the tested materials. All other CBR test procedures were conducted according to ASTM D 1883 guidelines, including the size and dimensioning of the test apparatus. Figures 3.6 to 3.9 show the soaking process, CBR test mold, loading frame, and typical indentation caused by the CBR piston. Both the metal sleeve used to confine the plastic mold in which each specimen was compacted and the 10-lb overburden weight placed on the surface of each specimen during testing are shown in Figure 3.7.

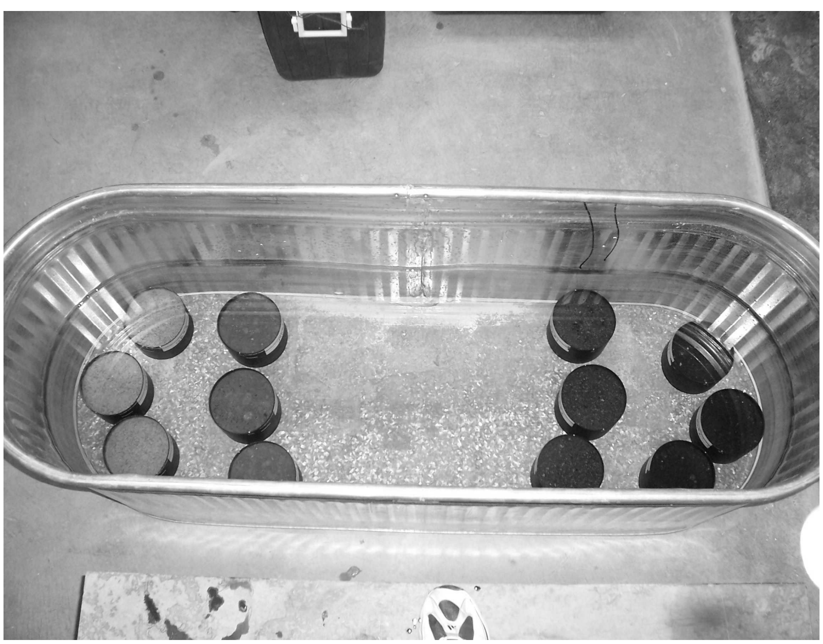

FIGURE 3.6 Soaking arrangements for CBR test specimens.

FIGURE 3.7 Metal mold used for CBR testing.

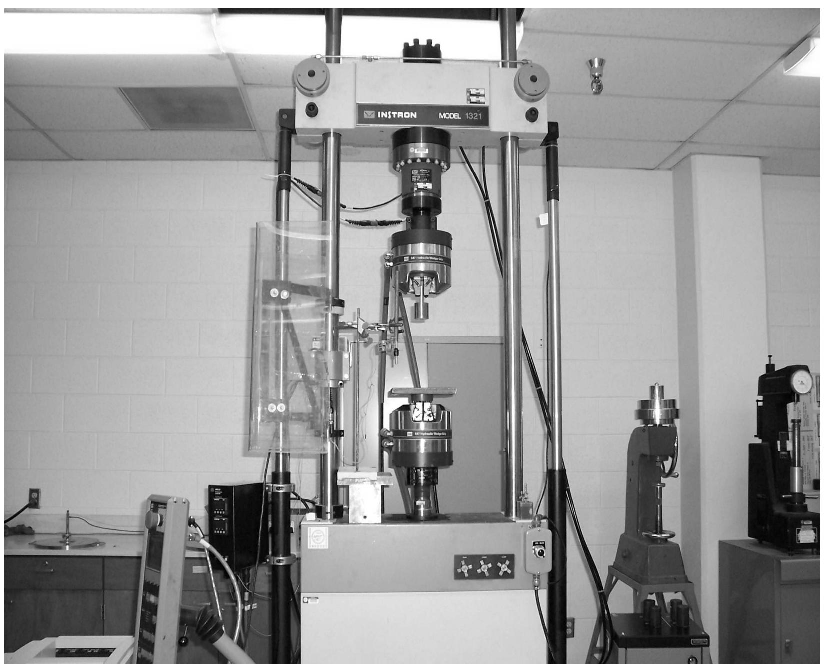

FIGURE 3.8 Loading frame used to conduct CBR testing.

FIGURE 3.9 Typical surface indentation following CBR testing.

3.4.2 Stiffness

In the free-free resonant column test, the stiffness of a material is determined based on its resonant frequency. Stress waves are generated parallel to the longitudinal axis of the specimen through the use of a hammer instrumented with a load cell, and the amplitudes and frequencies of waves generated within the specimen are recorded using an accelerometer. The resonant frequency of a given specimen can be identified by visual inspection of a computer plot of the wave arrivals and used to compute Young's modulus using Equation 3.2:

$$E = \frac{\frac{\gamma}{32.2} \cdot (2 \cdot l \cdot f)^2}{144} \qquad (3.2)$$

where E = Young's modulus, psi

γ = density of the specimen, pcf

l = length of the specimen, ft

f = resonant frequency of the specimen, Hz

The free-free resonant column test was performed by placing an accelerometer affixed to a small magnet to one of the screw heads accessible on the bottom of each specimen as depicted in Figure 3.10. Figure 3.11 shows the small metal disk that was placed on the top surface of the specimen to provide a hammer strike location. As mentioned previously, each specimen was tested at OMC immediately after compaction, after a 72-hour drying period in a 140°F oven, and again after a 24-hour soak under water prior to the CBR testing. At each measurement time, three readings were obtained at each of three different hammer strike locations for each specimen, constituting a total of nine measurements for each test conducted. The highest and lowest values of the nine readings were discarded, as they were usually associated with non-uniformities on the specimen surface, and the remaining seven readings were averaged.

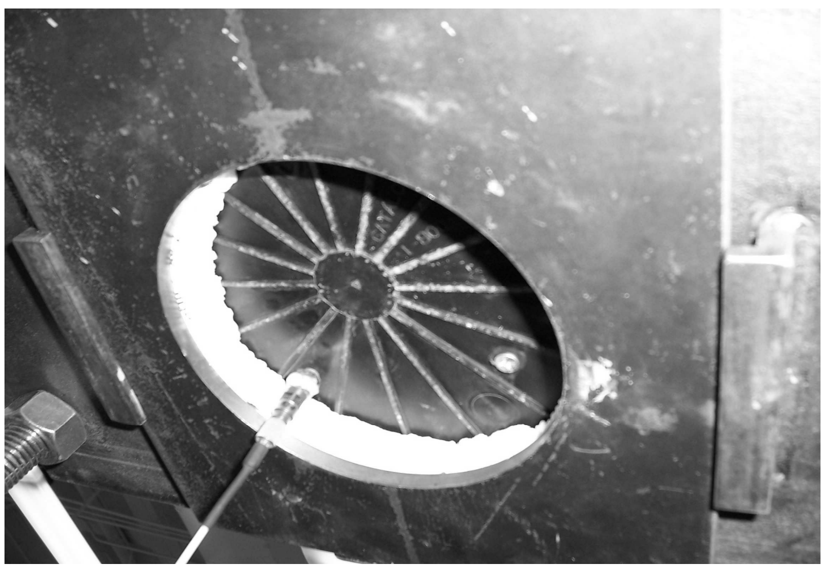

FIGURE 3.10 Placement of the accelerometer on the bottom of a specimen.

FIGURE 3.11 Striking the specimen surface with the instrumented hammer.

3.4.3 Moisture Susceptibility

Moisture-susceptibility testing was performed on three specimens of each of the four unblended materials to identify those materials that were moisture-susceptible. Then, the moisture-susceptible base materials were blended with both types of RAP in quantities of 25, 50, and 75 percent to investigate the effect of RAP content on moisture susceptibility. Again, three replicates of each material combination were tested.

Moisture-susceptibility testing was performed using the TST as outlined in Texas Department of Transportation Test Method Tex-144-E. For this test, the compacted specimens were dried in a forced-convection oven at 140°F for 72 hours and then allowed to cool to room temperature as shown in Figure 3.12. The specimens were then placed in a 0.5-in.-deep water bath enclosed within an ice chest and allowed to imbibe water over a 10-day soaking period as depicted in Figure 3.13. Enclosing the specimens in ice chests minimized water evaporation from the surfaces of the specimens and from the water bath and maintained a relatively constant temperature during the soaking period. The surface dielectric and electrical conductivity values were measured daily during this period using the electrical probe shown in Figure 3.14. Surface measurements were taken at five locations around the perimeter of each specimen and one in the center. The highest and lowest values of the six measurements were discarded, again to account for non-uniformities, and the four remaining values were averaged. The weight of each specimen was also measured daily.

FIGURE 3.12 Specimens after drying period.

FIGURE 3.13 Capillary soaking in ice chest.

FIGURE 3.14 Probe used to measure dielectric and electrical conductivity values.

The dielectric and electrical conductivity values of a soil medium are most sensitive to the presence of unbound water, which plays a primary role in numerous pavement damage mechanisms. For materials with high suction and sufficient permeability, substantial amounts of free water rise within the aggregate matrix, leading to higher values of these electrical properties 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 and electrical conductivity values at the end of the TST.

The interpretation of TST results is based on an empirical relationship between the final dielectric value and the expected performance of aggregate base materials (*15*). Aggregates whose final dielectric values in the TST are less than 10 are expected to provide superior performance, while those with dielectric values above 16 are expected to provide poor performance as base materials. Aggregates having final dielectric values between 10 and 16 are expected to be marginally moisture susceptible. Because dielectric values measured with the probe used in this study are only valid for electrical conductivity values less than 2000 μS/cm, both the dielectric and electrical conductivity were measured. The electrical conductivity is a measure of the amount of dissolved salts in the pore water near the specimen surface. Higher concentrations of dissolved salts will lead to higher electrical conductivity. Laboratory tests have confirmed a positive correlation between the TST moisture-susceptibility classifications and the strength loss characteristics of pavement base materials (*16, 17, 18*).

3.5 SUMMARY

The purpose of this research was to investigate the effects of RAP content, RAP type, and base type on the mechanical properties of recycled base materials. Specifically, the strength, stiffness, and moisture susceptibility of laboratory specimens were measured in a full-factorial experimental design. Five different RAP contents, two different RAP types, and two different base types were included in the study, and three replicate specimens of each possible combination were tested. Specimen mixtures consisted of 0, 25, 50, 75, or 100 percent RAP. One of the base materials was characterized by subrounded particles typical of river gravel, while the other was a crushed limestone. The two RAP samples were generated using full-size and portable asphalt recycling machines.

