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Effect of High Percentages of Reclaimed Asphalt Pavement on Mechanical Properties of Cement-Treated Base Material

Jacob Clark Tolbert
Brigham Young University - Provo

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Jacob C. Tolbert

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W. Spencer Guthrie, Chair
Grant G. Schultz
Gustavious P. Williams

Department of Civil and Environmental Engineering

Brigham Young University

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ABSTRACT

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Properties of Cement-Treated Base Material

Jacob C. Tolbert
Department of Civil and Environmental Engineering, BYU
Master of Science

Full-depth reclamation (FDR) is an increasingly common technique that is used to rehabilitate flexible pavements. Implementation of FDR on rehabilitation projects produces several desirable benefits. However, these benefits are not fully realized due to the fact that state department of transportation specifications typically limit the reclaimed asphalt pavement (RAP) content of pavement base material to 50 percent. The objective of this research was to evaluate the effects of RAP content, cement content, temperature, curing time, curing condition, and moisture state on the strength, stiffness, and deformation characteristics of cement-treated base (CTB) mixtures containing high percentages of RAP.

For this research, one aggregate base material and one RAP material were used for all samples. RAP content ranged from 0 to 100 percent in increments of 25 percent, and low, medium, and high cement levels corresponding to 7-day unconfined compressive strength (UCS) values of 200, 400, and 600 psi, respectively, were selected for testing. Moisture-density, UCS, resilient modulus, and permanent deformation tests were performed for various combinations of factors, and several statistical analyses were utilized to evaluate the results of the UCS, resilient modulus, and permanent deformation testing.

The results of this work show that CTB containing RAP can be made to achieve 7-day UCS values approaching 600 psi regardless of RAP content. With regards to stiffness, the data collected in this study indicate that the resilient modulus of CTB containing RAP is affected by temperature in the range from 72 to 140°F for the low cement level. Permanent deformation of CTB containing RAP is significantly affected by RAP content and cement level at the test temperature of 140°F. At the low cement level, temperature is also a significant variable. As the 7-day UCS reaches approximately 400 psi, permanent deformation is reduced to negligible quantities. The results of this research indicate that the inverse relationship observed between permanent deformation and 7-day UCS is statistically significant.

Given that the principle conclusion from this work is that CTB with high RAP contents can perform satisfactorily as a base material when a sufficient amount of cement is applied, agencies currently specifying limits on the percentage of RAP that can be used as a part of reclaimed base material in the FDR process should reevaluate their policies and specifications with the goal of allowing the use of high RAP contents where appropriate.

Key words: cement-treated base, full-depth reclamation, permanent deformation, resilient modulus, stiffness, unconfined compressive strength, reclaimed asphalt pavement

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1 INTRODUCTION

1.1 Problem Statement

Full-depth reclamation (FDR) is an increasingly common technique that is used to rehabilitate flexible pavements. The practice involves blending the surface asphalt course with the underlying base course material. Portland cement can be added during the blending process to improve the properties of the new base (ARRA 2001). Implementation of FDR on rehabilitation projects produces several desirable benefits. Recycling of the asphalt surface course into base material yields a reduction in waste material that must be hauled out initially, as well as a reduction in new material that must be brought to the site. The reduction in material movement results in faster construction as well as lower project costs; reduced material movement also leads to fewer truck trips made and an overall decrease in the environmental impact of a rehabilitation project (ARRA undated, PCA 2014).

Currently, these benefits are not fully realized due to the fact that state department of transportation (DOT) specifications often limit the amount of reclaimed asphalt pavement (RAP) that can be included as part of the base material to 50 percent (McGarrah 2007). Since the maximum specified loose layer depth for effective compaction in most states is 8 in. (Tascon 2011), this specification effectively limits the use of FDR to situations where the asphalt layer thickness is approximately 4 in. or less. If the surface course thickness is greater than 4 in., the excess asphalt must be milled and hauled away, thus reducing the positive impacts of FDR

(Wilson and Guthrie 2011). Allowing use of greater percentages of RAP would substantially increase the time and cost savings associated with FDR rehabilitation, as well as further decrease environmental impacts.

Determining the suitability of high RAP contents requires an understanding of the mechanical properties of the resulting reclaimed material. In particular, mechanical properties such as strength, stiffness, and deformation under loading, which govern the performance of base materials in the field, should be considered. While some studies indicate that high RAP contents can lead to increased stiffness in unbound base materials (Attia et al. 2009, Wu 2011), materials with high RAP contents also frequently exhibit significant decreases in strength and attendant increases in deformation (Bennert and Maher 2005, Cooley 2005), presumably attributable to inadequate inter-particle friction among the asphalt-coated aggregates. However, other research has demonstrated satisfactory performance of materials with high RAP contents in selected tests when a sufficient amount of cement is applied (Guthrie et al. 2007, Taha et al. 2002, Yuan et al. 2010).

In the literature review performed for this research on cement-treated base (CTB) material containing high percentages of RAP, several laboratory studies were identified that investigated CTB strength with respect to the effects of RAP and/or cement contents (Guthrie et al. 2007, Taha et al. 2002); however, only two studies were identified that explored stiffness (Puppala 2011, Yuan et al. 2010), and no studies were identified that specifically evaluated permanent deformation. Of the studies that investigated CTB strength or stiffness, all samples involved were tested at room temperature. No study was identified that examined the effect of higher test temperatures on the mechanical properties of CTB with high RAP percentages, although higher temperatures occur in the field and would be expected to further reduce the inter-particle friction between aggregate particles given that the viscosity of asphalt decreases upon heating. Furthermore, the sensitivity of CTB materials containing high RAP contents to curing time and condition and also to moisture state has received only limited attention (Guthrie et al. 2008, Guthrie and Young 2006, Taha et al. 2002). Due to the lack of information in the literature on these topics, additional research was needed to more fully characterize the mechanical properties of CTB materials containing high RAP contents.

1.2 Research Objective and Scope

The objective of this research was to evaluate the effects of RAP content, cement content, temperature, curing time and condition, and moisture state on the strength, stiffness, and deformation characteristics of CTB mixtures containing high percentages of RAP. To achieve this objective, locally-sourced base and RAP materials were separately acquired and then combined in the laboratory to create specimens with RAP contents ranging from 0 to 100 percent in 25 percent increments. Three levels of cement content were utilized, corresponding to 7-day unconfined compressive strength (UCS) values of 200, 400, and 600 psi. Testing was conducted to first determine the moisture-density relationships for each combination of RAP and cement content, then to evaluate the strength of each combination, and finally to investigate the stiffness and deformation characteristics of each material combination.

1.3 Outline of Report

This report consists of five chapters. Chapter 1 presents the problem statement, research objectives, and scope of work associated with the research. Background information about FDR with cement stabilization and the mechanical properties of CTB material containing high percentages of RAP is discussed in Chapter 2. Chapter 3 provides a description of the experimental design and the test procedures involved in the work. The test results, along with statistical analyses and discussion of the data, are presented in Chapter 4. Conclusions and recommendations based on the research are given in Chapter 5.

2 BACKGROUND

2.1 Overview

This chapter discusses the process of FDR with cement stabilization, as well as the mechanical properties of CTB material and factors that affect them.

2.2 Full-Depth Reclamation with Cement Stabilization

FDR with cement stabilization is a pavement rehabilitation technique that involves pulverization and blending of the asphalt surface course with a portion of the underlying base course material and a specified amount of portland cement. Although the process can be used to correct functional issues such as roughness or insufficient skid resistance, it is particularly applicable to situations in which the pavement has experienced structural failure (Cooley 2005). The use of cement stabilization in conjunction with FDR should be considered when the blended material exhibits inadequate strength and/or durability, especially with respect to moisture and/or frost (Guthrie et al. 2007, Guthrie and Young 2006).

In the FDR process, a machine known as a reclaimer is normally used to pulverize the asphalt and blend the materials together. Typically, the depth of blending is between 6 and 9 in. (ARRA undated). However, most state specifications limit compacted soil layers to a loose thickness of 8 in. (Tascon 2011). Following initial compaction and shaping, including removal of any excess material as required to match existing curb and gutter elevations, for example, cement powder is distributed over the surface, and the base/RAP blend is mixed with the cement and an appropriate amount of water using a reclaimer. Then, the material is compacted to the target density. Finally, water is sprayed onto the CTB surface periodically, or a prime coat is applied, to allow the material to cure properly. The resulting product is a stabilized base course with strength and durability characteristics superior to those of the original base layer. Once properly cured, a new surface course can be placed directly on the new base layer (PCA 2014).

The use of FDR in rehabilitating a pavement structure yields several important benefits. The process eliminates major forms of pavement distress and can improve the structural capacity and surface geometry of the pavement system (Kandhal and Mallick 1997). In addition, recycling the pavement structure normally costs 25 to 50 percent less than the traditional method of excavation and replacement (PCA 2014). Furthermore, since excavation is minimized and new aggregates do not need to be hauled to the site, the environmental impact of FDR is considerably less than alternative reconstruction methods. Total truck trips are greatly reduced, and valuable sources of quality aggregates are conserved for other uses. In addition, construction time is significantly reduced because of the greater efficiency associated with this procedure (ARRA undated).

The RAP produced through the FDR process generally consists of high quality aggregate that is coated with asphalt cement; however, the actual properties of RAP are very dependent on the constituent materials and can vary from source to source (RMRC 2014). The bearing capacity of base material containing RAP has been shown to decrease with increasing RAP content; in fact, granular base/RAP mixtures containing more than 25 percent RAP can be expected to have lower bearing capacity than mixtures containing no RAP (RMRC 2014). This lack of bearing capacity is an important basis for the limit of 50 percent RAP content that is in place at most state DOTs. Interestingly, in a national questionnaire survey, all of the studies cited by state materials engineers as justification for specifying RAP content limits were based on tests of granular base/RAP mixtures (McGarrah 2007), without consideration of cement stabilization.

2.3 Mechanical Properties of Cement-Treated Base Material

The mechanical properties of CTB containing RAP can potentially be affected by factors such as RAP content, cement content, temperature, curing time and condition, and moisture state. The following paragraphs explain the relevance of these factors and their potential impact on strength, stiffness, and deformation.

As described previously, the bearing capacity, or strength, of granular base material containing RAP decreases as RAP content increases. Previous studies have shown that the same trend is observed for base/RAP mixtures treated with various concentrations of cement (Crane and Guthrie 2007, Guthrie et al. 2007, Taha et al. 2002). Regarding stiffness, one study found that the resilient modulus of CTB decreases with increasing RAP content (Yuan et al. 2010). Regarding the effect of RAP content on the deformation characteristics of CTB/RAP mixtures, more research is needed, as no study on this topic was identified.

Common knowledge and experience indicate that the strength of soil-cement mixtures generally increases with increasing cement content, and studies have shown that base/RAP mixtures respond similarly (Guthrie et al. 2007, Miller et al. 2005). With regards to the effect of cement content on stiffness, one study found that modulus values increased with increasing cement content (Puppala et al. 2011). However, as the study was limited to samples comprised only of 100 percent RAP and either 2 or 4 percent cement, additional research is needed on this topic to better understand the relationship between cement content and resilient modulus.

Research is also needed to quantify the effect of cement content on the deformation characteristics of CTB containing RAP, as no studies were identified in the literature that specifically evaluated permanent deformation.

The temperature susceptibility of asphalt cement is one of its key attributes. To function properly in hot mix asphalt (HMA), asphalt cement must become less viscous at high mixing and compaction temperatures and then become sufficiently viscous at typical service temperatures to make the asphalt mixture stable (VDOT 2008). However, this property of asphalt cement is considered to be problematic in the case of RAP. Since RAP is produced by pulverizing HMA into individual particles partially coated with asphalt, the material loses the binding effect originally provided by the asphalt cement. Thus, in the context of FDR with cement stabilization, the asphalt coating on each particle no longer serves any beneficial purpose; instead, it becomes more of a particle lubricant. At normal service temperatures, the lubricating effect is not very pronounced since the asphalt is more viscous. However, during hot summer weather, particularly in southern locations, the base material in a pavement structure can potentially reach temperatures of 130 to 140°F (Mohseni 2005). Such temperatures cause reduced stiffness of base material containing RAP and consequently increase the potential for material deformation. One study that examined the effect of temperature on the resilient modulus of granular base material containing RAP found that samples tested at 140°F were less stiff than samples tested at 68°F (Wu 2011). However, no information is available in the literature regarding the effect of temperature on modulus or deformation characteristics of CTB material containing RAP.

Curing time has a well-documented effect on the strength of CTB; in the presence of sufficient moisture, as curing time increases, so does the material strength. This trend occurs regardless of the particle-size distribution or RAP content of the material (ACI 1990, Taha et al. 2002). If constructed correctly, CTB materials contain the appropriate moisture content necessary for the cement to hydrate. The moisture in the material must be retained, either through regular water spraying or the application of a prime coat, so that it does not dry out before adequate cement hydration can take place (PCA 1995). Even after compaction and curing, the moisture state of the CTB continues to influence the material properties. As a result of precipitation or groundwater infiltration, CTB may become soaked at some point during its service life. Saturation leads to a decrease in strength compared to that observed when the CTB is at optimum moisture content (OMC) (ACI 1990). Although material curing condition and time, as well as moisture state, have been shown in the literature to affect the strength of CTB, no studies were identified that quantified the effect of these factors on the stiffness or deformation characteristics of CTB containing high RAP percentages.

2.4 Summary

FDR with cement stabilization is a pavement rehabilitation technique that involves pulverization and blending of the asphalt surface course with a portion of the underlying base course material and a specified amount of portland cement. The use of FDR in rehabilitating a pavement structure yields several important benefits, such as improving pavement structural capacity and decreasing monetary and environmental costs. The RAP produced through the FDR process generally consists of high quality aggregate that is coated with asphalt cement; however, the actual properties of RAP are very dependent on the constituent materials and can vary from source to source. Lack of RAP bearing capacity is an important basis for the limit of 50 percent RAP content that is in place at most state DOTs.

The mechanical properties of CTB containing RAP can potentially be affected by factors such as RAP content, cement content, temperature, curing time and condition, and moisture state. The strength of CTB with high percentages of RAP has been shown to decrease with increasing RAP content and increase with increasing cement content. Limited research has suggested that CTB stiffness also decreases with rising RAP content, while no investigations were identified that studied the effect of RAP content on deformation of CTB with high RAP contents. High temperatures negatively affect the stiffness of granular base/RAP blends, but the effect on stabilized base/RAP blends has not been investigated. Similarly, the effects of curing condition and moisture state have not been specifically investigated, although increased curing time has been associated with an attendant increase in strength of CTB samples containing high RAP contents. Further research is needed to study the effects of these factors on the mechanical properties of CTB containing RAP.

3 PROCEDURES

3.1 Overview

This chapter describes the experimental design, materials characterization, mechanical property testing, and statistical analyses associated with this research.

3.2 Experimental Design

As shown in Table 3-1, each of the factors discussed in Chapter 2 was selected for inclusion in the experimental design prepared for this research. Specifically, RAP content, cement content, test temperature, curing time and condition, and moisture state were included. One aggregate base material and one RAP material were used in the preparation of all samples. RAP content ranged from 0 to 100 percent in intervals of 25 percent, and low, medium, and high cement levels corresponding to 7-day UCS values of 200, 400, and 600 psi, respectively, were selected for testing. Moisture-density, UCS, resilient modulus, and permanent deformation tests were performed for various combinations of factors as described in Table 3-1, with the resilient modulus and permanent deformation testing occurring over three phases; a hyphen in the table indicates that the given factor was not evaluated in the given test. In all of the testing except for evaluation of moisture-density relationships, two replicate specimens were prepared and tested for each unique combination. Unless otherwise noted, all samples were cured for 7 days prior to UCS, resilient modulus, or permanent deformation testing.

Table 3-1: Experimental Design

Factor	Test				
	Moisture-Density	UCS	Modulus and Deformation (Phase 1)	Modulus and Deformation (Phase 2)	Modulus and Deformation (Phase 3)
	Factor Levels				
RAP Content (%)	0, 25, 50, 75, 100	0, 25, 50, 75, 100	0, 25, 50, 75, 100	0, 25, 50, 75, 100	100
Cement Level	Low, Medium, High	Low, Medium, High	Low, Medium, High	Low	Low
Temperature (°F)	72	72	140	72	72
Curing Time (days)	-	7	7	7	28
Curing Condition	-	Sealed	Sealed	Sealed	Unsealed
Moisture State	-	OMC	OMC	OMC	Soaked

The high test temperature of 140°F shown in Table 3-1 was selected after careful examination of pavement temperature data provided in the LTPPBind software (Mohseni 2005). The goal in selecting the test temperature was to choose a value that would represent a reasonable worst-case scenario. While the LTPPBind software does not provide information on the temperature of aggregate base layers, it does facilitate calculation of the temperature at a specified depth within an asphalt pavement layer. Given that the temperature at the bottom of the asphalt layer can be assumed to be a good estimate of the temperature at the top of a base layer, the LTPPBind software was utilized to determine the maximum temperature that might be expected at the top of a CTB layer by calculating the maximum temperature that might be expected at the bottom of an overlying asphalt layer; this approach was deemed appropriate for use because the top of the CTB layer will also experience the greatest traffic-induced compressive stresses and would therefore be the location where problems with CTB strength, stiffness, and/or deformation would most likely be manifest. Based on data from several locations around the United States that exhibit very hot climates, temperatures at a target depth of 4 in. were found to generally range between 130 and 140°F; therefore, a conservative value of 140°F was selected as the elevated test temperature for use in the research. Room temperature, approximately 72°F, was selected as a control temperature for comparison purposes.

In addition to temperature, the effects of curing time, curing condition, and moisture state were also investigated. To investigate the effect of curing time, samples cured for 7 and 28 days were tested. Both of these curing times are commonly specified for CTB characterization. To investigate the effect of curing condition, both sealed and unsealed samples were tested; the unsealed condition simulated a lack of proper curing that sometimes occurs during construction of CTB layers. To investigate the effect of moisture state, testing was performed at moisture contents corresponding to OMC and to a soaked condition. The soaked samples were properly cured for 6 days and then completely immersed in water for the final 24 hours of curing prior to testing. The 24-hour soak simulated a worst-case scenario wherein the material is subjected to trafficking while at a high water content.

3.3 Materials Characterization

The aggregate base material used in this research was obtained from the Staker Parson Companies pit located in Salt Lake City, Utah, while the RAP material was procured from the Geneva Rock Products HMA batch plant located in Orem, Utah. Both materials were dried to constant weight prior to all other research activities. The base material was dried at 230°F, while the RAP material was dried at 140°F to avoid excessive oxidation of the asphalt binder. Both materials were then separated over the 1/2-in., 3/8-in., No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200 sieves. The weights retained on each sieve were used to develop master particle-size distributions, which were exactly duplicated in the preparation of all specimens tested in this research. In addition, washed sieve and hydrometer analyses, as well as Atterberg limits testing, were performed on the materials for the purpose of classifying them according to the Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) methods.

The initial cement levels used in this study were selected based on recommendations provided by the Portland Cement Association in the *Soil-Cement Laboratory Handbook* (PCA 1992). The handbook suggests a preliminary cement content based solely upon the classification of the soil that is to be stabilized. Lower and higher cement levels were then obtained by decreasing or increasing that value by two percentage points, respectively. Type I/II portland cement was used to achieve the selected cement contents for each sample combination. Once determined, each cement content was applied to each of the five base/RAP mixtures to establish a moisture-density relationship for each of the 15 combinations.

