Cement Treated RAP Mixes for Roadway Bases

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Reclaimed asphalt pavement (RAP) and granular base materials were collected from stockpiles in six TxDOT districts to evaluate the feasibility of using high RAP content mixes for base course applications. Mixes containing 100%, 75% and 50% RAP treated with Portland cement of 0%, 2%, 4% and 6% were evaluated in a full-factorial laboratory experiment. For mixes of 75% and 50% RAP, both virgin and salvage base materials, when available, were used. Experimental results indicate that, besides the cement content, the RAP content and fines content in RAP-granular base mixes significantly affect the properties of the RAP mixes, and that the effects of RAP type and asphalt content are very limited. To achieve a 300-psi unconfined compressive strength as required by TxDOT for cement-treated bases, the optimum cement contents are statistically about 4%, 3% and 2% for mixes with 100%, 75% and 50% RAP, respectively. Since the achievement of any specified strength and/or modulus may not always ensure the long-term durability of RAP mixes, a number of other parameters were also evaluated through laboratory testing. These parameters are necessary for a comprehensive evaluation of various mixes containing high RAP contents (50% or more). Based on the experimental results, guidelines for laboratory testing and mix design process of RAP mixes are provided with field verification data collected from actual construction projects.

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Abstract

Reclaimed asphalt pavement (RAP) and granular base materials were collected from stockpiles in six TxDOT districts to evaluate the feasibility of using high RAP content mixes for base course applications. Mixes containing 100%, 75% and 50% RAP treated with portland cement of 0%, 2%, 4% and 6% were evaluated in a full-factorial laboratory experiment. For mixes of 75% and 50% RAP, both virgin and salvage (when available) base were used. Experimental results indicate that, besides the cement content, the RAP content and fines content in RAP-granular base mixes significantly affect the properties of the RAP mixes, and that the effects of RAP type and asphalt content are very limited. To achieve a 300 psi unconfined compressive strength as required by TxDOT for cement-treated bases, the optimum cement contents are statistically about 4%, 3% and 2% for mixes with 100%, 75% and 50% RAP, respectively. Since the achievement of any specified strength and/or modulus may not always ensure the long-term durability of RAP mixes, a number of other parameters were also evaluated through laboratory testing. These parameters are necessary for a comprehensive evaluation of various mixes containing high RAP contents (50% or more). Based on the experimental results, guidelines for laboratory testing and mix design process of RAP mixes are provided with field verification data collected from actual construction projects.

Implementation Statement

In this report, a number of recommendations have been made to improve the mix design, construction and quality management for cement-treated base courses containing high RAP content. The recommendations are based on the test results of RAP and granular materials from six TxDOT districts.

At this time, the recommendations should be implemented on a number of new and ongoing projects to confirm their applicability and to adjust the limits and/or criteria recommended. As part of the implementation, a guide should be developed to disseminate to the TxDOT staff.

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Chapter 1

Introduction

Statement of Problem

The use of recycled materials in roadway maintenance, rehabilitation and reconstruction has become increasingly more prevalent over the past two decades. Both the Federal Highway Administration (FHWA) and Texas Department of Transportation (TxDOT) support and promote this use in an effort to preserve the natural environment, reduce waste, and provide cost effective materials for roadway pavement projects. One of recycled materials is the reclaimed asphalt pavement (RAP) that is created when existing asphalt concrete pavement is milled or completely removed. Based on a survey conducted by the FHWA, it was reported that approximately 100 million tons of hot-mix asphalt (HMA) is milled each year in the U.S. (www.moasphalt.org/facts/environmental/recycling.htm, 2007). In Texas, the total annual production of RAP by TxDOT districts and commercial producers was about 4 million tons in 2001 (Rathje et al., 2002).

According to the FHWA recycled materials policy, three key requirements must be satisfied for asphalt pavement recycling to be successful. The end product should be (1) cost effective, (2) environmentally responsible, and (3) perform well. Specific goals of the policy include increasing the number of highway construction and rehabilitation projects that use RAP and the amount of RAP in blends for specific projects. To reach this goal, the FHWA initiated in 2007 an Expert Task Group (ETG) on the use of RAP in the construction and rehabilitation of flexible pavements.

Historically, the primary use of RAP has been the reintegration of reclaimed millings into new bituminous material using either hot-mix or cold-mix recycling processes. However, a large amount of RAP remains unused due to the restrictions on its quality (including contamination of the old HMA with underlying base or soil) and quantity for the reintegration, and thus its further uses should be explored. The use of RAP or RAP blended with virgin or/and salvage aggregate as base materials may represent a solution to this waste problem. This is particularly true for TxDOT since the rehabilitation projects on farm-to-market (FM) roads and state highways (SH) may involve road widening that may require a significant amount of base materials. The use of

RAP in such projects could result in significant cost savings, especially for projects that require long-hauling distances for disposal of waste material or projects for which the availability of suitable aggregate is limited.

Provided the fact that the quality of base material is one of the most important factors for flexible pavements, the question that remains to be answered is how the use of RAP mixes as base materials affects the performance of a flexible pavement. There is a strong need to standardize the testing protocol, mix design process, construction practice and QA/QC procedure for this type of RAP usage in Texas. This report presents the results from a comprehensive laboratory testing program on cement-treated RAP mixes. Based on these results, guidelines for laboratory testing and the mix design process of RAP mixes are provided with field verification data collected from actual construction projects.

Objectives and Scope

The main objective of this research project was to examine the feasibility of using mixes of high RAP content for base course applications and to provide guidelines for this type of RAP usage. To achieve this objective, a number of tasks were proposed and completed. These tasks mainly included:

1. Collect RAP and granular base materials from stockpiles in six TxDOT Districts and use them for the baseline study of this research project.
2. Characterize the variability of RAP materials collected in terms of gradation, asphalt content and sand equivalency.
3. Evaluate cement-treated RAP mixes in terms of moisture-density characteristics, compressive strength, indirect tensile strength, modulus, moisture susceptibility, hydraulic conductivity and permanent deformation. Only the mixes containing 100%, 75% and 50% RAP were considered. For mixes of 75% and 50% RAP, both virgin and salvage base materials, when available, were used. Four levels of cement content (0, 2, 4 and 6%) by dry weight were utilized for all mixes except for 100% RAP. The optimum cement content was statistically determined for a given level of RAP content in a mix according to the results from this comprehensive evaluation program.
4. Conduct advanced study on those cement-treated RAP mixes passing the minimum strength requirement by TxDOT Specification Item 276 to ensure their durability or long-term performance. This study involved wetting/drying, leachate and mineralogical tests.
5. Perform field trial to verify the mix design model obtained from laboratory testing.

Organization of Report

This report consists of seven chapters.

Chapter 1 is the introduction to this report. Chapter 2 contains a summary of the literature review and information search on the general characteristics of RAP and the engineering properties of cement-treated RAP mixes. Results from a statewide survey to investigate the current status of RAP usage in base application in TxDOT projects are also included in this chapter.

Chapter 3 provides results from evaluative testing on the RAP materials collected and used in this research project. The common variation patterns of gradation, asphalt content and sand equivalency are summarized. A comparison of gradations of RAP and granular base materials is also provided in this chapter.
Chapter 4 describes the testing strategies/methods used in evaluation of RAP mixes and represents the results, which include the following items:

- Moisture-density characteristics of RAP mixes
- Variations of unconfined compressive strength, indirect tensile strength and modulus of RAP mixes with RAP content and cement content
- Consistency of different engineering or performance parameters used in defining the properties of RAP mixes
- Effects of different components (except for cement content) in a RAP mix on strength and modulus
- A simple mix design model for cement-treated RAP mixes
- Guidelines for Laboratory Testing and Mix Design Process

Chapter 5 summarizes the results from wetting/drying, leachate and mineralogical tests on the RAP mixes that meet the minimum strength requirement by TxDOT specifications.

Chapter 6 presents the results from initial field trials at three construction projects to verify the mix design model obtained from laboratory testing.

Chapter 7 contains the conclusions drawn from the research and recommendations for future study.

Chapter 2

Background and Information Search

Processing and Stockpiling of RAP

RAP is produced from existing asphalt concrete pavements by milling, ripping, breaking and crushing or by pulverizing. Milling and crushing are the predominant methods to produce RAP (Saeed, 2008). Crushing is generally done at an off-site facility and requires hauling ripped HMA to the processing facility. After crushing, the material is either stockpiled for later use or hauled immediately to the job site. A mobile plant is sometimes used if the material is to be used at the same job site. The general requirements proposed by FHWA (2006, 2008) for stockpiled RAP can be summarized as follows.

Inspection

To ensure that the final RAP product will perform as intended, inspection of incoming RAP and rejection of contaminated loads (excess granular material, surface treatment, joint sealant, etc.) should be undertaken. Some jurisdictions also require that RAP from a particular project not be blended or commingled with RAP from other projects.

Crushing and Screening

RAP must be processed to the desired aggregate gradation using conventional equipment consisting of a primary crusher, screening units, conveyors and a stacker. A typical screening unit used to prevent large RAP particles from entering mixture is shown in Figure 2.1.

Stockpiling

Once processed, RAP can be handled and stored as a conventional aggregate material. However, because of the variability of RAP in comparison with virgin aggregates, many agencies do not permit the blending of RAP from different sources or projects into combined stockpiles.

Figure 2.1 – Screening Unit Used to Prevent Large RAP Particles from Entering Mixture

The Asphalt Institute recommends that the height of RAP stockpiles be limited to a maximum of 10 ft to help prevent agglomeration of the RAP particles. Experience has proven that conical stockpiles are preferred to horizontal stockpiles and will not cause RAP to re-agglomerate or congeal in large piles. RAP has the tendency to form a crust (due to a solar/thermal effect) over the first 8 to 12 in. of pile depth for both conical and horizontal stockpiles.

RAP has a tendency to hold water and not to drain over time like an aggregate stockpile. Therefore, low, horizontal, flat stockpiles are subject to greater moisture accumulation than tall, conical stockpiles. It is not unusual to find RAP moisture content in the 7 to 8 percent range during the rainy season at facilities using low, horizontal stockpiling techniques

RAP stockpiles are typically left uncovered because covering with tarps can cause condensation under the tarp and add moisture to the RAP stockpile. For this reason, RAP stockpiles are either left uncovered or RAP is stored in an open-sided building, but under a roof.

Properties of RAP and RAP Blends

The properties of RAP are governed by the milling and crushing operation, as well as by the characteristics of the binder and aggregate in the old asphalt pavement from which the RAP is obtained. RAP produced from surface courses (compared to binder courses) is usually of a higher quality because of higher quality aggregates used in the original construction (Saeed, 2008).

When properly crushed and screened, RAP consists of high-quality, well-graded aggregates coated by asphalt cement. However, RAP derived from different sources can have significantly different engineering properties due to the differences in milling process, rock source, type and content of asphalt, etc. RAP combined from several sources may change the quality of the product throughout the construction project because of this variation. Some of the physical, mechanical and engineering properties of RAP and RAP blends are of particular interest when RAP is used in granular base or subbase applications. These properties include gradation, compacted density, moisture content, permeability, durability, bearing capacity and permanent deformation.

Gradation

The gradation for milled RAP is determined by the teeth spacing of the milling or pulverizing unit and the speed of pulverizing. Wider tooth spacing and higher speed result in larger particle sizes and coarser gradation. The gradation is also affected by the original HMA gradation and the temperature of the HMA during milling or pulverizing process. Results from sieve analysis of RAP are mixed, particularly for the fines content. Both low fines content and high fines content in stockpiled RAP have been observed. The particles passing the #200 sieve can be as high as more than 10% (Sullivan, 1996) and as low as less than 0.5 % (Rathje et al., 2002; McGarrah, 2007). Typical RAP gradations after milling or processing from FHWA (Chesner et al., 1998), TxDOT (Rathje et al., 2002), NJDOT (Bennett et al., 2000) and FDOT (Cosentino and Kalajian, 2001) are shown in Figure 2.2. The variation in gradation for the RAP materials from different sources is evident.

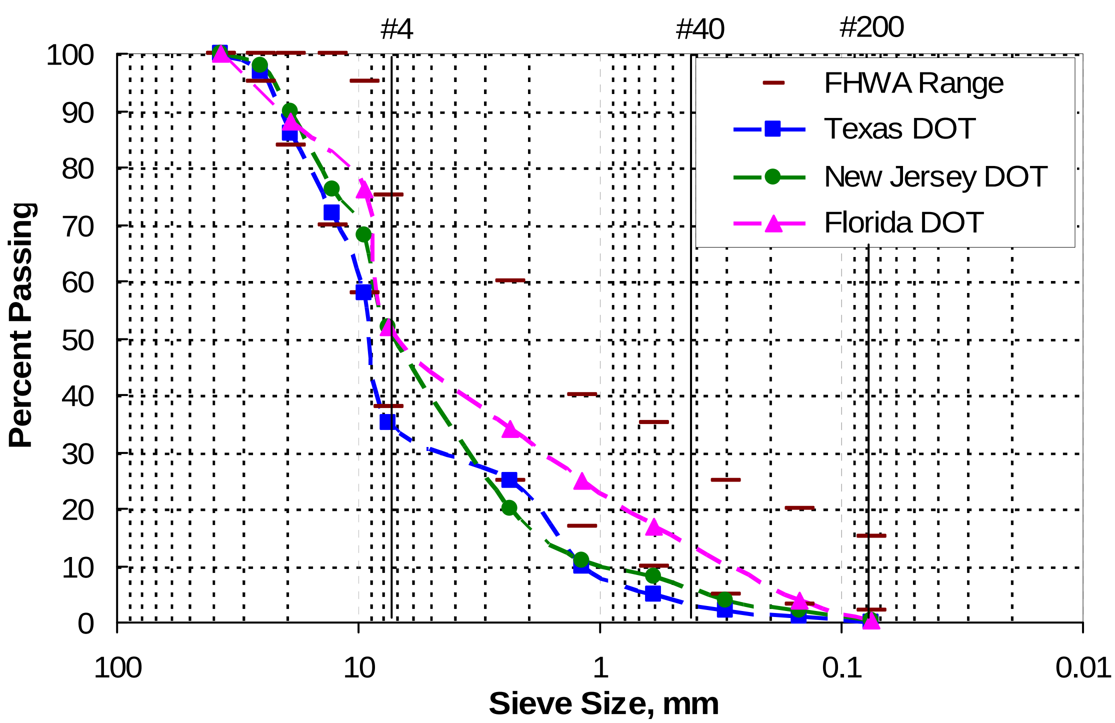


Figure 2.2 – Typical RAP Gradations

The gradation of the milled or crushed RAP is different from that of the original HMA. Milling and scrapping can cause RAP aggregate degradation which is normally finer and denser than the virgin aggregates. The degradation during milling is a function of the aggregate top size and gradation of the aggregate in the asphalt pavement. During milling, the aggregate fraction passing #4 sieve increases from a pre-milled range of 41 to 69% to a post-milled range of 52 to 72 %. Similarly, the fraction passing the No. 200 sieve increases from 6 to 10% to about 8 to 12% (Kandhal and Mallick, 1997). However, full depth pulverizing or scrapping does not cause as much degradation as milling (Ahmad et al., 2004). Further degradation might occur for milled or crushed RAP due to compaction; in particular, for particle sizes greater than 0.5 in. (Maher et al., 1997). Degradation of the larger particles is attributed to the debonding of the aggregates held together by the asphalt binder.

Density and Moisture Content

The difference in the maximum dry density (unit weight) among the compacted RAP materials from different sources is significant. The density may vary from less than 115 pcf to 130 pcf or more depending on the original source where the RAP is derived. Also, due to the coating of asphalt on the RAP aggregate which inhibits compaction, the compacted density of blended mixture tends to decrease with increasing RAP content (Senior et al., 1994; Taha, 1999; McGarrah, 2007). It is unknown how this difference will affect the performance of RAP blended mixtures.

The typical optimum moisture content of a compacted RAP blended material was reported to be lower than that for virgin granular material (Mokwa and Peebles, 2005, Guthrie et al., 2007a). However, for RAP blends from full-depth pulverizing operations, the optimum moisture content was reported to be higher due to higher fines content and the absorptive capacity of these fines (Hanks and Magni, 1989).

Permeability

Permeability of a granular material is directly related to the percentage of fines (particles passing the #200 sieve) present in the material. In general, the permeability of blended granular material containing RAP is higher than the virgin aggregates and increases as the percentage of RAP in the blend is increased as would be expected (Highter et al., 1997; Mokwa and Peebles, 2005). The Ontario Ministry of Transportation conducted permeability tests on virgin aggregate and compared them with a 60% RAP blend (40% virgin aggregate) and 100% RAP. Their results indicated that because of the coarser gradations of RAP blends, they had a higher permeability (Hanks and Magni, 1989) as would be expected. The addition of up to 50% RAP has little effect on the permeability of the original base or subbase material. The permeability of the subbase material containing more than 50% RAP increased by an order of magnitude (MacGregor et al., 1999). However, opposite results were obtained from a systematic investigation for New Jersey DOT; that is, the permeability of a RAP blend decreases as the percentage of RAP in the blend increases (Bennett and Maher, 2005).

Durability

The durability of RAP is mostly affected by the aggregate used in the original HMA mix. Since the quality of the virgin aggregates used in asphalt concrete usually exceeds the requirements for granular aggregates, there are generally no durability concerns regarding the use of RAP in granular base. However, due to the presence of a thin asphalt film on the aggregate, the properties of the original asphalt binder will have some effect on the performance of the RAP as aggregate in unbound pavement layers. Age hardening, during which asphalt binder oxidizes from oils to resins to asphaltenes, leads to higher asphalt binder viscosities and thus affects performance. Some RAP may also be obtained from pavements that have exhibited stripping. If this process continues when RAP is used as aggregate in granular base layers, then the strength of the layer as a whole may be affected. Thus, the design strength of RAP in unbound layers would need to be selected based on its potential for stripping and moisture damage (Saeed, 2008). In addition, it is unknown how the construction practice, environmental exposure and traffic loadings will impact the long-term durability of a RAP mixture, especially when RAP content in the mixture is high.

Bearing Capacity

Several parameters have been used to characterize the bearing capacity or performance of blended RAP materials. These parameters include unconfined compressive strength (UCS), California Bearing Ratio (CBR), resilient modulus, and direct shear strength. Results from studies on these parameters indicate that the bearing capacity of RAP blend material is strongly dependent on the proportion of RAP to conventional aggregate and, in general, decreases with increasing RAP content (Taha et al., 2002). However, the results also show some inconsistencies among these parameters. For instance, a number of studies show that the CBR decreases and the resilient modulus increases as the percentage of RAP in RAP blends is increased (Hanks and Magni, 1989; Highter et al., 1997; Taha et al., 1999; Mokwa and Peebles, 2005; Bennett and Maher, 2005). Figure 2.3 shows an example for this situation. The inconsistencies could be largely attributed to differences in the mechanism of testing methods and differences in the characteristics of the RAP and virgin materials. A similar trend was also reported by Guthrie et al. (2007a) where the Young's modulus is measured with a free-free resonant column device. It seems that the parameters of bearing capacity used for characterizing RAP mixtures should be evaluated on a project-by-project basis as necessary until enough data becomes available to evaluate statistically any trends that may exist.

Permanent Deformation

Not much permanent deformation testing has been conducted on RAP and RAP blends. The study conducted by Bennett and Maher (2005) indicates that the addition of RAP to virgin aggregate increases the accumulated permanent strain after 100,000 loading cycles when compared to the 100% virgin material and the permanent deformation increases as the percentage of RAP increases with the 100% RAP mixture achieving the largest permanent deformation.

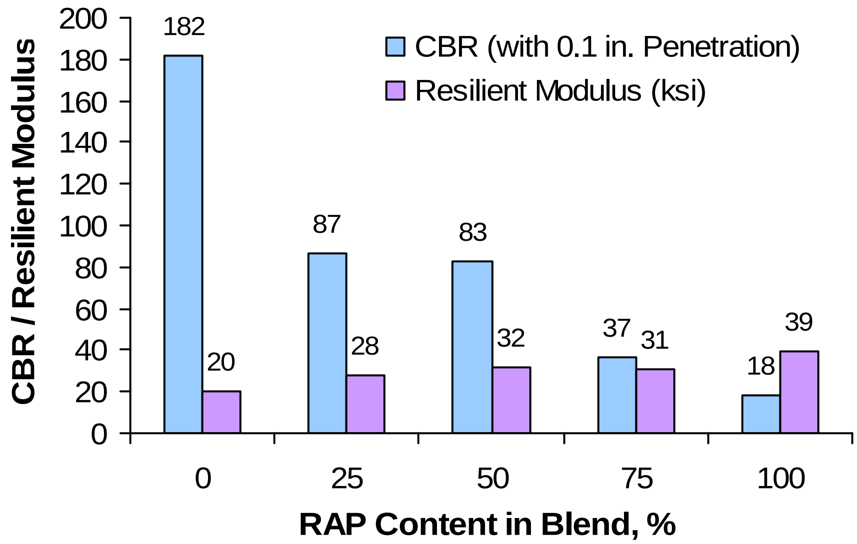


Figure 2.3 – Variations of CBR and Resilient Modulus with RAP Content (from Bennett and Maher, 2005)

In summary, there are consistent findings in many of the studies reviewed regarding the properties of RAP blends for use in base or subbase layers. However, there are also some inconsistencies among the studies covered regarding the engineering properties of RAP blends and their possible effects on pavement performance. These inconsistencies might be explained by the use of different materials and test methods, specimen preparation procedures and test protocols. In general, for use as base/subbase materials, the engineering characteristics of RAP and RAP blends have not been fully investigated; consequently, the long-term suitability and performance of this type of blended materials is unknown.

Current Status of Using RAP Mixes as Base Materials in Texas

As part of this research project, a statewide survey was conducted to investigate the current status of using RAP mixes in base course construction, to identify the districts that could benefit from the outcome of this study, and to solicit construction projects that could be incorporated in this study. The survey consists of the following main questions:

1. Have you used RAP (treated or not treated) for base construction/rehabilitation/repair in your district?
2. Approximately what percentages of projects in your district have used RAP in the base in the last 3 years?
3. Have you used RAP in full-depth reclamation (FDR) rehabilitation of your projects?
4. How would you rate the performance of the roadways constructed with RAP mixed bases in your district?
5. If you treat or stabilize the RAP mixes when used for bases, which additives do you use?

6. Based on your experiences, what is the maximum amount of RAP (by weight percentage) that could be allowed for base mixes?

Responses to the survey were received from 24 of 25 TxDOT districts and are summarized next.

Sixteen districts have used stockpiled RAP in roadway base/subbase application. These districts are Austin, Beaumont, Bryan, Childress, Corpus Christi, Dallas, Fort Worth, Houston, Laredo, Lubbock, Odessa, Paris, Pharr, San Antonio, Waco and Wichita Falls. Figure 2.4 shows the percentages of projects that involved RAP usage in nine of the sixteen districts. Childress, Fort Worth, Houston, Laredo, Lubbock, Pharr and Waco Districts seemed to be the main users of RAP. About 94% of these districts were very satisfied (44%) or satisfied (50%) with the performance of RAP mixed bases.

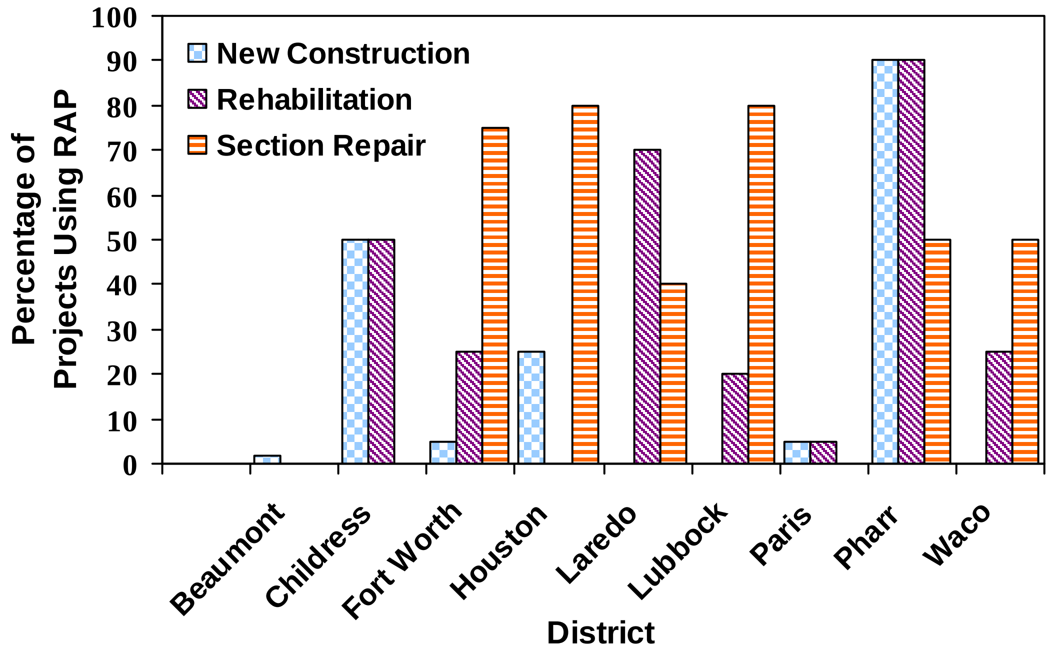


Figure 2.4 – Usage of RAP in Base Course Application by Districts

Twelve of sixteen districts reported to use portland cement to treat or stabilize their RAP mixes. Odessa District has used asphalt only for the treatment. San Antonio District has traditionally used asphalt emulsion for the treatment. Pharr District has used lime only. Besides cement, Lubbock District has also used fly ash and asphalt emulsion and Corpus Christi and Waco Districts have used lime for treatment.