The laboratory testing procedures consisted of materials characterizations, compaction of the individual test specimens, and subjection of the specimens to strength, stiffness, and moisture-susceptibility tests. Materials characterization tests included dry and washed sieve analyses, specific gravity and absorption tests, and liquid and plastic limits tests, and these data were used to classify the materials using both the AASHTO and Unified soil classification systems. Following determination of OMC and MDD, specimens were compacted using modified Proctor compaction energy. Strength was measured in terms of CBR, stiffness was measured using a free-free resonant column, and moisture susceptibility was assessed in the TST. All of the possible combinations of factors were evaluated in all of the tests except the TST, in which case combinations of RAP with only moisture-susceptible base materials were evaluated.

CHAPTER 4
RESULTS

4.1 OVERVIEW

The results of the laboratory testing and the statistical analyses performed on the collected data are presented in this chapter.

4.2 TEST RESULTS

The results of materials characterizations, specimen compaction tests, and strength, stiffness, and moisture-susceptibility tests are presented in the following sections.

4.2.1 Materials Characterizations

Materials characterization tests included dry and washed sieve analyses, apparent specific gravity and absorption tests, and liquid and plastic limits tests. The results of both the dry and washed sieve analyses are shown in Table 4.1, and Figures 4.1 and 4.2 compare the washed gradations of the two sources of RAP and base materials. The nominal maximum size aggregate was 0.75 in. for both RAP materials. The nominal maximum aggregate size for B1 was 0.75 in., and the nominal maximum aggregate size for B2 was 0.5 in.

The results of the apparent specific gravity, absorption, and Atterberg limits tests are shown in Table 4.2. In the AASHTO classification system, R1 and R2 were both classified as gravels (A-1-a). As for classification under the Unified soil classification system, R1 was found to be a well-graded gravel with silt and sand (GW-GM), and R2 was found to be a well-graded gravel with sand (GW). Both RAP materials had similar characteristics; however, the R2 gradation consisted of only 0.45 percent particles that were finer than the No. 200 sieve, while R1 had approximately 8 percent. Because the RAP materials represented different asphalt mixtures sampled at different locations using

TABLE 4.1 Particle-Size Distributions

Sieve Size	Percent Passing (%)							
	R1		R2		B1		B2	
	Dry	Washed	Dry	Washed	Dry	Washed	Dry	Washed
3/4 in.	97.8	98.2	95.4	95.4	85.8	87.2	--	--
1/2 in.	89.6	90.5	90.0	90.0	67.4	68.3	91.4	92.6
3/8 in.	81.4	82.0	84.0	83.0	59.6	59.8	82.7	82.7
No. 4	56.1	58.0	58.8	59.8	45.6	45.0	58.9	59.7
No. 8	41.6	43.9	37.1	38.2	37.9	37.9	39.7	40.1
No. 16	29.5	34.5	21.1	21.3	30.1	32.0	28.6	29.0
No. 30	15.5	23.6	11.7	12.1	19.8	25.5	22.4	22.9
No. 50	4.4	14.5	6.2	6.7	11.3	18.6	18.5	19.2
No. 100	1.0	10.8	1.6	2.3	3.1	13.4	13.0	14.4
No. 200	--	7.9	--	0.5	--	9.2	4.3	9.1

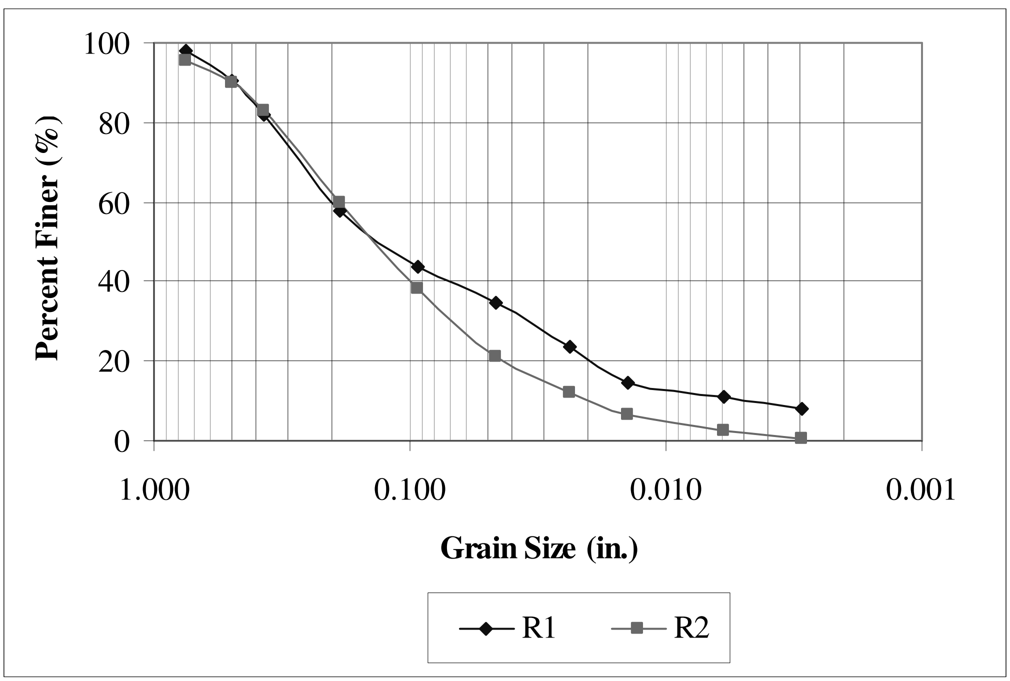

FIGURE 4.1 Gradation of RAP materials.

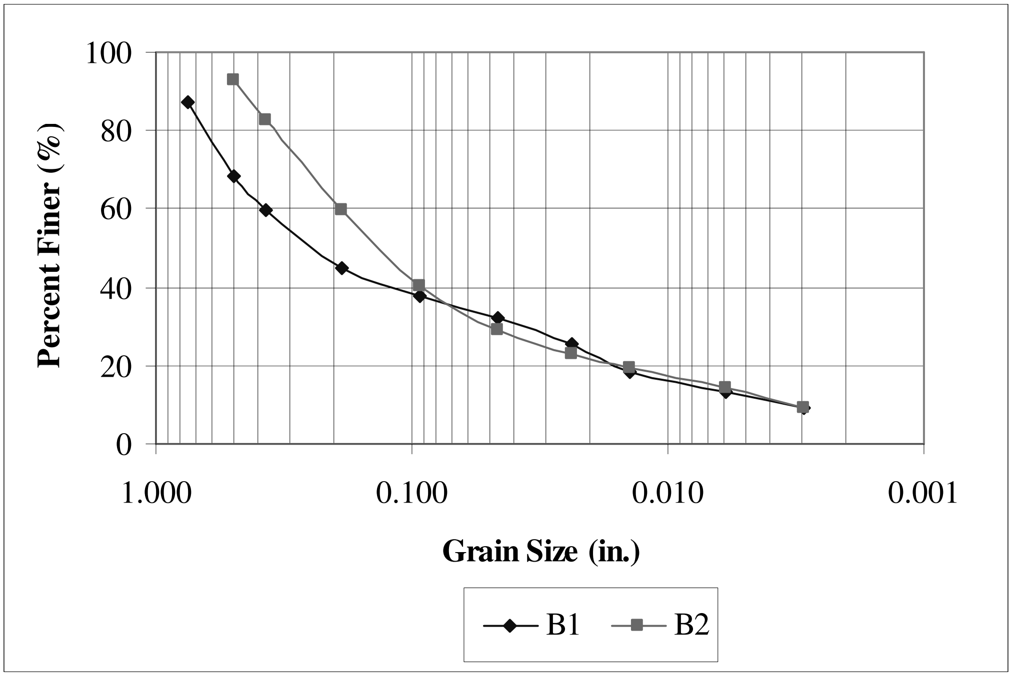

FIGURE 4.2 Gradation of base materials.

TABLE 4.2 Materials Characteristics

Test Type	R1	R2	B1	B2
Specific Gravity	2.47	2.47	2.64	2.68
Absorption (%)	4.22	3.28	5.27	2.98
Atterberg Limits	NP	NP	NP	NP

different asphalt recycling machines, the source of the differences in gradation could not be readily identified.

B1 was classified as a gravel (A-1-a) under the AASHTO classification system and as a well-graded sand with silt (GW-GM) in the Unified soil classification system. B2 was also classified as a gravel (A-1-a) in the AASHTO classification system, but as a well-graded gravel with sand and silt (GW-GM) under the Unified soil classification system. B1 had a different classification than B2 because its sand content was less than 15 percent, while B2 had a sand content higher than 15 percent.

4.2.2 Compaction

Table 4.3 lists the OMC and MDD values determined for each material blend using modified Proctor compaction energy. The typical trend of the specimens was that R1 and R2 had lower OMC and MDD values than B1 and B2. In particular, the low MDD of R2 is attributable to its low fines content. As displayed in Figures 4.3 and 4.4, an increase in the amount of RAP within the specimens caused the OMC and MDD to decrease. This occurred because the RAP consisted of aggregate particles that were encased in asphalt, which led to reduced specific gravity values. The presence of the asphalt cement also led to reductions in the amount of water required to achieve MDD.

With regard to differences between base materials, Figure 4.4 shows that the effect of base type on MDD depends on the type of RAP with which the base is mixed. That is, when the angular B2 is mixed with R2, the MDD is greater than that achieved when the comparatively smooth B1 is mixed with R2. However, the combination of B2 and R1 yield a MDD less than that achieved by the combination of B1 and R1.