For each combination of base/RAP material and cement, five samples were initially prepared and tested at various moisture contents to determine the moisture-density relationship and corresponding OMC and maximum dry density (MDD). Sample preparation was conducted in general accordance with American Society for Testing and Materials (ASTM) D558 (Standard Test Methods for Moisture-Density Relations of Soil-Cement Mixtures) Method B. The RAP content, an estimate of the dry density of the sample, and the known mold volume were used to calculate the weights of base and RAP materials needed for each sample. In the sample weigh-out process, the material was separated into the coarse fraction, or the material retained on the No. 4 sieve, and the fine fraction, or the material passing the No. 4 sieve. The coarse fraction was soaked in a volume of de-ionized water corresponding to the calculated sample moisture content for 24 hours prior to being mixed with the fine fraction. Cement was added to the fine fraction in a dry state, and the mixture was then thoroughly blended until a uniform color was achieved. Following the 24-hour soaking period, the fine fraction with cement was combined with the moistened coarse fraction. To mix the coarse and fine fractions, approximately one-third of the fine fraction was placed in a container with the coarse portion. The mixture was then blended until a uniform color and texture was reached. This process was repeated twice more until all of the material was adequately blended.

The sample was then compacted into a 4-in.-diameter mold with a height of 4.6 in. using standard Proctor compaction effort in general accordance with ASTM D698 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3)). Standard Proctor effort was selected because higher compaction effort may not be consistently achieved in the field when FDR is utilized. Each sample was compacted in three lifts with 25 blows from a 5.5-lb hammer dropped from a height of 12 in. using the automatic compaction machine shown in Figure 3-1. Following compaction, the height and weight of each sample were recorded, and the sample was extruded from the mold. All samples were dried at 140°F to constant weight after extrusion. The calculated moisture contents and dry densities were plotted in order to determine the moisture-density relationship. If needed, additional samples were prepared and tested to create reasonable moisture-density plots.

Figure 3-1: Automatic compaction machine.

3.4 Mechanical Property Testing

Additional samples were prepared for UCS, resilient modulus, and permanent deformation testing. The same cement contents used in the moisture-density testing were used together with the OMC and MDD values in the preparation of specimens for preliminary UCS testing, and samples were prepared for UCS testing in the same manner as described for moisture-density samples. However, following compaction and extrusion, each sample was placed into a sealed plastic bag and then placed into an ice chest for protection from environmental changes that might occur during the 7-day curing period.

Upon completion of the curing period, the UCS was determined for each sample according to ASTM D1633 (Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders) Method A. Prior to testing, each sample was capped with a high-strength mixture of gypsum and water. An example of a capped sample is displayed in Figure 3-2. Capping was performed to ensure that both sample ends were smooth and flat in order to minimize the occurrence of stress concentrations during testing. After the gypsum caps hardened sufficiently, each sample was placed into the UCS machine, shown in Figure 3-3, for testing. The testing machine featured both upper and lower floating heads to accommodate samples with non-parallel caps. All samples were tested at a constant strain rate of 0.05 in./minute. The peak load sustained by each sample was recorded and used to calculate the UCS.

The results of the preliminary phase of UCS testing were plotted to establish the relationship between cement content and UCS for each base/RAP mixture, and these relationships were then used to select low, medium, and high cement contents corresponding to 7-day UCS values of 200, 400, and 600 psi, respectively, for each mixture. Two replicate

Figure 3-2: Capped UCS test specimen.

Figure 3-3: UCS testing machine.

specimens of each combination of base/RAP mixture and cement content were then prepared and tested to evaluate the degree to which the target UCS values were achieved. As needed for this latter testing, the OMC and MDD values were interpolated or extrapolated for each combination of RAP and cement level from the relationships between cement content and the OMC and MDD values determined for the preliminary testing. The height and weight of each specimen were measured immediately following compaction.

For resilient modulus and permanent deformation testing, the same cement content, OMC, and MDD values used in the latter UCS testing were also employed, and samples were prepared in essentially the same manner as moisture-density and UCS samples with a few exceptions in the processes used. For this testing, all specimens were 6 in. in diameter and 12 in. in height. A custom-made steel split mold, pictured in Figure 3-4, was used for compaction of

Figure 3-4: Split mold used for preparing modulus and deformation test specimens.

all samples. Samples were necessarily compacted using a manually operated Proctor hammer because the automatic compactor used to create previous specimens did not accept the larger split mold. Consistent with the previous testing, standard Proctor compaction effort was again used for these samples, which was accomplished in six 2-in. lifts with 74 blows per lift, and the height and weight of each sample were measured. Following compaction, each sample was cured for 1.5 to 3 hours in the mold so that the material could begin to harden. Once a sample had set sufficiently, the mold was carefully removed from around it, and a cylindrical latex membrane was then placed around the sample using a membrane expander as shown in Figure 3-5. Finally, samples were sealed in plastic bags at room temperature to cure.

At the end of the specified curing period, each sample was subjected to resilient modulus and permanent deformation testing. Modulus testing was conducted in general accordance with

Figure 3-5: Membrane expander.

AASHTO T307 (Standard Test Method for Determining the Resilient Modulus of Soils and Aggregate Materials). The test consists of 15 sequences of 100 cycles each, where a cycle involves application of a deviatoric stress through a haversine-shaped load pulse over a 0.1-second time period, followed immediately by a 0.9-second rest period. Confinement stress is also applied throughout the test. Both stresses vary with each test sequence as required to determine the response of the material to different load combinations. The AASHTO T307 procedure is a non-destructive test, which means the stresses are not sufficient to permanently deform the sample under normal circumstances.

To investigate the permanent deformation characteristics of each material, another test procedure was applied immediately after completion of the AASHTO T307 procedure. The procedure is described in Appendix B of the National Cooperative Highway Research Program

(NCHRP) Report 598 and is entitled "Proposed Standard Test Method for Shear Strength of Aggregate by the Repeated Load Triaxial Test." The testing involves the same cycle durations as the AASHTO T307 procedure but requires application of 10 sequences of 1,000 cycles each. The confinement stress is constant at 15 psi throughout the test, while the deviatoric stress begins at 10 psi, increases by 10 psi after the first sequence, and then increases by 20 psi after each subsequent sequence.

Both the AASHTO T307 and NCHRP 598 test procedures require a sophisticated testing apparatus in order to execute the precise loadings and measurements necessary for successful test results. For this research, the computer-controlled, servo-hydraulic UTM-100 equipment available in the Brigham Young University Highway Materials Laboratory was utilized for the testing. Figure 3-6 displays the UTM-100 setup in the laboratory. The machine features two linear variable differential transformers to measure vertical sample displacements and an environmental chamber that provides the ability to control the test temperature from 5 to 140°F. Samples are tested inside an airtight triaxial cell that fits inside the environmental chamber.

For the AASHTO T307 and NCHRP 598 testing, one 0.5-in.-thick porous bronze disk was placed on top of the sample, while a matching bronze disk was placed on the bottom of the sample. An aluminum platen was then placed on the top and bottom of the sample, over and under the bronze disks, respectively. Next, the latex membrane was secured to both platens with rubber o-rings to provide an airtight seal around the sample as depicted in Figure 3-7. Finally, the triaxial cell was assembled and placed into the environmental chamber on the UTM-100 for modulus and deformation testing, as shown in Figure 3-8. The UTM-100 software reported the average resilient modulus for the last five cycles of each sequence of testing. As required in the AASHTO T307 instructions, the average resilient modulus was calculated for each specimen by

Figure 3-6: Modulus and deformation testing machine.

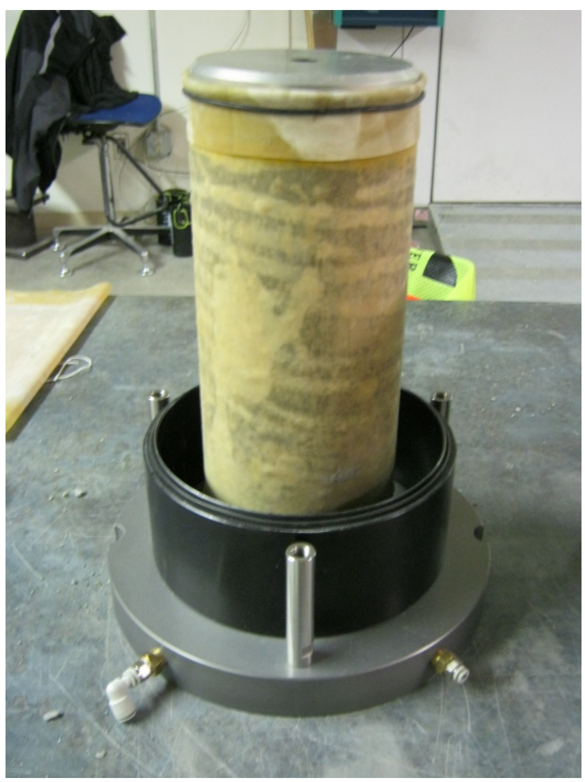

Figure 3-7: Modulus and deformation test specimen with membrane and platens.

Figure 3-8: Triaxial cell placed inside the environmental chamber.

averaging the modulus values for all 15 sequences. The permanent deformation experienced by each specimen was reported as the total deformation that accumulated over the course of the NCHRP 598 test procedure.

As described previously, some of the modulus and deformation testing was performed at 140°F. To ensure that each sample would be tested at the correct temperature, the heating characteristics of a typical sample were evaluated. The evaluation determined that each sample should be placed in an oven at 153°F for approximately 16 hours prior to testing in order for the entire sample to reach the test temperature. This procedure was consistently followed for each sample, and the plastic bags in which the samples were placed for curing were left in place to guard against moisture loss during heating. In addition, the triaxial cell, bronze disks, and aluminum platens were all placed into the heated UTM-100 environmental chamber to be heated to the target temperature prior to each test.

3.5 Statistical Analysis

After all of the testing was complete, the collected data were compiled, and several statistical analyses were performed, including analysis of variance (ANOVA) tests, two-sample *t*-tests, and linear regression analyses. The following sections describe the details of each analysis.

3.5.1 Analysis of Variance

An ANOVA was used to investigate the main effects and interactions of the independent variables, or experimental factors, for each of the dependent variables evaluated in UCS testing and in phases 1 and 2 of the modulus and deformation testing conducted for this research. First, the UCS data were analyzed, with the independent variables being RAP content and cement level and the dependent variable being UCS. Second, the data collected in phase 1 of the modulus and deformation testing were analyzed, with the independent variables being RAP content and cement level and the dependent variables being resilient modulus and permanent deformation. Third, data collected in phase 2 of the modulus and deformation testing were analyzed together with the data associated with the low cement level in phase 1 of the modulus and deformation testing; in this analysis, the independent variables were RAP content and test temperature, and the dependent variables were resilient modulus and permanent deformation.

For these analyses, the null hypothesis was that the dependent variable was not affected by the given independent variable, while the alternative hypothesis was that the dependent variable was affected by the given independent variable. For this study, the specified Type I error rate, or α, was 0.05. The level of significance, or *p*-value, of each main effect and interaction was compared to α in order to determine whether or not to reject the null hypothesis. If the *p*-value was less than or equal to α, then the null hypothesis was rejected, and the effect of the given independent variable was considered statistically significant. If the *p*-value was greater than α, then the conclusion was drawn that there was insufficient evidence to reject the null hypothesis. In the analysis, all main effects involved in statistically significant interactions were retained regardless of whether the main effects themselves were significant or not.

3.5.2 Two-Sample t-Test

Data collected in phase 3 of the modulus and deformation testing were analyzed together with the data associated with 100 percent RAP in phase 2 of the modulus and deformation testing. Specifically, two-sample *t*-tests were utilized to separately determine the significance of the effects of curing time, curing condition, and moisture state, which were the independent variables, on resilient modulus and permanent deformation, which were the dependent variables. Equal variance was assumed in all cases. In each analysis, data for samples tested under "normal" laboratory conditions, as defined by the conditions used in phase 2 of the modulus and deformation testing, were compared with data for samples tested under different laboratory conditions as specified for phase 3 of the modulus and deformation testing. For these analyses, the null hypothesis was that there was no difference in the dependent variable between samples tested in phases 2 and 3, while the alternative hypothesis was that there was a difference in the dependent variable between samples tested in phases 2 and 3. As with the ANOVA analyses, an α value of 0.05 was specified, and the same methodology previously described was employed to determine statistical significance.

3.5.3 *Linear Regression Analysis*

In order to evaluate the relationships between UCS, resilient modulus, and permanent deformation, linear regression analyses were performed. The results of interest in these analyses were the *p*-values obtained from performing a test on the slope of the regression line for each relationship, as well as the R^2 values obtained from examining the correlation between the two variables in each relationship. For each test on the slope of the regression line, the null hypothesis was that the slope was equal to zero, while the alternative hypothesis was that the slope was not equal to zero. Consistent with the other analyses, an α value of 0.05 was specified, and a *p*-value less than or equal to α indicated statistical significance. The calculated R^2 value in each case was the fraction of variation in one variable that could be explained by variation in the other, where a value of 1.0 indicates a perfect correlation (Ramsey and Schafer 2002). For the relationship between resilient modulus and permanent deformation, the data included in the analysis consisted of the values obtained for each sample tested in phase 1 of the modulus and deformation testing. For the relationship between resilient modulus and UCS and the relationship between permanent deformation and UCS, the data included in the analyses consisted of the average values obtained from testing two replicate UCS specimens and the average modulus or deformation values obtained from testing two replicate specimens in phase 1 of the modulus and deformation testing.

3.6 Summary

The specific factors investigated in this research were RAP content, cement level, test temperature, curing time, curing condition, and moisture state. One aggregate base material and one RAP material were used for all samples. RAP content ranged from 0 to 100 percent in intervals of 25 percent, and low, medium, and high cement levels corresponding to 7-day UCS values of 200, 400, and 600 psi, respectively, were selected for testing. Moisture-density, UCS, resilient modulus, and permanent deformation tests were performed for various combinations of factors, with the resilient modulus and permanent deformation testing occurring over three phases. To investigate the effect of temperature on resilient modulus and permanent deformation, 140°F was selected as the elevated test temperature for use in the research, while room temperature, approximately 72°F, was selected as a control temperature for comparison purposes.

The materials used in this research were characterized using washed sieve and hydrometer analyses, as well as Atterberg limits testing. Initial cement contents were selected based on the results of the characterization and then applied to each of the five base/RAP mixtures to establish a moisture-density relationship for each of the 15 combinations.

The same cement contents used in the moisture-density testing were used together with the OMC and MDD values in the preparation of specimens for preliminary UCS testing. The results of the preliminary phase of UCS testing were used to select cement contents corresponding to 7-day UCS values of 200, 400, and 600 psi for each mixture. Two replicate specimens of each combination of base/RAP mixture and cement content were then prepared and tested to evaluate the degree to which the target UCS values were achieved.

For resilient modulus and permanent deformation testing, the same cement content, OMC, and MDD values used in the latter UCS testing were also employed to prepare samples. Modulus testing was conducted in general accordance with AASHTO T307, while the procedure described in NCHRP Report 598 was used to conduct deformation testing.

The UCS, resilient modulus, and permanent deformation test results were evaluated using several statistical analyses. The UCS results, along with the results from phases 1 and 2 of the modulus and deformation testing, were evaluated using an ANOVA, while the comparison of data from phases 2 and 3 of the modulus and deformation testing were evaluated using two-sample *t*-tests. Linear regression was used to analyze the relationships between UCS, resilient modulus, and permanent deformation.

4 RESULTS

4.1 Overview

This chapter reports the results of materials characterization and testing conducted for this research. The results of statistical analyses that were performed to evaluate the collected data, along with relevant discussions of the results, are also included.

4.2 Materials Characterization

Materials characterization included washed sieve and hydrometer analyses, as well as Atterberg limits testing. The material gradations for both the base and RAP materials are presented in Figure 4-1. Because more than 10 percent of the base material was finer than the No. 200 sieve, Atterberg limits testing was performed for that material, which was determined to be non-plastic. Based on the resulting data, the soil classifications for each material were determined according to both the AASHTO and USCS methods. Both the base and RAP were classified as A-1-a materials according to the AASHTO system. According to the USCS method, the base was classified as SP-SM, poorly graded sand with silt and gravel, while the RAP was classified as SW, well-graded sand with gravel.

For an A-1-a AASHTO classification, the *Soil-Cement Laboratory Handbook* (PCA 1992) recommends a cement concentration of 5 percent; lower and higher cement levels were then selected to be 3 and 7 percent, respectively. These initial cement levels were used for

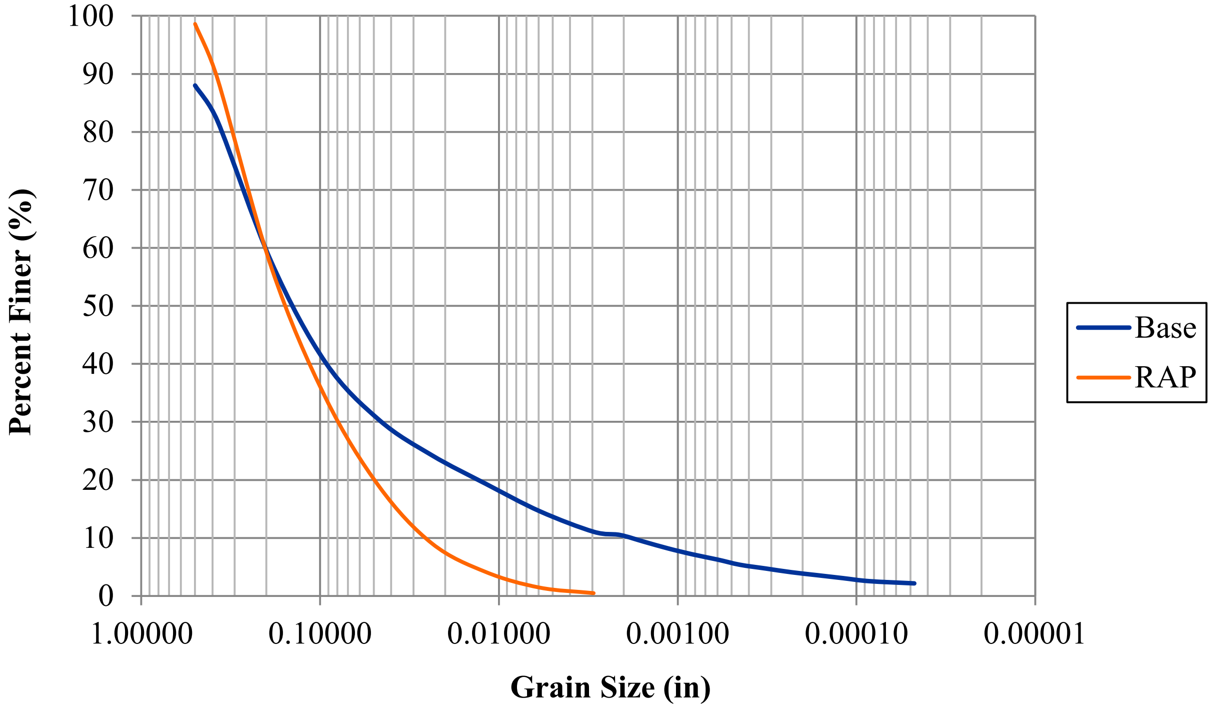

Figure 4-1: Particle-size distributions.

determining moisture-density relationships for the base/RAP material mixtures. Individual moisture-density curves resulting from testing at these initial cement contents are presented in Appendix A, and Tables 4-1 and 4-2 present the individual OMC and MDD values, respectively, selected for each material combination. OMC and MDD values for samples containing 25 percent RAP were not determined directly but were instead interpolated from the results for samples containing 0 and 50 percent RAP, which were very similar.