The maximum amount of RAP allowed in base course construction varies among the sixteen districts (see Table 2.1). Most districts restricted the amount to not more than 50%. Recently, however, at least two districts, Fort Worth and Yoakum, have used mixes containing 60% or more RAP (existing plus hauled) in their base layer constructions.

Table 2.1 - Maximum Amount of RAP Allowed for Base Course Mixes

District	Max. Amount Allowed, %		Remark
	Base	Subbase	
Austin	25	100	
Beaumont	100		cement treated under concrete
Bryan	50		
Childress	50		
Corpus Christi	25 - 30		
Dallas	30 - 50		
Fort Worth	50		
Houston	30 (50 for State owned)		
Laredo	40		
Lubbock	30		
Odessa	35		
Paris	50		
Pharr	50		with minimum thickness requirement
San Antonio	33		
Waco	> 50		
Wichita Falls	No Opinion		

Chapter 3

Evaluation of RAP

RAP is a highly variable material due to different original sources and milling processes. One of the objectives of this research project was to evaluate the variability of RAP stockpiles in terms of gradation, asphalt content and sand equivalency. These parameters may provide necessary information for understanding the properties of RAP and RAP blended with granular base materials and developing a performance test protocol for mix design.

Material Collection

Based on the survey results from TxDOT districts and the interaction with the PMC of the research project, unfractionated RAP and granular base materials from six districts, Childress, El Paso, Fort Worth, Lubbock, Pharr and Waco, were collected for this study. At each RAP stockpile, samples were collected randomly at four to six locations. A brief description of the collected materials is provided in Table 3.1.

Table 3.1 – Description of Collected RAP and Granular Base Materials

District	RAP		Base	
	Ownership	Rock Type of Aggregate	Virgin	Salvage
Childress	State	Limestone and Granite	Gravel	NA
El Paso	Private	Limestone and Dolomite	Hard Limestone	NA
Fort Worth	State	Limestone	Limestone	NA
Lubbock	State	Most Limestone	Limestone	Mostly Limestone
Pharr	Private	Most Silica Shard	Marlstone (a soft Limestone)	Gravel and Limestone
Waco	State	Most Limestone	Soft Limestone	NA

Variability of RAP

Asphalt Content

RAP contains asphalt, which is one of the major differences from the natural granular materials and would be a concern on the chemical compatibility of RAP and calcium-based additives. Asphalt contents of RAP materials were determined by using the NCAT ignition oven method (Tex-236-F). The RAP sampled from each location of a stockpile was divided into the following three bins:

Bin 1: particles retained on 0.5 in.-sieve;
Bin 2: particles passing 0.5 in.-sieve and retained on #4 sieve
Bin 3: materials passing #4 sieve

As examples, Figure 3.1 shows the asphalt contents of the RAP materials from El Paso and Childress Districts by bin and sampling location. The asphalt contents of RAP materials from Fort Worth, Lubbock, Pharr and Waco have the similar patterns as one of the Childress RAP.

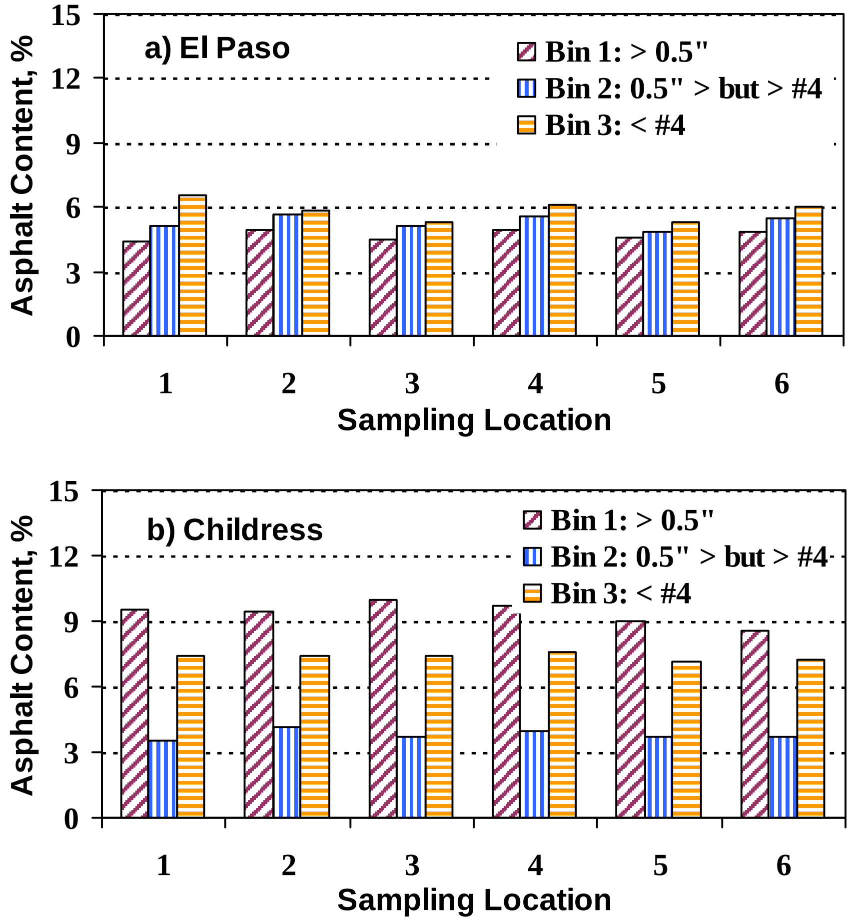


Figure 3.1 – Asphalt Contents of RAP Materials by Bin and Sampling Location

The average asphalt contents of the RAP materials from all six stockpiles are summarized in Figure 3.2. The error bars in the figure denotes plus-one and minus-one standard deviation. The coefficient of variation (COV) varies from about 2% to 10%. Except for the RAP from El Paso, the distribution of asphalt contents from the three bins shows similar pattern; that is, the lowest asphalt contents were observed from bin 2.

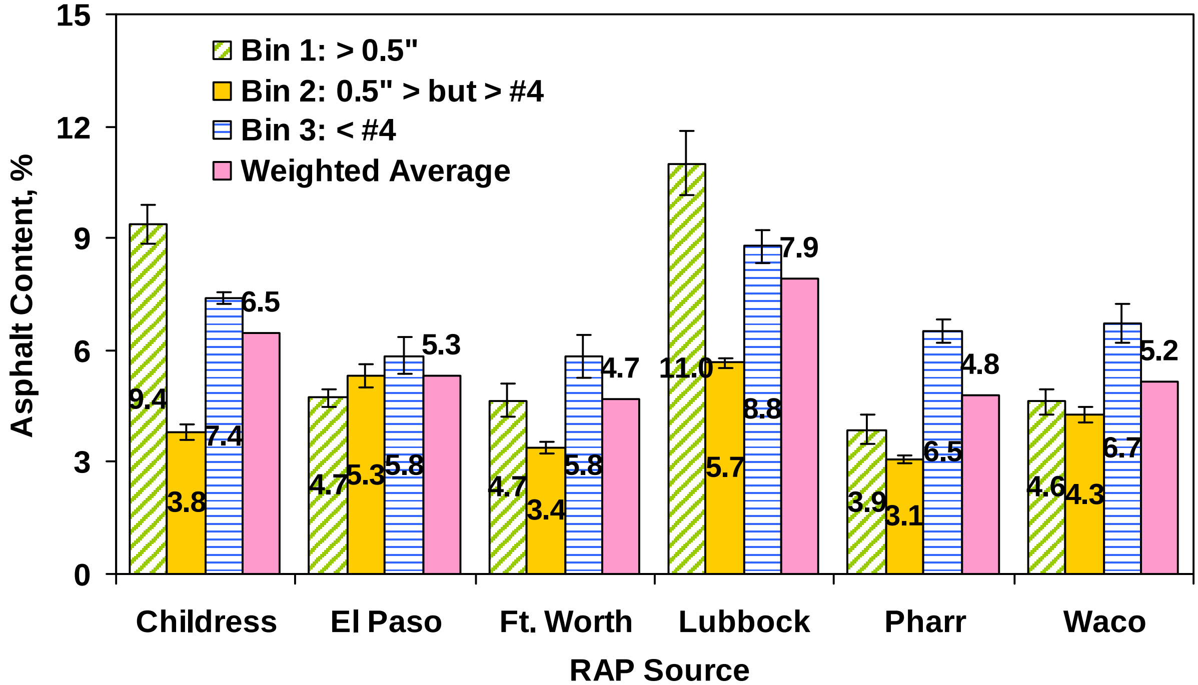


Figure 3.2 – Comparison of Asphalt Contents of RAP Materials from All Six Stockpiles

The weighted average asphalt content varies among the RAP materials from the six stockpiles, which is as low as 4.7% for the Fort Worth stockpile and as high as 7.9% for the Lubbock stockpile. The presence of asphalt chips in the Lubbock RAP (see Figure 3.3) is probably the main reason for the high asphalt content, even though the large-size chips were removed before the ignition oven test.

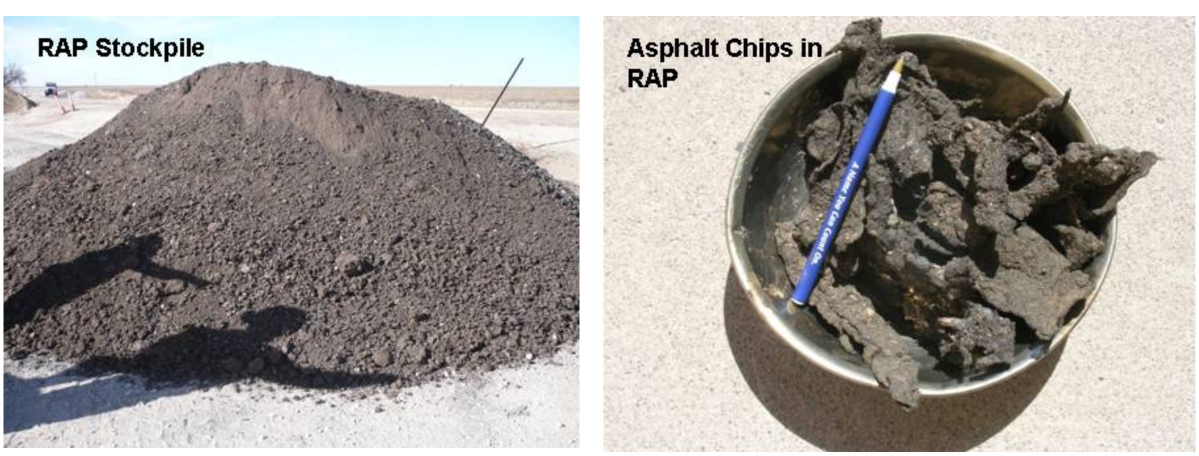


Figure 3.3 – Lubbock RAP and Asphalt Chips in RAP

Gradation

For a compacted mix of granular base material, the particle size distribution is an indication of mechanical stability of the mix. However, the significance of the gradation of RAP on the engineering properties and performance characteristic of a RAP mix (especially high RAP content mix) treated with cement has not been rigorously studied.

Sieve analysis (by adding #200 sieve to the stack) was conducted on each sample randomly collected from each RAP stockpile in order to investigate the variability in gradation. As an example, the results from sieve analyses on Lubbock RAP are shown in Figure 3.4. For comparison, the upper and lower limits of particle sizes for Grade 1 base materials required by TxDOT Specification Item 247 are also included in this figure.

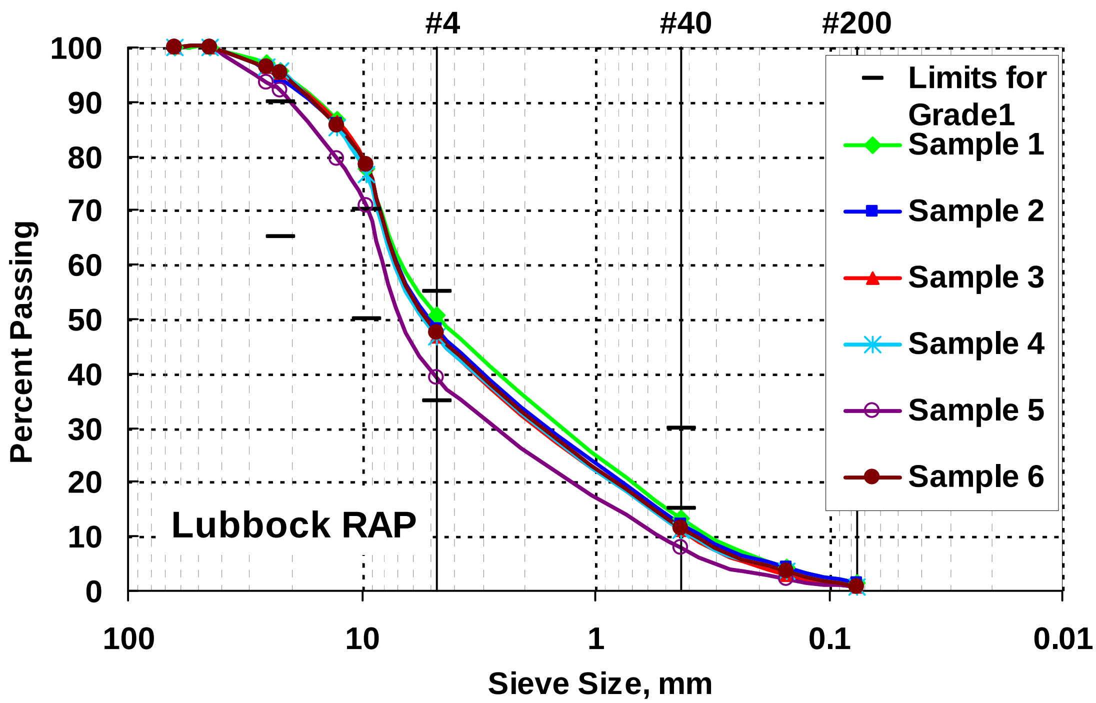


Figure 3.4 – Gradations of RAP Collected from Different Locations at Lubbock Stockpile

Figure 3.5 shows the average gradations of the RAP from all the six stockpiles. The variation in gradation among all six RAP materials is not very large and the largest deviation in particle size occurs around 0.2 in. (#4 sieve) with a maximum difference of about 15%. For all of the RAP materials, the particles passing #40 sieve are considerably less than 15% which is the lower limit for Grade 1 base in Item 247.

To compare the gradations of the six RAP materials with the gradations of granular base materials, the gradations of the eight base materials used in this study are also included in Figure 3.5. In the figure, letters V and R stand for virgin and recycled (salvaged), respectively. Unlike the RAP materials, most of the granular base materials meet or marginally meet the Grade 1 gradation requirement of Item 247.

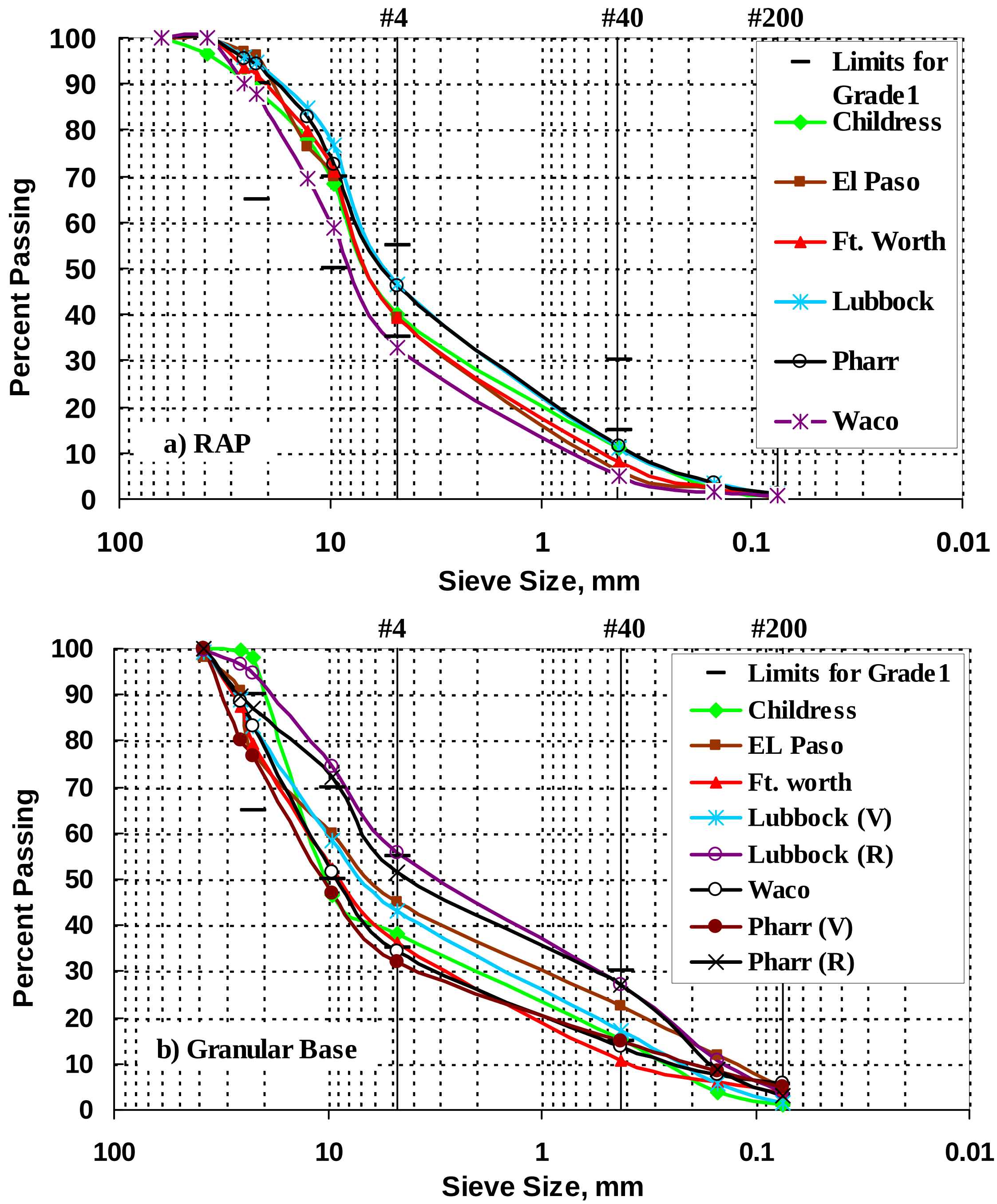


Figure 3.5 – Comparison of Gradations of RAP and Granular Base Materials

To have a clearer insight into the matter, the particle size distributions of the RAP materials from the six stockpiles are presented in Figure 3.6 by using the terms of gravel, coarse sand, fine sand and fines. The lack of finer aggregates, in particular, fines (particles passing #200 sieve) is the common characteristic of all RAP materials. This is highly consistent with the result from a previous study (Rathje et al., 2002) as shown in Figure 2.2.

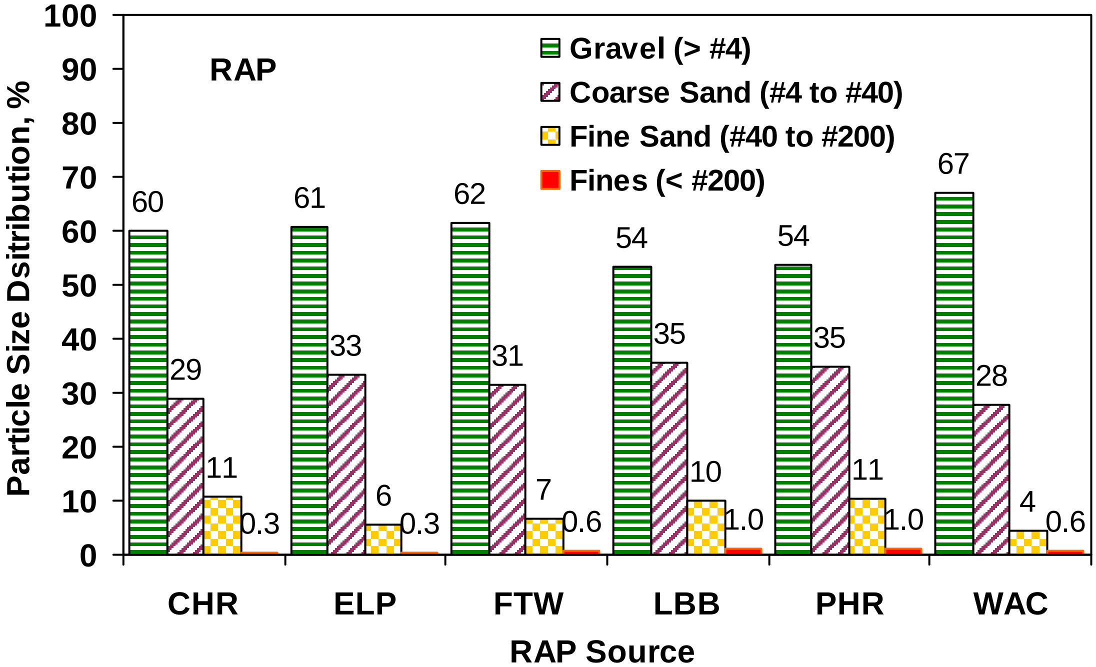


Figure 3.6 – Average Particle Size Distributions of RAP Materials

It should be noted that there are no links between the gradation and asphalt content of RAP. For example, the asphalt contents are 7.9% for the Lubbock RAP and 4.8% for the Pharr RAP, the gradations of the two RAP materials, as shown in Figure 3.7, are very similar.

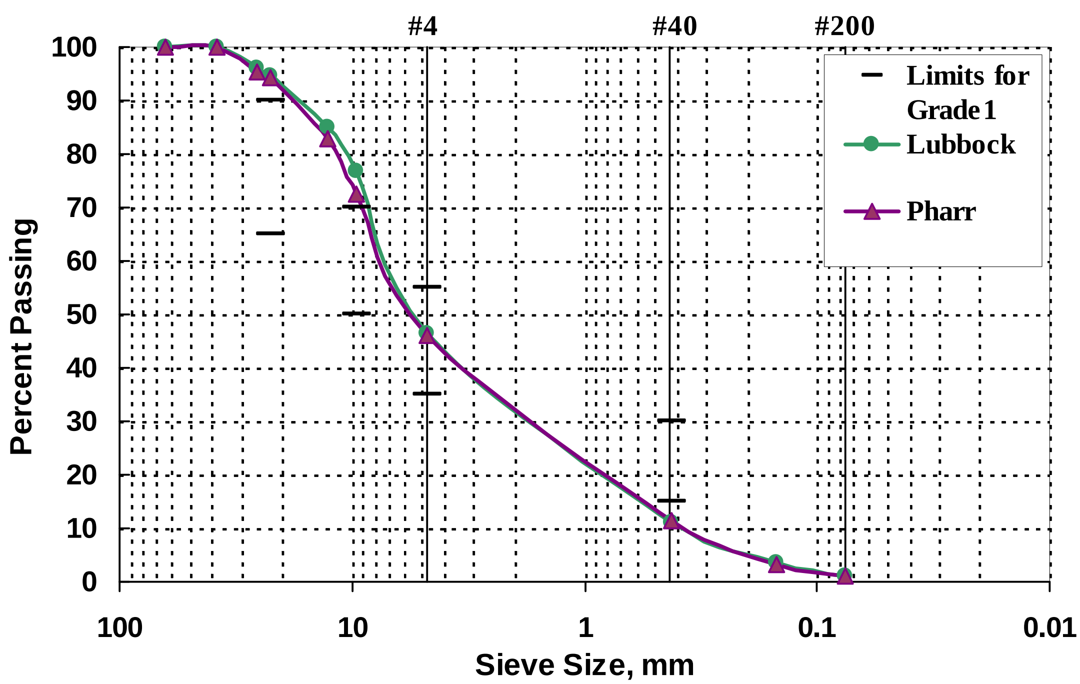


Figure 3.7 – Comparison of Gradations of RAP

The gradation of the original or recovered aggregate of RAP after oven burning is a different matter. Figure 3.8 shows a comparison of gradations of recovered aggregates from Lubbock and Pharr RAP materials. The recovered aggregate from Lubbock RAP is finer than that from Pharr RAP for all particle sizes.