TABLE 4.3 Compaction Characteristics

Material	RAP Content (%)	Base Content (%)	Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)
R1	100	0	129.7	5.62
R2	100	0	115.3	5.78
B1	0	100	135.5	6.62
B2	0	100	137.8	7.08
R1-B1	75	25	131.8	5.67
	50	50	132.0	6.13
	25	75	132.9	6.44
R1-B2	75	25	132.6	5.57
	50	50	133.8	6.02
	25	75	135.2	6.40
R2-B1	75	25	123.5	5.88
	50	50	129.2	5.92
	25	75	133.6	6.60
R2-B2	75	25	120.4	5.82
	50	50	126.7	6.89
	25	75	132.7	6.92

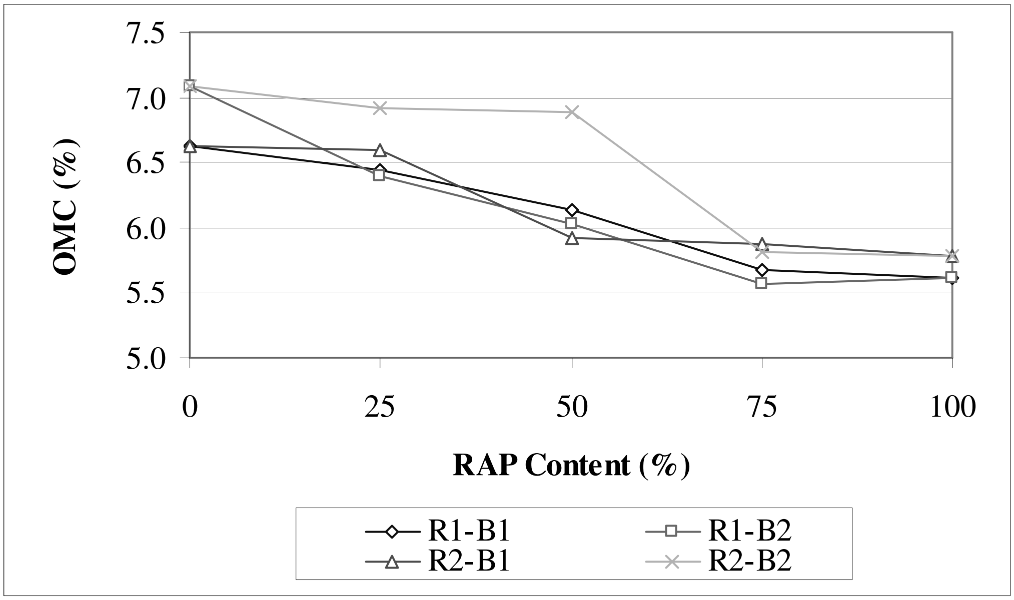

FIGURE 4.3 Optimum moisture contents.

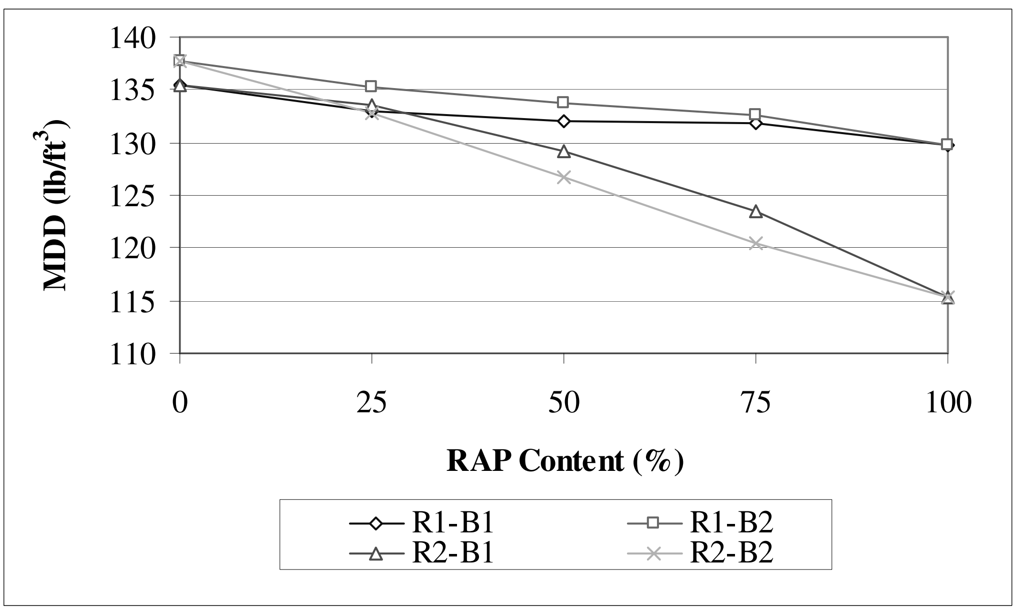

FIGURE 4.4 Maximum dry densities.

4.2.3 Testing

The results of the strength, stiffness, and moisture-susceptibility tests are presented in Tables 4.4, 4.5, and 4.6, respectively, and Table 4.7 presents the dry density of each tested specimen. Statistical analyses and discussion of the results are provided in the following section.

TABLE 4.4 CBR Test Results

Material	RAP Content (%)	Base Content (%)	Specimen	Moisture Content (%)	CBR (%)
R1	100	0	1	5.20	25
			2	5.45	22
			3	5.23	19
R2	100	0	1	2.54	23
			2	2.98	22
			3	3.29	18
B1	0	100	1	7.46	29
			2	7.74	25
			3	7.69	38
B2	0	100	1	5.46	63
			2	5.37	72
			3	5.42	54
R1-B1	75	25	1	6.20	22
			2	6.23	28
			3	6.50	24
	50	50	1	6.79	24
			2	6.79	21
			3	6.51	24
	25	75	1	7.16	23
			2	6.99	21
			3	7.05	25
R1-B2	75	25	1	5.09	28
			2	5.43	38
			3	5.45	27
	50	50	1	5.60	32
			2	5.82	33
			3	5.58	32
	25	75	1	5.55	36
			2	5.70	34
			3	5.69	39

TABLE 4.4 CBR Test Results (Continued)

Material	RAP Content (%)	Base Content (%)	Specimen	Moisture Content (%)	CBR (%)
R2-B1	75	25	1	6.62	22
			2	7.27	22
			3	6.71	20
	50	50	1	7.03	33
			2	7.12	28
			3	7.05	25
	25	75	1	7.25	36
			2	7.21	32
			3	7.00	33
R2-B2	75	25	1	7.08	24
			2	7.43	28
			3	7.30	22
	50	50	1	8.04	32
			2	7.98	33
			3	8.07	32
	25	75	1	6.14	40
			2	6.20	45
			3	6.08	36

TABLE 4.5 Stiffness Test Results

Material	RAP Content (%)	Base Content (%)	Specimen	Moisture Content (%)			Young's Modulus (ksi)		
				OMC	Dry	Soaked	OMC	Dry	Soaked
R1	100	0	1	5.52	0.06	5.20	41.9	118.2	58.0
			2	5.53	0.06	5.45	42.4	83.9	62.7
			3	5.52	0.06	5.23	43.1	86.3	65.7
R2	100	0	1	5.85	0.10	2.54	17.2	90.4	62.6
			2	5.84	0.10	2.98	14.0	78.0	28.1
			3	5.82	0.09	3.29	21.1	85.6	49.8
B1	0	100	1	6.51	0.11	7.46	43.2	127.8	15.6
			2	6.51	0.09	7.74	29.8	144.9	17.0
			3	6.52	0.11	7.69	43.3	173.9	16.3
B2	0	100	1	6.87	0.03	5.46	9.7	93.5	7.9
			2	6.88	0.03	5.37	9.0	77.6	8.2
			3	6.88	0.03	5.42	8.1	73.2	8.1

TABLE 4.5 Stiffness Test Results (Continued)

Material	RAP Content (%)	Base Content (%)	Specimen	Moisture Content (%)			Young's Modulus (ksi)		
				OMC	Dry	Soaked	OMC	Dry	Soaked
R1-B1	75	25	1	4.97	0.10	6.20	26.8	111.8	46.8
			2	5.00	0.10	6.23	27.3	107.7	52.9
			3	4.95	0.10	6.50	27.4	99.4	80.5
	50	50	1	6.02	0.11	6.79	9.0	73.9	37.5
			2	6.02	0.10	6.79	7.8	63.0	55.7
			3	6.00	0.11	6.51	9.8	128.8	41.6
	25	75	1	6.18	0.14	7.16	10.6	126.0	58.4
			2	6.19	0.13	6.99	7.8	135.9	52.6
			3	6.20	0.13	7.05	9.0	115.1	30.6
R1-B2	75	25	1	5.42	2.57	5.09	10.7	120.6	77.3
			2	5.39	2.76	5.43	12.7	111.7	58.2
			3	5.40	2.72	5.45	12.4	117.6	55.9
	50	50	1	5.89	2.24	5.60	5.2	127.3	68.2
			2	5.89	2.25	5.82	5.4	136.2	65.5
			3	5.87	2.21	5.58	4.8	125.3	59.0
	25	75	1	6.32	1.41	5.55	0.8	155.7	142.3
			2	6.34	1.40	5.70	1.0	184.2	141.9
			3	6.34	1.32	5.69	1.1	182.2	66.6
R2-B1	75	25	1	5.84	0.12	6.62	4.9	64.4	39.2
			2	5.84	0.11	7.27	4.9	64.1	18.3
			3	5.84	0.13	6.71	5.4	49.1	42.2
	50	50	1	5.94	0.11	7.03	8.4	97.0	52.4
			2	5.97	0.12	7.12	8.5	97.6	25.8
			3	6.11	0.11	7.05	5.9	149.4	59.3
	25	75	1	6.53	0.11	7.25	5.8	169.7	59.2
			2	6.55	0.13	7.21	3.6	147.0	42.3
			3	6.52	0.11	7.00	4.5	62.8	65.0
R2-B2	75	25	1	5.83	0.44	7.08	4.5	62.8	65.0
			2	5.82	0.42	7.43	4.3	54.9	55.2
			3	5.83	0.37	7.30	4.7	51.4	24.9
	50	50	1	7.00	0.44	8.04	3.5	113.4	60.2
			2	6.97	0.53	7.98	3.1	155.1	61.4
			3	6.98	0.46	8.07	3.3	112.6	65.0
	25	75	1	6.83	0.46	6.14	1.5	176.0	44.4
			2	6.84	0.45	6.20	1.5	199.5	110.8
			3	6.83	0.44	6.08	3.2	201.2	66.4

TABLE 4.6 Moisture-Susceptibility Test Results

Material	RAP Content (%)	Base Content (%)	Specimen	Moisture Content (%)	Dielectric Value	Electrical Conductivity (µS/cm)
R1	100	0	1	3.72	6.8	1
			2	3.61	6.1	0
			3	3.57	5.6	0
R2	100	0	1	0.52	3.7	0
			2	0.53	3.7	0
			3	0.51	3.5	0
B1	0	100	1	6.71	19.8	381
			2	6.75	14.3	353
			3	6.78	15.0	231
B2	0	100	1	5.13	6.4	4
			2	5.08	7.1	11
			3	5.07	5.8	5
R1-B1	75	25	1	3.71	6.4	6
			2	3.68	6.8	4
			3	3.66	5.6	2
	50	50	1	5.25	20.5	283
			2	5.87	19.6	513
			3	4.83	13.1	41
	25	75	1	6.39	24.5	1052
			2	6.29	22.1	1002
			3	6.35	23.1	1043
R2-B1	75	25	1	4.64	15.7	73
			2	4.73	12.0	87
			3	4.62	13.2	122
	50	50	1	5.74	20.8	315
			2	5.72	17.3	326
			3	5.73	20.0	568
	25	75	1	6.35	18.2	624
			2	6.41	22.3	880
			3	6.30	26.0	936