Table 4-1: OMC Values for Preliminary Testing

RAP Content (%)	Cement Content (%)		
	3	5	7
	OMC (%)		
0	8.3	8.2	8.1
25	8.3	8.3	8.1
50	8.3	8.3	8.1
75	7.1	7.3	7.8
100	6.8	6.6	6.9

Table 4-2: MDD Values for Preliminary Testing

RAP Content (%)	Cement Content (%)		
	3	5	7
	MDD (pcf)		
0	137.8	138.6	138.6
25	133.8	134.6	135.5
50	129.7	130.6	132.4
75	120.6	123.6	125.6
100	114.2	115.9	118.6

4.3 Mechanical Property Testing

Mechanical property testing consisted of tests to determine UCS, resilient modulus, and permanent deformation. As described in Chapter 3, preliminary UCS tests were conducted using the cement levels that were included in moisture-density testing. The resulting UCS values, which are presented in Table 4-3, were utilized to establish the cement contents corresponding to 7-day strengths of 200, 400, and 600 psi for each base/RAP mixture. These cement contents, presented in Table 4-4 and Figure 4-2, were then consistently applied in all remaining testing. The trend of increasing cement content to achieve a target UCS as RAP content increases is typical of CTB with RAP (Yuan et al. 2010). As needed for preparing samples at these selected cement contents, OMC and MDD values were interpolated or extrapolated for each combination of RAP and cement level from the relationships presented in Tables 4-1 and 4-2 between cement content and the OMC and MDD values determined for the preliminary testing. The selected OMC and MDD values are shown in Tables 4-5 and 4-6, and the trends are shown in Figures 4-3 and 4-4. The trends illustrated in both figures generally match those obtained in previous research, with the exception of the lack of change in OMC between samples containing 0 and 50 percent RAP (Guthrie et al. 2007).

Table 4-3: UCS Values from Preliminary Testing

RAP Content (%)	Cement Content (%)		
	3	5	7
	UCS (psi)		
0	517	1062	1775
25	323	564	1058
50	194	427	694
75	69	287	410
100	59	152	234

Table 4-4: Cement Contents Selected for Evaluation

RAP Content (%)	Cement Level		
	Low	Medium	High
	Cement Content (%)		
0	2.00	2.75	3.50
25	2.50	3.75	5.00
50	3.00	4.75	6.50
75	4.00	7.00	9.00
100	7.00	9.50	12.00

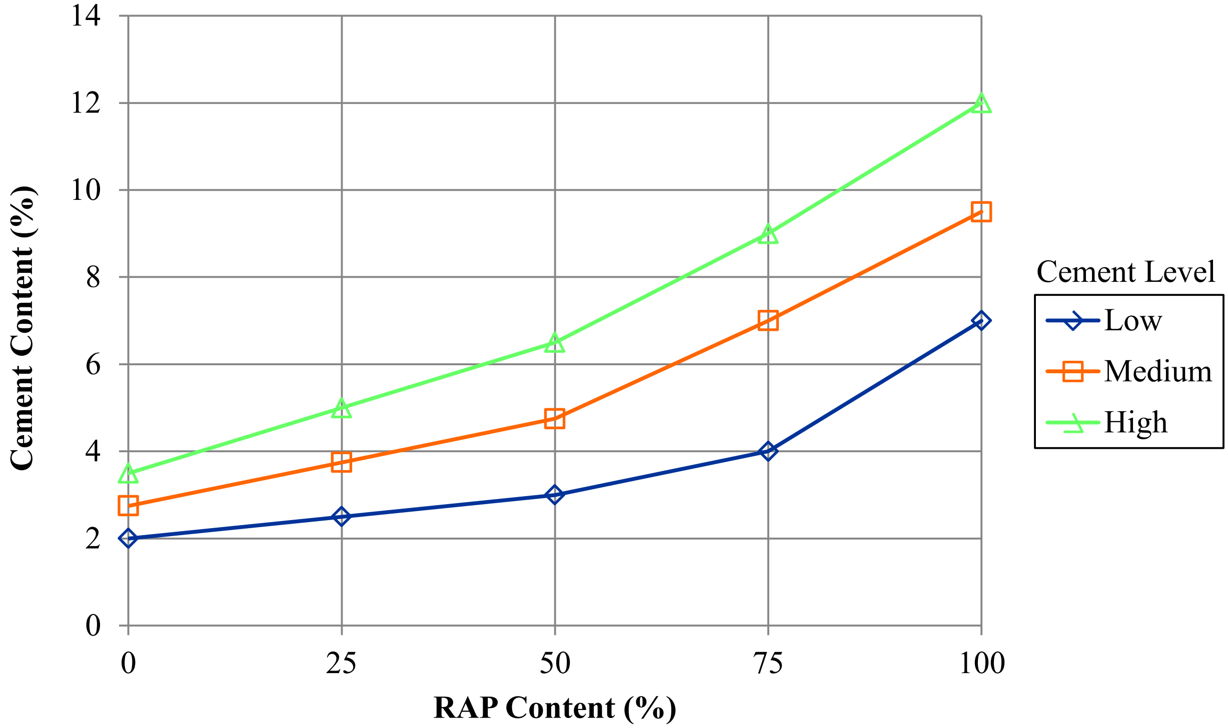

Figure 4-2: Cement contents selected for evaluation.

Table 4-5: OMC Values

RAP Content (%)	Cement Level		
	Low	Medium	High
	OMC (%)		
0	8.3	8.3	8.3
25	8.3	8.3	8.3
50	8.3	8.3	8.1
75	7.2	7.8	8.0
100	6.9	7.0	7.2

Table 4-6: MDD Values

RAP Content (%)	Cement Level		
	Low	Medium	High
	MDD (pcf)		
0	137.8	137.8	138.0
25	133.8	134.2	135.2
50	129.7	130.6	132.4
75	122.1	125.6	127.6
100	118.6	121.1	123.7

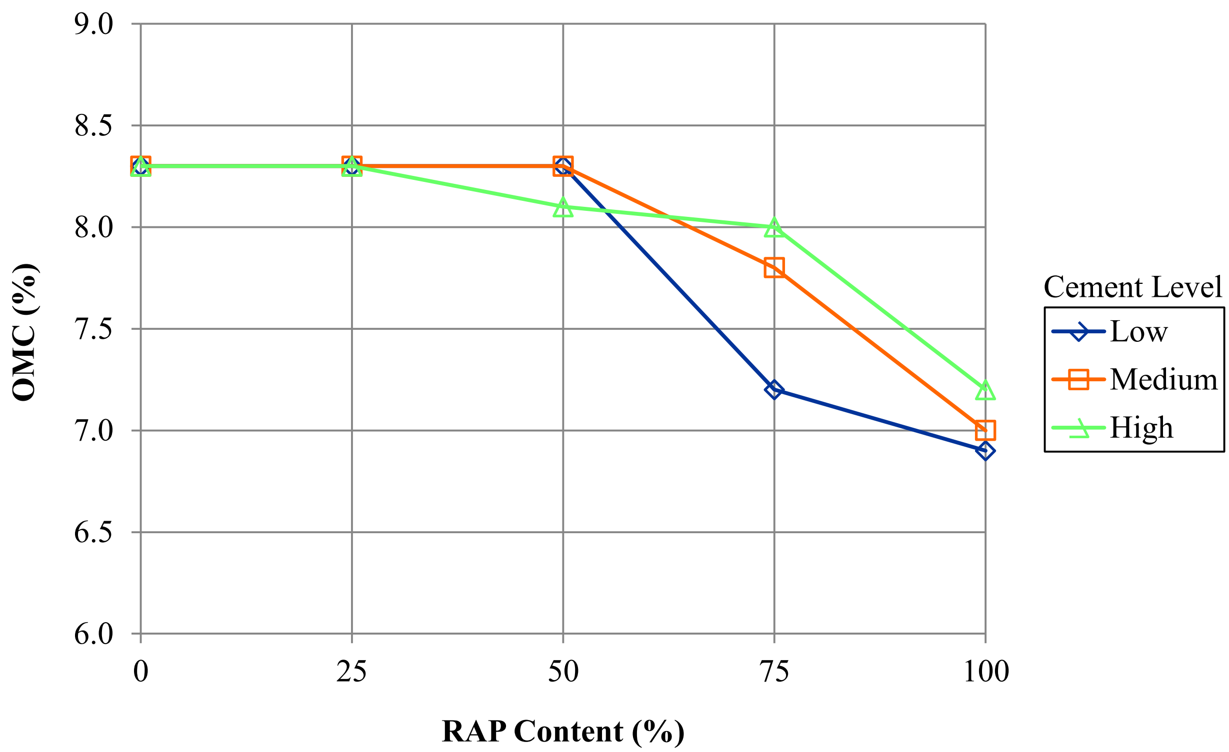

Figure 4-3: OMC values.

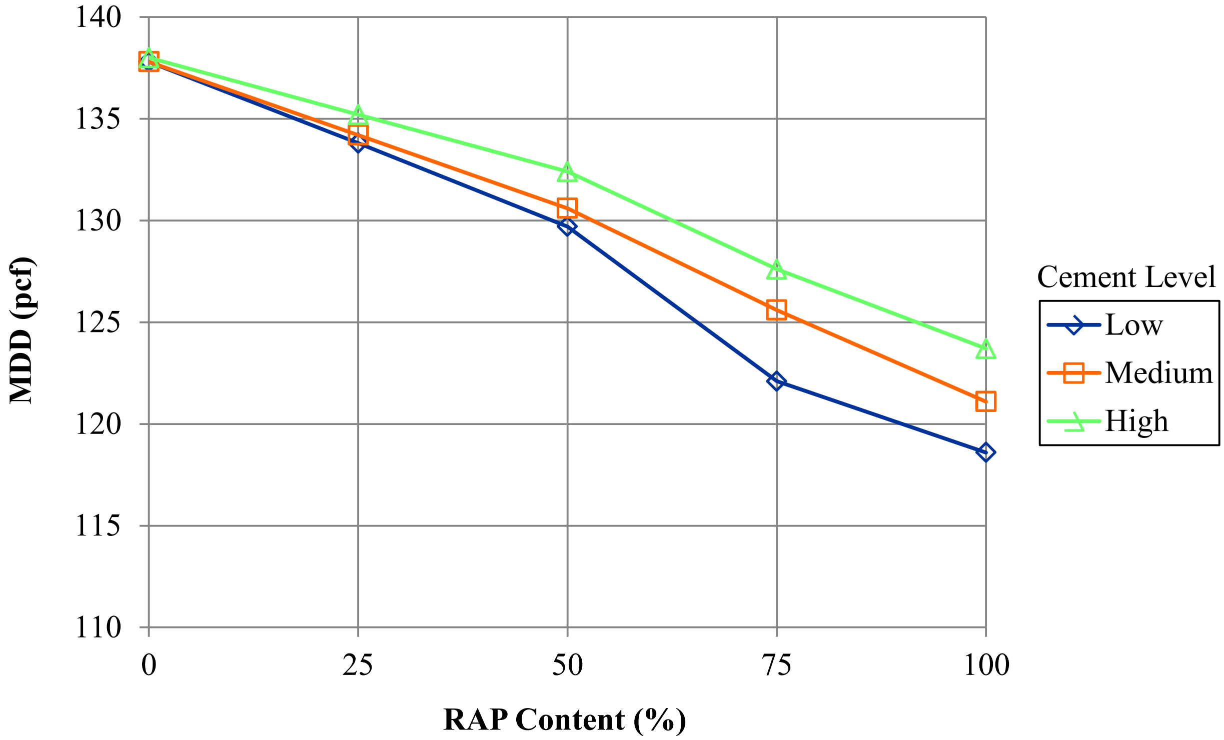

Figure 4-4: MDD values.

The average UCS values obtained from testing at the cement contents presented in Table 4-4 are displayed in Table 4-7, in which each value in the table is the average of two samples; test results for individual samples are presented in Appendix B. This testing was conducted to evaluate the degree to which the selected cement contents actually corresponded to the target UCS values. Although the data show that most of the material combinations contain the appropriate cement content, treatment of 100 percent RAP at the high cement level yielded a comparatively low UCS value; however, a higher value was not used because the cement concentration of 12 percent that was specified in this case is considered to be the likely upper threshold for constructability in the field. Other minor variations in UCS from the target values may be attributable to the effects of extrapolation and/or rounding applied in analyzing the preliminary UCS results.

Table 4-7: Average UCS Values

RAP Content (%)	Cement Level		
	Low	Medium	High
	UCS (psi)		
0	261	416	587
25	252	408	629
50	175	401	640
75	198	417	677
100	237	403	535

The results of resilient modulus and permanent deformation testing are presented separately for each of the three phases shown in Table 3-1. The results of phase 1, which involved testing of all RAP and cement levels at 140°F, are presented in Table 4-8. The results of phase 2, which involved testing of all RAP levels but only the low cement level at 72°F, are presented in Table 4-9. Finally, the results of phase 3, which involved testing of only 100 percent RAP at the low cement level at room temperature, are displayed Table 4-10. The "Normal" label in Table 4-10 indicates samples that were cured in a sealed plastic bag for 7 days and tested at OMC, while each of the other labels indicate different conditions to which the samples were subjected prior to testing. Each value in Tables 4-8 to 4-10 is the average of two samples. In all cases, any permanent deformation that occurred during the AASHTO T307 testing is not represented in the results of the permanent deformation testing performed using the NCHRP 598 procedure. Test results for individual samples for all three phases of testing are presented in Appendix B.

Table 4-8: Average Resilient Modulus and Permanent Deformation Values for Phase 1

RAP Content (%)	Cement Level					
	Low	Medium	High	Low	Medium	High
	Resilient Modulus (ksi)			Permanent Deformation (in.)		
0	74	87.2	84.7	0.11	0.031	0.022
25	87.2	69.8	93.2	0.172	0.041	0.022
50	89.1	98.4	99.1	0.261	0.032	0.019
75	87.2	103.3	87.1	0.239	0.025	0.024
100	97.3	90.5	101.4	0.446	0.035	0.027

Table 4-9: Average Resilient Modulus and Permanent Deformation Values for Phase 2

RAP Content (%)	Resilient Modulus (ksi)	Permanent Deformation (in.)
0	74.2	0.145
25	90.7	0.052
50	85.4	0.068
75	94.1	0.039
100	58.8	0.021

Table 4-10: Average Resilient Modulus and Permanent Deformation Values for Phase 3

Factor	Resilient Modulus (ksi)	Permanent Deformation (in.)
Unsealed	87.1	0.447
Soaked	90.7	0.030
28-Day	86.3	0.033

4.4 Statistical Analysis

The results of the ANOVA tests, two-sample *t*-tests, and linear regression analyses performed on the mechanical property test data are presented and discussed in the following sections.

4.4.1 Analysis of Variance

The results of the ANOVA tests used to analyze the data collected from the UCS tests and the first two phases of modulus and deformation testing are presented in Table 4-11. In this table, main effects or interactions that were either not included in a particular experiment or were not statistically significant are explicitly indicated. Plots of all the statistically significant main effects and interactions are presented in Figures 4-5 to 4-15 for UCS, resilient modulus, and permanent deformation.

Table 4-11: ANOVA Results

Test Data Used in Analysis	Factor				
	RAP Content	Cement Level	Temperature	RAP Content * Cement Level	RAP Content *Temperature
	p-value				
UCS (All Samples at 72°F)	0.2304	<0.0001	Not Applicable	0.0218	Not Applicable
Modulus (All Samples at 140°F)	0.0680	Not Significant	Not Applicable	Not Significant	Not Applicable
Deformation (All Samples at 140°F)	0.0028	<0.0001	Not Applicable	0.0012	Not Applicable
Modulus (All Samples at Low Cement Level)	0.0128	Not Applicable	0.0458	Not Applicable	0.0025
Deformation (All Samples at Low Cement Level)	0.0502	Not Applicable	<0.0001	Not Applicable	0.0013

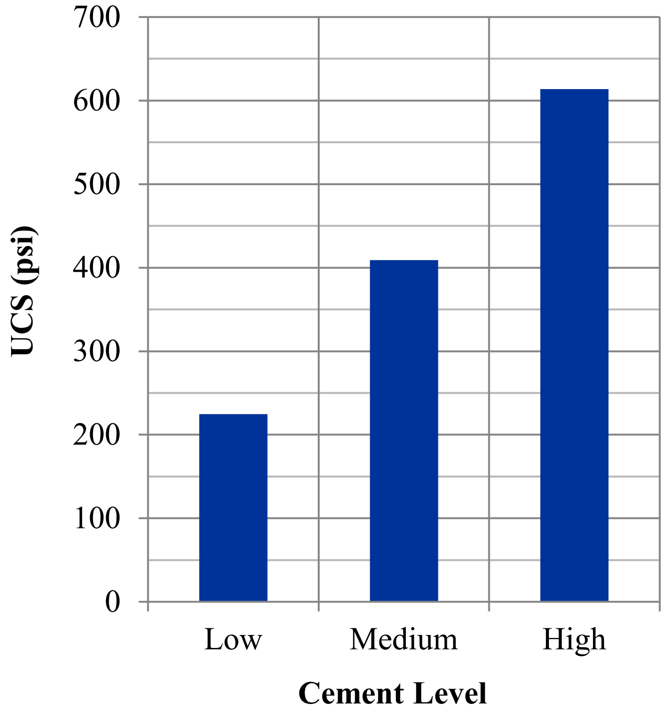

Figure 4-5: Main effect of cement level on UCS.

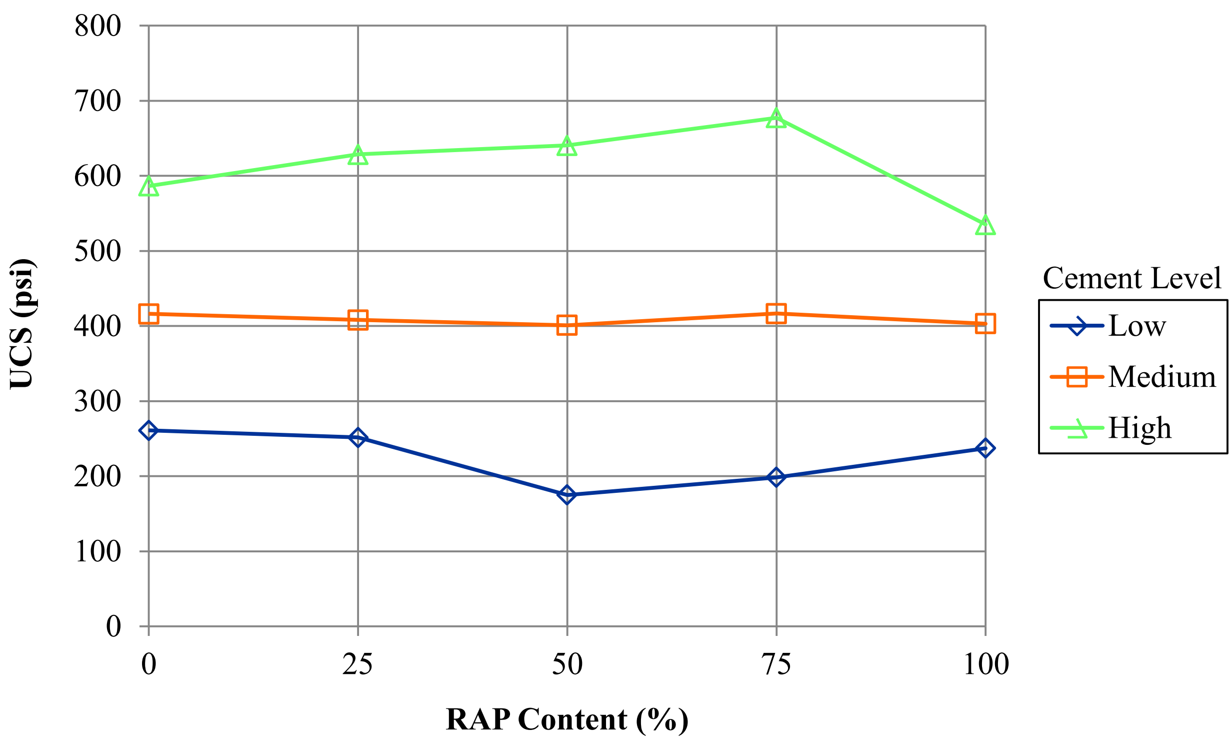

Figure 4-6: Interaction between RAP content and cement level for UCS.