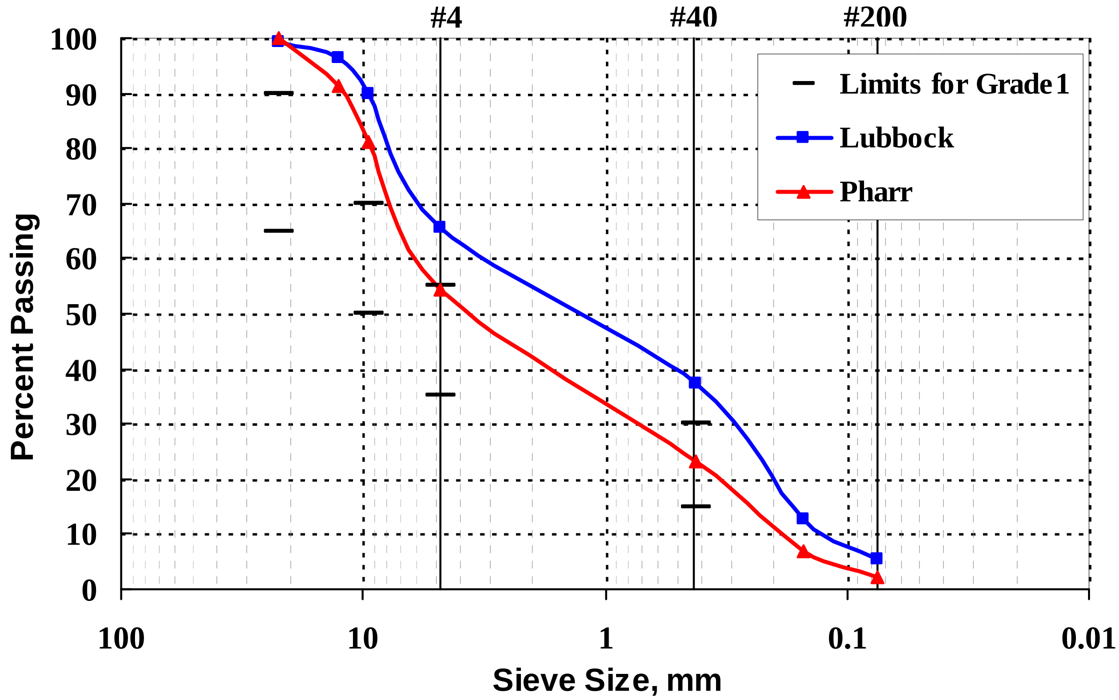


Figure 3.8 – Comparison of Gradations of Recovered Aggregates of RAP

Sand Equivalency

For HMA aggregate, excessive clay-like fine particles (low sand equivalent value) can contribute to a lack of stability (rutting or shoving) or moisture damage and stripping. For RAP mixes in base course application, the sand equivalency of a RAP material may have different meaning.

Tests for sand equivalent values of RAP materials were performed as per TxDOT Test Procedure Tex-203-F. For each RAP material, six samples were tested. The average sand equivalent values for the six RAP materials with plus and minus one standard deviation are shown in Figure 3.9. In general, the sand equivalent values are quite high, which is consistent with the results from the sieve analysis of the RAP materials.

Summary

The RAP variability was evaluated in terms of gradation, asphalt content and sand equivalency based on the RAP materials collected from stockpiles in six districts. The significance of these parameters and their effects on RAP mixes used as base materials, particularly when mixes contain high RAP content and treated with cement, will be discussed in Chapter 4.

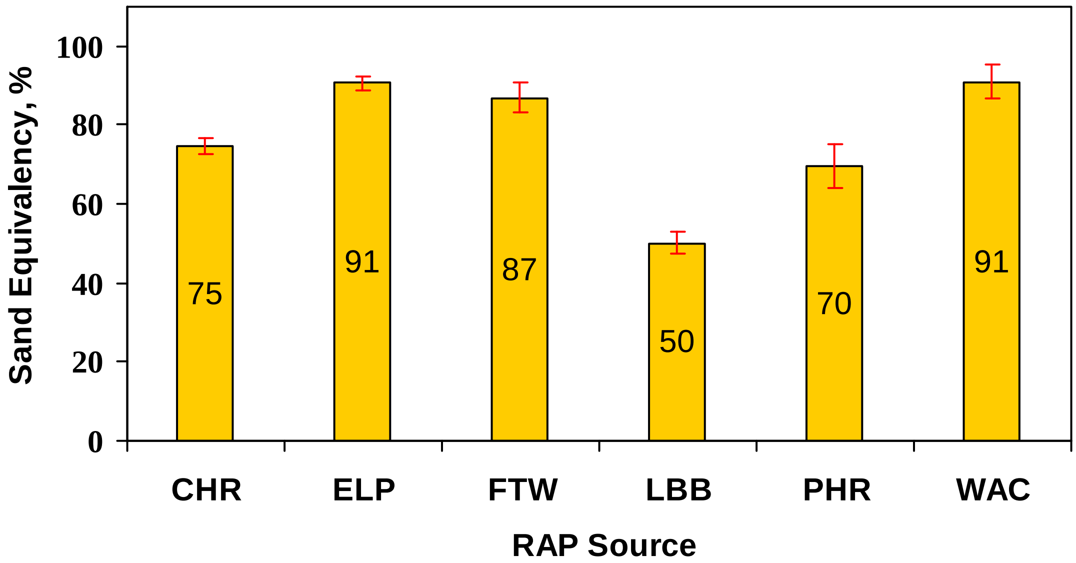


Figure 3.9– Sand Equivalent Values of RAP Materials from all Six Stockpiles

Chapter 4

RAP Mixes and Mix Design

Introduction

Performance of a flexible pavement can be largely attributed to the performance of its foundation, which is comprised of the base layer and subgrade. As documented in Guidelines for Modification and Stabilization of Soils and Base for Use in Pavement Structures (TxDOT, 2005), a base layer must provide the followings:

- ***shear strength*** *– ability to resist shear stresses developed as a result of traffic loading,*
- ***modulus (stiffness)*** *– ability to respond elastically and minimize permanent deformation when subjected to traffic loading,*
- ***resistance to moisture*** *– the ability to resist the absorption of water, thus maintaining shear strength and modulus, and decreasing volumetric swell,*
- ***stability*** *– the ability to maintain its physical volume and mass when subjected to load or moisture, and*
- ***durability*** *– the ability to maintain material and engineering properties when exposed to environmental conditions such as moisture changes.*

To achieve these objectives and to develop realistic mix designs for stabilized RAP mixes, a number of parameters which are more or less relevant to performance, long-term durability and certain environmental concern was considered. These parameters are necessary for a comprehensive evaluation of mixes containing high RAP contents (50% or more) but may not lend themselves to the day-to-day mix design and operation by TxDOT. These parameters and the related tests for measuring them are listed in Table 4.1. On the other hand, in the current TxDOT specifications for cement-treated base mixes such as Specification Item 276, only one performance parameter, unconfined compressive strength, is quantitatively required. This parameter was evaluated and used as a base for other parameters.

In this chapter, results from laboratory evaluation on Parameters 1 through 8 in Table 4.1 are represented and discussed. Based on the results, statistical model of mix design for mixes of

Table 4.1 – Parameters and Testing Methods for RAP Mixes

Parameter	Test Method/Procedure
1. Gradations of RAP and Base	Tex-110-E (by adding #200 sieve)
2. Asphalt Content in RAP	NCAT Ignition Oven (Tex-236-F)
3. Moisture-Density Characteristics	Tex-113-E
4. Unconfined Compressive Strength	Tex-117-E and Tex-120-E
5. Indirect Tensile Strength	Tex-226-F and Tex-120-E
6. FFRC Modulus	Draft Tex-148-E (Free-Free Resonant Column or FFRC Test)
7. Resilient Modulus and Permanent Deformation	AASHTO T 307
8. Moisture Susceptibility: Dielectric Constant Retained Strength Retained Modulus Permeability (Hydraulic Conductivity)	Draft Tex-144-E (tube suction test) and ASTM D-6525
9. Long Term Durability: Retained Strength Volume Change	ASTM D 559 (Wet-Dry Test)
10. Asphalt-Cement Compatibility	X-Ray Diffraction and Scanning Electron Microscope
11. Leachability (permanency of cement stabilization	UTA Test Setup and Procedure

different levels of RAP contents is provided. Evaluations of Parameters 9 through 11 in Table 4.1 are presented in Chapter 5.

Factorial of Testing

RAP Content

Mixes containing 100%, 75% and 50% RAP were considered. For 75% and 50% RAP mixes, both virgin and salvage (when available) granular base materials were used. In addition, for the El Paso materials, an effort to develop an optimized mix that met closely the average gradation of Specification Item 247 for Grade 1 base was made. This effort resulted in a mix consisting of 60% RAP and 40% granular base.

Cement Content

Four levels of cement content, 0%, 2%, 4% and 6% by dry weight, were used for all mixes except for 100% RAP. Stable specimens could not be made with the untreated (0% cement) 100% RAP. Since six RAP materials and eight granular base materials were used in this project there are 18 (3 x 6) mixes for 100% RAP, 32 (4 x 8) mixes for 75% RAP and 32 (4 x 8) mixes for 50% RAP.

Other Additives

Cement is the most robust additive in terms of construction for many base stabilization projects. However, because of the concerns with the availability and cost, it would be prudent to explore the possibility of utilizing other calcium-based additives to stabilize RAP mixes. Some TxDOT districts (e.g., Lubbock and Amarillo) have long preferred fly ash to cement because of the rich resources and low cost. For this reason, two trial mixes from El Paso materials with 7% fly ash were evaluated. The two mixes are 100% RAP and the optimized one (60% RAP blended with 40% granular base).

Description of Testing

Moisture-Density Characteristic

Based on the study on the El Paso materials, the optimum moisture contents (OMC) and maximum dry densities (MDD) were determined (TxDOT Test Procedure Tex-113-E) in a simplified manner. For each RAP content, moisture-density curves were developed on the mixes with 0% and 6% cement contents. The OMC and MDD values for mixes with 2% and 4% cement contents were estimated through linear interpolation of the OMC and MDD values obtained from the mixes of 0% and 6% cement contents. To get early-age information on strength and modulus, the specimens used for moisture-density tests were also subjected to modulus and strength tests at their ages of 24 hrs.

Strength

TxDOT Specification Item 276 requires a 7-day unconfined compressive strength (UCS) of 300 psi as per TxDOT Test Procedure Tex-120-E for Class L cement-treated base materials. This is the only quantitative requirement for engineering properties of RAP mixes. In this evaluation program, the criteria for cement content, modulus, moisture susceptibility, durability and other parameters will be established on the basis of this UCS criterion. Each of the specimens for the UCS test was 6 in. in diameter and about 8 in. in height.

It was reported that the indirect tensile strength (ITS) was a primary parameter for evaluation and qualification of asphalt emulsion-treated base mixes including those containing RAP up to 80% (Franco et al., 2009). To study the significance of this parameter for cement-treated RAP mixes, the ITS tests as per TxDOT Test Procedure Tex-226-F were performed for all mixes. Each of the specimens for ITS test was 6 in. in diameter and about 4.5 in. in height.

Modulus and Permanent Deformation

Moduli of stabilized materials can be measured through resilient modulus (RM) tests (AASHTO T 307) and free-free resonant column (FFRC) test (draft TxDOT Test Procedure Tex-148-E).

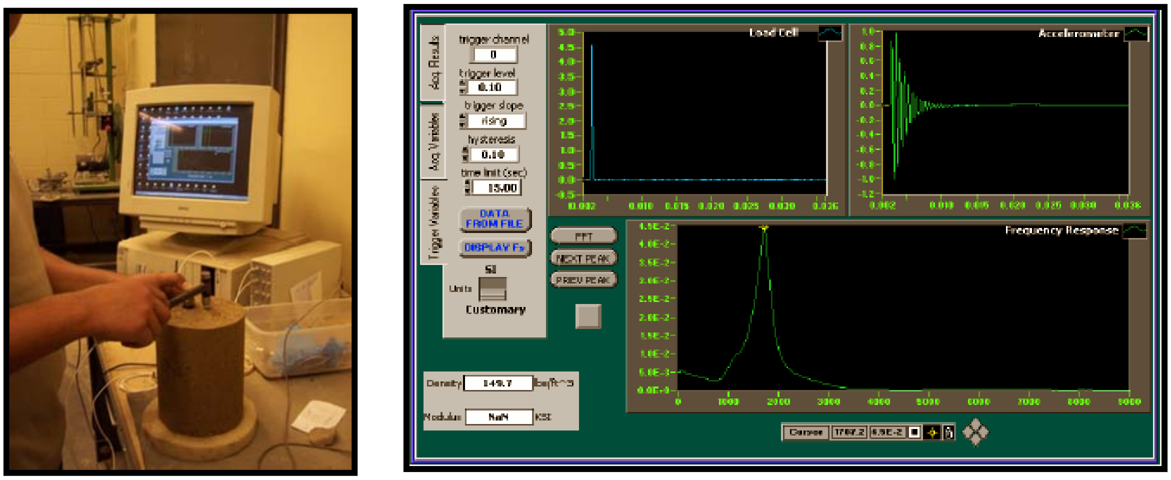
The RM test is a widely accepted testing method since it attempts to simulate vehicular loading conditions on pavement structures even though the test is time consuming, complicated and less accurate, particularly for stabilized materials. As part of a comprehensive evaluation program in this study, the RM-permanent deformation test was applied to those mixes with the optimum cement contents or with maximum cement content of 4%. Each of the specimens for the RM test was 6 in. in diameter and about 12 in. in height. Figure 4.1 shows the equipment and setup used for RM- permanent deformation test in this study.

Figure 4.1 – Equipment and Setup for Resilient Modulus and Permanent Deformation Tests

The FFRC test is rapid, reliable and easy to perform for stabilized materials (see Figure 4.2). FFRC tests were performed on all UCS and RM specimens prior to UCS and RM testing to see the feasibility for establishing the relationships between the moduli from the FFRC test and RM tests and further for the relationship between the results from the laboratory and field modulus tests. This test was performed on a daily basis.

Moisture Susceptibility

Moisture susceptibility is a major concern in the use of RAP mixes in pavement base courses. This parameter was evaluated in two different manners: through moisture-conditioning using the tube-suction test (similar to the procedure described in Draft Tex-144-E) and by saturating the specimens using the hydraulic conductivity test (e.g., ASTM D 6525). These two tests were applied to mixes with the optimum cement contents.



a) FFRC Test

b) Records from a FFRC Test

Figure 4.2 - Free-Free Resonant Column (FFRC) Test

Outputs from the tube-suction test on moisture-conditioned specimens include the retained strength, retained FFRC modulus and dielectric constant. The retained strength is here defined as the ratio (in percentage) of the UCS measured after a 2-day oven curing and an 8-day capillary moisture conditioning to the UCS measured as per TxDOT Test Procedure Tex-120-E. The current acceptance criterion for retained UCS is about 80%. It would seem reasonable to propose the same criterion for the retained ITS and FFRC modulus.

The hydraulic conductivity test (see Figure 4.3) takes a direct way to characterize the moisture susceptibility of a compacted material (unsaturated or saturated) by measuring the speed of water flow through pore spaces in the material. Hydraulic conductivity of a granular material is directly related to the percentage of fines (particles passing #200 sieve) present in the material (Trzebiatowski and Benson, 2005). To study this parameter, a backpressure moisture conditioning system (Veisi et al., 2010) was used. Each of the specimens for this test was 6 in. in diameter and about 4.5 in. in height.

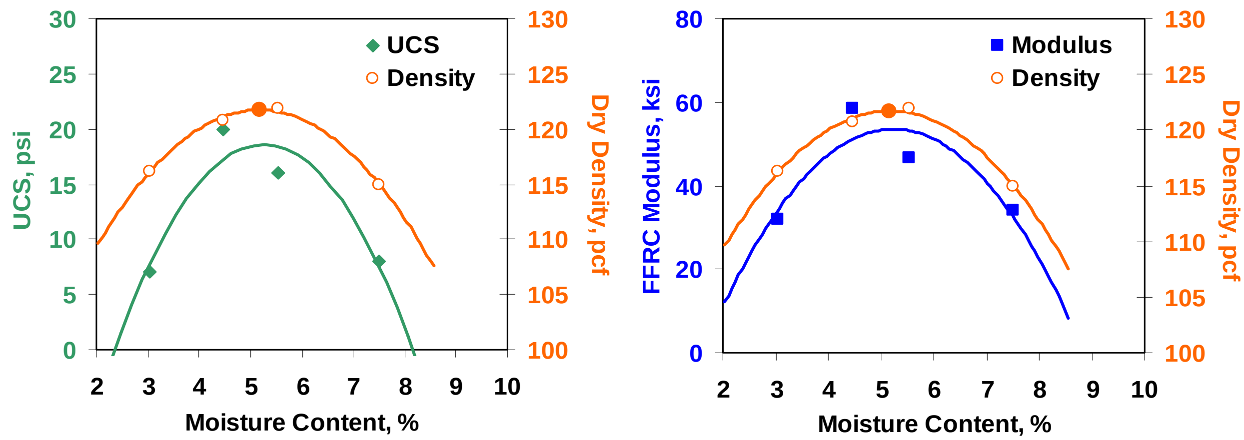
Figure 4.3 – Setup for Hydraulic Conductivity Test

Presentation and Discussions of Results

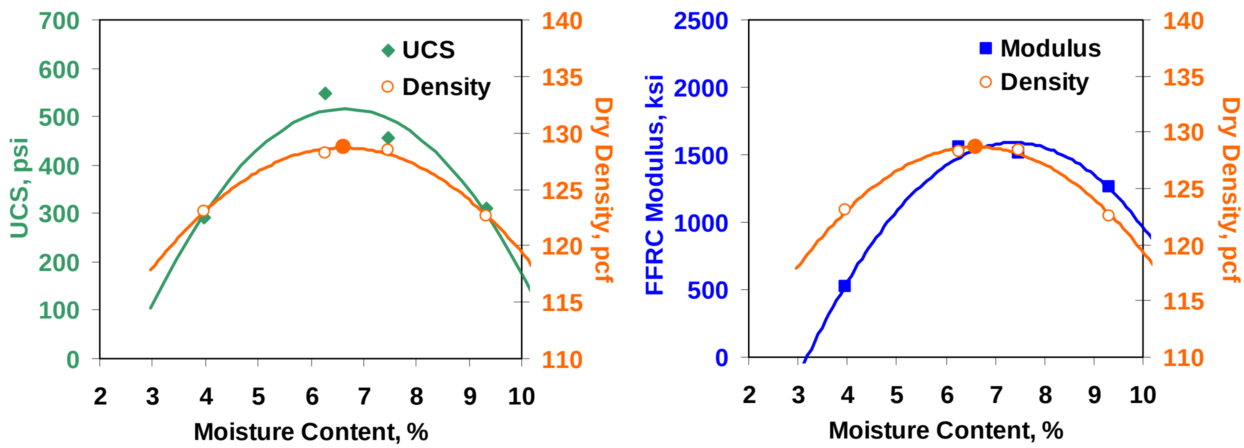
Moisture-Density Characteristics

Moisture-density characteristics of compacted RAP mixes include the effects of RAP content and cement content on the OMC and MDD. As an example, Figure 4.4 shows the moisture-density curves of mixes without chemical treatment (0% cement) and treated with 6% cement. The mixes consisted of 75% RAP and 25% virgin base from the Fort Worth stockpiles.

The variations of the 24-hour FFRC modulus and UCS are also included in this figure. The significance of including the 24-hour modulus and strength measurements in the moisture-density test is that they can be used to predict approximately the 7-day modulus and strength for cement-treated mixes. For instance, as shown in Figure 4.4b, the maximum UCS and FFRC modulus are about 510 psi and 1590 ksi, respectively, which are 63% of the 7-day UCS (816 psi) and 71% of the 7-day FFRC modulus (2216 ksi). The two ratios gradually decrease as cement content decreases.



a) Without chemical treatment



b) Treated with 6% cement

Figure 4.4 – Moisture-Density and 24-hour UCS and FFRC Modulus Curves

The variations in OMC and MDD with RAP contents in the untreated mixes (0% cement) are summarized in Figure 4.5. The granular materials in these mixes are the local virgin bases. In general, both OMC and MDD decrease as RAP content increases except for OMC with Fort Worth mixes. The observations on OMC and MDD are consistent with those obtained by Papp et al. (1998), Cooley (2005), and Bennett and Maher (2005).

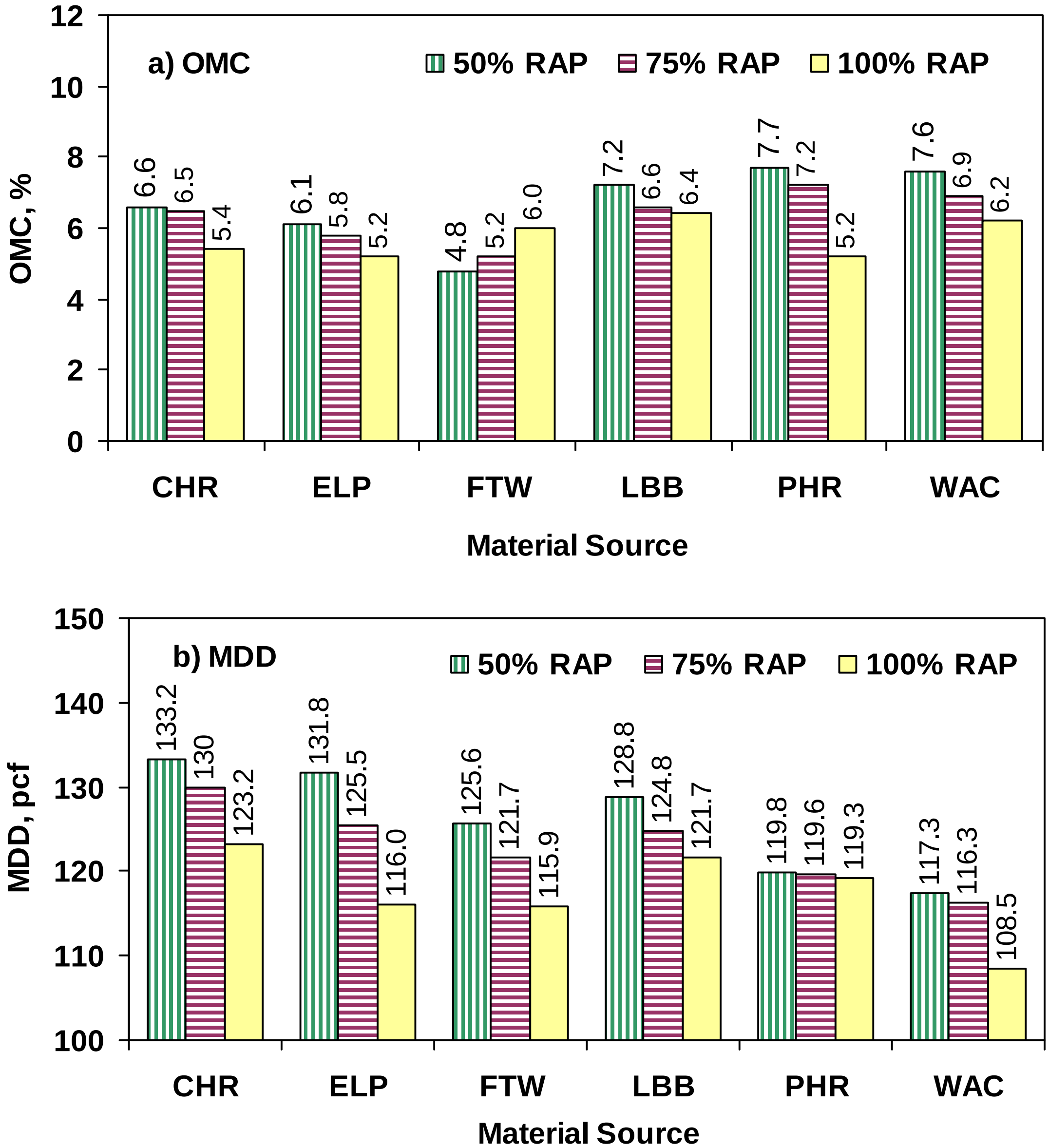


Figure 4.5 – Variations of OMC and MDD with RAP Content in Untreated Mixes

Figure 4.6 compares the OMC and MDD for mixes of 100% RAP without chemical treatment and with 6% cement. Both the OMC and MDD of all mixes with 6% cement are higher than those without treatment. A similar trend was also observed on other RAP blended mixes used in this study. The average differences are about 1.2% for OMC and 4 pcf for MDD; that is, about 0.2% increase in OMC and 0.7 pcf increase in MDD for each 1% cement increment. In practice, if only one MD curve is determined for a RAP mix without chemical treatment, An increase of about 0.2% for each percentage of cement increase can be used for cement treatment, depending on the content of the finer aggregate in the mix.