TABLE 4.7 Dry Densities

Material	RAP Content (%)	Base Content (%)	Specimen	Dry Density (lb/ft^3)
R1	100	0	1	130.3
			2	130.0
			3	130.4
R2	100	0	1	116.0
			2	116.2
			3	116.9
B1	0	100	1	134.5
			2	132.0
			3	134.1
B2	0	100	1	139.7
			2	137.5
			3	139.0
R1-B1	75	25	1	129.5
			2	131.0
			3	130.3
	50	50	1	133.1
			2	132.7
			3	133.1
	25	75	1	133.8
			2	135.5
			3	135.2
R1-B2	75	25	1	132.8
			2	131.9
			3	133.2
	50	50	1	133.5
			2	134.0
			3	131.0
	25	75	1	135.3
			2	134.3
			3	135.5

TABLE 4.7 Dry Densities (Continued)

Material	RAP Content (%)	Base Content (%)	Specimen	Dry Density (lb/ft^3)
R2-B1	75	25	1	123.6
			2	122.4
			3	122.4
	50	50	1	128.6
			2	127.5
			3	128.9
	25	75	1	132.0
			2	132.5
			3	133.6
R2-B2	75	25	1	122.1
			2	120.7
			3	121.0
	50	50	1	126.7
			2	127.2
			3	125.7
	25	75	1	134.0
			2	132.4
			3	133.0

4.3 STATISTICAL ANALYSES

Once all the testing was completed, a fixed effects ANOVA was performed on each of the test results, or dependent variables; these included CBR, stiffness at all three moisture conditions, dielectric value, electrical conductivity, and dry density. The independent variables in the analysis were RAP content, RAP type, and base type, together with all their interactions. Table 4.8 indicates the level of significance, or *p*-value, associated with each independent variable for each test conducted. The null hypothesis in each case was that the value of the dependent variable did not depend on the value of the independent variable, while the alternative hypothesis was that the value of the dependent variable did depend on the value of the independent variable. When the *p*-value is less than or equal to the standard error rate of 0.05, the null hypothesis can be rejected, leading to acceptance of the alternative hypothesis. However, when the *p*-value is greater than 0.05, one must conclude that insufficient evidence exists to reject the null hypothesis. In situations where interactions are significant, one may conclude that the influence of one independent variable on a given dependent variable depends upon the value of another independent variable.

According to Table 4.8, the influence of RAP content was significant for every dependent variable. The influence of RAP type was significant for stiffness at OMC and in the soaked condition, as well as for dry density. Dependent variables in which the influence of base type was significant include CBR, stiffness at OMC and in the soaked condition, and dry density. All of the interactions were significant under the multivariate analysis. Therefore, they were included in the univariate analyses even though they were not significant for many of the dependent variables. The results of the statistical analyses pertaining to the main effects and the interactions are presented in the following sections.

TABLE 4.8 Significance Levels for Main Effects and Interactions

Factor	*p*-values						
	CBR	Young's Modulus			Dielectric Value	Electrical Conductivity	Dry Density
		OMC	Dry	Soaked			
RAP Content	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
RAP Type	0.4543	<0.0001	0.1780	0.008	0.2364	0.9831	<0.0001
Base Type	<0.0001	<0.0001	0.7718	0.0027	--	--	<0.0001
RAP Content * RAP Type	0.0248	<0.0001	<0.0001	0.2730	0.0197	0.0980	<0.0001
RAP Content * Base Type	<0.0001	<0.0001	<0.0001	0.0014	--	--	<0.0001
RAP Type * Base Type	0.1888	0.008	0.2471	0.4830	--	--	0.0212
RAP Content * RAP Type * Base Type	0.8313	0.0075	0.8356	0.4275	--	--	0.0221

4.3.1 Main Effects

Tables 4.9 through 4.11 list the least square mean values associated with the main effects of RAP content, RAP type, and base type, respectively. The least square mean is the best estimate of the subpopulation mean for a given level of a given factor (*19*).

TABLE 4.9 Least Square Mean Values for Main Effects of RAP Content

Response Variable		0	25	50	75	100
CBR (%)		47	33	29	25	22
Young's Modulus (ksi)	OMC	23.9	4.1	6.2	12.2	30.0
	Dry	115.2	161.4	115.0	84.6	90.4
	Soaked	12.2	70.3	54.3	51.4	54.5
Dielectric Value		16.4	22.7	18.5	9.9	4.9
Electrical Conductivity (μS/cm)		322	923	341	49	0
Dry Density (lb/ft^3)		136.1	133.9	130.2	126.7	123.3

TABLE 4.10 Least Square Mean Values for Main Effects of RAP Type

Response Variable		R1	R2
CBR (%)		31	32
Young's Modulus (ksi)	OMC	19.6	10.9
	Dry	116.3	110.3
	Soaked	54.6	42.5
Dielectric Value		13.9	15.0
Electrical Conductivity (μS/cm)		327	326
Dry Density (lb/ft^3)		133.1	127.0

TABLE 4.11 Least Square Mean Values for Main Effects of Base Type

Response Variable		B1	B2
CBR (%)		26	37
Young's Modulus (ksi)	OMC	19.9	10.6
	Dry	112.7	114.0
	Soaked	41.6	55.5
Dielectric Value		--	--
Electrical Conductivity (μS/cm)		--	--
Dry Density (lb/ft^3)		129.6	130.6

The means related to the main effect of RAP content, as shown in Table 4.9, indicate that CBR values decrease with increasing RAP contents. The addition of 25 percent RAP causes a 29 percent decrease in strength compared to the neat base material, and the strength declines 13 to 15 percent with each additional 25 percent increase in RAP content. For the mean values associated with the stiffness test at OMC, the general trend was a decrease in stiffness from 0 to 25 percent RAP, followed by a steady increase in stiffness as the RAP content was increased from 25 to 100 percent. Following the 72-hour drying period, however, the general trend reversed; an increase in stiffness occurred as the RAP content was increased from 0 to 25 percent, and a steady decrease in stiffness was observed for RAP contents above 25 percent. The significance of the drying period was that, as the specimens containing RAP were exposed to heat within the drying oven, the asphalt surrounding the RAP particles began to soften. Once the samples cooled, the asphalt hardened and effectively enhanced the bonding between particles within the aggregate matrix, causing immediate gains in specimen strength and stiffness.

As described in Chapter 3, each of the neat materials was tested to identify those that were moisture-susceptible. The resulting TST data indicated that B1 was the only material of the four that had dielectric values higher than the threshold value of 10 after the 10-day capillary soak. In fact, in less than 24 hours of soaking, water reached the surfaces of all three of the B1 specimens as shown in Figure 4.5. Therefore, further testing was performed on B1 blended with both types of RAP. In the TST, both dielectric and electrical conductivity values increased with the addition of 25 percent RAP but steadily declined with higher RAP contents. The TST data suggest that additions of 25

Figure 4.5 Water at surfaces of moisture-susceptible specimens.

and 50 percent RAP actually increase the moisture susceptibility of the recycled material compared to the neat base, although the blended material is classified as non-moisture-susceptible when the RAP content exceeds 75 percent. Like the CBR values, the dry density values steadily decreased with increasing RAP content.

Based on the least square means listed in Table 4.10 for RAP type, a slight increase in the CBR and dielectric values associated with R2 compared to R1 can be observed, but neither difference was significant. For the remaining response variables, the trend was an increase in the values associated with R1 over R2, although only three of the five differences were significant. The trends were most likely related to the fact that R1 had a higher percentage of fines than R2.

Based on the least square means listed in Table 4.11 for base type, B2 showed close to a 40 percent increase in CBR over B1, which was most likely caused by the increased particle angularity associated with B2. At OMC, B1 was stiffer than B2, but in the soaked condition, B2 was stiffer than B1; in the dry condition, the difference was not statistically significant. Another trend associated with the base least square mean values was that the dry density associated with B2 was larger than that associated with B1, probably because the particle-size distribution of B2 was finer overall than that of B1. The difference between the B1 and B2 dry densities was less than 1 percent, however, as opposed to a difference of approximately 5 percent between the dry densities of R1 and R2. Because B2 was found to be non-moisture-susceptible, no testing was performed on mixtures of B2 with RAP. For this reason, the main effect of base type on TST results could not be assessed.

4.3.2 Interactions

Significant two-way interactions included RAP content by RAP type, RAP content by base type, and RAP type by base type. A significant three-way interaction also existed for stiffness at OMC and for dry density, but because the purpose of the statistical analysis was only to identify significant factors, the implications of the three-way interaction will not be discussed further.

The interaction of RAP content by RAP type was significant for all of the response variables except for Young's modulus in the soaked condition and electrical conductivity. Table 4.12 lists the least square mean values for each of the response variables, and Figures 4.6 to 4.12 illustrate the extent to which the effects of RAP content depend on RAP type for each response variable.

Similarly, Table 4.13 lists the least square mean values for each of the response variables for the interaction of RAP content by base type, and Figures 4.13 to 4.17 illustrate the extent to which the effects of RAP content depend on base type for each response variable. In particular, Figure 4.13 shows that the addition of RAP will cause greater reductions in CBR in angular materials than in uncrushed stone products; B2 consistently exhibited greater CBR values than B1. As RAP was introduced to the base materials in increasing quantities, however, the differences decreased as the CBR value approached that of the RAP material. Because the TST was performed on blends of RAP with just one base type, however, the interaction between RAP content and base type for dielectric and electrical conductivity values could not be evaluated.