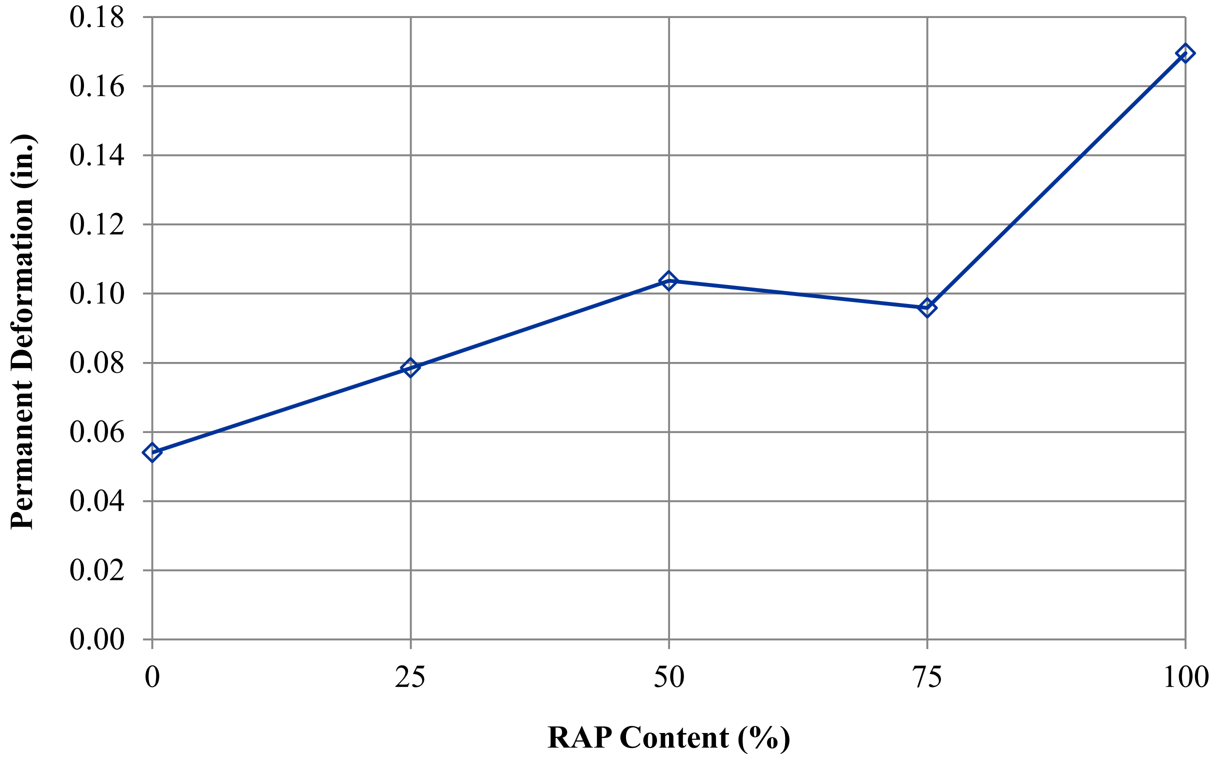

Figure 4-7: Main effect of RAP content on permanent deformation at 140°F.

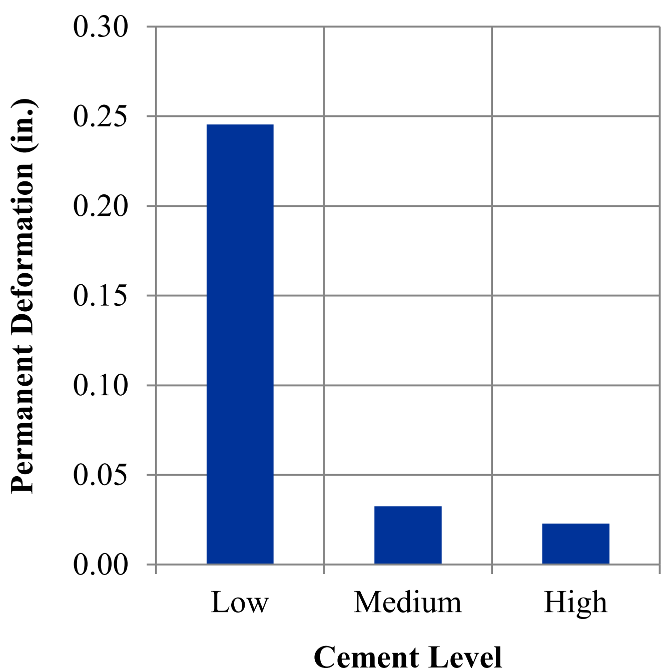

Figure 4-8: Main effect of cement content on permanent deformation at 140°F.

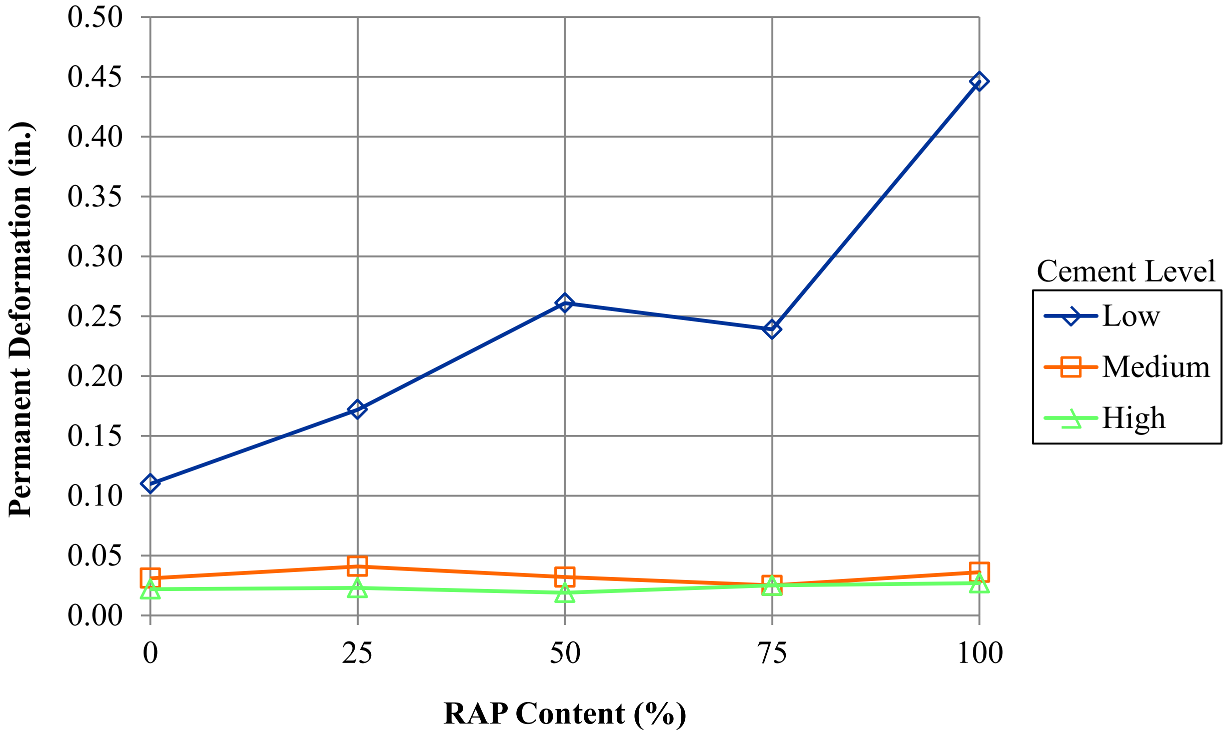

Figure 4-9: Interaction between RAP content and cement level for permanent deformation at 140°F.

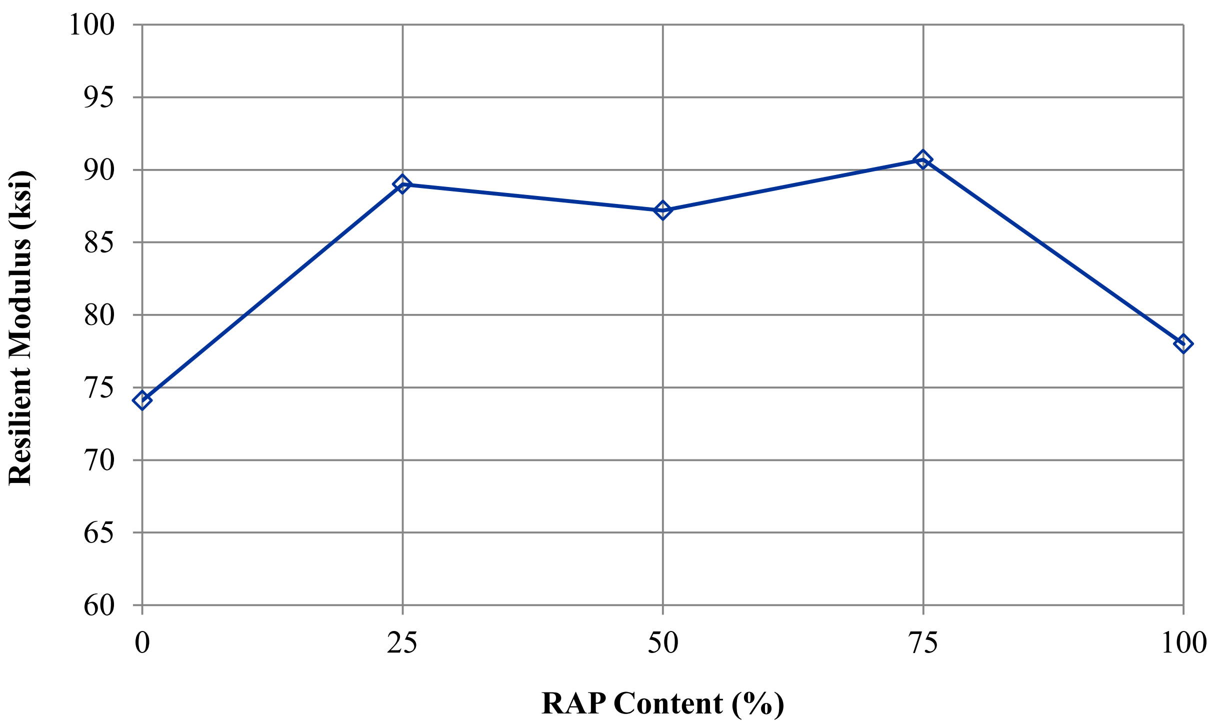

Figure 4-10: Main effect of RAP content on resilient modulus at low cement level.

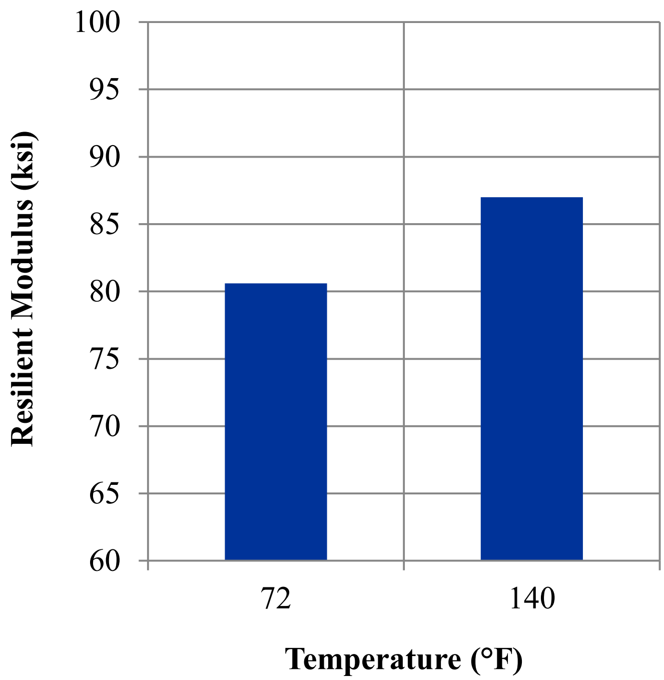

Figure 4-11: Main effect of temperature on resilient modulus at low cement level.

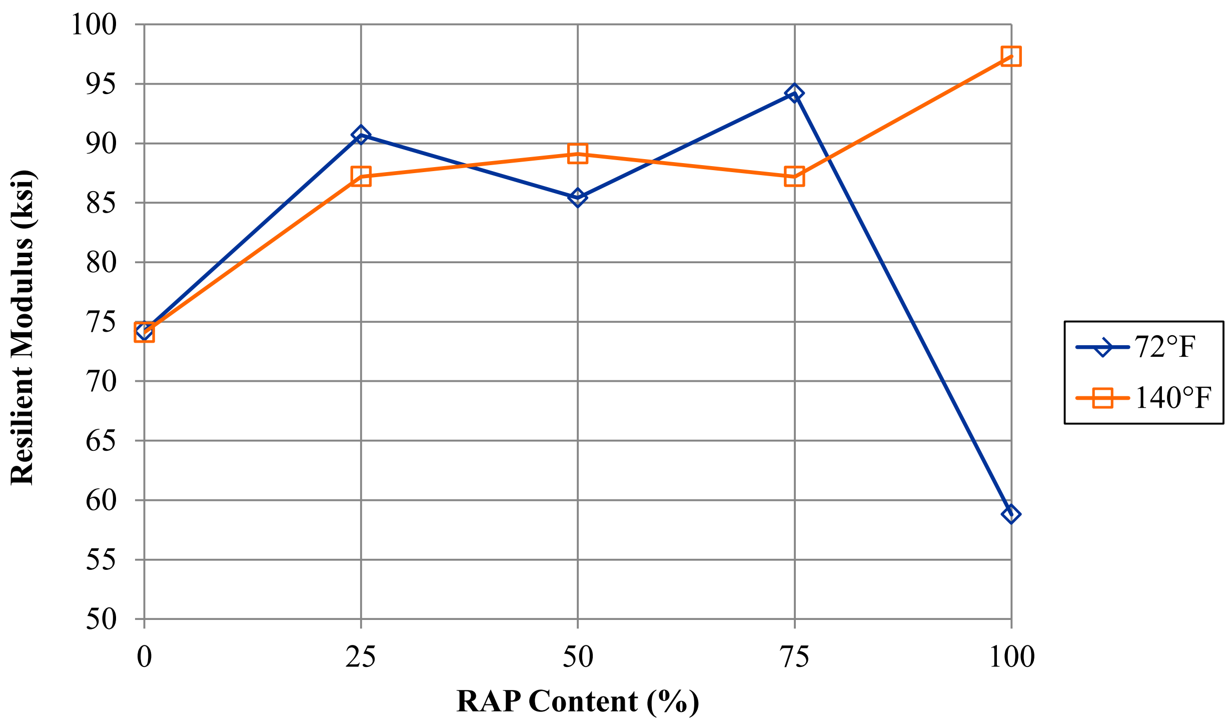

Figure 4-12: Interaction between RAP content and temperature for resilient modulus at low cement level.

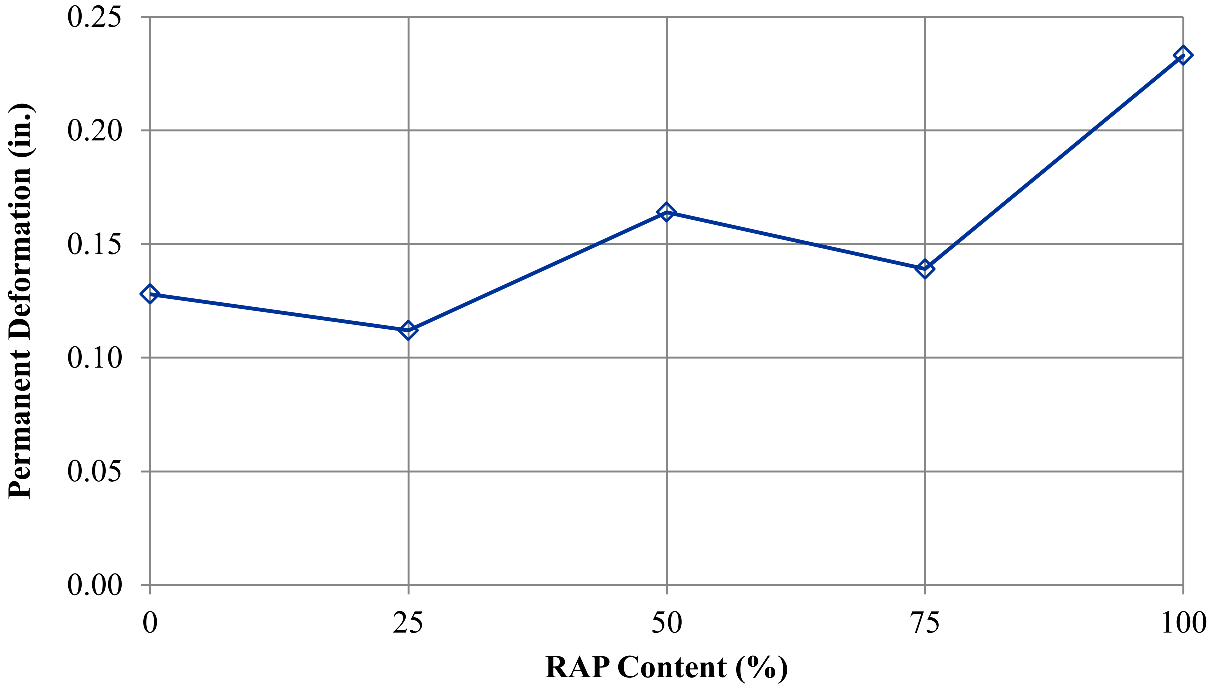

Figure 4-13: Main effect of RAP content on permanent deformation at low cement level.