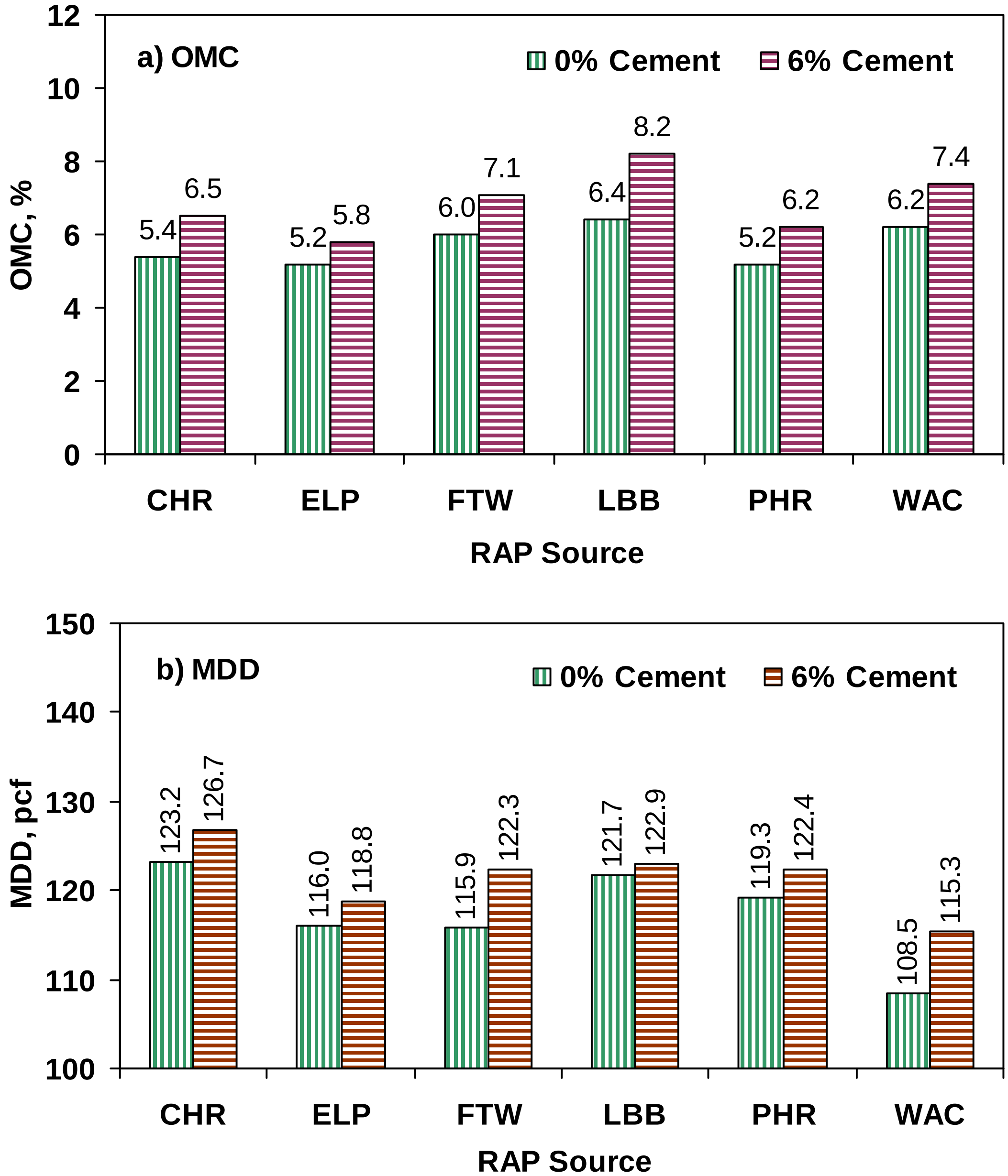


Figure 4.6 – Comparisons of OMC and MDD of 100% RAP Mixes without Treatment and Treated with 6% Cement

Strength and Modulus vs. RAP Content and Cement Content

In terms of average, results from the UCS, ITS and FFRC modulus tests on all mixes of different cement contents and different RAP contents are summarized in Figure 4.7 and Table 4.2.

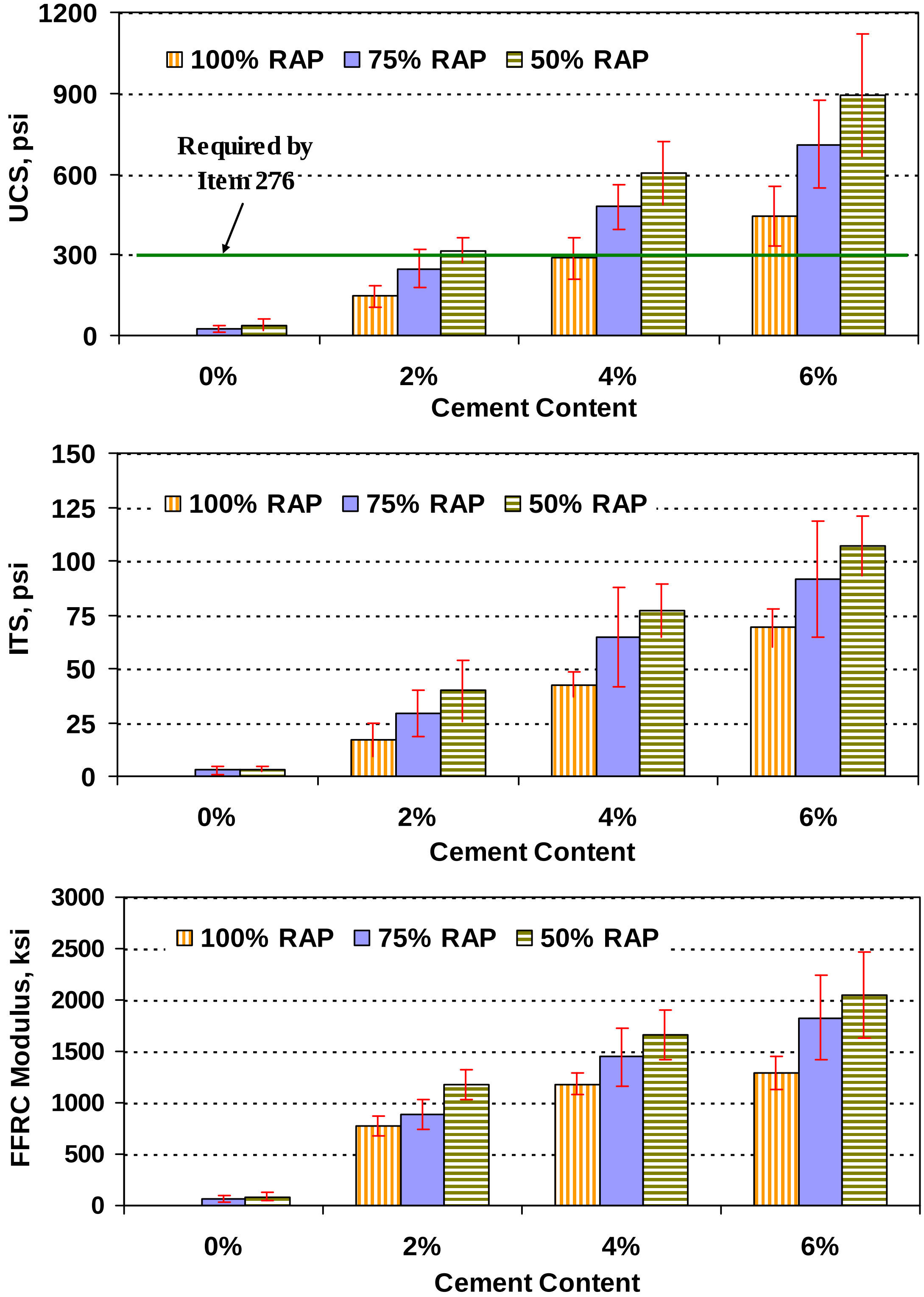


Figure 4.7 – Variations of Average UCS, ITS and FFRC Modulus with Cement Content for All mixes

The error bars in Figure 4.7 represent plus and minus one standard deviation. The large values of coefficient of variation, COV, can be attributed to the variability in the RAP and granular base materials from different sources. The larger variations for the ITS may also be attributed to the mechanism of indirect tensile testing.

Table 4.2 – Statistical Information on UCS, ITS and FFRC Modulus for all Mixes

Parameter	Cement Content	Mix					
		100% RAP		75% RAP		50% RAP	
		Mean	COV	Mean	COV	Mean	COV
UCS (psi)	0%	Not Tested*		24	48%	39	59%
	2%	146	27%	249	28%	316	14%
	4%	286	26%	479	17%	601	19%
	6%	441	25%	711	23%	894	25%
ITS (psi)	0%	Not Tested*		3	-**	3	-**
	2%	17	45%	29	36%	40	36%
	4%	43	13%	65	36%	77	16%
	6%	69	13%	91	29%	107	13%
FFRC Modulus (ksi)	0%	Not Tested*		67	50%	84	45%
	2%	631	16%	886	17%	1172	25%
	4%	1029	11%	1445	19%	1663	15%
	6%	1307	12%	1828	23%	2047	20%

*** -** Stable specimens could not be made. **** -** Strengths are within margin of error of ITS test.

The results from the optimized mix (60% RAP blended with 40% granular base) are similar to those from the mix of 50% RAP for El Paso materials, and thus are not included in the Statistics.

Mix Design Model

Based on the results from the full-factorial laboratory experiment summarized above, a preliminary model of mix design for cement-treated RAP mixes was developed. Figures 4.8a shows the variations in the average UCS values with cement content for mixes of different RAP contents. Linear relationships represent well the variations of average UCS with cement content for all mixes. In terms of per one percent cement by weight, the average rates of increase in UCS (the slopes of the lines which are not shown in the figure) are as follows:

- 73 psi for 100% RAP content,
- 115 psi for 75%RAP content, and
- 145 psi for 50% RAP content

Moreover, the variations of average ITS and FFRC modulus with cement content for mixes of different RAP content are also shown in Figures 4.8. Again, linear relationships can represent the variations for these two parameters with cement content. Similarly to the UCS, the average rates of increase in these two parameters in terms of per one percent cement can be obtained. The results shown in Figure 4.8 indicate that:

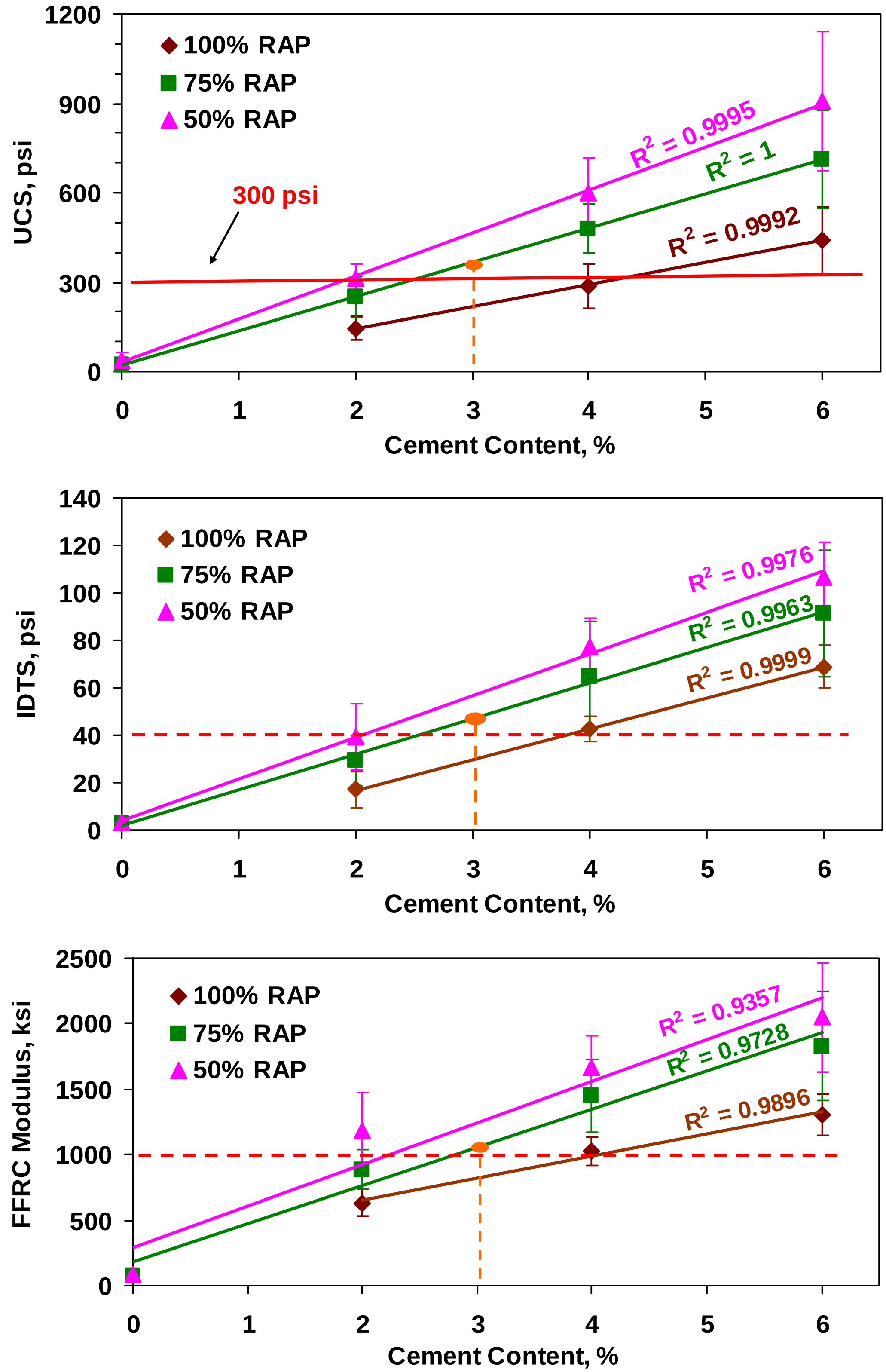


Figure 4.8 – Relationships between of Average UCS, ITS and Modulus and Cement Content

1. In terms of average values, the results from the UCS, ITS and FFRC modulus tests are highly consistent.
2. For a 300-psi UCS requirement (Item 276), the preliminary optimum cement contents are about 4%, 3% and 2% for mixes with 100% RAP, 75% RAP and 50% RAP, respectively.
3. Corresponding to a 300-psi UCS value, the ITS would be about 40 psi and the FFRC modulus would be about 1000 ksi.
4. If a minimum UCS of 175 psi (for Class M as per Item 276) or other value is required, the optimum cement content can also be estimated from the figure.

Such relationships, however, need to be further refined or modified when a larger database becomes available. It should also be noted the large standard deviation associated with each average value. This means that the typical cement contents proposed in Item 3 should be validated through laboratory tests for a given mix before they are used in construction. As shown later in this chapter, the content of total finer aggregates in a RAP mix is an important factor to be considered.

Resilient Modulus and Permanent Deformation

The mixes subjected to resilient modulus and permanent deformation tests and the results from the tests are summarized in Table 4.3. These mixes either met the UCS requirement of 300 psi with minimum cement content or had maximum cement content up to 4% for practical consideration. With 4%-cement treatment, most mixes met that requirement. The results indicate that the resilient modulus increases as the RAP content decreases in RAP blends treated with the same level of cement content, which is consistent with those reported by several previous studies (e.g., Hanks and Magni, 1989; Taha et al., 1999; Mokwa and Peebles, 2005; Bennett and Maher, 2005). However, there is no certain pattern for the relationship between permanent deformation and RAP content.

Figure 4.9 shows the relationships between individual values of RM and individual values of UCS and FFRC modulus. With linear fitting, the R^2 are about 0.8 for the RM-UCS relationship and close to 0.6 for the RM-FFRC modulus one. In general, the relatively low R^2 can be attributed to the measurement errors and the difference in specimen compaction. Despite the low R^2, a UCS of 300 psi or a FFRC modulus 1000 ksi is corresponding to a resilient modulus of about 250 ksi, which further substantiates the results shown in Figure 4.8.

Moisture Susceptibility

The mixes listed in Table 4.3 were also subjected to moisture susceptibility (tube-suction and hydraulic conductivity) tests.

Retained Strength and Modulus

The average retained values of UCS, ITS and FFRC modulus for all mixes subjected to the tube-suction moisture conditioning are shown in Figure 4.10. All these values are observed to meet, or closely meet the acceptance criterion of 80% The relatively small retained ITS can be attributed to the shorter specimen heights relative to those used for the UCS and modulus tests, hence capillary moisture is expected to have more effect on the properties of these specimens.

Table 4.3 – Statistical Information on UCS, RM and Permanent Deformation

Material Source	RAP Content (%)	Cement Content (%)	UCS (psi)	RM (ksi)	Permanent Deformation (micro)
Childress	100	4	392	323	124
	75 (VB)	4	495	412	95
	50 (VB)	4	551	431	30
El Paso	100	4	182	231	328
	75 (VB)	4	465	253	168
	50 (VB)	2	301	269	249
Fort Worth	100	4	250	245	375
	75 (VB)	4	424	474	218
	50 (VB)	2	342	287	377
Lubbock	100	4	303	264	468
	75 (VB)	4	379	356	124
	50 (VB)	4	438	378	123
	75 (SB)	4	456	403	170
	50 (SB)	4	458	388	262
Pharr	100	4	344	372	193
	75 (VB)	2	325	250	89
	50 (VB)	2	359	291	145
	75 (SB)	2	330	315	114
	50 (SB)	2	396	413	77
Waco	100	4	246	234	592
	75 (VB)	4	425	458	223
	50 (VB)	4	600	606	62

VB: blended with virgin base, SB: blended with salvage base.

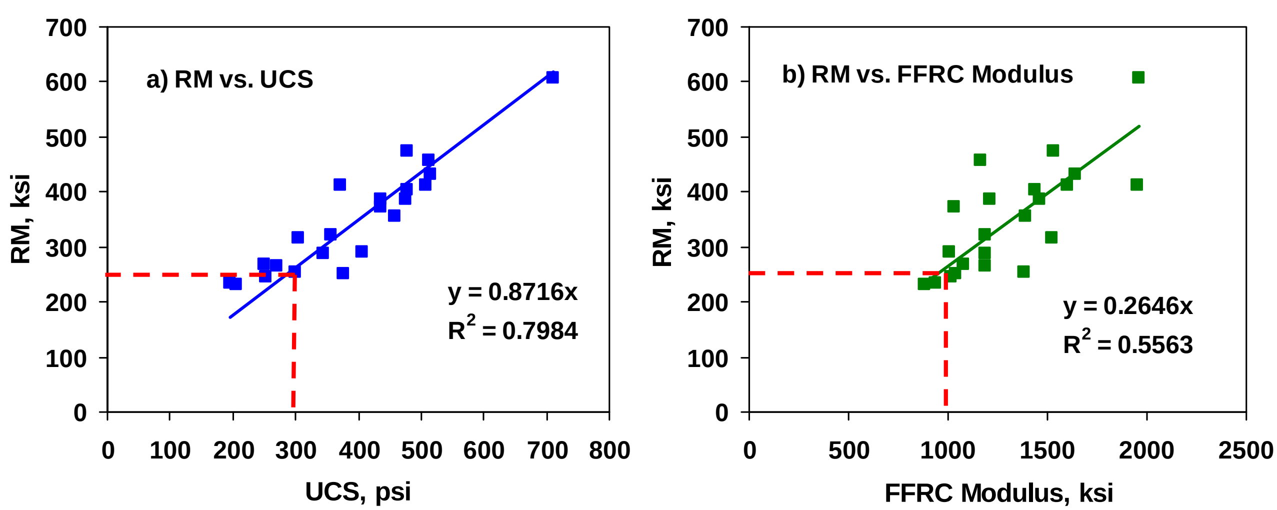


Figure 4.9 – Resilient Modulus vs. UCS and FFRC Modulus

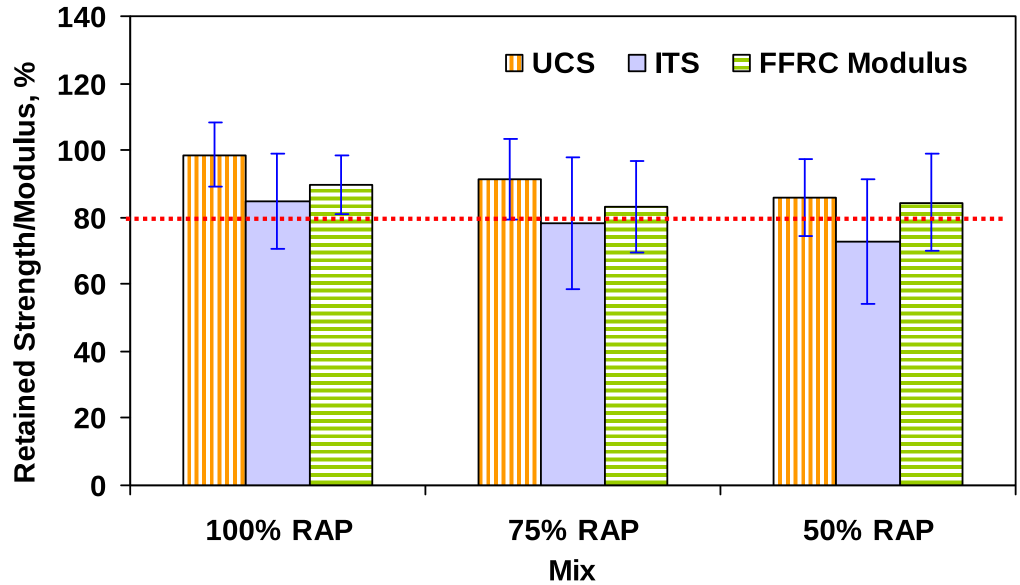


Figure 4.10 – Average Retained Strengths and Modulus

Dielectric constant measurement was applied to all specimens involved in the tube-suction study. All dielectric values were significantly less than 10 (a recommended limit by draft TxDOT Test Procedure Tex-144-E). Thus, the dielectric constant measurement seems to have less meaning for cement-treated materials.

Hydraulic Conductivity

Figure 4.11 shows the hydraulic conductivities of different mixes treated with 4% or 2 % cement. The letter S in parentheses stands for salvage bases; otherwise virgin bases were used.

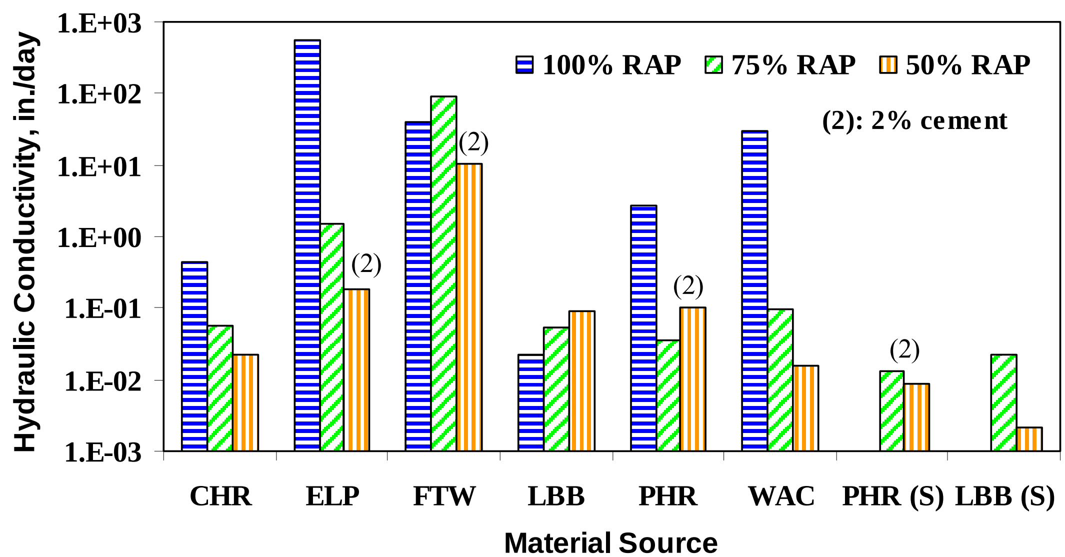


Figure 4.11– Hydraulic Conductivities of Different Mixes

In general, the hydraulic conductivity of cement-treated RAP mixes increases as RAP content increases. Except for the Lubbock and Fort Worth mixes, the 100% RAP mixes are two to three orders of magnitude more permeable than the mixes blended with aggregates. The Lubbock and Fort Worth mixes may represent the case documented by Bennett and Maher (2005). Their study showed that the hydraulic conductivity decreases as the RAP content increases.

There are no concrete acceptance criteria for hydraulic conductivity of cement-treated RAP mixes. Some hydraulic conductivity values of untreated 100% RAP mixes under standard proctor compaction have been reported and cover a range from 2.4 x 10^{-5} m/s (82 in./day) to 9.0 x 10^{-5} m/s (306 in./day) with an average of 5 x 10^{-5} m/s (170 in./day) (Trzebiatowski and Benson, 2005). As shown in Figure 4.11, the hydraulic conductivity of the mixes consisting of 100% RAP and treated with 4% cement varied widely from less than 1 in./day for the Childress and Lubbock RAP and to 560 in./day for the El Paso RAP.

Factors Affecting Strength and Modulus

Asphalt Content

As reflected in Figure 3.2, the asphalt contents of the RAP materials collected from the six districts cover a quite large range from 4.7% to 7.9%. The effects of asphalt content on the strength and modulus of mixes consisting of 100% RAP are shown in Figures 4.12 and 4.13. Both strength and modulus are independent from asphalt content, regardless of the level of cement treatment. Even not included here, the similar patterns were also observed for the ITS.