TABLE 4.12 Least Square Means for RAP Content by RAP Type Interaction

RAP Type	RAP Content (%)	CBR (%)	Young's Modulus (ksi)			Dielectric Value	Electrical Conductivity (μS/cm)	Dry Density (lb/ft^3)
			OMC	Dry	Soaked			
R1	0	47	23.9	115.2	12.2	16.4	322	136.1
	25	30	5.1	149.8	82.1	23.2	1032	134.9
	50	28	7.0	109.1	54.6	17.7	279	132.9
	75	28	19.5	111.5	61.9	6.2	4	131.4
	100	22	42.4	96.2	62.1	6.1	0	130.2
R2	0	47	23.9	115.2	12.2	16.4	322	136.1
	25	37	3.1	173.0	58.5	22.1	814	132.9
	50	31	5.5	120.9	54.0	19.3	403	127.4
	75	23	4.8	57.8	40.8	13.6	94	122.0
	100	21	17.5	84.7	46.9	3.6	0	116.4

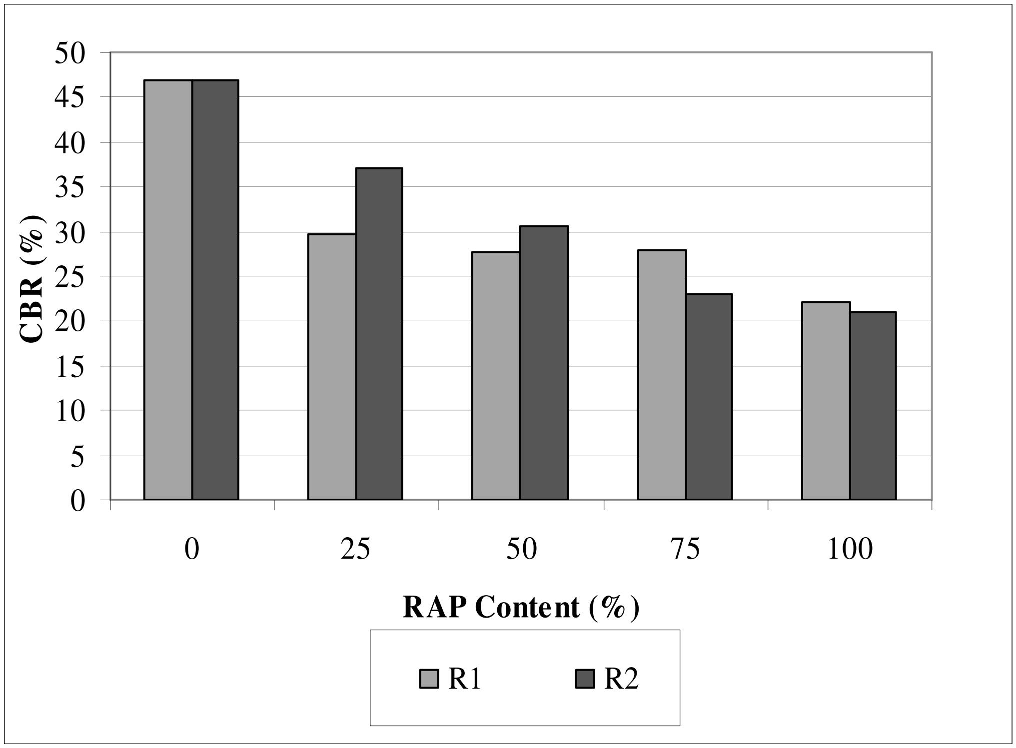

FIGURE 4.6 RAP content by RAP type interaction for CBR.

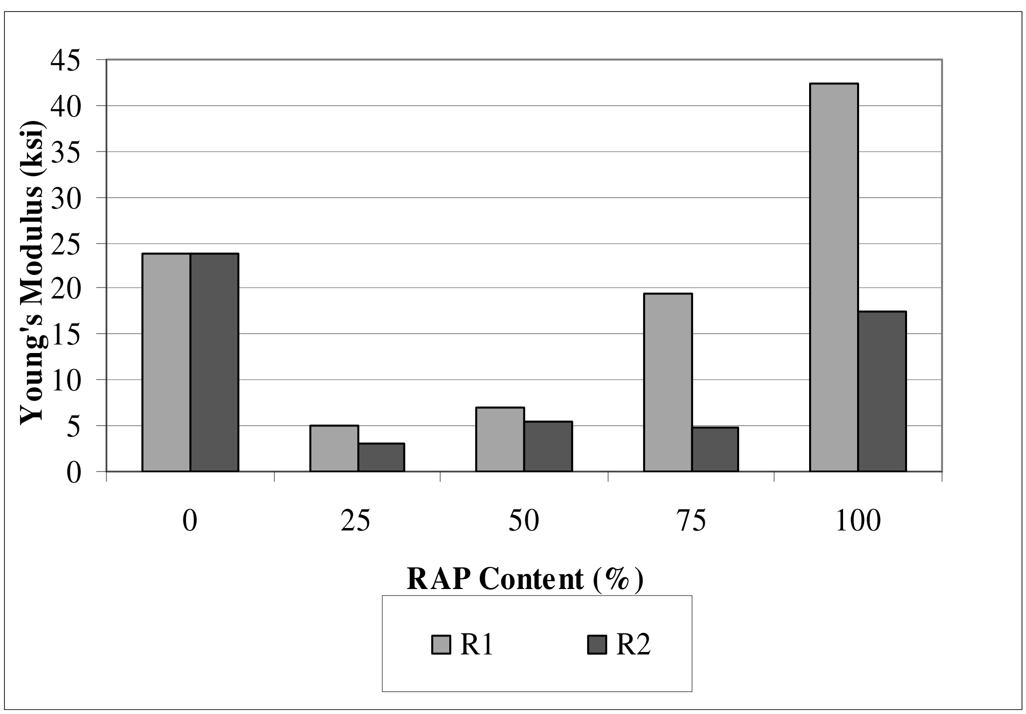

FIGURE 4.7 RAP content by RAP type interaction for stiffness at OMC.

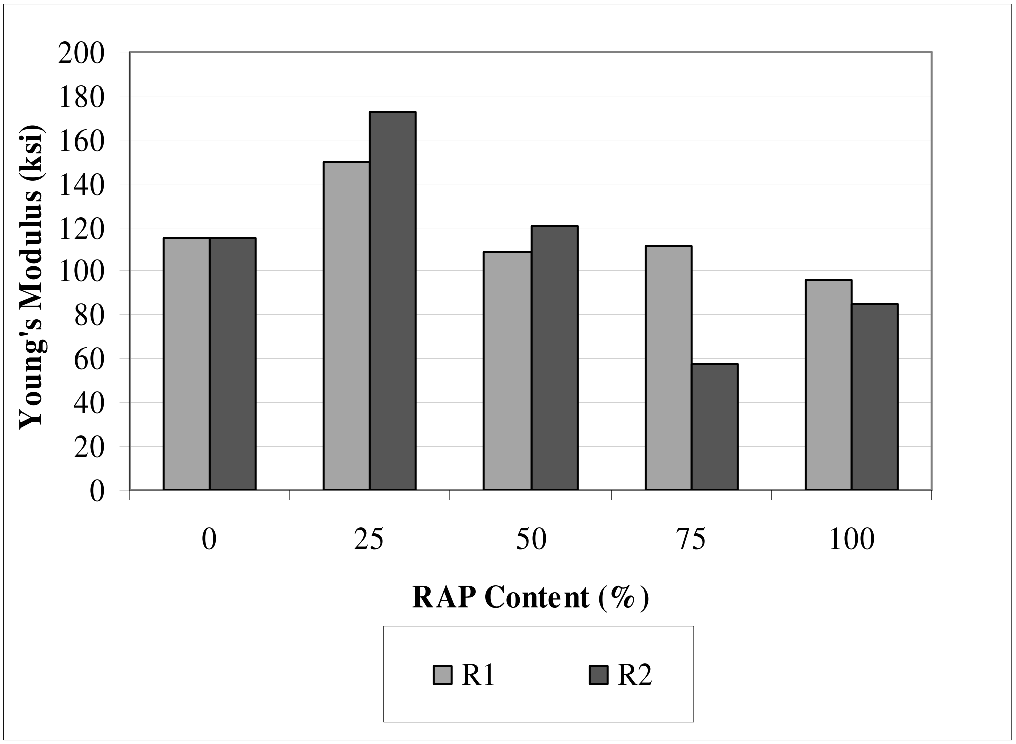

FIGURE 4.8 RAP content by RAP type interaction for stiffness in dry condition.

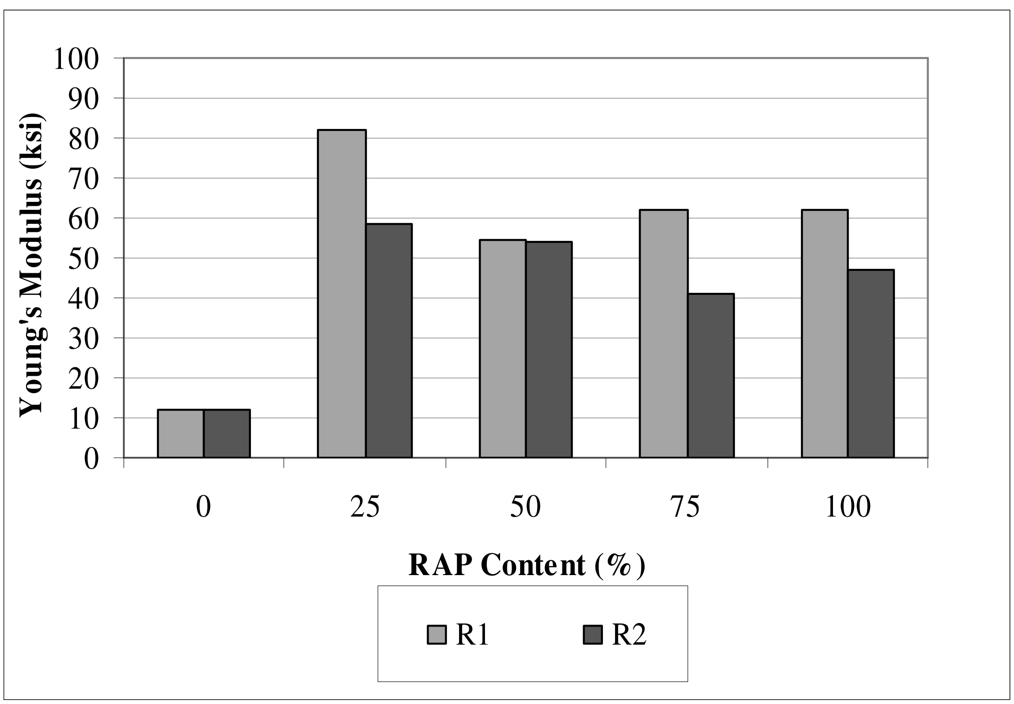

FIGURE 4.9 RAP content by RAP type interaction for stiffness in soaked condition.