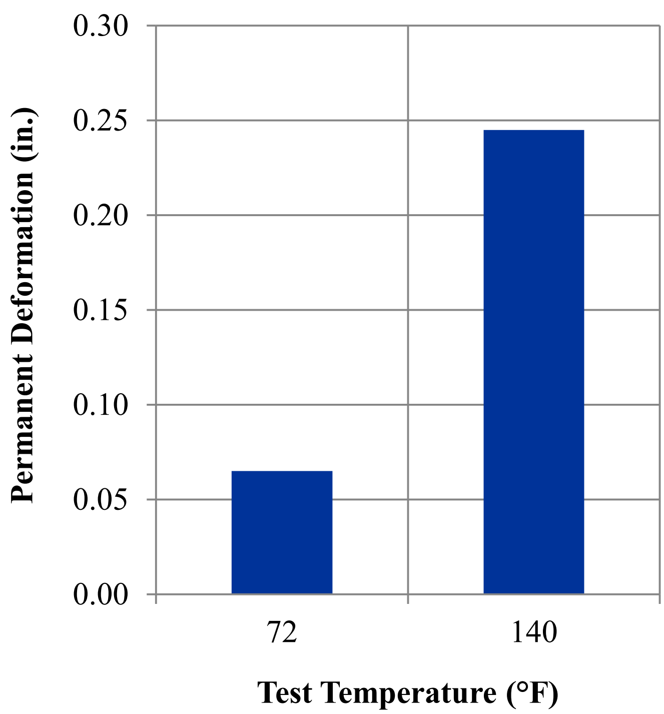

Figure 4-14: Main effect of temperature on permanent deformation at low cement level.

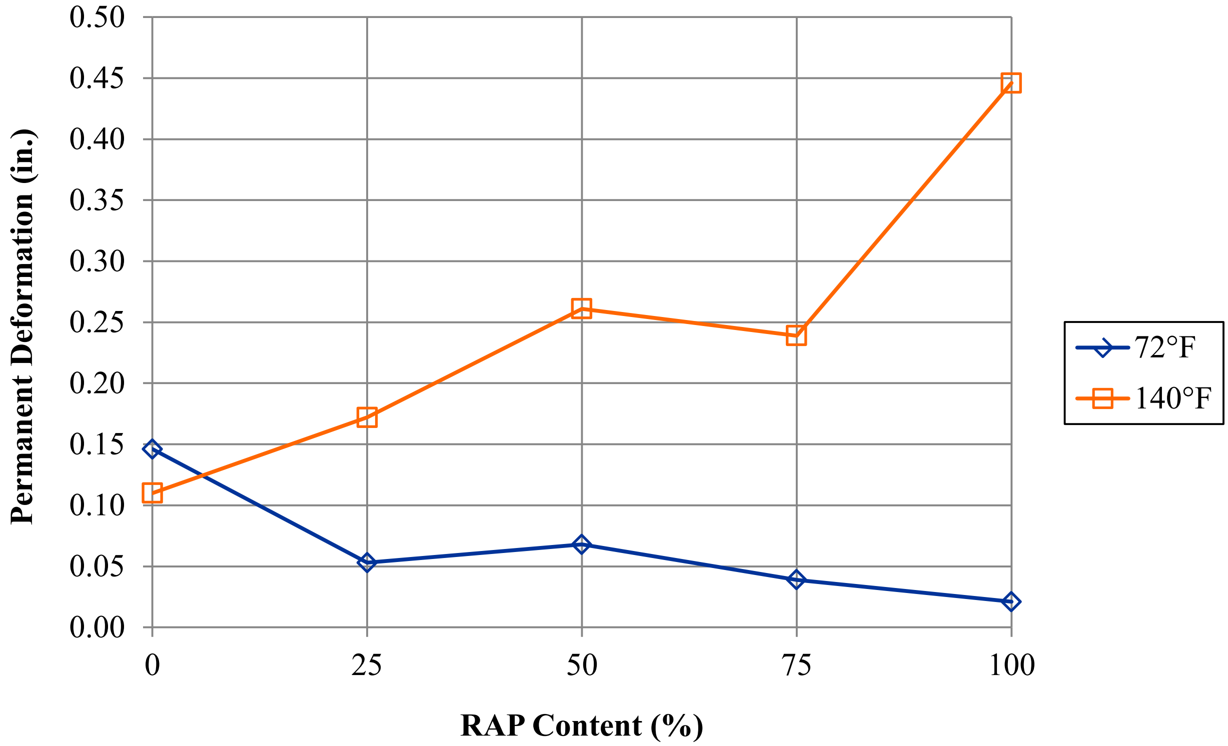

Figure 4-15: Interaction between RAP content and temperature for permanent deformation at low cement level.

Figure 4-5 shows that UCS increases uniformly as the cement level increases from low to high. Since the experiment was designed to produce samples that achieved 7-day UCS values of 200, 400, and 600 psi at low, medium, and high cement levels, respectively, these results were anticipated. Figure 4-6 shows that the effect of RAP content or cement level on UCS depends on the level of the other factor. However, insufficient evidence exists from the analysis to conclude that UCS was affected by RAP content because the effect of RAP content was compensated for at a given cement level by changing the cement concentration to reach the target UCS values.

The results of the analysis also indicate that insufficient evidence exists to conclude that the resilient modulus values of samples tested at 140°F were affected by RAP content, cement level, or the interaction of those two variables. Therefore, these data do not directly support previously conducted research in which an inverse relationship between RAP content and modulus was reported (Yuan et al. 2010).

As expected, Figure 4-7 shows that permanent deformation increases as RAP content increases for samples tested at 140°F; specifically, deformation increases by 214 percent from 0.054 to 0.170 in., on average, as RAP content increases from 0 to 100 percent. Figure 4-8 shows that deformation decreases with increasing cement level; the results indicate that deformation decreases by 91 percent from 0.245 to 0.023 in., on average, from the low to high cement levels, with the largest reduction occurring between the low and medium cement levels. Figure 4-9 shows that the effect of either RAP content or cement level on permanent deformation depends on the level of the other factor. For example, on average, as RAP content increases from 0 to 100 percent, deformation increases by 305 percent from 0.110 to 0.446 in. for the low cement level but only by 16 percent from 0.031 to 0.036 in. for the medium cement level and 23 percent from 0.022 to 0.027 in. for the high cement level. In all cases, deformation is reduced to negligible quantities at the medium cement level regardless of the deformation experienced at the low cement level for the materials tested in this research. Essentially, even 100 percent RAP can be made to exhibit the same mechanical properties as material containing no RAP at a 7-day UCS value of 400 psi. Interestingly, little to no benefit with respect to permanent deformation is derived from increasing the cement level from medium to high.

At the low cement level, although the effect of RAP content on resilient modulus is statistically significant, Figure 4-10 shows that the effect does not follow any logical trend or pattern. Regarding the effect of temperature, Figure 4-11 shows that increasing the test temperature from 72°F to 140°F leads to an 8 percent increase in resilient modulus from 80.6 to 87.0 ksi, on average, which is contrary to initial expectations. Figure 4-12 shows that the effects of RAP content and test temperature on resilient modulus are dependent on the level of the other factor. For example, on average, as RAP content increases from 0 to 100 percent, modulus decreases 21 percent from 74.2 to 58.8 ksi for samples tested at 72°F but increases 31 percent from 74.1 to 97.3 ksi for samples tested at 140°F. These results are peculiar since decreasing asphalt viscosity at 140°F should theoretically result in decreased stiffness values when compared to samples tested at 72°F. The trends in Figure 4-12 indicate that the source of statistical significance for this interaction is likely the different behavior of the samples comprised of 100 percent RAP when tested at 72 or 140°F; additional research is needed to examine this issue.

Also at the low cement level, the effect of RAP content on permanent deformation is generally consistent with expectations, as shown in Figure 4-13. Increasing the RAP content from 0 to 100 percent leads to an 82 percent increase in deformation from 0.128 to 0.233 in., on average. Figure 4-14 shows the effect of test temperature on deformation; as the temperature increases from 72°F to 140°F, deformation increases by 277 percent from 0.065 to 0.245 in. for the low cement level. Because the stiffness of asphalt decreases as temperature increases, this result was expected and demonstrates that the low cement level was not sufficient to properly restrict material deformation. Figure 4-15 shows that the effects of RAP content and test temperature on permanent deformation depend on the level of the other factor. For example, on average, as RAP content increases from 0 to 100 percent, deformation decreases by 86 percent from 0.146 to 0.021 in. at 72°F but increases by 305 percent from 0.110 to 0.446 in. at 140°F. Thus, as the temperature increases from 72 to 140°F, these data indicate that both the modulus and deformation increase with increasing RAP content for the low cement level. While interactions between the applied stress, inter-particle friction between the aggregates, and viscosity of the asphalt coating on the RAP particles are probably the basis for these results, investigating the specific mechanisms at play was beyond the scope of the present research.

Nonetheless, to consider these results in a broader perspective, a mechanistic pavement analysis was performed on a hypothetical pavement section using KENPAVE software (Huang 2004). Table 4-12 presents the layer characteristics that were used as input values in the analysis; the modulus of the CTB layer, which was assumed to be 100 percent RAP, is the same as that measured in this research at 72°F for the low cement level. The results show that a 6-in.-thick CTB layer beneath a comparatively thin 4-in.-thick HMA surface course will experience vertical stresses of only 30 to 40 psi under an equivalent single axle load. Given that the permanent deformation test used in this research subjected samples to stresses up to 180 psi, the conclusion can be drawn that CTB containing high RAP contents will likely perform better in actual service than in laboratory testing. (The details of this stress analysis are provided in Appendix C).

Table 4-12: Layer Input Values for KENPAVE Analysis

Layer Type	Thickness (in.)	Modulus (ksi)	Poisson's Ratio
HMA	4	400.0	0.35
CTB (100% RAP)	6	58.8	0.15
Subgrade	-	5.0	0.45

4.4.2 Two-Sample t-Test

The results of the two-sample *t*-tests used to compare the data collected in phase 3 of the modulus and deformation testing with "normal" data collected in phase 2 of the modulus and deformation testing are presented in Table 4-13. The effects of curing time, curing condition, and moisture state on resilient modulus and permanent deformation of 100 percent RAP were evaluated. Among all of these analyses, however, only the effect of moisture state on resilient modulus was found to be statistically significant. Soaking the material increased the moisture content by approximately 1 percent, and, as illustrated in Figure 4-16, increased the modulus by 54 percent from 58.8 to 90.7 ksi, on average, compared to the modulus of the material tested at OMC. This increase may be attributable to accelerated cement hydration that occurred once the soaked samples were under water; a similar result would not be expected if the material were soaked once most of the cement hydration was completed, such as following a 28-day curing time. In this research, insufficient data existed to conclude that the moisture state had a significant effect on permanent deformation or that a longer curing time or an improper curing condition had a significant effect on either resilient modulus or permanent deformation. Additional research is needed to more fully investigate these effects.

Table 4-13: Two-Sample *t*-Test Results

Dependent Variable	Factor		
	Curing Time	Curing Condition	Moisture State
	p-value		
Resilient Modulus	0.0916	0.1029	0.0384
Permanent Deformation	0.5209	0.1351	0.4540

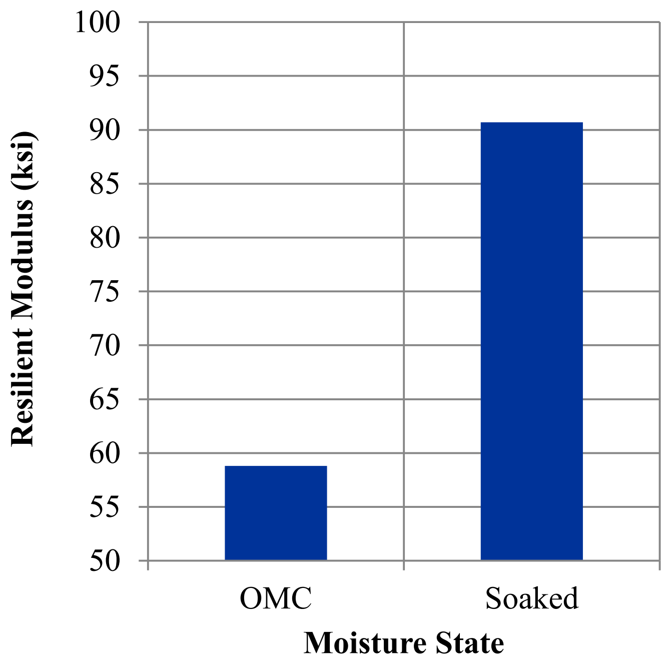

Figure 4-16: Effect of moisture state on resilient modulus.

4.4.3 Linear Regression Analysis

Prior to conducting linear regression analyses on the UCS, resilient modulus, and permanent deformation data, the relationships among these variables were examined visually to evaluate the potential benefits of applying transformations. Figures 4-17 to 4-19 specifically show the relationships between deformation and modulus, modulus and UCS, and deformation and UCS, respectively. In Figure 4-17, part of the data exhibit a relatively linear increase in deformation as modulus increases; these data points are associated with samples tested at the low cement level, while the remaining data points are associated with samples tested at the medium and high cement levels. Because of the divergent trends, the overall relationship would not likely improve with the application of a transformation; the same observation applies to the data presented in Figure 4-18, which appear as a "cloud" of points. However, a logarithmic-type trend was observed for the relationship presented in Figure 4-19; consequently, logarithmic transformations were applied to improve the linearity of the data prior to regression analysis. Since the deformation values used in the analysis were less than 1, a constant value of 1 was added to each value to avoid negative numbers in the transformed data.

The results of the regression analyses are given in Table 4-14. As expected, the relationships presented in Figures 4-17 and 4-18 are characterized by high *p*-values and very low R^2 values. However, the relationship presented in Figure 4-20 has a low *p*-value and a comparatively high R^2 value; these results indicate that this relationship between deformation and UCS is statistically significant. Equation 4-1 presents the mathematical expression for the inverse relationship between deformation and UCS illustrated by the trend line shown in Figure 4-20:

$$\log(\mathit{deformation}+1) = -0.1958 * \log(\mathit{UCS}) + 0.5445 \quad (4\text{-}1)$$

where *deformation* = deformation measured in NCHRP 598 procedure at 140°F, in.

UCS = 7-day UCS measured at 72°F, psi

Although this relationship applies specifically to the materials tested in this research, a similar relationship may exist for other materials as well.

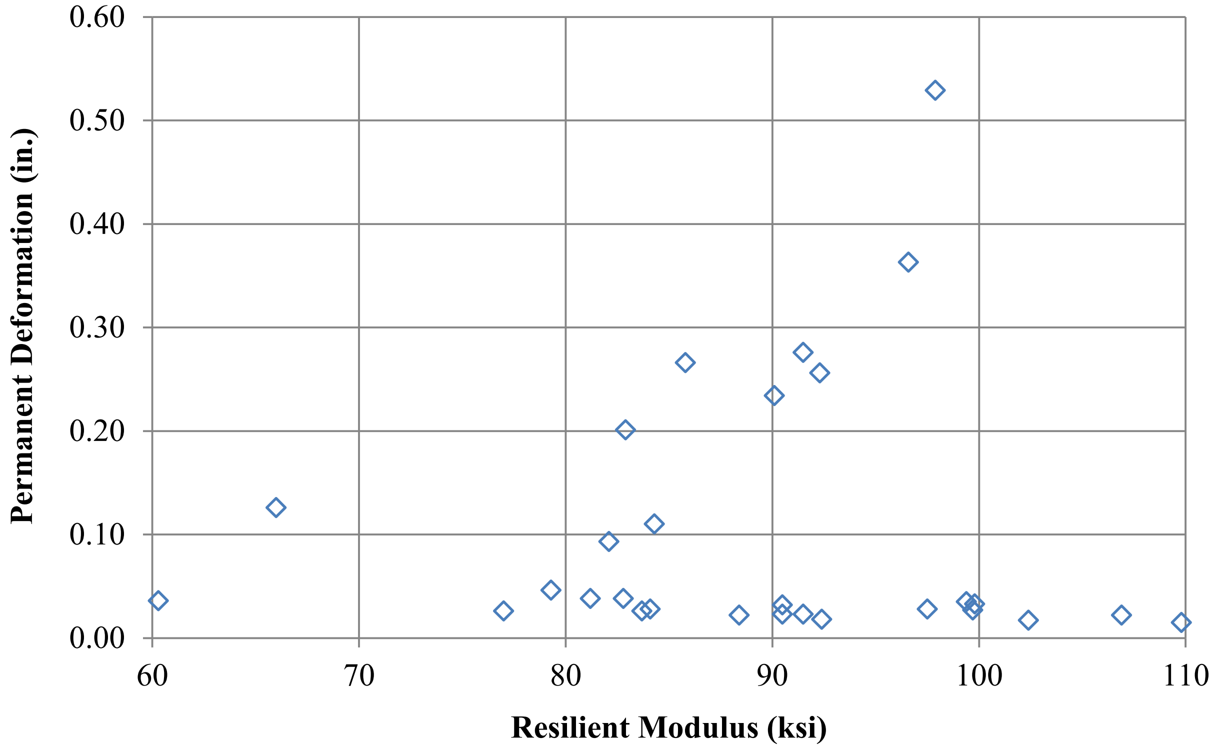

Figure 4-17: Relationship between deformation and modulus.

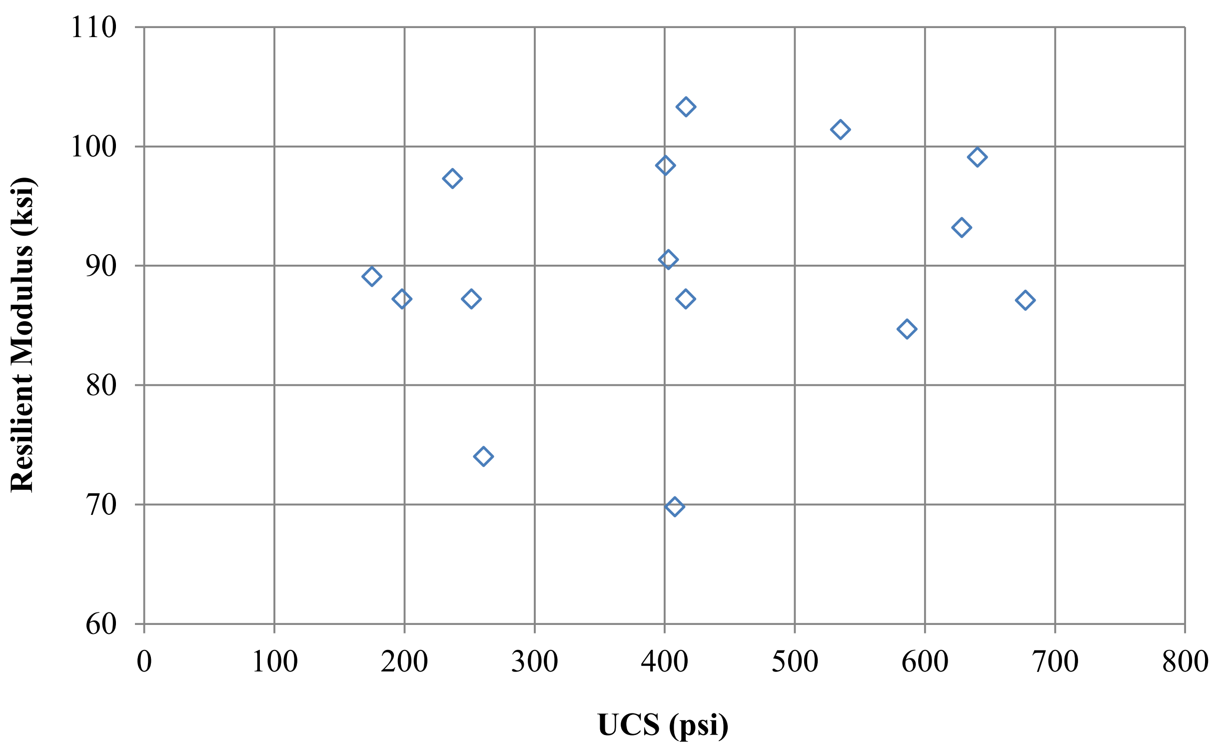

Figure 4-18: Relationship between modulus and UCS.