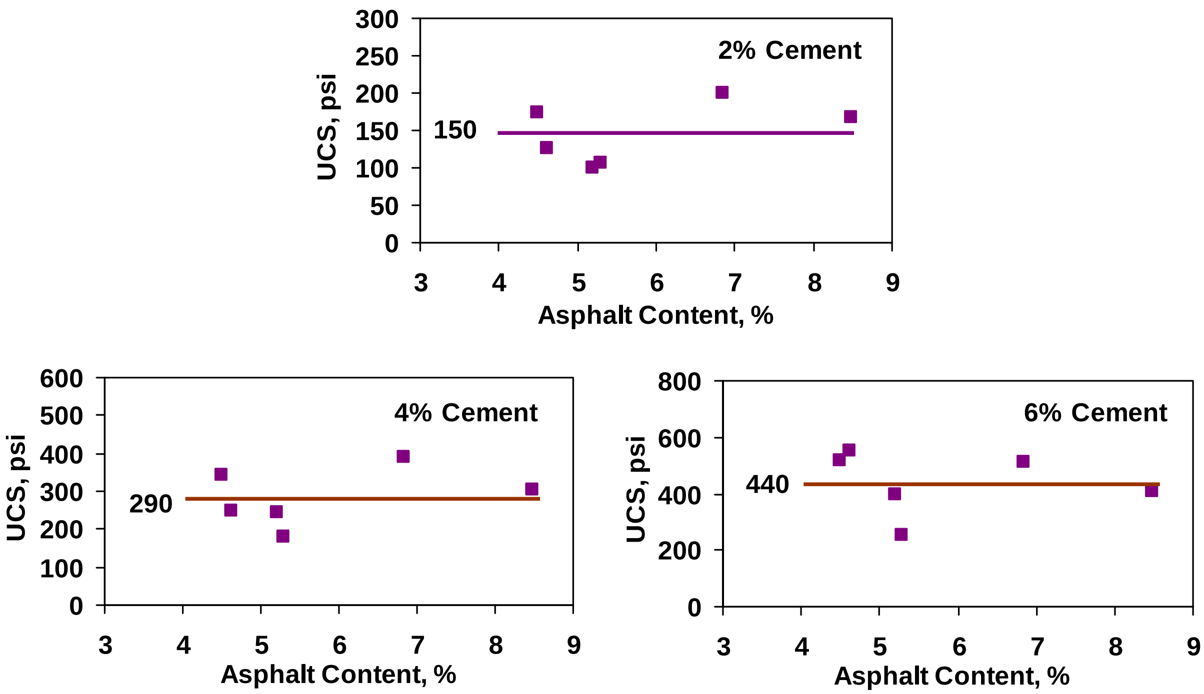


Figure 4.12 – Variations of UCS with Asphalt Content in Mixes of 100% RAP

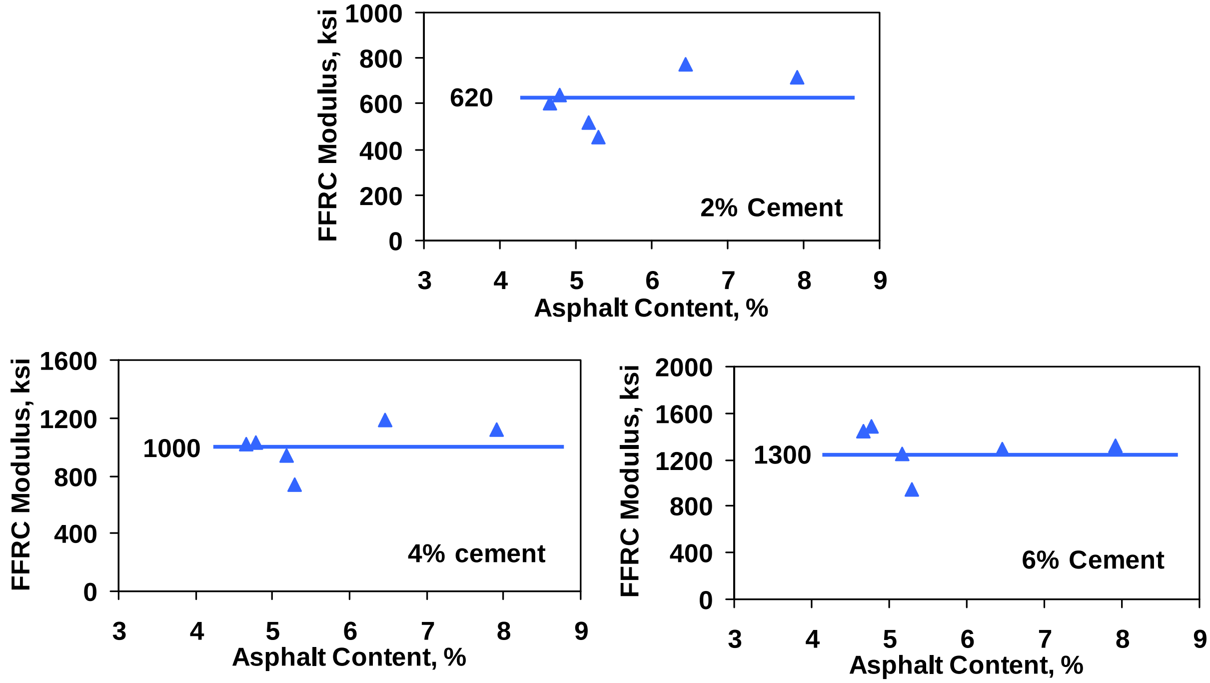


Figure 4.13 – Variations of FFRC Modulus with Asphalt Content in Mixes of 100% RAP

The independency of the strength and FFRC modulus of RAP mixes from asphalt content in RAP regardless of the level of cement treatment may also be an indirect indicator that there is no detrimental interaction of cement and asphalt binder in RAP.

Finer Aggregate Content

As show in Figure 3.5a and Figure 3.6, the lack of finer aggregates (fine sand and fines or particles passing #40 sieve) in the collected RAP materials is quite apparent. In particular, the fines (materials passing #200 sieve) from traditional sieve analysis are 1% or less. This occurs because the fines in RAP manifest themselves as larger particle sizes in the presence of binder. For the mixes of RAP only, the effect of finer aggregates on the UCS can be illustrated by Figure 4.14. Generally, the UCS increases as finer aggregates increase.

On the other hand, the fines (from 1% to 5.6%) in the collected granular base materials are significantly higher than those in the RAP materials. Thus, in the RAP blended mixes, the total fines are higher than those in the RAP only. Figure 4.15 shows the effect of fines content on strength and modulus with the mixes of the El Paso materials; that is, both UCS and FFRC modulus increase as fines content increases.

The effect of finer aggregates in cement treatment RAP mixes can also be verified in an alternative manner. That is, simply adding a certain amount of finer aggregates from local quarries to the RAP to improve the gradation so that the mix has 15% particles passing #40 sieve and 5% particles passing #200 sieve. Figure 4.16 shows a comparison of gradation curves of the natural RAP and RAP mixed with finer aggregates from Fort Worth District. The added materials include 6% fine sand and 5.3% fines. The same practice was applied to the RAP materials collected from the other districts. The amounts of finer aggregates added are provided in Table 4.4.

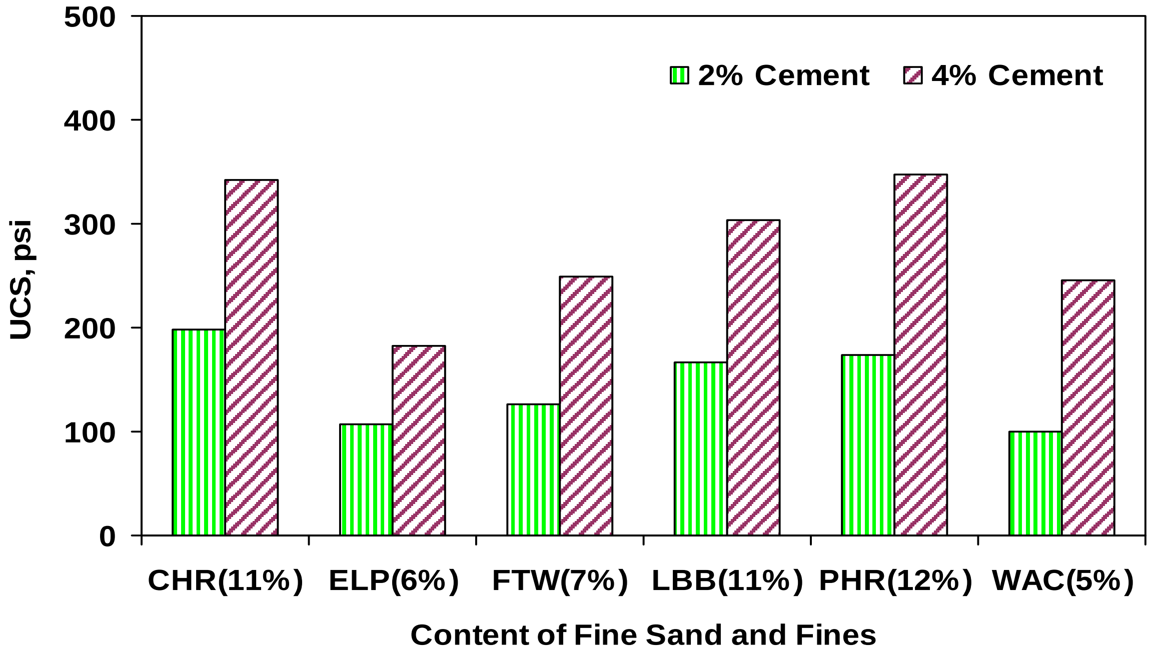


Figure 4.14 – Effect of Finer Aggregates (Passing #40 Sieve) on UCS of Mixes of 100% RAP

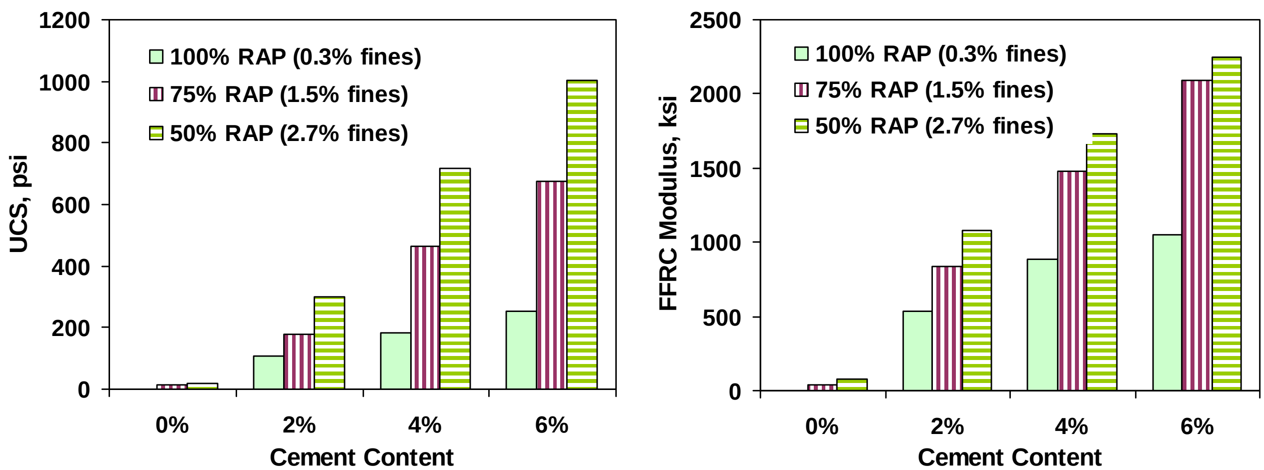


Figure 4.15 – Effect of Fines (Passing #200 Sieve) Content on UCS and FFRC Modulus of El Paso Mixes

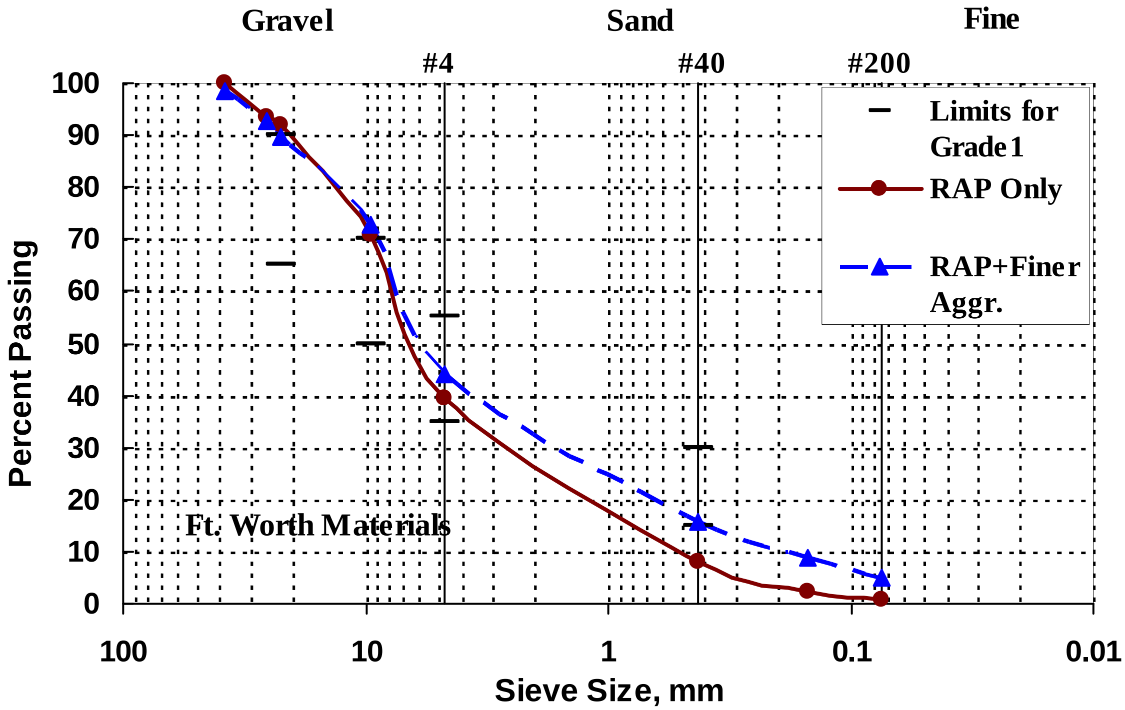


Figure 4.16 – Comparison of Gradations of Natural RAP and Modified RAP Mixes

Table 4.4 – Amounts of Fine Aggregates Added to RAP

Aggregate	Particle Size by Sieve	Finer Aggregate Added (%)				
		Childress	El Paso	Ft. Worth	Pharr	Waco
Fine Sand	#100	0	3.4	2.1	0	3.2
	#200	2	2.7	3.9	1.2	4.3
Fines	<#200	5.5	5.4	5.3	4.5	5.7
Total		7.5	11.5	11.2	5.7	13.2

Figure 4.17 represents the differences between the UCS, ITS and FFRC modulus of mixes of RAP only and the mixes of RAP blended with finer aggregates from each local base source. Two percent cement was used for all mixes. Except for the Childress and Pharr mixes, the two RAP mixes with a minimal amount of finer aggregates added, the strength and modulus are substantially higher with the addition of the finer aggregates.

Since the lack of fine aggregates is a common character of Texas RAP, a mix of RAP blended with granular base material having a certain amount of finer aggregate may significantly improve the engineering properties of the mix. In many old low volume roads in Texas, base layers were built with materials that contain relatively higher finer aggregate contents. This fact may result in cost effective rehabilitation or reconstruction of these roads with base courses of RAP mixes. Alternatively cheaper finer aggregates from quarries can be used to improve properties of RAP mixes.

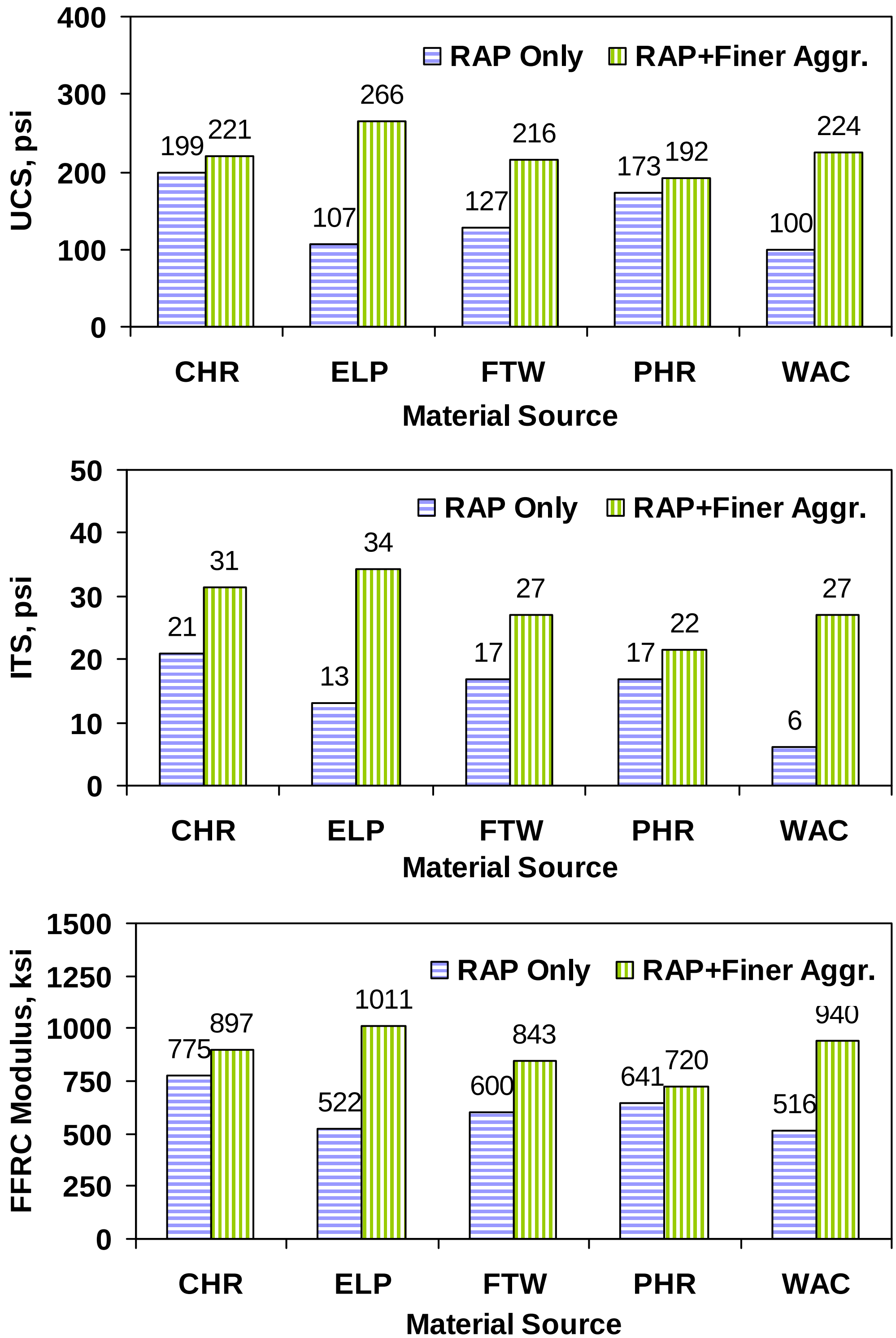


Figure 4.17 – Strength and Modulus of Mixes of RAP only and RAP Blended with Finer Aggregates

Coarser Aggregate Content

Figure 4.18 shows the gradations of RAP, salvage base and virgin base collected from Pharr District. The particle size distributions of the two base materials are very different except for the finer particles (fine sand and fines). However, with 2% cement treatment, the mix of 50% RAP plus 50% salvage base and the mix of 50% RAP plus 50% virgin base yield quite similar strength and modulus values: 396 vs. 359 psi for UCS, 51 vs. 46 psi for ITS and 1350 vs. 1233 ksi for FFRC modulus.

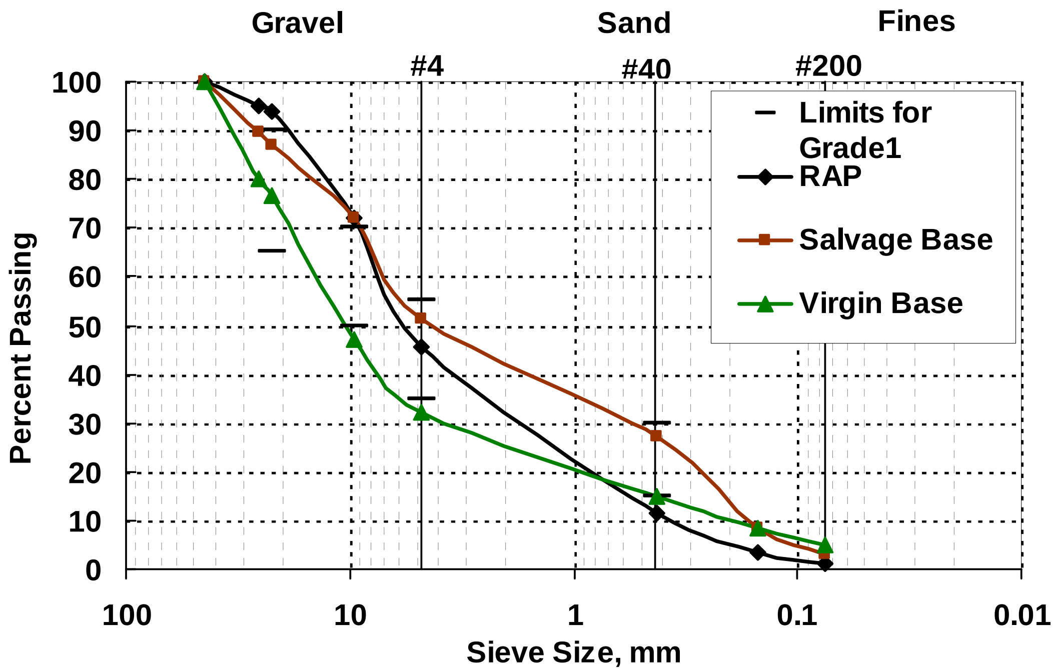


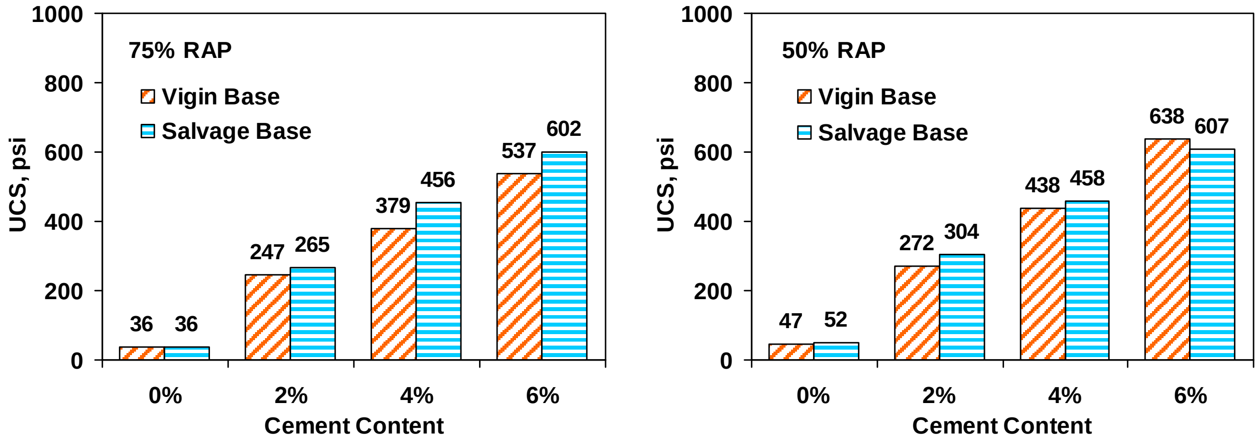
Figure 4.18 – Gradations of RAP, Salvage Base and Virgin Base from Pharr District

This example indicates that the particle size distribution of coarser aggregate has a minor impact on the strength and modulus of cement-treated RAP mixes. The significance of this phenomenon is that with cement treatment more RAP resources can be used in base course application.

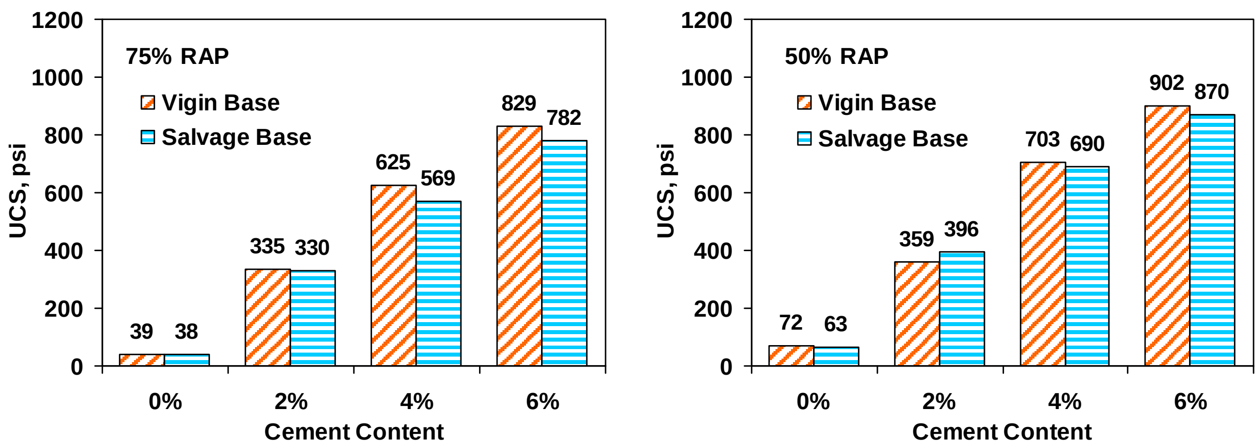
Virgin Base vs. Salvage Base

Both virgin and salvage granular base materials collected from Lubbock and Pharr Districts were blended with the local RAP from each of the two districts. Figure 4.19 indicates that the virgin and salvage granular materials blended with RAP yield similar UCS values at each cement content. The same patterns were also found for ITS and FFRC modulus as well as resilient modulus (see Table 4.3).