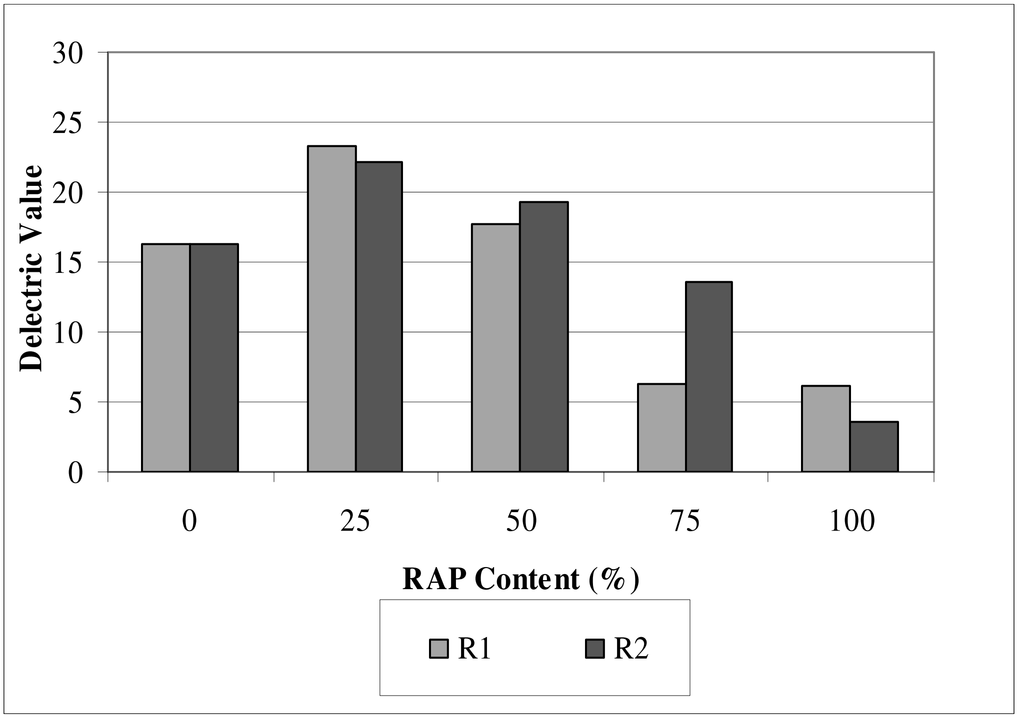

FIGURE 4.10 RAP content by RAP type interaction for dielectric value.

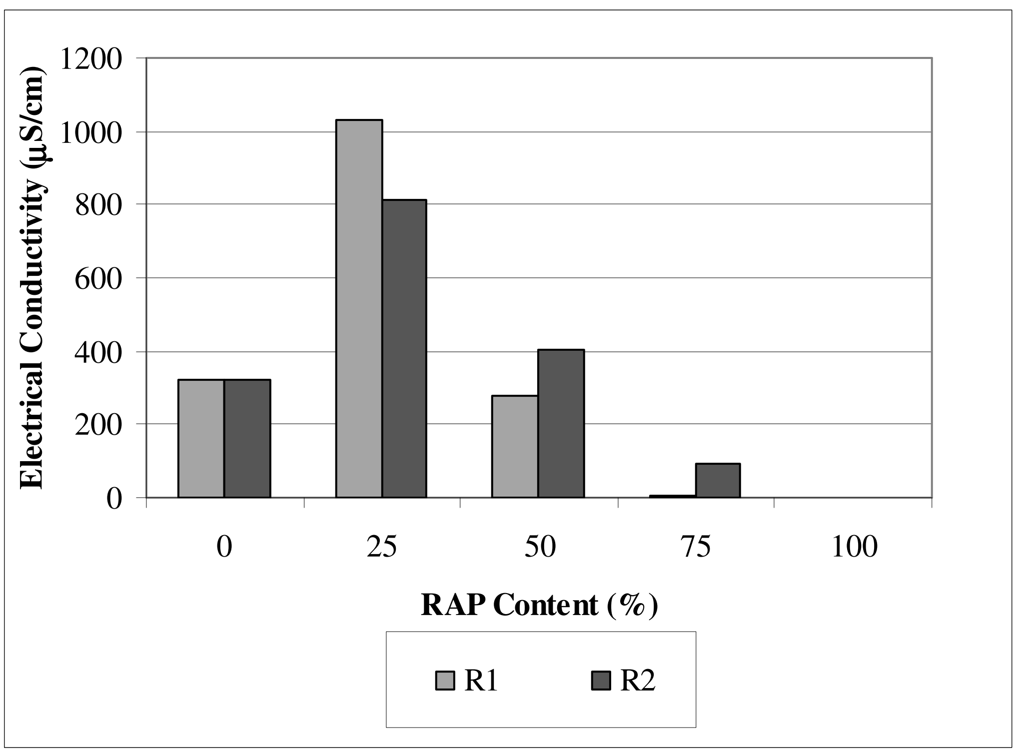

FIGURE 4.11 RAP content by RAP type interaction for electrical conductivity.

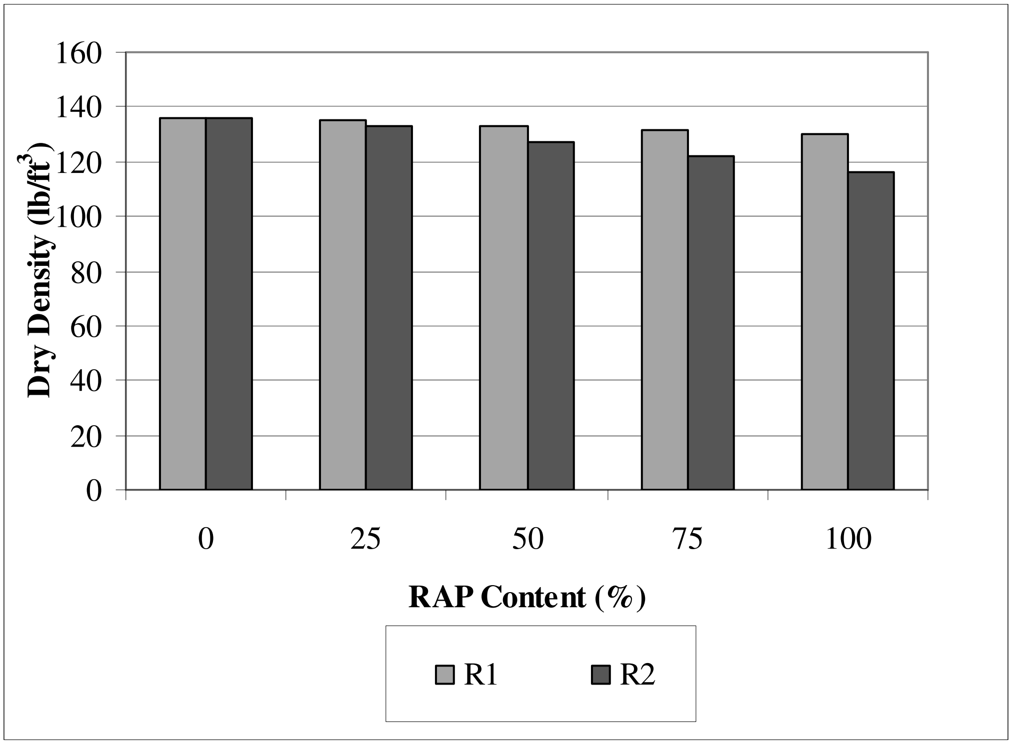

FIGURE 4.12 RAP content by RAP type interaction for dry density.

TABLE 4.13 Least Square Means for RAP Content by Base Type Interaction

RAP Type	RAP Content (%)	CBR (%)	Young's Modulus (ksi)			Dielectric Value	Electrical Conductivity (µS/cm)	Dry Density (lb/ft^3)
			OMC	Dry	Soaked			
B1	0	31	38.8	148.9	16.3	--	--	133.6
	25	28	6.6	139.7	45.2	--	--	133.8
	50	26	8.2	101.6	45.4	--	--	130.6
	75	23	16.1	82.8	46.7	--	--	126.5
	100	22	30.0	90.4	54.5	--	--	123.3
B2	0	63	8.9	81.4	8.1	--	--	138.7
	25	38	1.5	183.1	95.4	--	--	134.1
	50	32	4.2	128.3	63.2	--	--	129.7
	75	28	8.2	86.5	56.1	--	--	126.9
	100	22	30.0	90.4	54.5	--	--	123.3

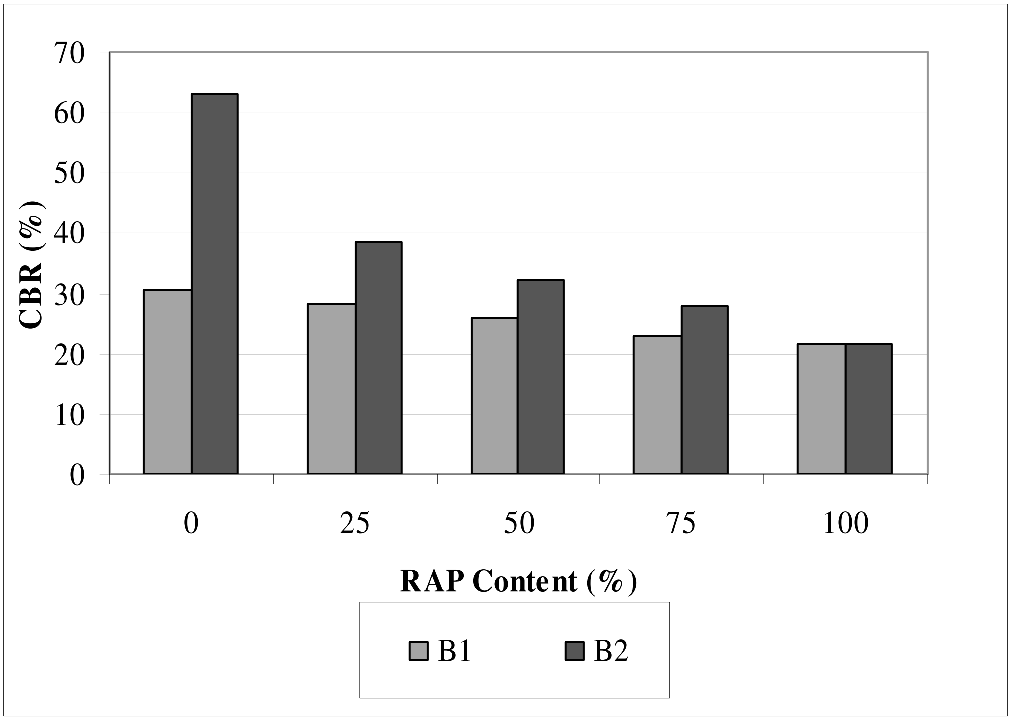

FIGURE 4.13 RAP content by base type interaction for CBR.