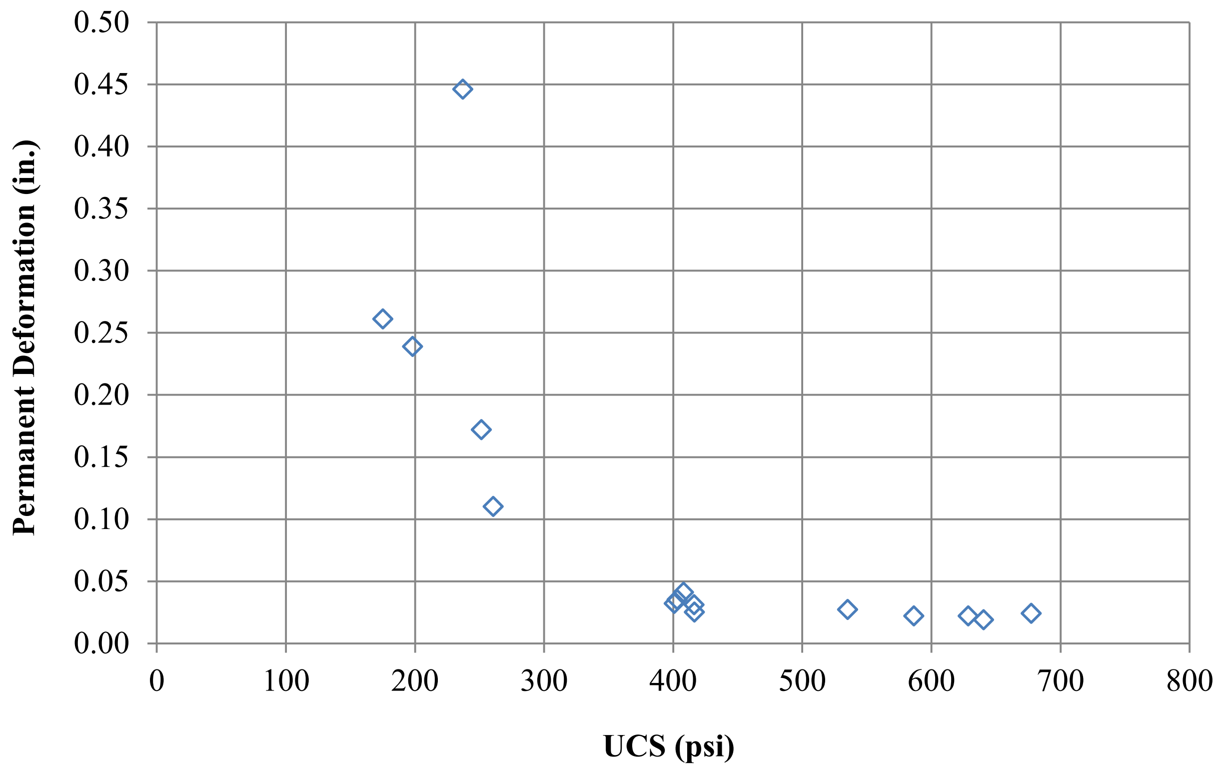

Figure 4-19: Relationship between deformation and UCS.

Table 4-14: Linear Regression Results

Relationship	*p*-Value	R^2
Deformation and Modulus	0.9512	0.0001
Modulus and UCS	0.4283	0.0489
Deformation and UCS	0.0002	0.6937

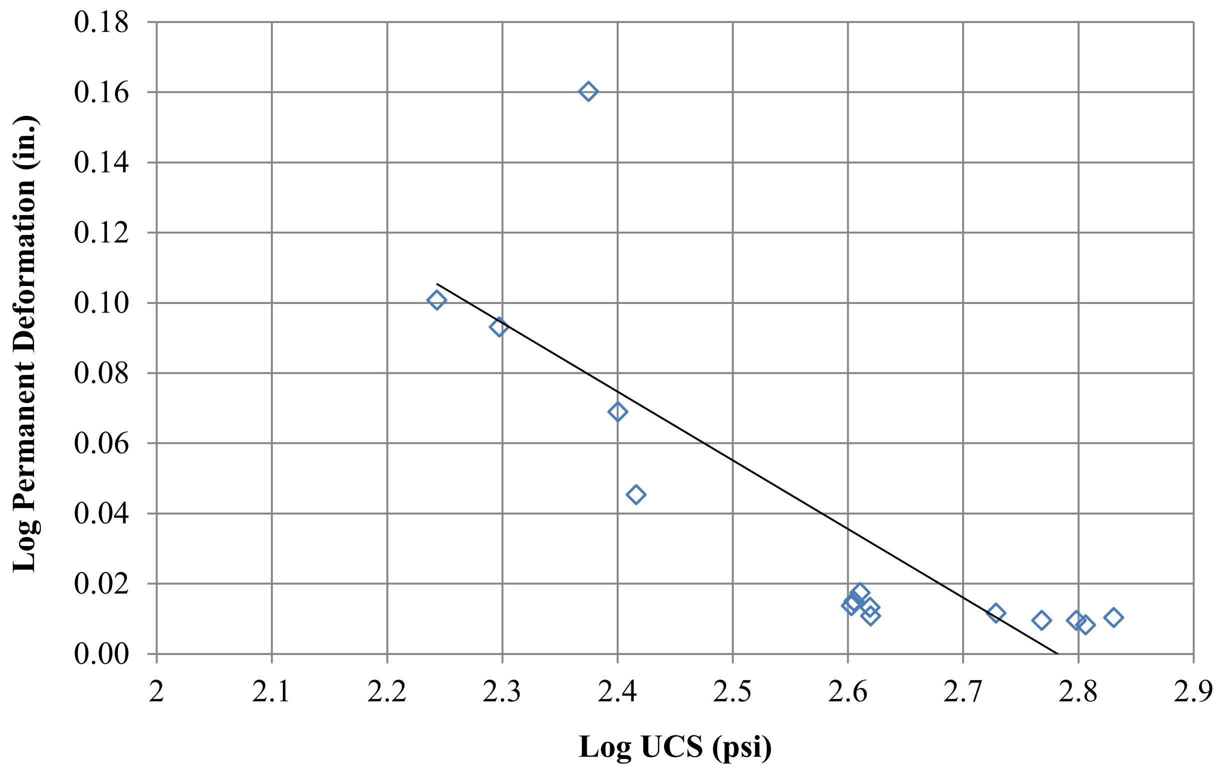

Figure 4-20: Relationship between deformation and UCS with logarithmic transformations.

4.5 Summary

The base and RAP materials used in this study were both classified as A-1-a materials according to the AASHTO system. Using the USCS method, the base material was classified as SP-SM, poorly graded sand with silt and gravel, and the RAP was determined to be SW, well-graded sand with gravel. Using the AASHTO classifications, the initial cement contents selected for moisture-density and preliminary UCS testing were 3, 5, and 7 percent. Following analysis of the preliminary UCS results, cement contents corresponding to 7-day UCS values of 200, 400, and 600 psi were selected for each base/RAP mixture.

The results of ANOVA testing indicate that insufficient evidence exists to conclude that the resilient modulus values of samples tested at 140°F were affected by RAP content, cement level, or the interaction of those two variables. However, the results do show that permanent deformation is affected by RAP content and cement level for samples tested at 140°F and that deformation is reduced to negligible quantities at the medium cement level regardless of the deformation experienced at the low cement level for the materials tested in this research. At low cement levels, the ANOVA results indicate that modulus decreases as RAP increases from 0 to 100 percent for samples tested at 72°F and increases for samples tested at 140°F over the same range of RAP contents. Also at low cement levels, permanent deformation increases when the test temperature is raised from 72°F to 140°F.

The results of the two-sample *t*-tests indicate that only the effect of moisture state on resilient modulus was statistically significant. In this research, insufficient data existed to conclude that the moisture state had a significant effect on permanent deformation or that a longer curing time or an improper curing condition had a significant effect on either resilient modulus or permanent deformation.

Prior to conducting linear regression analyses on the UCS, resilient modulus, and permanent deformation data, the relationships among these variables were examined visually to evaluate the potential benefits of applying transformations; subsequently, logarithmic transformations were applied to both the independent and dependent variables for the relationship between deformation and UCS. Linear regression analyses of the three relationships showed that only the relationship between permanent deformation and UCS is statistically significant, and an equation for the inverse relationship between these two variables was developed.

5 CONCLUSION

5.1 Summary

FDR is an increasingly common technique that is used to rehabilitate flexible pavements. Implementation of FDR on rehabilitation projects produces several desirable benefits. However, these benefits are not fully realized due to the fact that state DOT specifications typically limit the RAP content of pavement base material to 50 percent; this limitation is caused by a general concern about the performance of base material containing high percentages of RAP. Consequently, the objective of this research was to evaluate the effects of RAP content, cement content, temperature, curing time and condition, and moisture state on the strength, stiffness, and deformation characteristics of CTB mixtures containing high percentages of RAP.

One aggregate base material and one RAP material were used for all samples in this research. RAP content ranged from 0 to 100 percent in increments of 25 percent, and low, medium, and high cement levels corresponding to 7-day UCS values of 200, 400, and 600 psi, respectively, were selected for testing. Moisture-density, UCS, resilient modulus, and permanent deformation tests were performed for various combinations of factors, with the resilient modulus and permanent deformation testing occurring over three phases. Several statistical analyses were utilized to evaluate the results of the UCS, resilient modulus, and permanent deformation testing.

5.2 Conclusions

Based on the results of this work, several conclusions can be drawn regarding the mechanical properties of CTB with high RAP contents. With regards to strength, CTB containing RAP can be made to achieve 7-day UCS values approaching 600 psi regardless of RAP content; for materials similar to those tested in this research, achieving such strengths requires adding up to 12 percent portland cement by dry weight of material, which is considered to be the likely upper threshold for constructability in the field.

Regarding resilient modulus, the results of the analysis indicate that insufficient evidence exists to conclude that the resilient modulus values of samples tested at 140°F are affected by RAP content or cement level. However, the data collected in this study indicate that the resilient modulus of CTB containing RAP is affected by temperature in the range from 72 to 140°F for the low cement level; contrary to initial expectations, material stiffness can be expected to increase as pavement temperatures rise.

The results of this study indicate that permanent deformation of CTB containing RAP is significantly affected by RAP content and cement level at the test temperature of 140°F. At the low cement level, temperature is also a significant variable, with increasing deformation occurring with increasing temperature; because the stiffness of asphalt decreases as temperature increases, this result was expected and demonstrates that the low cement level is not sufficient to properly restrict material deformation. Regarding the medium and high cement levels, as the 7-day UCS of the material reaches approximately 400 psi, permanent deformation is reduced to negligible quantities; interestingly, little to no benefit with respect to permanent deformation is derived from increasing the cement level from medium to high. Indeed, the results of this research indicate that the inverse relationship observed between permanent deformation and 7-day UCS is statistically significant.

One key aspect of the results of this research is that all of the significant results were achieved by testing samples after 7 days of curing. Consequently, the strength, stiffness, and deformation characteristics of the material used in this work can be expected to improve to the degree that cement hydration is able to continue beyond 7 days. However, even with only 7 days of curing, the results of this work show that, when a sufficient amount of cement is applied, CTB containing high percentages of RAP can be expected to demonstrate satisfactory mechanical properties under loading. In fact, given that the stress levels to which the CTB samples were subjected in the laboratory are estimated to be considerably higher than those commonly experienced in the field, the conclusion can be drawn that CTB containing high RAP contents will likely perform better in actual service than in laboratory testing.

5.3 Recommendations

Given that the principle conclusion from this work is that CTB with high RAP contents can perform satisfactorily as a base material when a sufficient amount of cement is applied, agencies currently specifying limits on the percentage of RAP that can be used as a part of reclaimed base material in the FDR process should reevaluate their policies and specifications with the goal of allowing the use of high RAP contents where appropriate. In this way, the numerous benefits of using FDR for rehabilitation of flexible pavements can be more fully realized. UCS testing, at minimum, should be conducted as a part of the CTB design process to ensure satisfactory performance of base/RAP mixtures with high RAP contents. In addition, in areas where frost action is a concern, appropriate conditioning should be performed prior to testing (Crane and Guthrie 2007, Guthrie et al. 2008); further research may be needed to examine the frost susceptibility of CTB with high RAP contents in these cases. Further research is also warranted to investigate the interactions between the applied stress, inter-particle friction between the aggregates, and viscosity of the asphalt coating on the RAP particles at different temperatures during testing. A detailed study of these topics would be expected to yield helpful information about specific mechanisms affecting the mechanical properties of CTB materials with high RAP contents.

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APPENDIX A MOISTURE-DENSITY RELATIONSHIPS

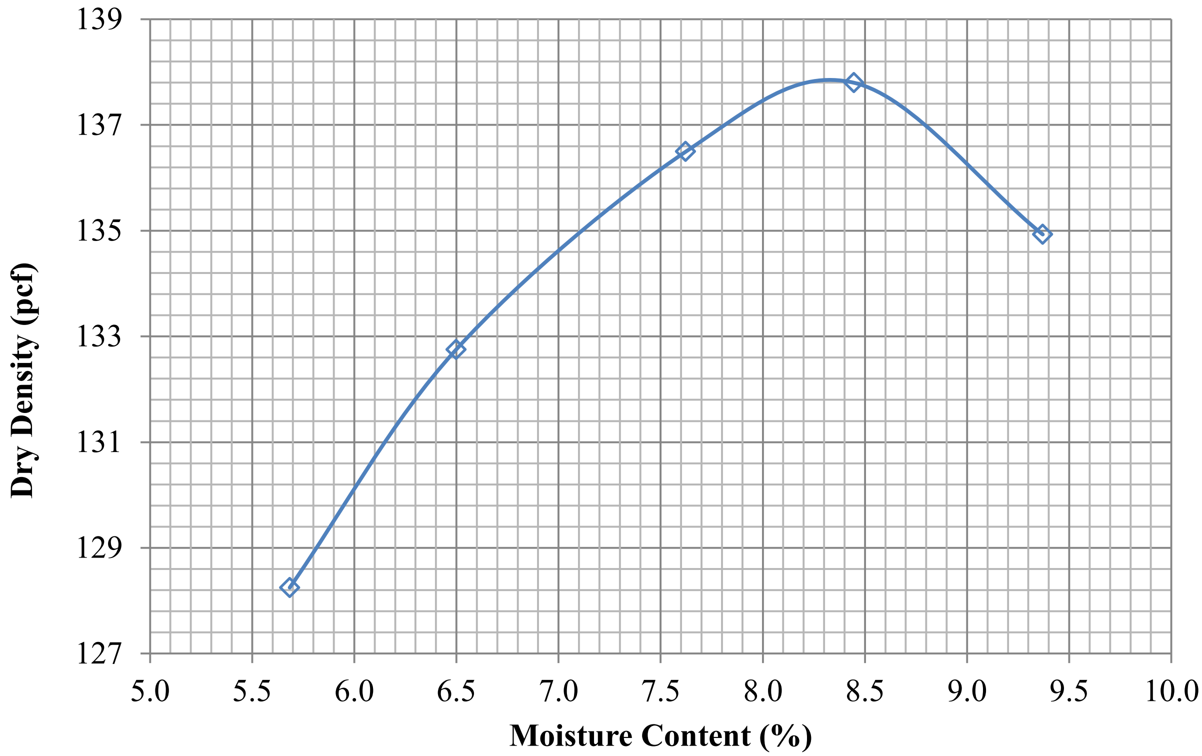

Figure A-1: Moisture-density curve for 0 percent RAP and 3 percent cement.

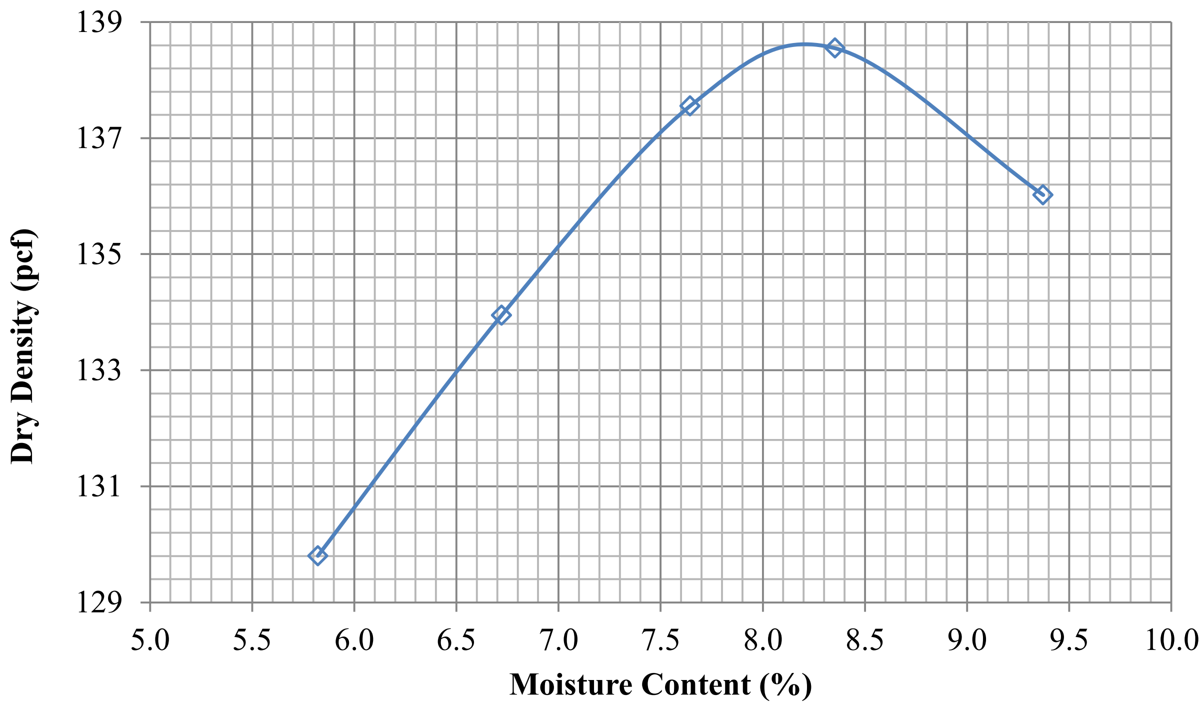

Figure A-2: Moisture-density curve for 0 percent RAP and 5 percent cement.