The significance of this result is that the use of existing (salvage) base material as opposed to transporting the virgin aggregate for roadway rehabilitation can be a cost effective way to build the new base courses with cement-treated RAP blends.



a) Lubbock Materials



b) Pharr Materials

Figure 4.19 – Comparison of RAP Blended with Virgin and Salvage Granular Base Materials

Stiffness of Aggregates

The stiffness of the original aggregate in the RAP matrix is of less a concern for RAP mixes since the quality of the aggregate used for HMA is generally higher than that used for granular bases in Texas. In fact, the breakage of the RAP aggregates has never been observed during this study, even for the mixes with 6% cement. On the other hand, the stiffness of the aggregate in the granular base material may be a concern when RAP blended base is treated with higher percentage cement and the pavement has a thin surface layer. Breaking of base aggregate in a specimen under strength testing is shown in Figure 4.20. The specimen was made from a mix consisting of 75% RAP and 25% virgin base from Waco District. The specimen has a UCS of 425 psi and an ITS of 93 psi. A similar situation also observed for the virgin base from Pharr District even when treated with 2% cement.

Figure 4.20 – Breaking of Virgin Base Aggregate in RAP Blend from Waco District

Comparison of Treatments with Cement and Fly Ash

Figure 4.21 shows a comparison of UCS values of cement-treated RAP mixes and fly ash-treated RAP mixes from El Paso materials. For the same mix of 60% RAP plus 40% base (the optimized one as mentioned early in this chapter), the UCS value of the mix treated with 7% fly ash is even less than that of the same mix without chemical treatment.

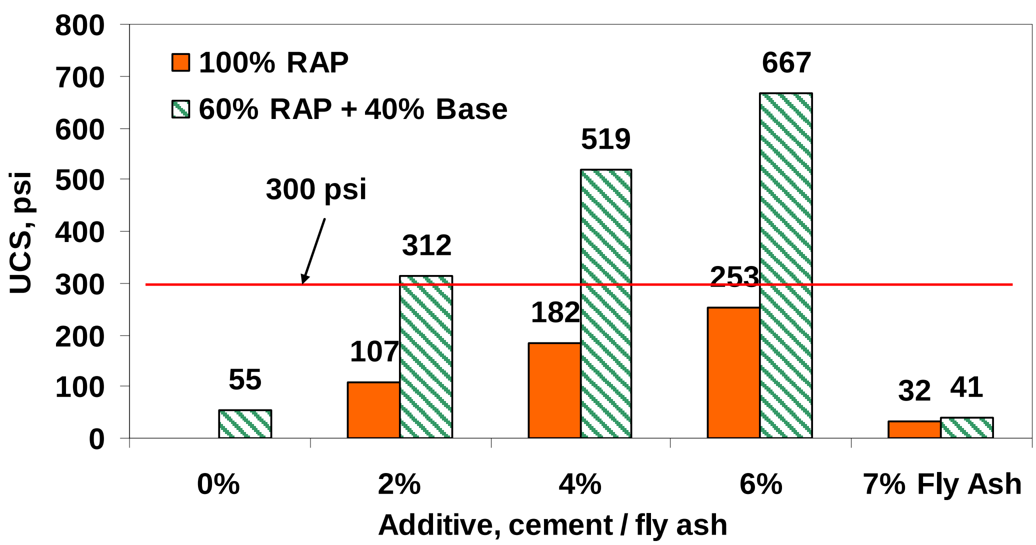


Figure 4.21 – UCS Values of Cement-Treated and Fly Ash-Treated El Paso RAP Mixes

Guidelines for Laboratory Testing and Mix Design Process

Under current TxDOT specifications, cement treated bases fall under either Item 275 (for road mix) or Item 276 (for plant mix). For road mixes, there are not enough data and experiences to make adjustment for the current Item 275. But based on this study and the previous studies at UTEP, the modified Item 275 proposed in Project 0-5223 with the modifications suggested herein to Tex-120-E (see Appendix G of Garibay et al., 2008) should be appropriate.

For the most part, the current TxDOT Specification Item 276 with some modifications is quite reasonable for cement-treated RAP mixes in the plant. According to the results from this research project, the day-to-day laboratory testing and mix design process for cement-treated RAP mixes at the TxDOT district level can be simplified. A modified version of Tex-120-E and a modified version of TxDOT Item 276 are provided in Appendix A and Appendix B, respectively.

Mix Design Process

Sieve Analysis

It is well known that for granular base materials, the gradation of aggregate is an indication of mechanical stability. However, the RAP aggregates consisting of crushed rock or gravel covered by asphalt binder exhibit mechanical properties that are much different from the aggregates in typical granular base materials. Therefore, the stiffness and mechanical stability of a cement-treated RAP mix is mainly determined by cement hydration rather than the properties and shape of the aggregate, in particular, for the mixes having high RAP content.

Attention should be paid to the percentage amounts of finer aggregates and fines in a given RAP materials, which can be used in consideration of selecting optimum granular base materials and cement content for mixing.

Development of Moisture-Density Curve

Moisture-density curve should be developed to determine the OMC and MDD as per Tex-113-E for any raw mix before it is treated with cement. Development of the moisture-density curve of a cement-treated mix may not be necessary. The OMC and MDD can be estimated on the basis of the OMC and MDD for the untreated mix as stated in this chapter.

Determination of Cement Content

It can be done on the basis of the mix design model provided in this chapter 4 in consideration of total finer aggregate content and fines content in the mix.

Strength and Modulus Tests

Compressive strength testing on the specimens of designed mix should be performed as per TxDOT Test Procedure Tex-120-E. The optional laboratory tests include indirect tensile strength (TxDOT Test Procedure Tex-226-F), FFRC modulus (draft TxDOT Test Procedure Tex-148-E), moisture susceptibility (draft TxDOT Test Procedure Tex-144-E) and resilient modulus (e.g., AASHTO T 307). The advantages and limitations with some these optional tests are summarized in Table 4.5:

Table 4.5 - Optional Tests for Characterization of Cement Treated RAP

Test	Advantages	Limitations
Indirect Tensile Strength (Tex-226-F)	provides supplementary information	relatively large measurement variation
Resilient Modulus (AASHTO T 307)	provides stiffness information of a mix under traffic loading condition	time consuming, measurement errors and availability in TxDOT district level
FFRC Modulus (draft Tex-148-E)	easy to use for cement-treated mixes and test results can be related to those from field modulus tests	available only in few district labs

Summary

RAP mixes of different RAP contents and treated with different levels of cement were evaluated in terms of strength, modulus and moisture susceptibility. The results from this evaluation program indicate the followings:

- RAP content and cement content in a RAP mix has a strong impact on the properties of the mix.
- RAP mixed with granular base materials of relatively higher finer aggregate, particularly fines content, can improve the quality of a RAP mix.
- The use of salvage base as opposed to transporting the virgin aggregate can be a cost effective way to build the new base courses of cement-treated RAP mixes.
- For a 300 psi UCS requirement, the optimum cement contents are about 4%, 3% and 2% for mixes of 100% RAP, 75% RAP and 50% RAP, respectively.
- The results from the UCS, ITS and FFRC modulus tests are highly consistent.
- Corresponding to a 300 psi UCS, the ITS would be 40 psi and the FFRC modulus would be about 1000 ksi.
- Treatment with fly ash only is not an option for RAP mixes.

In the next chapter the results of an advanced testing program are presented to determine whether the permanency or the interaction between the binder and cement should be of concern and should be considered in the protocol recommend here.

Chapter 5

Advanced Evaluation of RAP Mixes

Experimental Procedures

This chapter describes the procedures followed for durability studies (wetting/drying, leachate, and mineralogical tests) conducted on RAP mixes that met the minimum strength requirement of 300-psi UCS or have the maximum cement up to 4% (for 100% RAP), as per TxDOT Specification Item 276 and according to the findings documented in Chapter 4.

Specimen Preparation

RAP and base aggregates were mixed by fractional weights based on their respective gradations as illustrated in Table 5.1. Each specimen for durability test was prepared as per Tex-113-E at optimum moisture content and was allowed to mellow for 30 minutes to initiate the hydration process and then was cured for 7 days as per Tex-120-E.

Table 5.1 – Example Mixing of 75% RAP + 25% Base Aggregate for El Paso RAP

Sieve Size	Retained Percentage (%)		Specimen 6"x 4.5"	
	RAP	Base	RAP (lbs)	Base (lbs)
7/8 in.	4.00	22.5	0.36	0.67
3/8 in.	40.58	17.5	3.65	0.52
#4	26.58	15.0	2.39	0.45
#40	24.33	22.5	2.19	0.67
#100	3.25	10.5	0.29	0.31
#200	0.83	7.0	0.07	0.21
Pan	0.42	5.0	0.03	0.15
			Total = 12 lbs	

Cyclic Wetting-Drying Studies

According to ASTM D 559, the RAP specimens should be prepared and cured, then submerged in water for 5 hrs for one wetting cycle and then oven dried at 160º F for 48 hrs to complete one cycle, as illustrated in Figure 5.1. The specimens were allowed to swell and shrink in both lateral and vertical directions. Vertical movement was measured with the help of a dial gauge while the radial movements were measured using a so-called “pi tape.” After 3, 7, and 14 wetting-drying cycles, the specimens were subjected to UCS testing. Test results obtained provide adequate information on whether the cement treated RAP materials are durable or fail prematurely.

In addition, wire brush test was performed as per ASTM D 560 method, which is typically used to study the effects of freeze and thaw on the strength behavior of stabilized soils. However, in this research, the wire brush test was conducted on cement treated RAP samples to assess the percentage loss of weight due to any crumbling process at the end of wet/dry cycles. The test was carried out by immersing the samples in water at room temperature for 5 hrs and then oven-drying at 160º F for 42 hrs. The sample was finally subjected to firm brushing on each surface and in both directions for a total of 18-25 brush strokes. This process was repeated for up to 14 cycles. After 14 test cycles, the samples were oven-dried to a constant weight at 200º F, and the weight loss with respect to the initial weight is calculated.

(a) (b)

Figure 5.1 – Test Setup for Wetting/Drying Process: (a) Wetting, (b) Drying

Leachate Studies

McCallister (1990) developed a test procedure at UT-Arlington to quantify the permanency of chemical stabilization subject to moisture flow during rainfall events. The test utilizes a flexible wall mold that houses the compacted and stabilized aggregate specimen. Figure 5.2 illustrates a schematic of the test setup used in this research.

Each specimen was prepared at the optimum moisture content and maximum dry densities using the procedure outlined in the previous section. These samples were cured in moisture room for 7 days before subjecting them to leachate studies. The cured specimen was then subjected to moisture flow from a water tank at a constant pressure. A few preliminary tests were conducted to finalize the pressures to be applied to the water such that one pore volume per day would

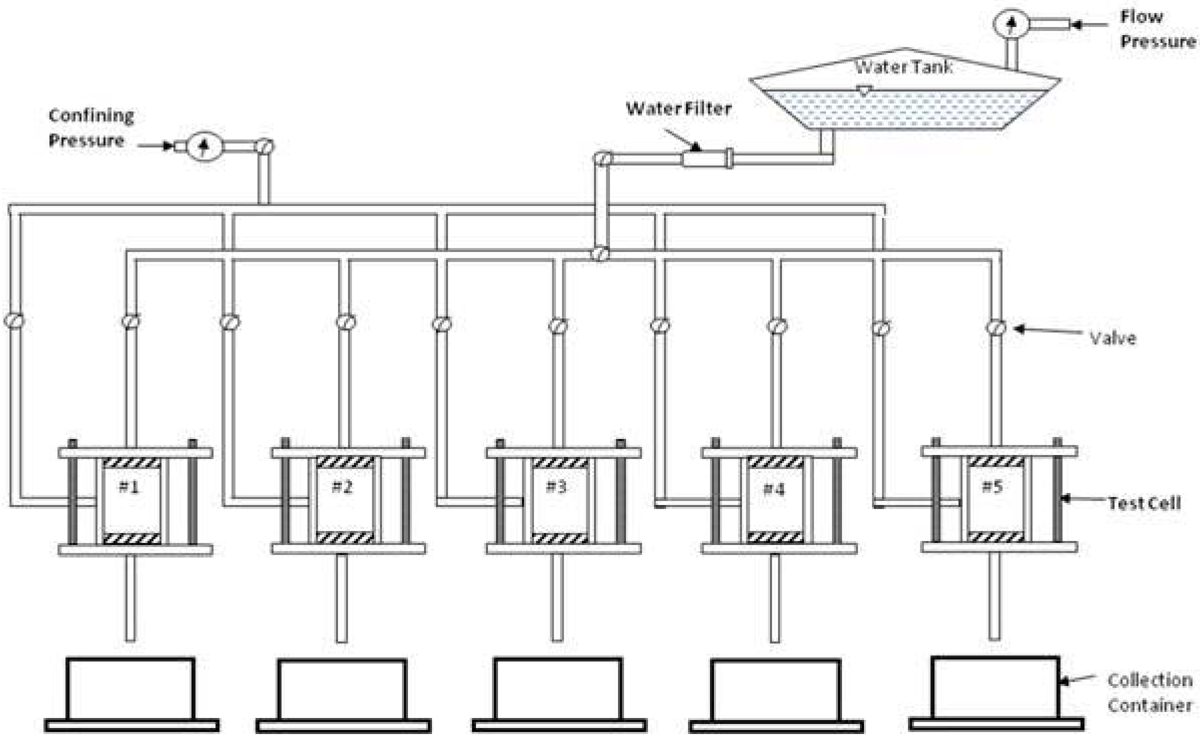


Figure 5.2 – Schematic of Leachate Process (Chittoori, 2008)

percolate through the specimen. One leaching cycle here is defined as the amount of leachate volume collected that is equal to the total voids/pores (air voids + water voids) present in a compacted specimen. A detailed explanation of the calculation of specimen void volume is given by Chittoori (2008).

The cured specimens were kept inside the cell and the top plate was fastened into place using the fasteners shown in Figure 5.3. A confining pressure 5 psi greater than the flow pressure was applied through the confining pressure inlet. The water was allowed to go through the top of the sample under a constant flow pressure through the flow pressure inlet, and the leachate was collected in the 20 liter carboys shown in Figure 5.4.

Leachate tests were conducted on several identically prepared and cured specimens. Leachate was collected after 3, 5, 7, 11, and 14 cycles of leaching, while the UCS tests were conducted at the end of 14 cycles of leaching. Leachate specimens collected were tested for the pH changes and for the amount of calcium present after the corresponding leachate cycles. Results were statistically analyzed to address the loss of stabilizer due to leaching. In this test an attempt was made to correlate leaching cycles with field moisture movements from rainfall events.

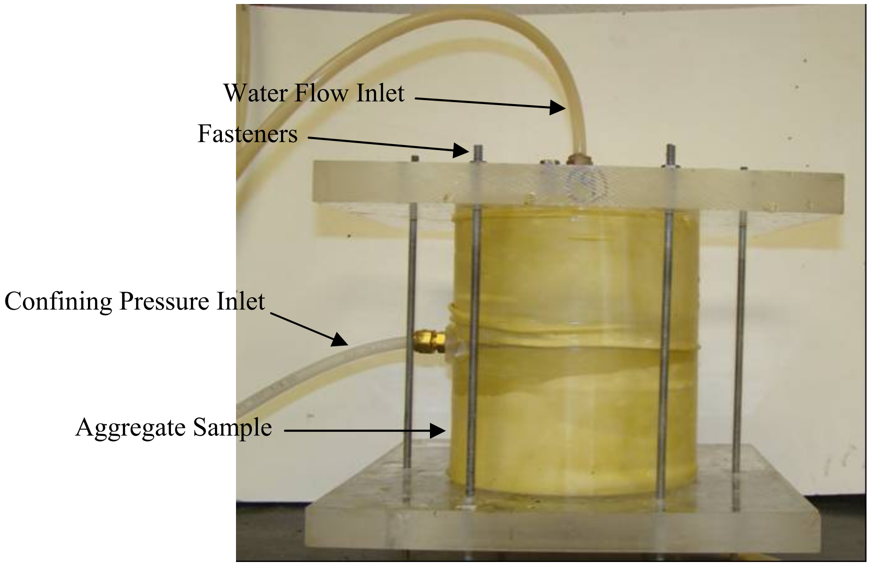


Figure 5.3 – Leachate Cell

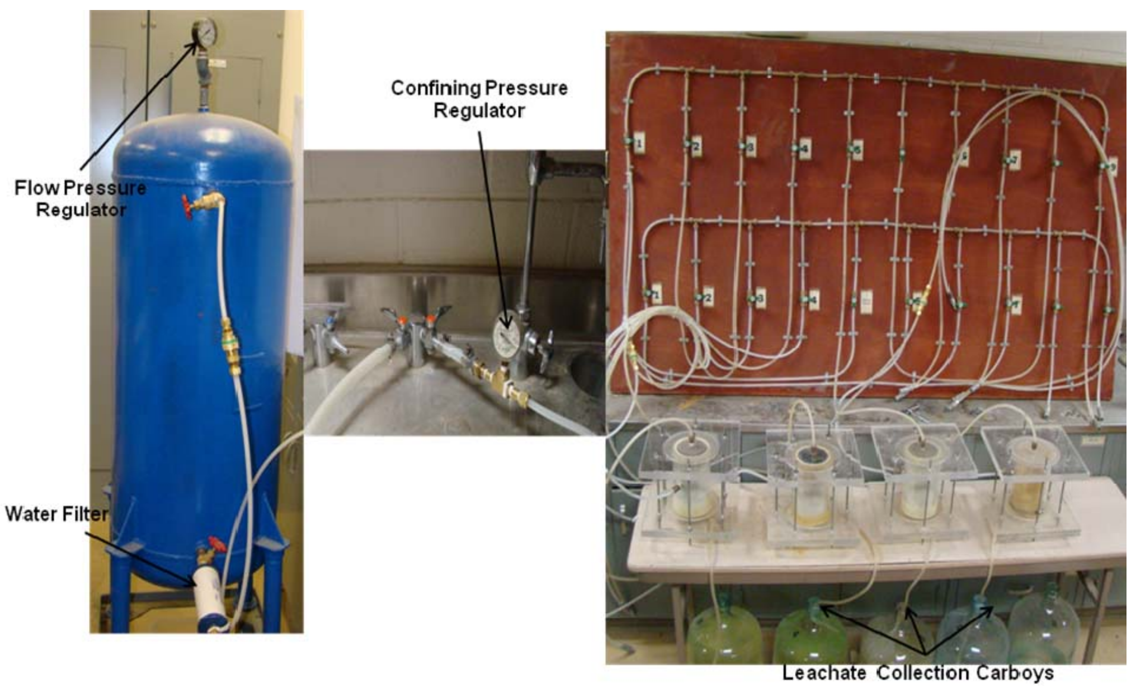


Figure 5.4 – Test Setup for Leachate Studies (Chittoori, 2008)

Unconfined Compression Test

Unconfined compression tests were performed on RAP samples after 0, 3, 7 and 14 cycles of wetting/drying, and at the end of 14 leachate cycles. These UCS test results were analyzed to address any potential loss of strength in cement stabilized RAP after different cycles of durability studies. The equipment used for UCS testing of RAP mixes is shown in Figure 5.5.

Figure 5.5 – Unconfined Compression Test Machine

Compatibility of Asphalt and Cement Tests

X-Ray Diffraction (XRD) Studies

X-ray diffraction screening studies were conducted on all RAP mixes to qualitatively identify the minerals formed during the blending of RAP, aggregate, and cement. The test procedure involves subjecting a powdered sample of the mix to an intense X-ray beam and detecting the diffracted beam with the help of a detector. The detector then converts the analog signal into digital data which can be plotted. Using Bragg's law, the distances between the planes of the atoms, called d-spacing, is measured. The d-spacing is compared with standard powder diffraction files (PDF) of different minerals. The presence of certain mineral is confirmed if at least 5 to 6 matches of the mineral are found.

Prior to X-ray diffraction test, the RAP mixes were air dried and hand crushed such that most of the material passed through a #200 sieve. Oven drying and pulverizing were not carried out since they may modify the mineralogical structure inside the sample and hence some of the peaks may not be observed (Chew et al., 2004). The powdered sample was placed in a sample holder as shown in Figure 5.6, and X-ray diffraction studies were carried out using a D-500 X-ray Diffractometer as shown in Figure 5.7, with an input voltage of 40 kV and current of 30 mA. The sample was run using CuKα radiation and the run speed was two degrees per second.

A step scan mode with a step size of 0.03º of 2-theta angle and a dwell time of 2s were selected. When the step scan was finished, the peaks were analyzed by identifying the minerals from software called JADE, where the peaks obtained were matched with the minerals present in the software. No previous studies on these RAP mixes to identify the predetermined minerals formed due to chemical reaction between RAP, aggregates and cement, could be found.

Figure 5.6 – Sample Holder with Typical Powdered RAP Mix

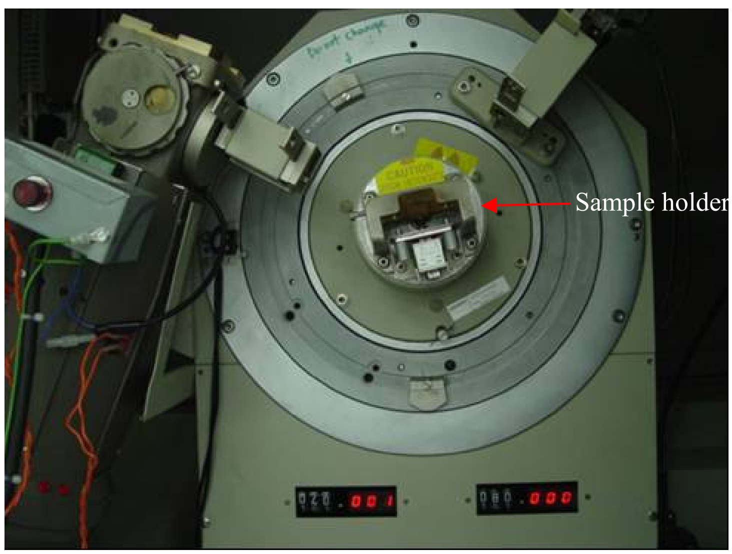


Figure 5.7 – D 500 X-Ray Diffractometer

Scanning Electron Microscope (SEM) Studies

The scanning electron microscope (SEM) is essentially a closed television system comprising a camera viewing the specimen with a scanned electron beam and a console on which a scanned raster is displayed. It is used to understand the shape and structure of the minerals formed due to the chemical reaction between and among components in the RAP mixes. The magnifications and voltages in the test setup are altered to get a clear digital image. SEM works in two modes namely Secondary Electron mode and Back Scattering Electron mode. Each mode helps to scan a clear image depending upon the type of material (conductive/nonconductive). This SEM has a 3.0 nm resolution at high vacuum and 4.0-nm resolution at low vacuum. It is a computer controlled system for ultimate ease of use. A typical set up of the Scanning Electron microscope is shown in Figure 5.8.

SEM test is typically done in a high vacuum, as gas molecules interfere with the electron beam and the emitted secondary and backscattered electrons are used for imaging. The sample is coated with silver before subjecting them to scanning because it is nonconductive in nature. This coated specimen is mounted on a sample holder (Figure 5.9) and inserted into the chamber. Then a high vacuum mode is applied inside the chamber for working on the sample. The working distances and magnifications are varied to get a clear view of the mineral structure.

This SEM apparatus is also equipped with Electron Dispersive System (EDS) which also gives the chemical composition and electron mapping. In this technique, electrons are bombarded with the desired elemental area composition; the elements present in the selected area will be emitting characteristic X-rays which are then recorded on a detector. This EDS can be simultaneously done on the SEM sample by selecting a particular area in the scanned picture which can be utilized to get the chemical composition in the selected spot.

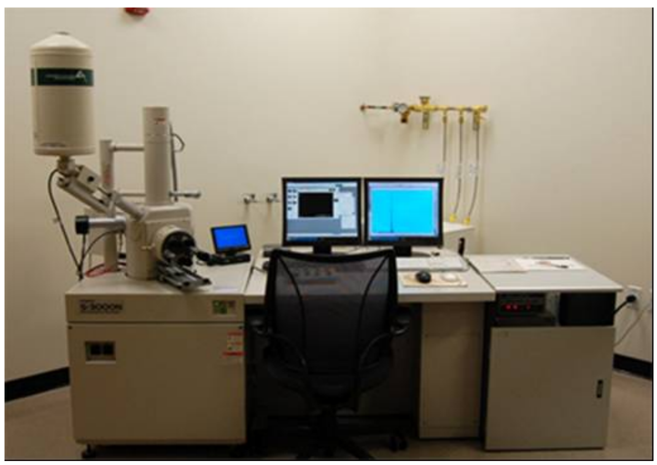


Figure 5.8 – Scanning Electron Microscope (SEM) Test Setup

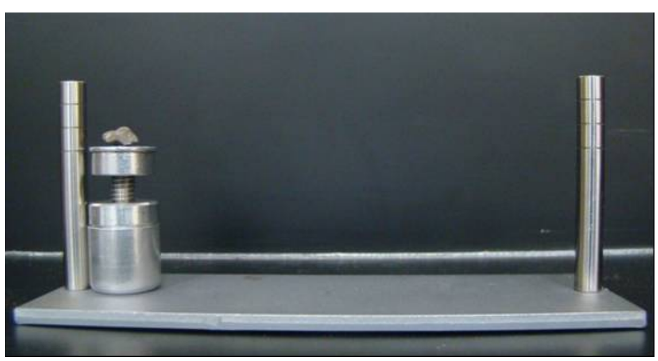


Figure 5.9 – Sample Holder for SEM Analysis

Summary of Test Results and Analyses

Cyclic Wetting-Drying Studies

This section is devoted to a detailed analysis of cyclic wetting-drying test results for RAP mixes from El Paso District. Summary tables for RAP mixes from Fort Worth, Childress, Waco, Pharr and Lubbock districts are presented at the end of the section. The mixtures studied for El Paso district are listed in Table 5.2, along with the corresponding notation for sample identification.