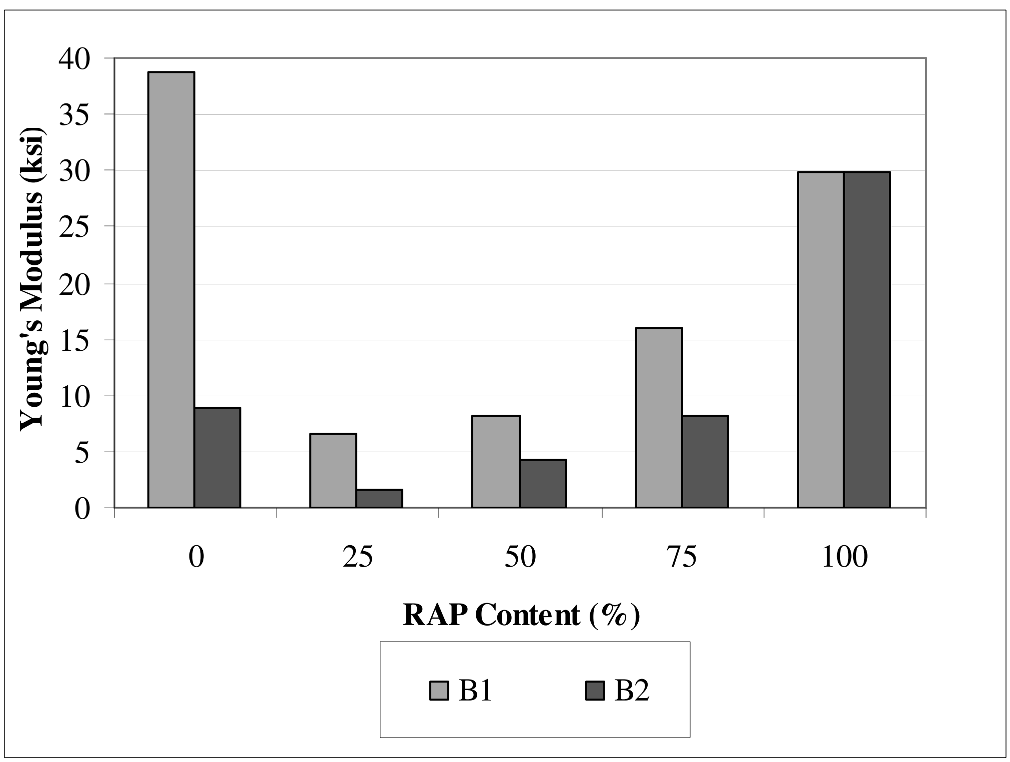

FIGURE 4.14 RAP content by base type interaction for stiffness at OMC.

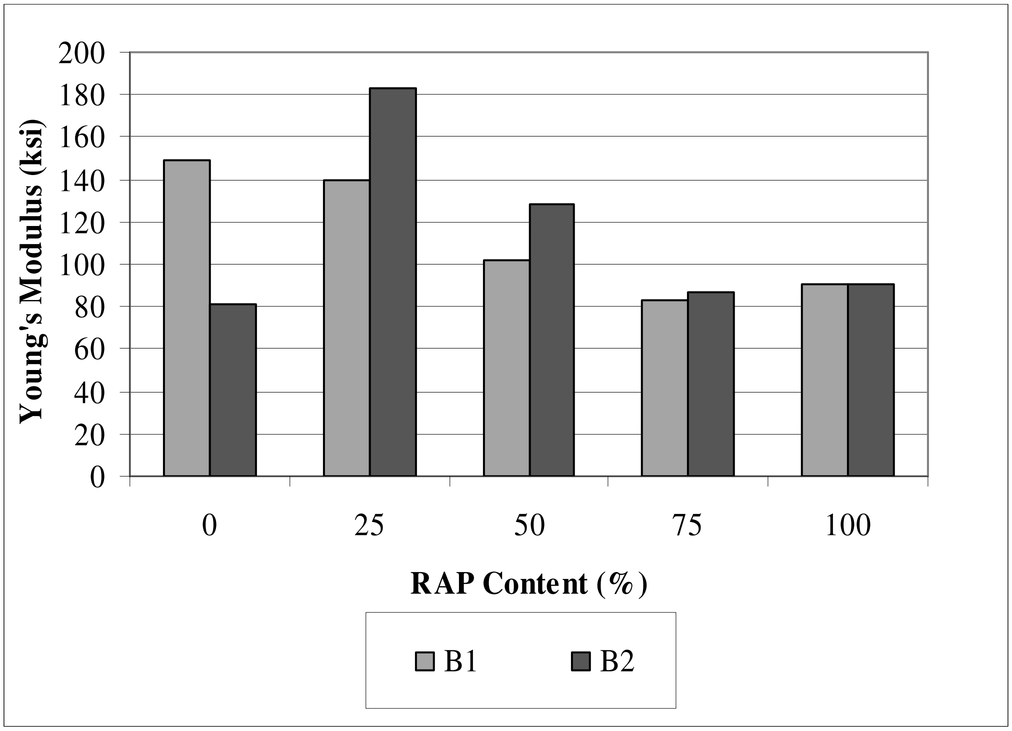

FIGURE 4.15 RAP content by base type interaction for stiffness in dry condition.

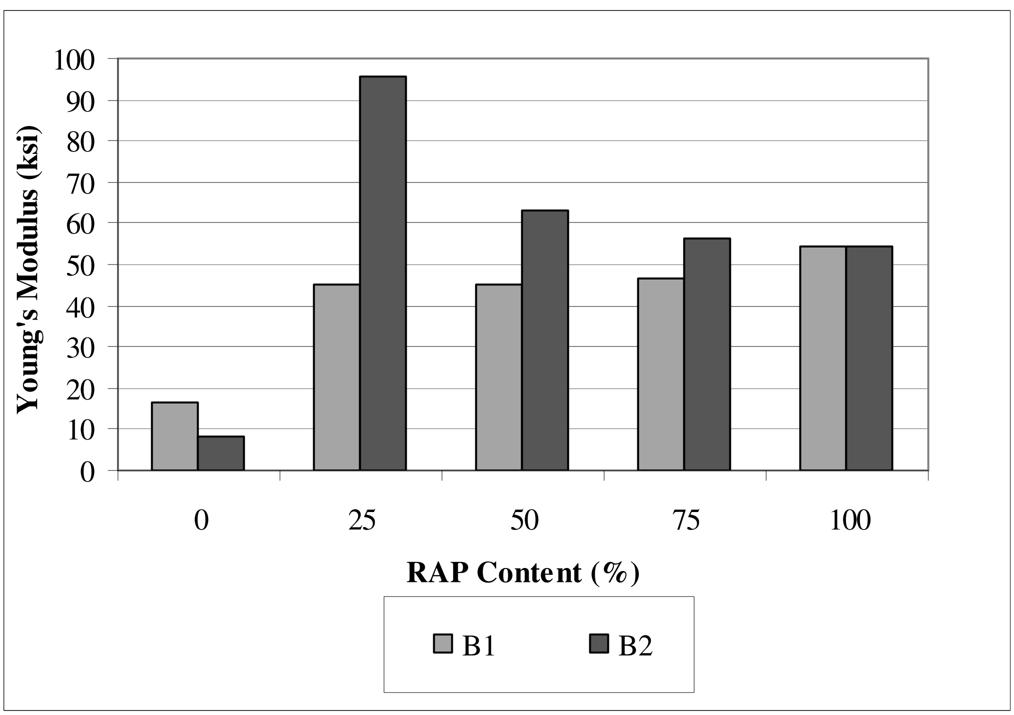

FIGURE 4.16 RAP content by base type interaction for stiffness in soaked condition.

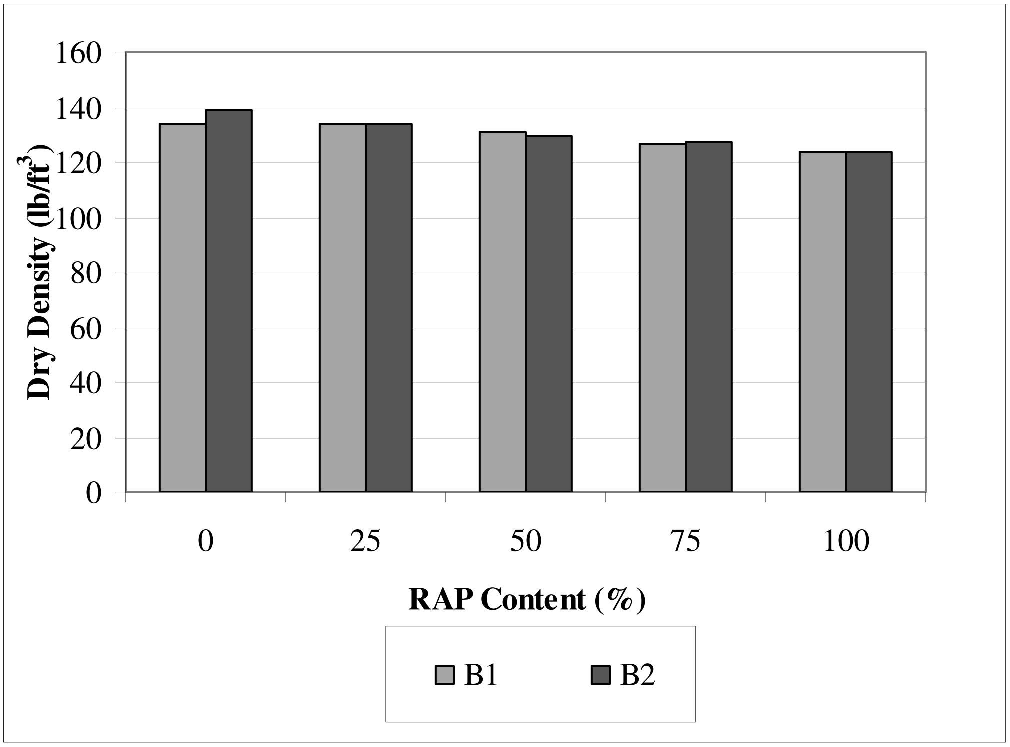

FIGURE 4.17 RAP content by base type interaction for dry density.