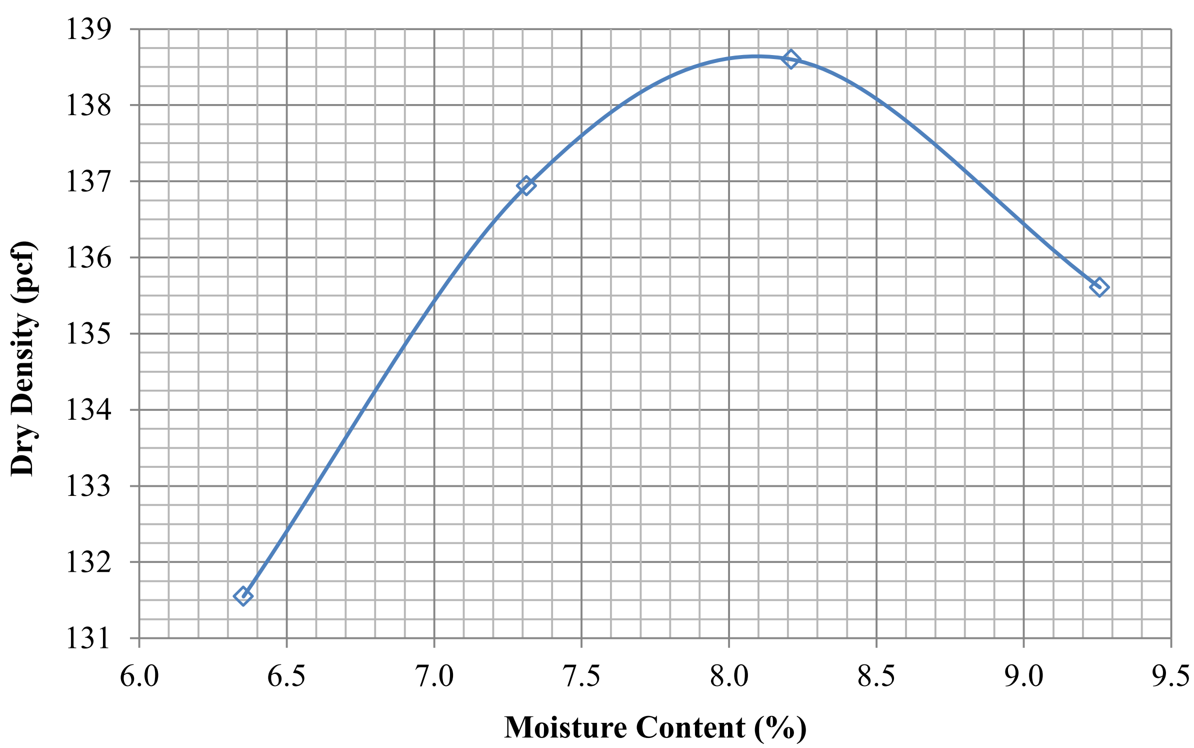

Figure A-3: Moisture-density curve for 0 percent RAP and 7 percent cement.

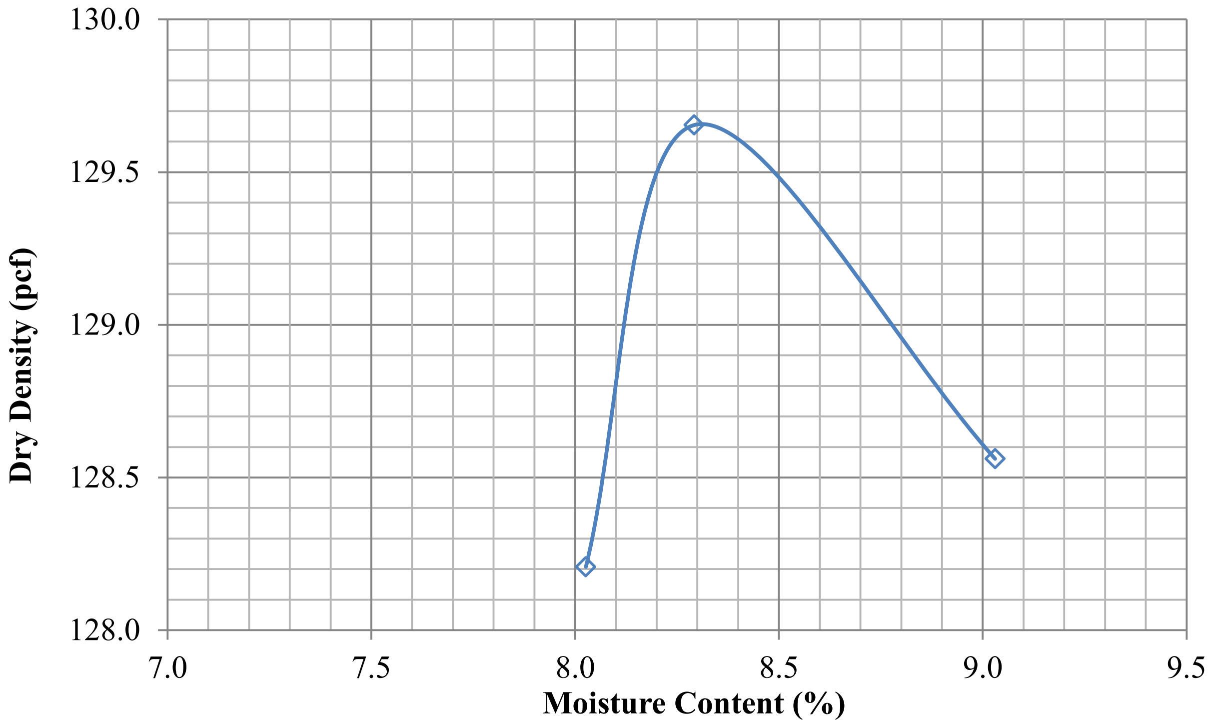

Figure A-4: Moisture-density curve for 50 percent RAP and 3 percent cement.

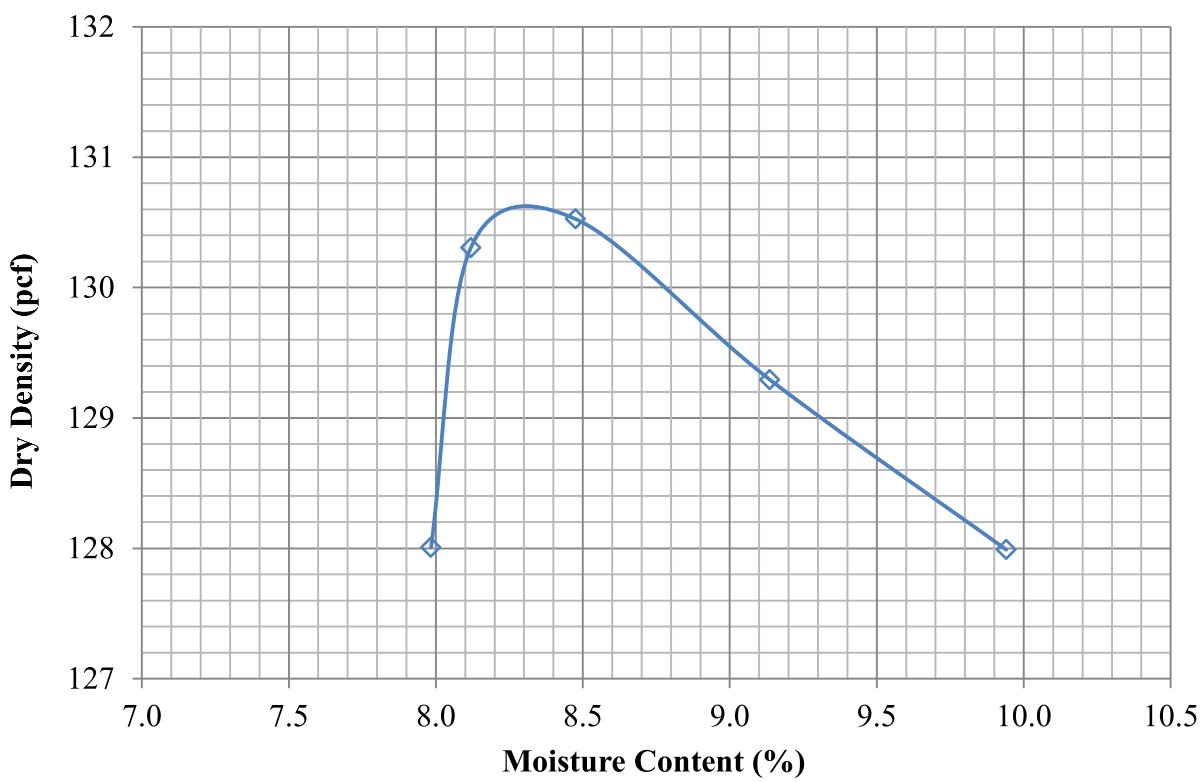

Figure A-5: Moisture-density curve for 50 percent RAP and 5 percent cement.

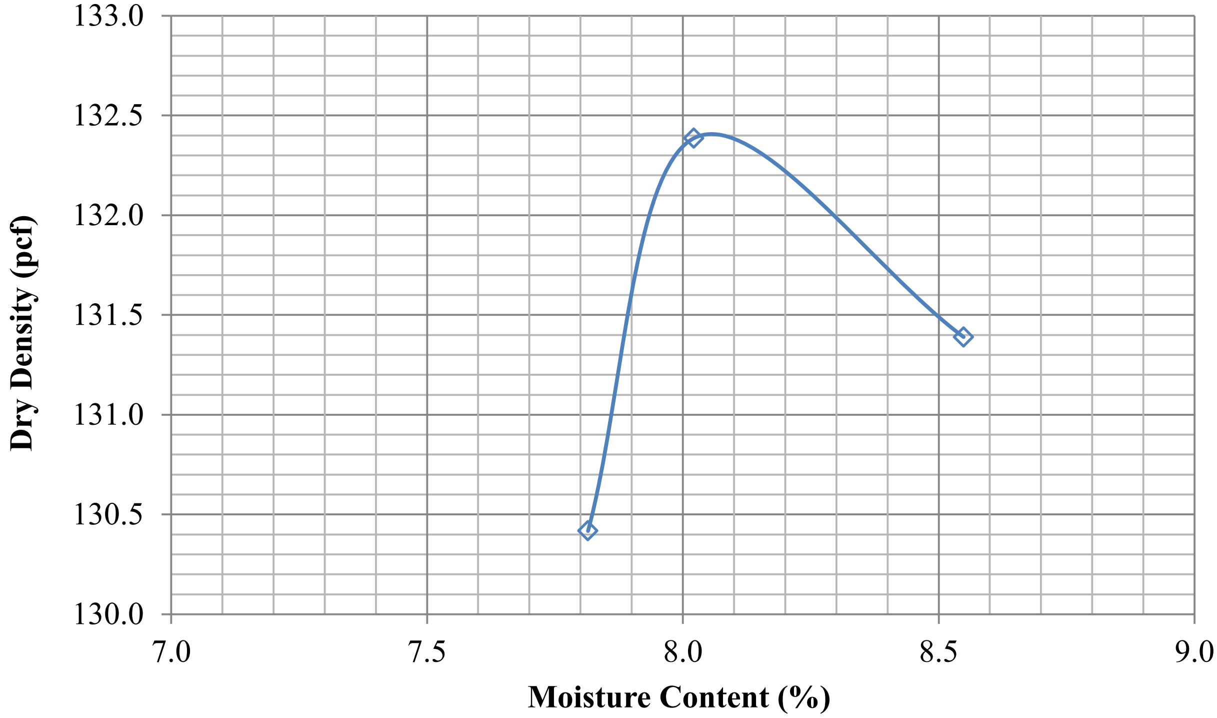

Figure A-6: Moisture-density curve for 50 percent RAP and 7 percent cement.

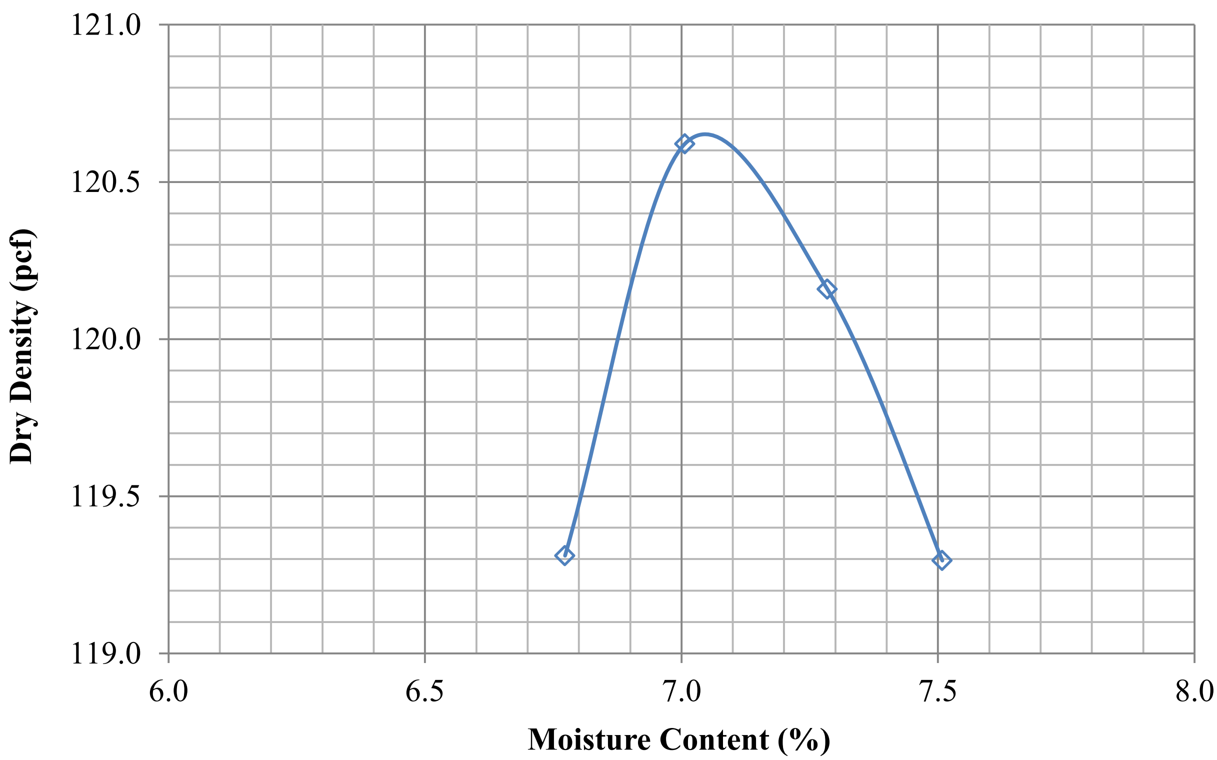

Figure A-7: Moisture-density curve for 75 percent RAP and 3 percent cement.

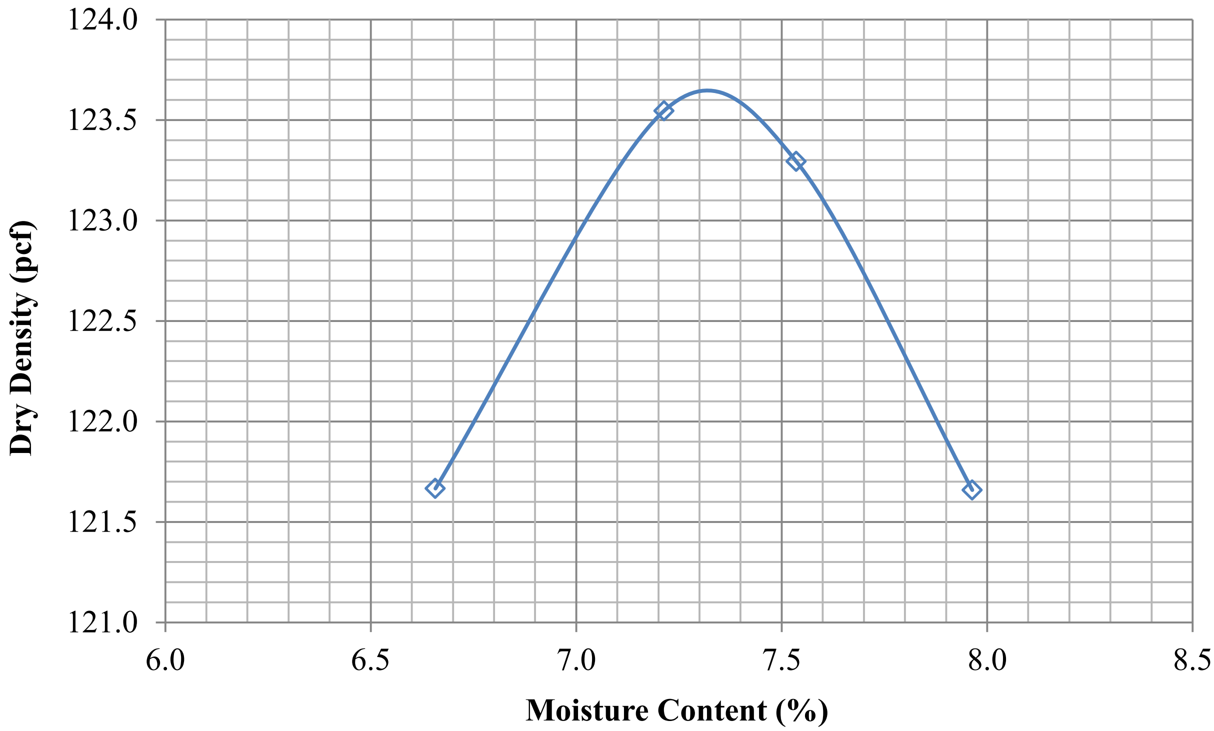

Figure A-8: Moisture-density curve for 75 percent RAP and 5 percent cement.

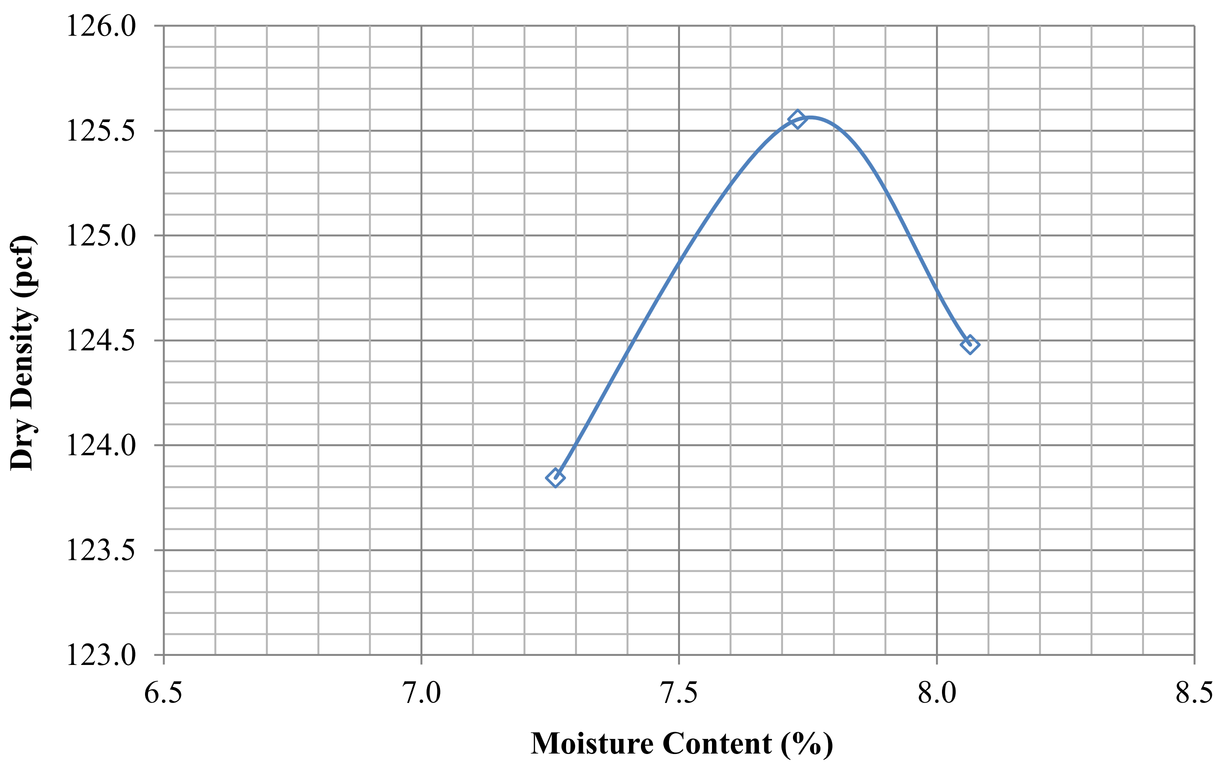

Figure A-9: Moisture-density curve for 75 percent RAP and 7 percent cement.