Table 5.2 – Details of El Paso RAP Mixes

Mix Type	Notation
100% RAP (0% Cement)	100R_0C
100% RAP (6% Cement)	100R_6C
100% RAP (7% Fly ash)	100R_7F
75% RAP + 25% Base (2% Cement)	75R_2C
60% RAP + 40% Base (0% Cement)	60R_0C
60% RAP + 40% Base (2% Cement)	60R_2C
60% RAP + 40% Base (7% Fly ash)	60R_7F
50% RAP + 50% Base (2% Cement)	50R_2C

Photos of typical RAP and RAP blends from El Paso district prior to wetting/drying testing are shown in Figure 5.10. No representative samples could be made from 100% RAP and 100% RAP with 7% Fly ash.

The samples were subjected to UCS testing after 0, 3, 7, and 14 cycles to determine the retained strength with respect to original strength. A total of four samples were prepared for each designed mix to carry out these studies. Wire brush test (ASTM D 560) was also performed on all cement treated RAP mixes at the end of 14 wet/dry cycles, and the percentage of weight loss, with respect to the initial weight, was measured. For all cement treated mixes, the average percentage of weight loss was found to be less than 7% which can be considered negligible.

In general, since RAP mixes are aggregate base materials, very low changes in volumetric strain during cyclic wetting-drying were observed (less than 1% on average). Photos of typical RAP and RAP blends from El Paso District, after 14 wet/dry cycles, are shown in Figure 5.11. At a first glance, the detrimental effect of cyclic wetting-drying on all RAP mixes is quite apparent; however, results from UCS testing form the basis for more substantiated conclusions.

Table 5.3 presents a summary of all cyclic wetting-drying test results for El Paso mixes. The blend of 60% RAP and 40% base aggregates, treated with 2% cement (60R_2C mix) performs the best. This mix yields a very low volumetric change after 3, 7 and 14 wet/dry cycles, and has a consistent retained strength even after 14 wet/dry cycles. Another mix with similar performance to that of 60R_2C mix is the 75R_2C mix, because it also yields a low volumetric strain change and standard decrease in strength for all the performed W/D cycles. Fly ash treated samples were relatively weak in strength and virtually crumbled after 7 wet/dry cycles.

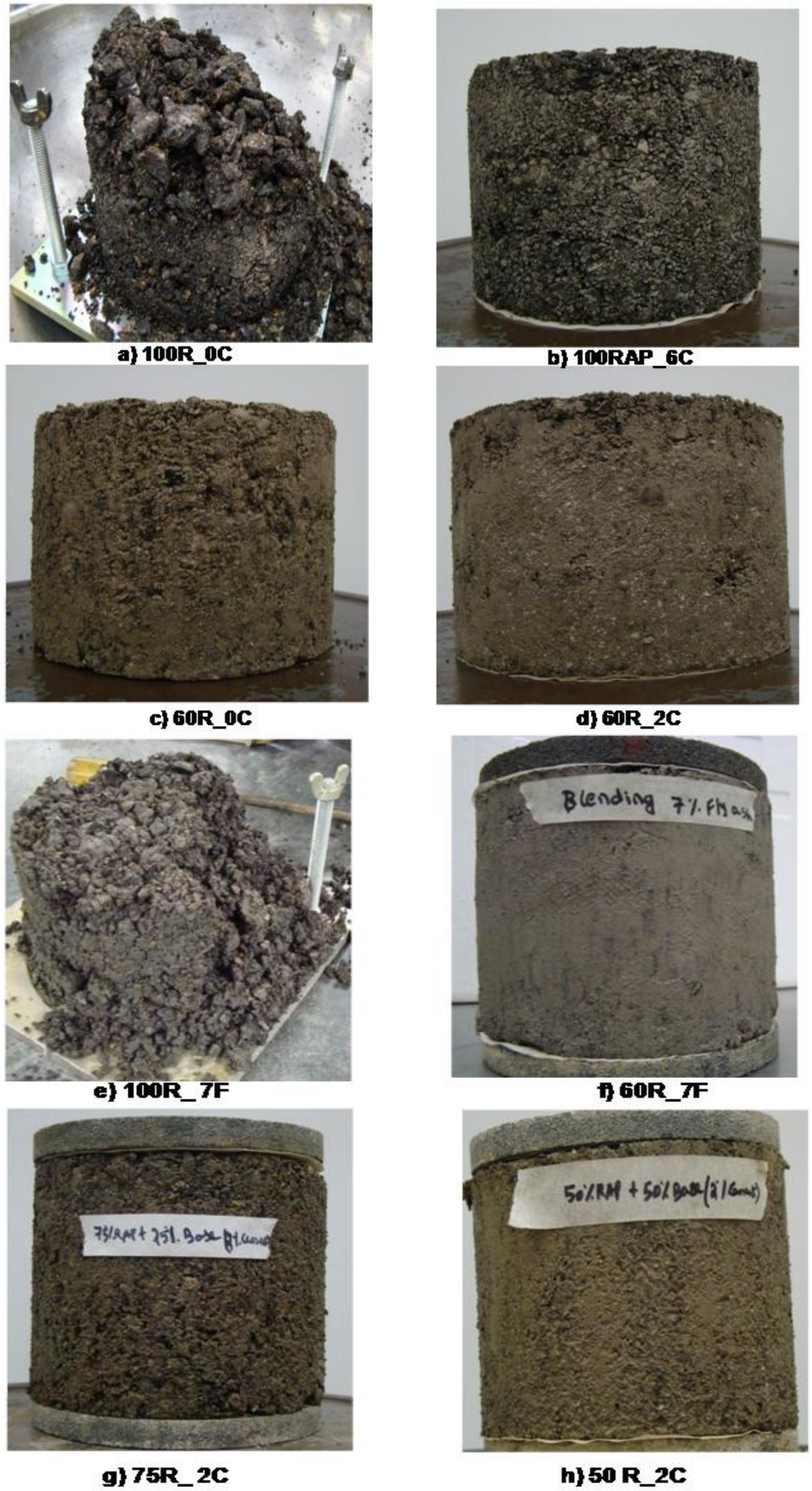


Figure 5.10 – Typical RAP and RAP Blends from El Paso District Prior to Wetting/Drying

a) 100R_6C

b) 60R_0C

c) 60R_2C

d) 75R_2C

e) 50R_2C

Figure 5.11 – Typical RAP and RAP Blends from El Paso District after 14 Wet/Dry Cycles

Table 5.3 – Summary of Cyclic Wetting/Drying Test Results for El Paso RAP Mixes

Mix Type	No. of W/D Cycles	Total Volumetric Strain (%)	Retained UCS (psi)	No. of W/D Cycles Sample Survived	Rank
100R_6C	3	0.64	200	14	**IV**
	7	0.30	185		
	14	0.49	145		
75R_2C	3	0.90	150	14	**II**
	7	0.89	135		
	14	0.48	120		
60R_0C	3	1.41	153	14	**V**
	7	0.81	145		
	14	0.79	123		
60R_2C	3	0.54	300	14	**I**
	7	0.56	285		
	14	0.09	272		
60R_7F	3	1.65	45	7	**VI**
	7	2.50	35		
	14	–	–		
50R_2C	3	0.36	260	14	**III**
	7	1.27	223		
	14	0.94	204		

While 100R_6C shows a low volumetric strain change, its strength decreased well below the required 300-psi standard after 14 w/d cycles. Another important reason for not considering this mix is that it may become uneconomical to use 6% cement for base layer stabilization. The 50R_2C mix also shows some steady retained strength with little change in volumetric strain after 7 and 14 W/D cycles.

As documented in Chapter 4, for a 300-psi UCS requirement, the optimum cement contents seem to be about 4%, 3%, and 2% for mixes with 100% RAP, 75% RAP and 50% RAP, respectively. Hence, further durability testing on mixes from Fort Worth, Childress, Waco, Pharr and Lubbock districts was performed on RAP and RAP blends having only 100%, 75% and 50% RAP. Results from cyclic wetting-drying tests on these mixes are summarized in Tables 5.4 through 5.8.

In general, it can be concluded that 75% RAP, when blended with 25% base aggregates and treated with 3% Cement, yields best performance after 14 wet/dry cycles. Moreover, 50% RAP blended with 50% Base aggregates and treated with only 2% cement also performs similarly. However, 75% RAP was ranked first since maximum utilization of RAP for base construction purposes would result in a more environmental friendly and economical design.

Table 5.4 – Summary of Cyclic Wetting/Drying Test Results for Fort Worth RAP Mixes

Mix Type	No. of W/D Cycles	Total Volumetric Strain (%)	Retained UCS (psi)	No. of W/D Cycles Sample Survived	Rank
100R_4C	3	0.93	220	14	**III**
	7	0.92	203		
	14	0.77	194		
75R_4C	3	0.29	411	14	**I**
	7	0.52	384		
	14	0.17	364		
50R_2C	3	0.66	324	14	**II**
	7	0.39	297		
	14	0.30	274		

Table 5.5 – Summary of Cyclic Wetting/Drying Test Results for Childress RAP Mixes

Mix Type	No. of W/D Cycles	Total Volumetric Strain (%)	Retained UCS (psi)	No. of W/D Cycles Sample Survived	Rank
100R_4C	3	0.56	330	14	**III**
	7	0.85	270		
	14	0.94	192		
75R_4C	3	0.09	430	14	**I**
	7	0.08	410		
	14	0.06	362		
50R_4C	3	0.45	450	14	**II**
	7	0.58	400		
	14	0.43	323		

Table 5.6 – Summary of Cyclic Wetting/Drying Test Results for Waco RAP Mixes

Mix Type	No. of W/D Cycles	Total Volumetric Strain (%)	Retained UCS (psi)	No. of W/D Cycles Sample Survived	Rank
100R_4C	7	1.11	279	14	**III**
	14	0.73	205		
75R_4C	7	0.37	507	14	**I**
	14	0.66	465		
50R_4C	7	0.57	759	14	**II**
	14	0.76	651		

Table 5.7 – Summary of Cyclic Wetting/Drying Test Results for Pharr RAP Mixes

Mix Type	No. of W/D Cycles	Total Volumetric Strain (%)	Retained UCS (psi)	No. of W/D Cycles Sample Survived	Rank
100R_4C	7	0.24	235	14	**IV**
	14	0.75	560		
75R_SB_2C	7	0.50	666	14	**III**
	14	0.29	525		
75R_VB_2C	7	1.08	347	14	**I**
	14	0.58	355		
50R_2C	7	0.97	415	14	**II**
	14	0.36	303		

VB: blended with virgin base, SB: blended with salvage base.

Table 5.8 – Summary of Cyclic Wetting/Drying Test Results for Lubbock RAP Mixes

Mix Type	No. of W/D Cycles	Total Volumetric Strain (%)	Retained UCS (psi)	No. of W/D Cycles Sample Survived	Rank
100R_4C	7	1.02	567	14	**III**
	14	0.42	202		
75R_SB_4C	7	1.13	686	14	**I**
	14	0.76	662		
50R_SB_2C	7	0.94	172	14	**IV**
	14	1.77	82		
50R_VB_4C	7	0.52	1004	14	**II**
	14	0.34	1141		

VB: blended with virgin base, SB: blended with salvage base.

Leachate Studies

Leachate testing on mixes originated from El Paso, Fort Worth, Childress, Waco, Pharr and Lubbock districts was also performed on RAP and RAP blends having 100%, 75% and 50% RAP. The variations in pH and calcium ion concentration were measured at the end of 3, 5, 7, 11 and 14 leachate cycles (see Fig. 5.4) to assess the potential leaching out of cement stabilizer from the RAP mixes. In general, the amount of calcium ion concentration leached out from any treated mix was found to be less than 50 ppm. Calcium ion concentration leached out from natural soils treated with lime/cement has been found between 250 and 700 ppm (Chittoori 2008). Hence, the leaching of cement stabilizer is not of great concern in the long-term performance of RAP mixes.

UCS tests were conducted on all mixes after 14 leaching cycles to assess the retained strength after the leaching process. Results are summarized in Tables 5.9 through 5.14. In general, all mixes show a reasonably high retention of strength (more than 80% on average), with 75% RAP

Table 5.9 – Summary of Leachate Test Results for El Paso RAP Mixes

Mix Type	UCS (psi)		Retained Strength after 14 Leachate Cycles (%)
	0 cycles	14 cycles	
100R_6C	220	185	84
75R_2C	185	162	88
60R_2C	320	289	90
50R_2C	300	254	85

Table 5.10 – Summary of Leachate Test Results for Fort Worth RAP Mixes

Mix Type	UCS (psi)		Retained Strength after 14 Leachate Cycles (%)
	0 cycles	14 cycles	
100R_4C	272	188	69
75R_4C	430	397	92
50R_2C	345	287	83

Table 5.11 – Summary of Leachate Test Results for Childress RAP Mixes

Mix Type	UCS (psi)		Retained Strength after 14 Leachate Cycles (%)
	0 cycles	14 cycles	
100R_4C	385	129	34
75R_4C	465	353	75
50R_4C	510	366	71

Table 5.12 – Summary of Leachate Test Results for Waco RAP Mixes

Mix Type	UCS (psi)		Retained Strength after 14 Leachate Cycles (%)
	0 cycles	14 cycles	
100R_4C	393	185	47
75R_4C	581	465	69
50R_4C	783	500	64

Table 5.13 – Summary of Leachate Test Results for Pharr RAP Mixes

Mix Type	UCS (psi)		Retained Strength after 14 Leachate Cycles (%)
	0 cycles	14 cycles	
100R_4C	235	460	196
75R_SB_2C	422	465	110
75R_VB_2C	260	325	125
50R_2C	435	280	64

VB: blended with virgin base, SB: blended with salvage base.

Table 5.14 – Summary of Leachate Test Results for Lubbock RAP Mixes

Mix Type	UCS (psi)		Retained Strength after 14 Leachate Cycles (%)
	0 cycles	14 cycles	
100R_4C	649	178	27
75R_SB_4C	759	581	77
50R_SB_2C	238	65	27
50R_VB_4C	949	945	100

VB: blended with virgin base, SB: blended with salvage base.

blended with 25% Base aggregates and treated with 2% Cement yielding best performance after 14 leaching cycles, which substantiate the findings from the previous section.

X-Ray Diffraction (XRD) Studies

As previously mentioned, mineralogical tests, including X-Ray Diffraction (XRD) and Scanning Electron Microscope (SEM), were conducted on RAP and RAP blends to study the dominating minerals in the mixes and to assess whether any pozzalonic compounds were formed during the chemical stabilization of the RAP mixes. The present and following sections are devoted to a detailed analysis of XRD and SEM test results for RAP mixes from El Paso District. Conclusions can be readily applied to mixes from Fort Worth, Childress, Waco, Pharr and Lubbock districts since similar XRD and SEM patterns were observed from all of these mixes.

A typical XRD plot from 60% RAP blended with 40% base aggregates and treated with 2% Cement (60R_2C mix) from El Paso District is shown in Figure 5.12. Several groups of minerals, such as polymers, zeolites and cementitious compounds, were searched with the aid of the XRD software to match the peaks of the minerals present in each group with the peaks of required RAP mix. The minerals determined by using this procedure were considered to be found only in traces in the mixes since the intensities with which these peaks matched were less than 30% of the original peaks. A few of the compounds detected in cement and fly ash stabilized RAP mixes are Aluminum Oxide (Al_2O_3), Aluminum Calcium (Al_4Ca), Silicon Oxide (SiO_2), and Calcium Aluminum Borate ($CaAl_2B_2O_7$), and the presence of these minerals indicate partial nature of cementing compounds in the cement treated RAP mixes.

Scanning Electron Microscope (SEM) Studies

The main purpose of conducting SEM studies is to observe the different patterns formed due to chemical stabilization of RAP mixes. EDS provides the quantitative spot chemical composition for the particular area selected in the SEM pattern. The EDS analysis uses a high range of X-ray beam that was made to fall onto the selected area of sample that has been analyzed in the SEM study, and then the corresponding peaks were obtained. These peaks were then matched with peaks of elements present in the periodic table via computer software (Revolution) to identify the presence of a particular element. A high range of X-ray beam was made to fall under a high vacuum mode to perform the scanning on the specimen. The voltages and magnifications in the test setup were altered until a more refined picture was observed.

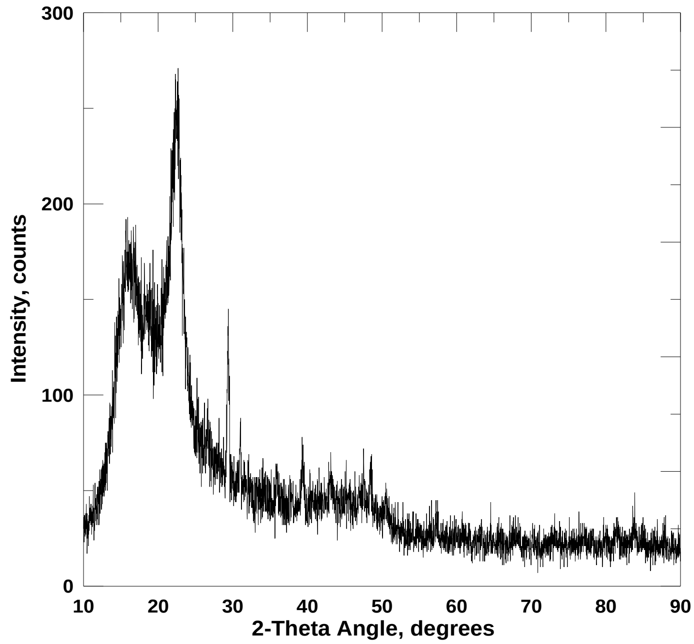


Figure 5.12 – Typical XRD Plot for 60R_2C Mix (Powered) from El Paso District

Typical SEM images from RAP mixes originated from El Paso District are shown in Figures 5.13 through 5.18. Predominant cementing compounds detected include calcium silicate hydrate gel (C-S-H), manifested in bundles, and calcium hydroxide (CH) crystals. The presence of these cementing compounds is indicative of strength enhancements from chemical treatment. Minimal formation of needle-like *Ettringite* mineral is observed in Figures 5.17 and 5.18.