4.4 SUMMARY

The laboratory testing performed in this research included materials characterizations, specimen compaction tests, and strength, stiffness, and moisture-susceptibility tests. A fixed effects ANOVA was performed on each of the test results, or dependent variables; these included CBR, stiffness at all three moisture conditions, dielectric value, electrical conductivity, and dry density. The independent variables in the analysis were RAP content, RAP type, and base type, together with all their interactions.

For the most part, each of the materials had the same soil classifications, although slight differences in the amounts of fines associated with the individual materials were observed. The base materials had slightly higher OMC, MDD, and specific gravity values than the RAP materials.

CBR values followed the same trend documented in previous studies; strength decreased as the RAP content increased. The results of the CBR testing also indicated that, while the angular base material had higher strengths than the material consisting of subrounded particles, it experienced a greater percentage of strength loss compared to the subrounded base material when blended with equal amounts of RAP.

The results of the free-free resonant column test indicated that the tested materials exhibited greater stiffness after being subjected to 72 hours of drying at 140ºF and subsequent soaking than just after compaction at OMC. At OMC, the stiffness values of the specimens tended to decrease as the RAP content increased from 0 to 25 percent RAP. Following the initial decrease, the stiffness then increased as the RAP content increased from 25 to 100 percent. After oven-drying, however, the trend reversed; as the amount of RAP increased, the stiffness values measured following the drying period also increased. The significance of the drying period was that, as the specimens containing RAP were exposed to heat within the drying oven, the asphalt surrounding the RAP particles began to soften. Once the samples cooled, the asphalt hardened and effectively enhanced the bonding between particles within the aggregate matrix, causing immediate gains in specimen strength and stiffness.

The TST data indicated that all of the materials except B1 were non-moisture-susceptible. This being the case, blends of B1 and both sources of RAP were tested to investigate the effect of RAP content on moisture susceptibility. The data indicated that additions of 25 and 50 percent RAP actually increase the moisture susceptibility of the recycled material compared to the neat base, although the blended material was classified as non-moisture-susceptible when the RAP content was greater than or equal to 75 percent.

CHAPTER 5
CONCLUSION

5.1 SUMMARY

Reuse of RAP in the FDR process is an environmentally responsible method of asphalt pavement reconstruction. Although FDR has been used for several years in some locations, the effect of RAP on the mechanical properties of recycled base materials has not been well documented. Many professionals within the pavement industry believe that 50 percent is an optimum RAP content and that the addition of RAP enhances the structural value of the recycled layer. However, one published study indicates that the strength of the base layer actually decreases with increasing RAP content and that the maximum RAP content should be limited to 60 percent in recycled base materials similar to those tested in that research. Given that both the quantity and source of RAP can affect the mechanical properties of recycled base materials, this study was designed to investigate the influence of RAP on the mechanical properties of recycled base materials typical of northern Utah.

For this research, subrounded and angular aggregate base materials were tested, as well as RAP from two different locations. RAP contents of 0, 25, 50, 75, and 100 percent were utilized in a full-factorial experimental design with three replicates of each unique combination. Testing procedures consisted of classifying each of the four individual materials and determining the OMC and MDD associated with each of the 20 combinations. Testing was then conducted to investigate the strength, stiffness, and moisture susceptibility of each material blend. The CBR test was used to measure strength, the free-free resonant column test was used to measure stiffness, and the TST was used to measure moisture susceptibility. Once all the testing was completed, a fixed effects ANOVA was performed on each of the test results, or dependent variables. The independent variables were RAP content, RAP type, and base type, together with all their interactions. Results of the ANOVA were used to quantify the effects of RAP on the mechanical properties of the base materials.

5.2 FINDINGS

Results of the materials characterizations were used to classify each tested material in the AASHTO and Unified soil classification systems. In the AASHTO classification system, R1 and R2 were both classified as gravels (A-1-a). As for classification under the Unified soil classification system, R1 was found to be a well-graded gravel with silt and sand (GW-GM), and R2 was found to be a well-graded gravel with sand (GW). Both RAP materials had similar characteristics; however, the R2 gradation consisted of only 0.45 percent particles that were finer than the No. 200 sieve, while R1 had approximately 8 percent. Because the RAP materials represented different asphalt mixtures sampled at different locations using different asphalt recycling machines, the source of the differences in gradation could not be readily identified.

B1 was classified as a gravel (A-1-a) under the AASHTO classification system and as a well-graded sand with silt (GW-GM) in the Unified soil classification system. B2 was also classified as a gravel (A-1-a) in the AASHTO classification system, but as a well-graded gravel with sand and silt (GW-GM) under the Unified soil classification system. B1 had a different classification than B2 because its sand content was less than 15 percent, while B2 had a sand content higher than 15 percent.

Regarding compaction characteristics, the general trend for OMC and MDD was that, as RAP content increased, the OMC and MDD values decreased. R1 and R2 had lower OMC and MDD values than B1 and B2, so increasing RAP contents caused OMC and MDD values to decrease. This occurred because the RAP consisted of aggregate particles that were encased in asphalt, which led to reduced specific gravity values. The presence of the asphalt cement also led to reductions in the amount of water required to achieve MDD.

The ANOVA performed on the test results showed that the influence of RAP content was significant for every dependent variable. The influence of RAP type was significant for stiffness at OMC and in the soaked condition, as well as for dry density.

Dependent variables in which the influence of base type was significant include CBR, stiffness at OMC and in the soaked condition, and dry density. All of the interactions were significant under the multivariate analysis and were therefore included in the univariate analyses even though they were not significant for many of the dependent variables.

The means related to the main effect of RAP content indicate that CBR values decrease with increasing RAP contents. The addition of 25 percent RAP causes a 29 percent decrease in strength compared to the neat base material, and the strength declines 13 to 15 percent with each additional 25 percent increase in RAP content. For the mean values associated with the stiffness test at OMC, the general trend was a decrease in stiffness from 0 to 25 percent RAP, followed by a steady increase in stiffness as the RAP content was increased from 25 to 100 percent. Following the 72-hour drying period, however, the general trend reversed; an increase in stiffness occurred as the RAP content was increased from 0 to 25 percent, and a steady decrease in stiffness was observed for RAP contents above 25 percent. The significance of the drying period was that, as the specimens containing RAP were exposed to heat within the drying oven, the asphalt surrounding the RAP particles began to soften. Once the samples cooled, the asphalt hardened and effectively enhanced the bonding between particles within the aggregate matrix, causing immediate gains in specimen strength and stiffness.

Regarding moisture-susceptibility testing, the TST results indicated that B1 was the only material of the four that had dielectric values higher than the threshold value of 10 after the 10-day capillary soak. Therefore, further testing was performed on B1 blended with both types of RAP to investigate the effect of RAP content on moisture susceptibility. The TST data suggest that additions of 25 percent and 50 percent RAP actually increase the moisture susceptibility of the recycled material compared to the untreated base, although the blended material is classified as non-moisture-susceptible when the RAP content exceeds 75 percent. Like the CBR values, the dry density values steadily decreased with increasing RAP content.

Based on the least square means obtained through the ANOVA test, a slight increase in the CBR and dielectric values associated with R2 compared to R1 was observed, but neither difference was significant. For the remaining response variables, the trend was an increase in the values associated with R1 over R2, although only three of the five differences were significant. The trends were most likely related to the fact that R1 had a higher percentage of fines than R2.

Concerning the main effect of base type, B2 showed close to a 40 percent increase in CBR over B1, which was most likely caused by the increased particle angularity associated with B2. At OMC, B1 was stiffer than B2, but in the soaked condition, B2 was stiffer than B1; in the dry condition, the difference was not statistically significant. Another trend associated with the base least square mean values was that the dry density associated with B2 was larger than that associated with B1, probably because the particle-size distribution of B2 was finer overall than that of B1. The difference between the B1 and B2 dry densities was less than 1 percent, however, as opposed to a difference of approximately 5 percent between the dry densities of R1 and R2. Because B2 was found to be non-moisture-susceptible, no testing was performed on mixtures of B2 with RAP. For this reason, the main effect of base type on TST results could not be assessed.

Significant two-way interactions included RAP content by RAP type, RAP content by base type, and RAP type by base type. The interaction of RAP content by RAP type was significant for all of the response variables except for Young's modulus in the soaked condition and electrical conductivity. For the interaction of RAP content by base type, all response variables were significant. B2 consistently exhibited greater CBR values than B1, although the difference decreased with increasing RAP content as the CBR values approached that of the RAP material. Because the TST was performed on blends of RAP with just one base type, the interaction between RAP content and base type for dielectric and electrical conductivity values could not be evaluated.

5.3 RECOMMENDATIONS

In this research, the greatest reductions in strength and increases in moisture susceptibility occurred with the addition of 25 percent RAP. Further additions of RAP were associated with lesser reductions in CBR and, in fact, improvements in moisture susceptibility compared to treatment with 25 percent RAP. Although at 50 percent RAP the moisture susceptibility was still worse than that of the neat base material, at 75 percent RAP the recycled material became non-moisture-susceptible according to the criteria used in the TST. However, at 75 percent RAP, the CBR was only about 50 percent of the value of the neat base material, suggesting that thicker pavement base layers would be required to provide the same structural value as a thinner layer of untreated material when high RAP contents are used. The utilization of as much RAP as possible is desirable, however, to reduce pavement reconstruction costs and demonstrate environmental responsibility.

When reduced RAP contents are used, the poor moisture-susceptibility rating may negate simultaneous gains in strength and stiffness, suggesting that stabilization should be considered in conjunction with FDR at relatively low RAP contents when the materials are similar to those evaluated in this study. A sufficient amount of stabilizing agent, such as Portland cement, fly ash, or hydrated lime, should be added to the material to reduce the dielectric value in the TST to below 10 to ensure adequate resistance to moisture and frost damage. The use of RAP to improve a moisture-susceptible material to a non-moisture-susceptible condition may be especially valuable in areas with high water tables, repeated freeze-thaw cycles, sustained freezing temperatures that lead to frost heave, or poor drainage. Since base stabilization can be easily performed in conjunction with the FDR process, the cost savings associated with the use of RAP may still well exceed the additional costs required for base stabilization.

Because of the marked impact of RAP content on the mechanical properties of recycled base materials, engineers should accurately determine asphalt layer thicknesses prior to pavement reconstruction and carefully determine the optimum blending depth for each project. While asphalt milling or base overlays may be required in some locations to avoid excessively high RAP contents, reduced blending depths may be warranted in other areas to prevent the use of low RAP contents. In summary, while the use of RAP in the FDR process is environmentally responsible and offers potentially significant cost savings, thicker pavement base layers, base stabilization, or both may be required in many instances to ensure adequate long-term pavement performance.

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