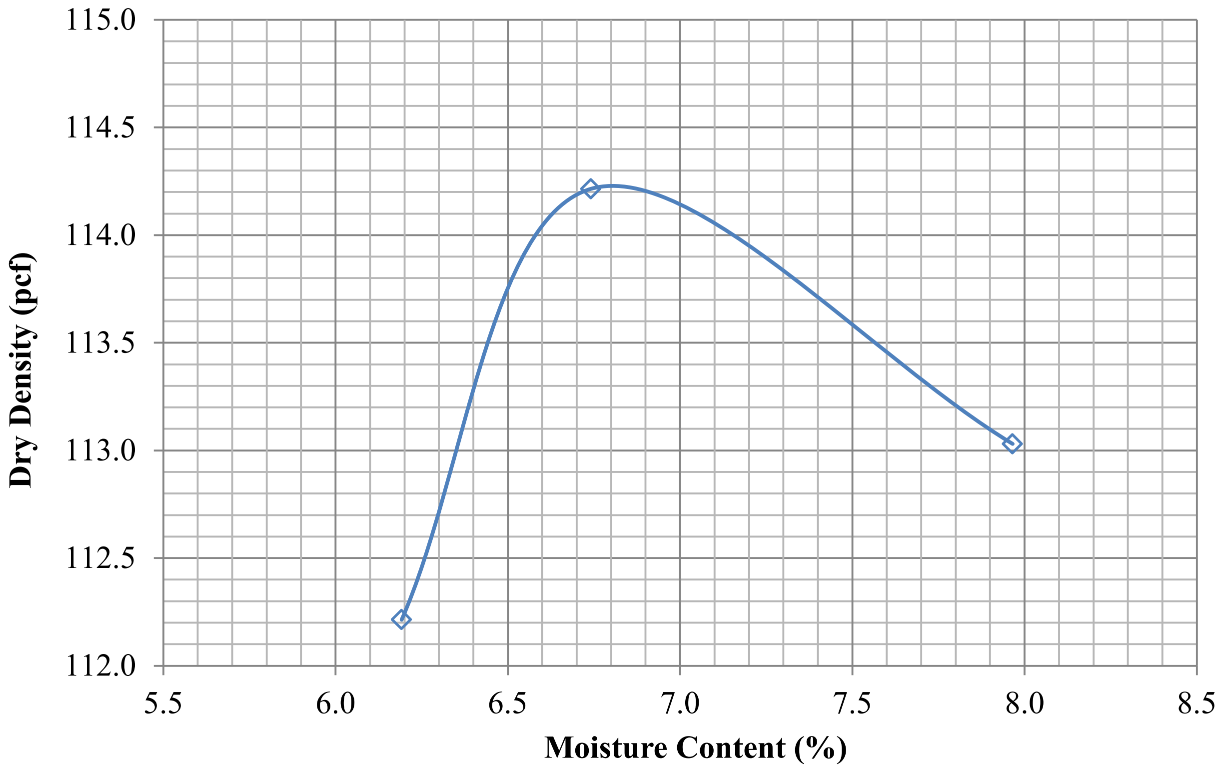

Figure A-10: Moisture-density curve for 100 percent RAP and 3 percent cement.

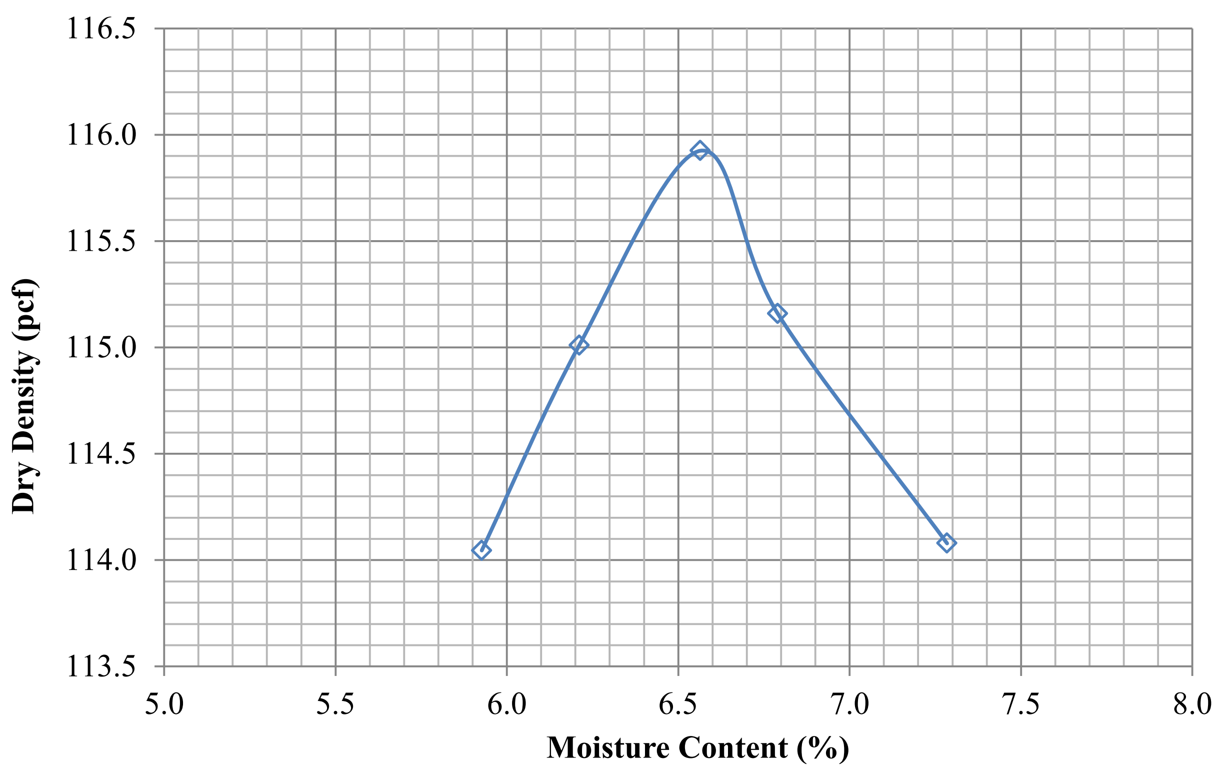

Figure A-11: Moisture-density curve for 100 percent RAP and 5 percent cement.

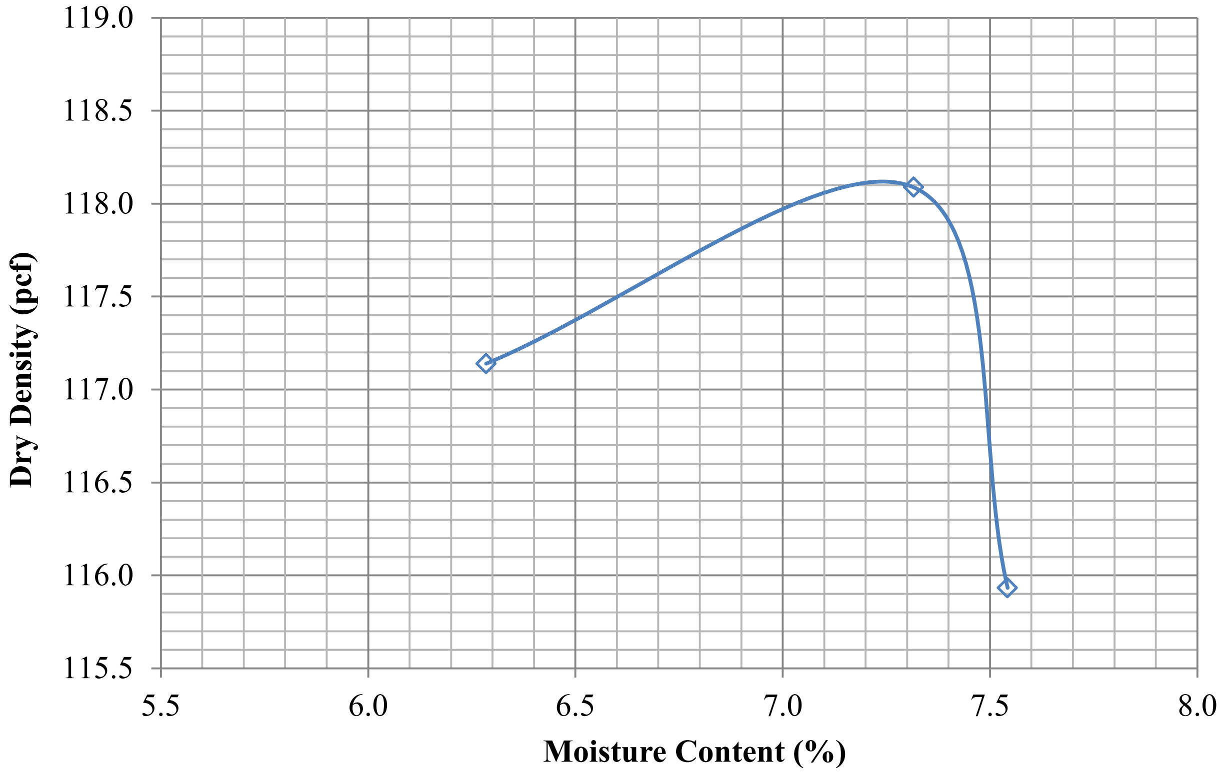

Figure A-12: Moisture-density curve for 100 percent RAP and 7 percent cement.

APPENDIX B MECHANICAL PROPERTY TEST DATA

Table B-1: UCS Test Results

RAP Content (%)	Cement Level	Specimen	Height (in.)	Weight (lb)	Target Moisture Content (%)	Estimated Dry Density (pcf)	UCS (psi)
0	Low	1	4.47	4.87	8.3	138.5	249
		2	4.61	4.98	8.3	137.2	273
	Medium	1	4.45	4.83	8.3	137.9	417
		2	4.42	4.77	8.3	136.9	415
	High	1	4.50	4.93	8.3	139.0	609
		2	4.53	4.89	8.3	137.3	564
25	Low	1	4.57	4.84	8.3	134.5	240
		2	4.58	4.79	8.3	132.9	263
	Medium	1	4.46	4.71	8.3	134.1	400
		2	4.54	4.75	8.3	132.9	416
	High	1	4.50	4.79	8.3	135.1	693
		2	4.46	4.70	8.3	133.7	564
50	Low	1	4.58	4.61	8.3	127.9	194
		2	4.71	4.71	8.3	126.9	156
	Medium	1	4.43	4.48	8.3	128.4	393
		2	4.44	4.56	8.3	130.2	409
	High	1	4.58	4.67	8.1	129.7	639
		2	4.48	4.66	8.1	132.5	641
75	Low	1	4.56	4.30	7.2	121.0	172
		2	4.78	4.54	7.2	121.9	224
	Medium	1	4.64	4.54	7.8	124.7	410
		2	4.55	4.49	7.8	125.9	423
	High	1	4.62	4.63	8.0	127.7	664
		2	4.52	4.55	8.0	128.1	691

Table B-1: Continued

RAP Content (%)	Cement Level	Specimen	Height (in.)	Weight (lb)	Target Moisture Content (%)	Estimated Dry Density (pcf)	UCS (psi)
100	Low	1	4.68	4.32	6.9	118.6	234
		2	4.56	4.16	6.9	117.4	240
	Medium	1	4.53	4.25	7.0	120.7	394
		2	4.48	4.24	7.0	121.5	413
	High	1	4.50	4.34	7.2	123.9	574
		2	4.47	4.28	7.2	122.9	496

Table B-2: Resilient Modulus and Permanent Deformation Values for Phase 1

RAP Content (%)	Cement Level	Specimen	Height (in.)	Weight (lb)	Target Moisture Content (%)	Estimated Dry Density (pcf)	Resilient Modulus (ksi)	Permanent Deformation (in.)
0	Low	1	11.63	29.29	8.3	137.3	82.1	0.093
		2	11.83	29.77	8.3	137.4	66.0	0.126
	Medium	1	11.78	29.57	8.3	136.7	82.8	0.038
		2	11.87	29.93	8.3	138.5	91.5	0.023
	High	1	11.98	30.18	8.3	138.1	92.4	0.018
		2	11.91	29.98	8.3	137.7	77.0	0.026
25	Low	1	12.16	29.92	8.3	135.3	90.1	0.234
		2	11.94	29.38	8.3	134.8	84.3	0.110
	Medium	1	12.06	29.58	8.3	133.9	79.3	0.046
		2	12.05	29.57	8.3	134.0	60.3	0.036
	High	1	11.99	29.58	8.3	135.5	102.4	0.017
		2	11.94	29.48	8.3	135.1	84.1	0.028
50	Low	1	11.93	28.67	8.3	131.1	92.3	0.256
		2	11.95	28.66	8.3	130.6	85.8	0.266
	Medium	1	12.12	29.08	8.3	131.6	97.5	0.028
		2	12.01	28.83	8.3	131.4	99.4	0.035
	High	1	12.12	29.23	8.1	132.0	109.8	0.015
		2	12.04	29.08	8.1	132.4	88.4	0.022

Table B-2: Continued

RAP Content (%)	Cement Level	Specimen	Height (in.)	Weight (lb)	Target Moisture Content (%)	Estimated Dry Density (pcf)	Resilient Modulus (ksi)	Permanent Deformation (in.)
75	Low	1	12.17	27.61	7.2	125.1	91.5	0.276
		2	12.16	27.82	7.2	126.4	82.9	0.201
	Medium	1	11.90	27.62	7.8	127.5	99.7	0.027
		2	11.96	28.12	7.8	129.4	106.9	0.022
	High	1	11.97	28.22	8.0	129.1	90.5	0.023
		2	11.89	28.01	8.0	129.3	83.7	0.026
100	Low	1	11.98	26.42	6.9	122.5	96.6	0.363
		2	12.18	26.67	6.9	121.3	97.9	0.529
	Medium	1	12.13	27.22	7.0	123.9	99.8	0.033
		2	11.97	26.77	7.0	123.6	81.2	0.038
	High	1	12.18	28.02	7.2	126.8	112.3	0.022
		2	11.87	27.02	7.2	125.6	90.5	0.032

Table B-3: Resilient Modulus and Permanent Deformation Values for Phase 2

RAP Content (%)	Specimen	Height (in.)	Weight (lb)	Target Moisture Content (%)	Estimated Dry Density (pcf)	Resilient Modulus (ksi)	Permanent Deformation (in.)
0	1	11.93	30.08	8.3	137.5	70.6	0.154
	2	11.93	30.08	8.3	138.3	77.8	0.137
25	1	11.95	29.43	8.3	134.7	86.9	0.053
	2	11.98	29.53	8.3	135.1	94.5	0.052
50	1	12.13	29.06	8.3	131.3	88.1	0.089
	2	12.03	28.63	8.3	130.8	82.7	0.046
75	1	12.10	27.37	7.2	124.7	97.7	0.031
	2	12.07	27.07	7.2	124.4	90.6	0.047
100	1	11.96	26.22	6.9	121.0	65.2	0.018
	2	11.96	26.11	6.9	121.0	52.3	0.023

Table B-4: Resilient Modulus and Permanent Deformation Values for Phase 3

Factor	Specimen	Height (in.)	Weight (lb)	Target Moisture Content (%)	Estimated Dry Density (pcf)	Resilient Modulus (ksi)	Permanent Deformation (in.)
Unsealed	1	12.20	26.62	6.9	121.8	94.5	0.622
	2	11.93	26.22	6.9	121.4	79.6	0.272
Soaked	1	11.88	26.02	6.9	121.4	90.7	0.020
	2	11.97	26.07	6.9	121.4	90.7	0.040
28-Day	1	12.00	26.12	6.9	119.3	80.1	0.049
	2	11.91	26.07	6.9	121.4	92.6	0.017

APPENDIX C KENPAVE ANALYSIS OUTPUT

MATL = 1 FOR LINEAR ELASTIC LAYERED SYSTEM
NDAMA = 0, SO DAMAGE ANALYSIS WILL NOT BE PERFORMED
NUMBER OF PERIODS PER YEAR (NPY) = 1
NUMBER OF LOAD GROUPS (NLG) = 1
TOLERANCE FOR INTEGRATION (DEL) -- = 0.001
NUMBER OF LAYERS (NL)------------- = 3
NUMBER OF Z COORDINATES (NZ)------ = 1
LIMIT OF INTEGRATION CYCLES (ICL)- = 80
COMPUTING CODE (NSTD)------------- = 9
SYSTEM OF UNITS (NUNIT)------------= 0

Length and displacement in in., stress and modulus in psi
unit weight in pcf, and temperature in F

THICKNESSES OF LAYERS (TH) ARE : 4, 6
POISSON'S RATIOS OF LAYERS (PR) ARE : 0.35, 0.15, 0.45
VERTICAL COORDINATES OF POINTS (ZC) ARE: 4.001
ALL INTERFACES ARE FULLY BONDED

FOR PERIOD NO. 1 LAYER NO. AND MODULUS ARE : 1 4.000E+05, 2 5.875E+04,
3 5.000E+03

LOAD GROUP NO. 1 HAS 2 CONTACT AREAS
CONTACT RADIUS (CR)--------------- = 3.78
CONTACT PRESSURE (CP)------------- = 100
NO. OF POINTS AT WHICH RESULTS ARE DESIRED (NPT)-- = 3
WHEEL SPACING ALONG X-AXIS (XW)------------------- = 0
WHEEL SPACING ALONG Y-AXIS (YW)------------------- = 13.5

RESPONSE PT. NO. AND (XPT, YPT) ARE: 1 0.000, 0.000; 2 0.000, 3.780;
3 0.000, 6.750

PERIOD NO. 1 LOAD GROUP NO. 1

POINT NO.	VERTICAL COORDINATE	VERTICAL DISPL. (HORIZONTAL P. STRAIN)	VERTICAL PRINCIPAL STRESS (STRAIN)	MAJOR PRINCIPAL STRESS (STRAIN)	MINOR PRINCIPAL STRESS (STRAIN)	INTERMEDIATE STRESS (STRAIN)
1	4.00100	0.03292	30.601	31.227	-10.533	-8.157
	(STRAIN)	-2.382E-04	5.670E-04	5.792E-04	-2.382E-04	-1.917E-04
2	4.00100	0.03352	19.844	21.030	-10.091	-2.841
	(STRAIN)	-2.182E-04	3.678E-04	3.910E-04	-2.182E-04	-7.628E-05
3	4.00100	0.03345	12.258	12.258	-9.286	2.113
	(STRAIN)	-1.948E-04	2.270E-04	2.270E-04	-1.948E-04	2.838E-05