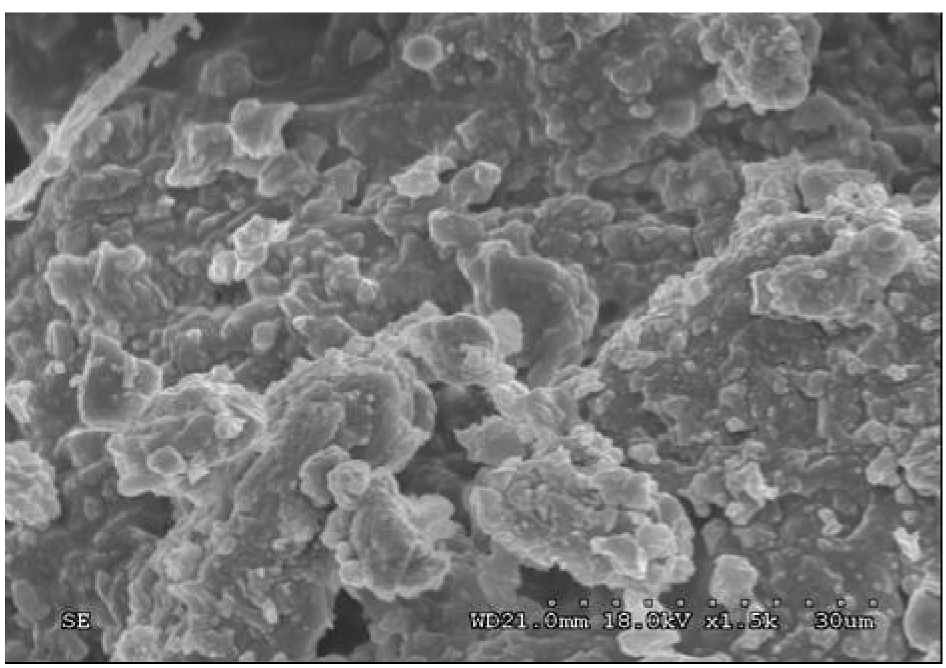


Figure 5.13 – Typical SEM Image for 100R_0C Mix (Powered) from El Paso District

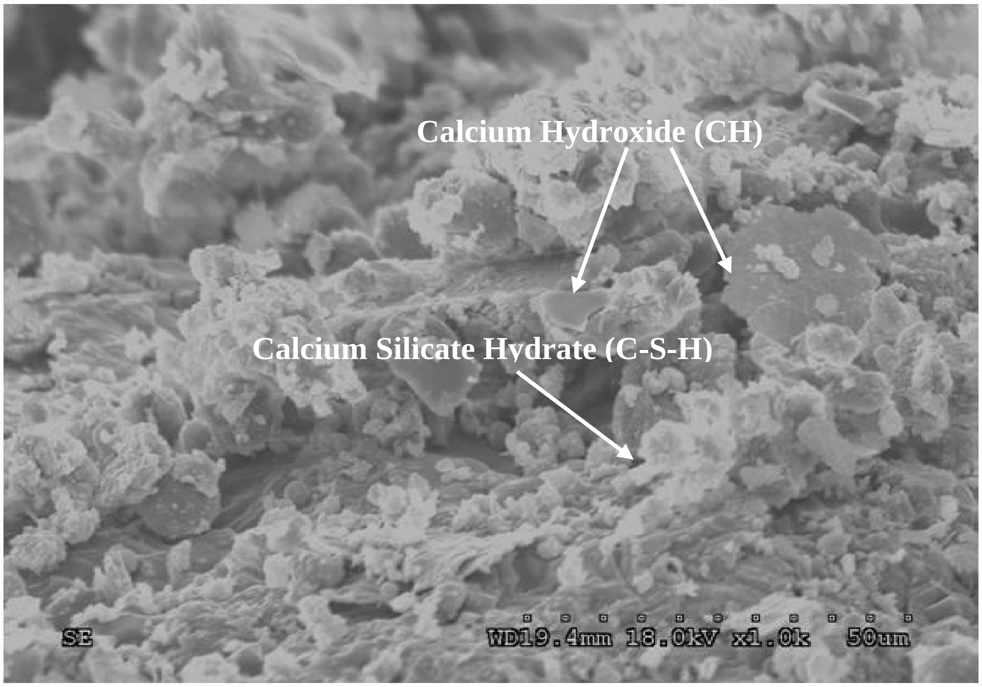


Figure 5.14 – Typical SEM Image for 100R_6C Mix (Powered) from El Paso District

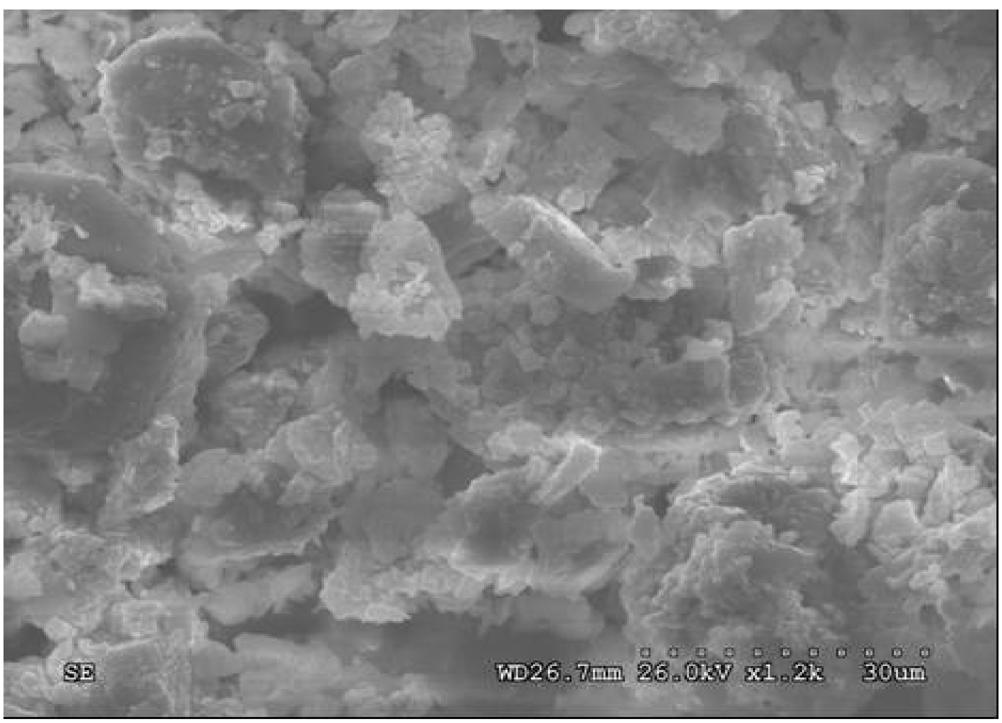


Figure 5.15 – Typical SEM Image for 60R_0C Mix (Powered) from El Paso District

Figure 5.16 – Typical SEM Image for 60R_2C Mix (Powered) from El Paso District

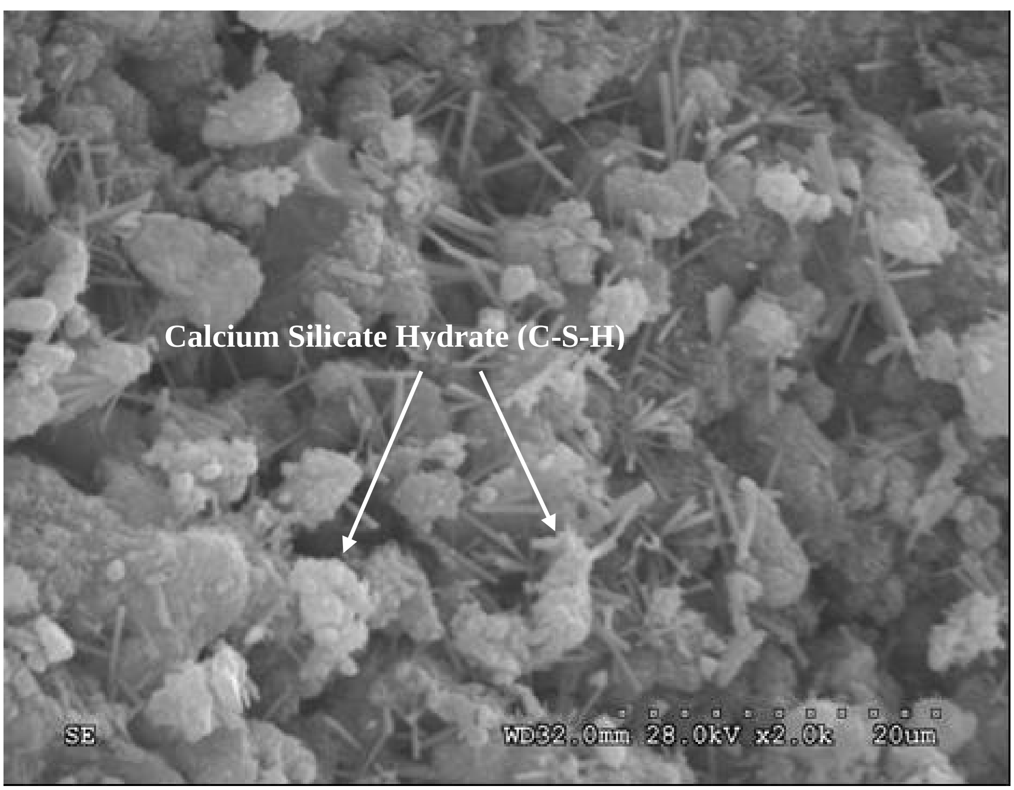


Figure 5.17 – Typical SEM Image for 75R_2C Mix (Powered) from El Paso District

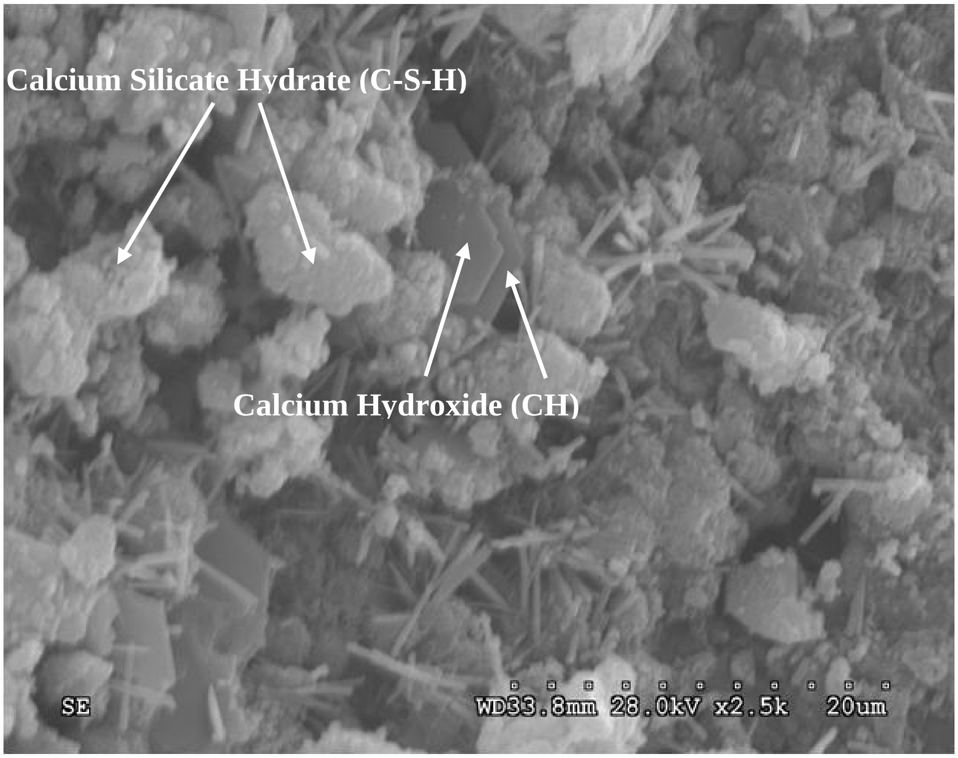


Figure 5.18 – Typical SEM Image for 50R_2C Mix (Powered) from El Paso District

Typical results from EDS analyses performed on untreated and treated 100% RAP are shown in Figures 5.19 and 5.20, respectively. The percentage of calcium significantly increased after chemical treatment. In addition, the presence of oxygen, silicon and aluminum elements in traces is further indication that pozzalonic reactions occurred between the fines and cement particles.

As previously mentioned, similar mineralogical studies were also conducted on treated/untreated RAP mixes from Fort Worth, Childress, Waco, Pharr and Lubbock districts. Reasonably similar patterns were observed from all of these mixes, with predominant presence of calcium silicate hydrate gel (C-S-H) and calcium hydroxide (CH) compounds in the powered samples.

Summary

Studies reported to date on stabilized RAP mixes are limited and mostly based on short-term strength and stiffness properties (e.g., Taha, 2002; Potturi, 2006; Gutherie 2007b). However, achievement of specified strength/stiffness does not always ensure the durability of the stabilized mixes. In this work, a comprehensive series of durability tests, including cyclic wetting/drying, leachate, and mineralogical tests, were conducted on RAP mixes that met the minimum strength requirement of 300-psi UCS, as per TxDOT Specification Item 276, and according to the findings documented in Chapter 4. Results from this evaluation program indicate all of the following:

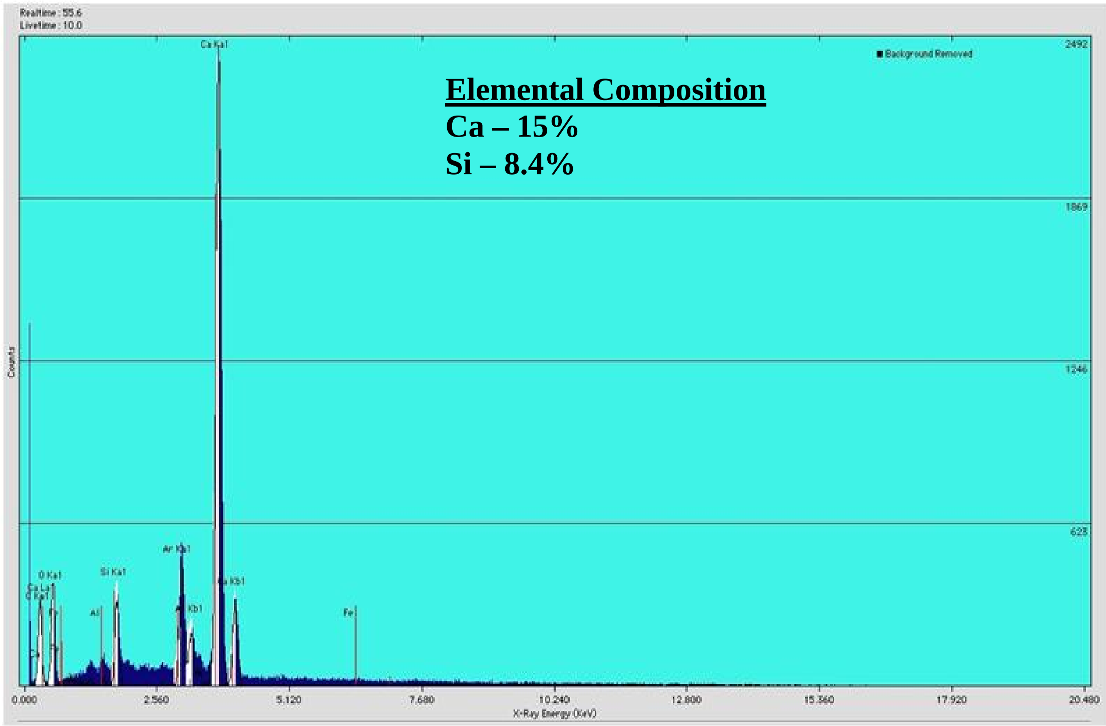


Figure 5.19 – Typical EDS Plot for 100R_0C Mix (Powered) from El Paso District

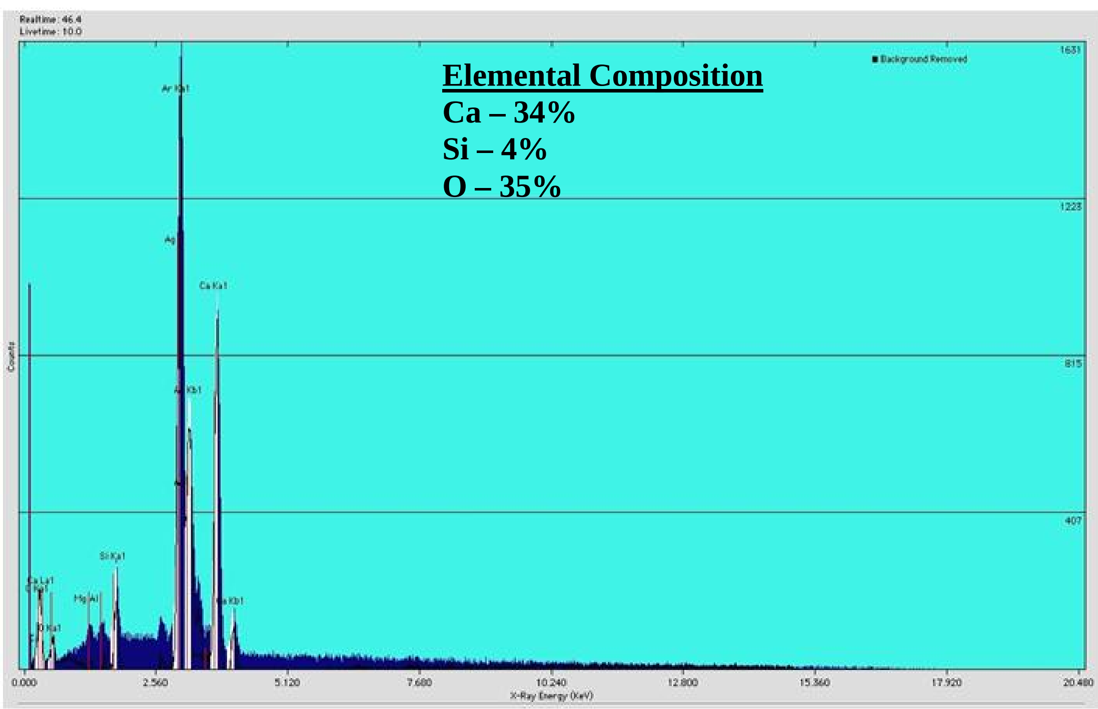


Figure 5.20 – Typical EDS Plot for 100R_6C Mix (Powered) from El Paso District

- Change in volumetric strain after various wet/dry cycles (3, 7 and 14) was observed to be less than 1% for all RAP mixes studied. Ranking of the best performing mixes was based on volume change and retained strength criteria. The mix showing the lowest volumetric change for all 3, 7 and 14 wet/dry cycles and highest percentage of retained strength is ranked as highly performing mix. In general, 75% RAP treated with 2 and 4% cement rank first, followed by 50% RAP treated with 2 and 4% cement and 100% RAP treated with 4 and 6% cement, substantiating the findings in Chapter 4.
- Variations in pH and calcium ion concentration were measured at the end of 3, 5, 7, 11 and 14 leachate cycles to assess the extent of stabilizer leaching from the RAP mixes. In general, the amount of calcium ion concentration leached out from all treated mixes was detected to be less than 50 ppm, significantly less than that observed in lime/cement treated natural soils (250-700 ppm).
- UCS tests were conducted at the end of 14 leachate cycles to measure the retained strength with respect to the original strength of treated mixes. Again, 75% RAP treated with 2 and 4% cement yields best performance, with more than 80% strength retained on average.
- Mineralogical studies conducted on powered RAP mixes via X-ray diffraction (XRD) show a partial presence of pozzalonic compounds contributing to the chemical stabilization. Likewise, predominant cementing compounds detected via Scanning Electron Microscope (SEM) include calcium silicate hydrate gel (C-S-H) and calcium hydroxide (CH) crystals. The presence of these cementing compounds is further indication of strength enhancements from chemical treatment. Further studies, however, are required to identify the specific type of pozzalonic compounds.

One main conclusion of this chapter is that if the mix design process recommended in Chapter 4 is followed, one should not be concerned with the permanency of the stabilization or the negative interaction between the cement and binder. As such, the advanced tests carried out in this chapter are only necessary when the district labs have concern with marginal mixes.

Chapter 6

Field Trial

Introduction

During this research period, one maintenance (roadway widening) project with low RAP content (25%) in Lubbock District and two rehabilitation projects with high RAP content (more than 50%) in Yoakum and Fort Worth Districts were available for field trials. For each project, the major research activities included material collections, laboratory tests on the collected materials treated with the given cement contents and initial field tests on the newly-constructed base courses. This chapter presents the results from these tests.

The materials collected from each project site were subjected to the following tests:

- sieving analysis
- moisture-density
- unconfined compressive strength (UCS)
- indirect tensile strength (ITS)
- Free-Free Resonance Column (FFRC) modulus
- Retained strength/FFRC modulus (for two rehabilitation projects only)

Field modulus tests were performed with a Portable Seismic Pavement Analyzer (PSPA) Falling Weight Deflectometer (FWD) or Light Weight Deflectometer (LWD). The nuclear density gauge (NDG) testing was performed by TxDOT on the newly constructed base courses at each of the two rehabilitation project sites in Yoakum and Fort Worth Districts.

Moduli Measured with FFRC and PSPA Devices

Modulus of each layer in a pavement plays an important role in any mechanistic-empirical procedures for structural design of flexible pavements. In this research project, the modulus measured through FFRC testing in the laboratory has been considered as one of the major parameters for evaluating cement-treated RAP mixes. On the other hand, the PSPA was used in the field to measure the in-place modulus of the cement-treated base course during construction.

To implement mechanistic pavement design procedures or to develop modulus-based QA/QC specifications, links between the moduli measured in the laboratory and in the field are needed through the following two steps:

Conversion of Moduli from PSPA and FFRC Tests

For a homogeneous and isotropic material or mix at the same levels of moisture content, compaction and curing, the modulus from a PSPA-type measurement, E_{PSPA}**,** can be analytically related to the modulus from a FFRC measurement, E_{FFRC}, as follows (Richart et al., 1970):

$$E_{PSPA} / E_{FFRC} = (1 + \nu)(1 - 2\nu) / (1 - \nu) \quad (6.1)$$

where ν is the Poisson's ratio of the compacted material or mix. Poisson's ratio has a significant impact on the ratio of E_{PSPA}/E_{FFRC}, which decreases as Poisson's ratio increases. For instance, when Poisson's ratios are 0.2, 0.3 and 0.4, E_{PSPA} / E_{FFRC} will be 0.90, 0.74 and 0.47, respectively. For a given material or mix, its Poisson's ratio can be assumed reasonably based on the documented values in the literature.

To achieve the accurate Poisson's ratio values for the conversion, FFRC tests were performed on the specimens made from the mixes collected from two rehabilitation projects with 2% cement and 4% cement, respectively. Each specimen was 6 in. in diameter and 12 in. in length. Tests were performed on a daily basis from 1 day to 7 days. The variations of Poisson's ratio with specimen curing age are shown in Figure 6.1. This practice showed that 1) the variation of Poisson's ratio with curing age was not significant after the specimens had been cured for 24 hrs and 2) the mix with 2% cement and the mix with 4% cement had a similar Poisson's ratio of 0.22. For a Poisson's ratio of 0.22, E_{PSPA} / E_{FFRC} is 0.87.

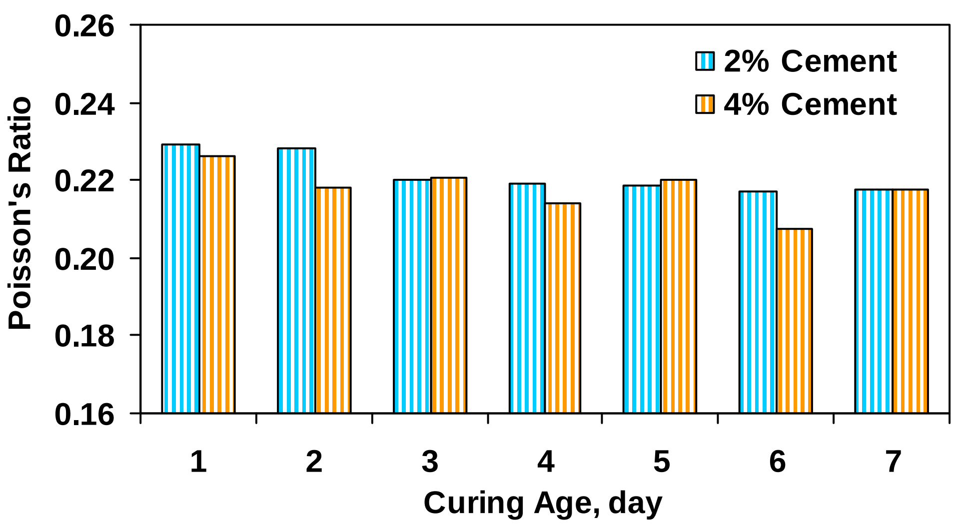


Figure 6.1 – Variations of Poisson's Ratio with Curing Age

Adjustment for Curing Age

Like strength, the modulus of a cement-treated material increases with curing age. Throughout this research project, the FFRC modulus and the UCS of a number of specimens were measured at the curing age of 7 days per TxDOT Test ProcedureTex-120-E for design. For moduli measured with a PSPA on a cement-treated base course at earlier curing ages, adjustment must be applied. Approximate adjustment factors can be obtained through FFRC tests. Statistical results from the FFRC tests on cement-treated RAP mixes show that one-day and three-day moduli are about 65% and 85% of the 7-day modulus, respectively as shown in Figure 6.2.

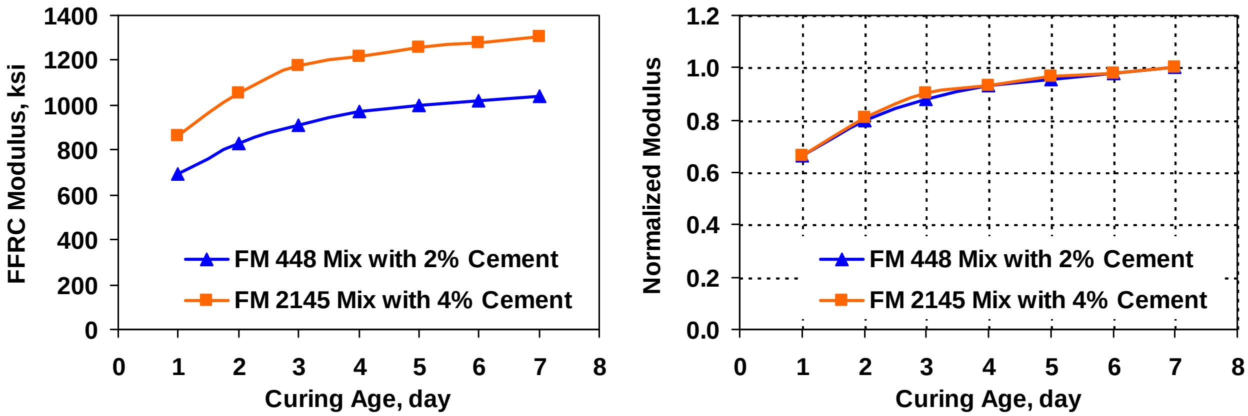


Figure 6.2 – FFRC Modulus Gain with Curing Age

Representation of Results

Roadway Widening Project in Lubbock District

This short (less than one-mile long) single side roadway widening project was located along FM 378 in Floyd County of Lubbock District as shown in Figure 6.3. The base course of this project was built by the TxDOT Floydada Maintenance Office staff.

Figure 6.3 – Location of the Roadway Widening Project on FM 378

The roadside stockpile mix used in the base course consisted of 25% RAP, 25% salvage aggregates and 50% virgin aggregates. Three road sections with cement contents of 2%, 1.7% and 1.2% were constructed at this site.

Results from Laboratory Tests

Figure 6.4 shows the gradation of the mix used in this project. For comparison, the gradation curves of the original RAP, and virgin and salvage aggregates are also included in the figure. The final mix and the virgin aggregates met TxDOT Specification Item 247 requirement for Grade 1 base material with about 4% and 2% fines (passing #200 sieve), respectively.

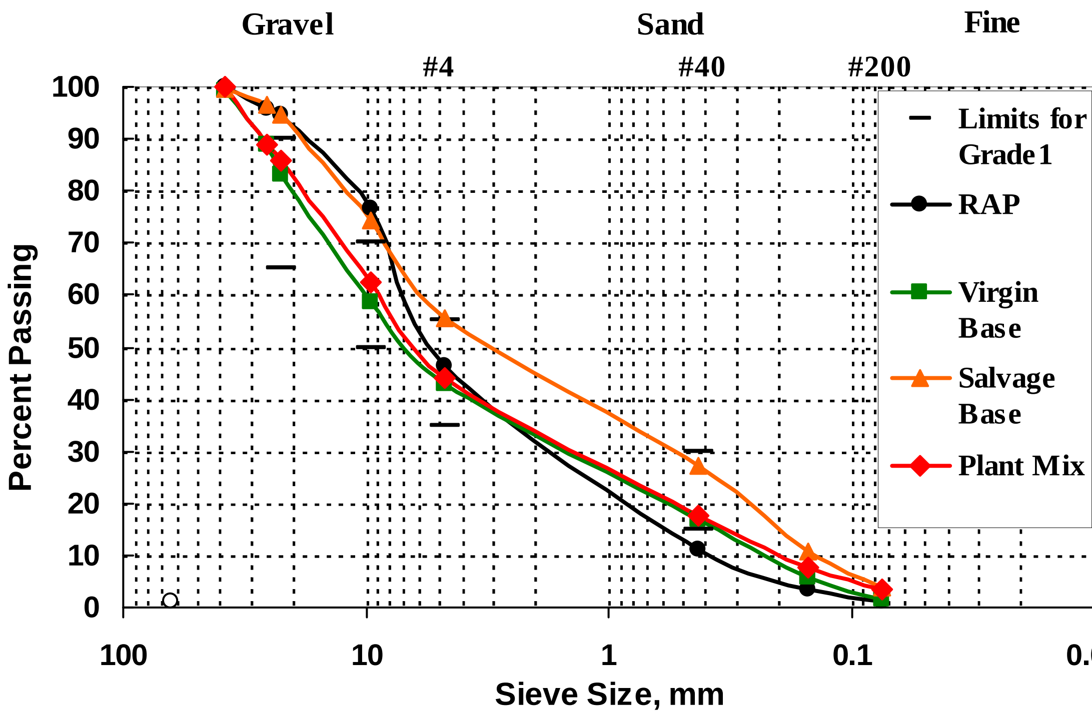


Figure 6.4 – Gradation of the Mix Used in the FM 378 Project

Since the same RAP and base materials were also used for the evaluation of the RAP mixes as reflected in Chapters 4 and 5, it would be interesting to see the effects of RAP content and different aggregates on the properties of mixes. Figure 6.5 shows a comparison of the 7-day UCS, ITS and FFRC modulus of mixes containing different RAP contents and different granular materials treated with 2% cement. In the figure, VB and SB stand for virgin base and salvage base, respectively. The results shown in this figure indicate the following:

- Both strength and modulus generally decrease as RAP content in mixes increases.
- Strength and modulus of the mix containing 25% RAP are not significantly different from those of the mixes of 50% RAP, in particular, for the mix containing salvage base.
- Effect of finer aggregate (largely contributed by the salvage base in this case) on the strength and modulus of the RAP mixes is evident as mentioned in Chapter 4.

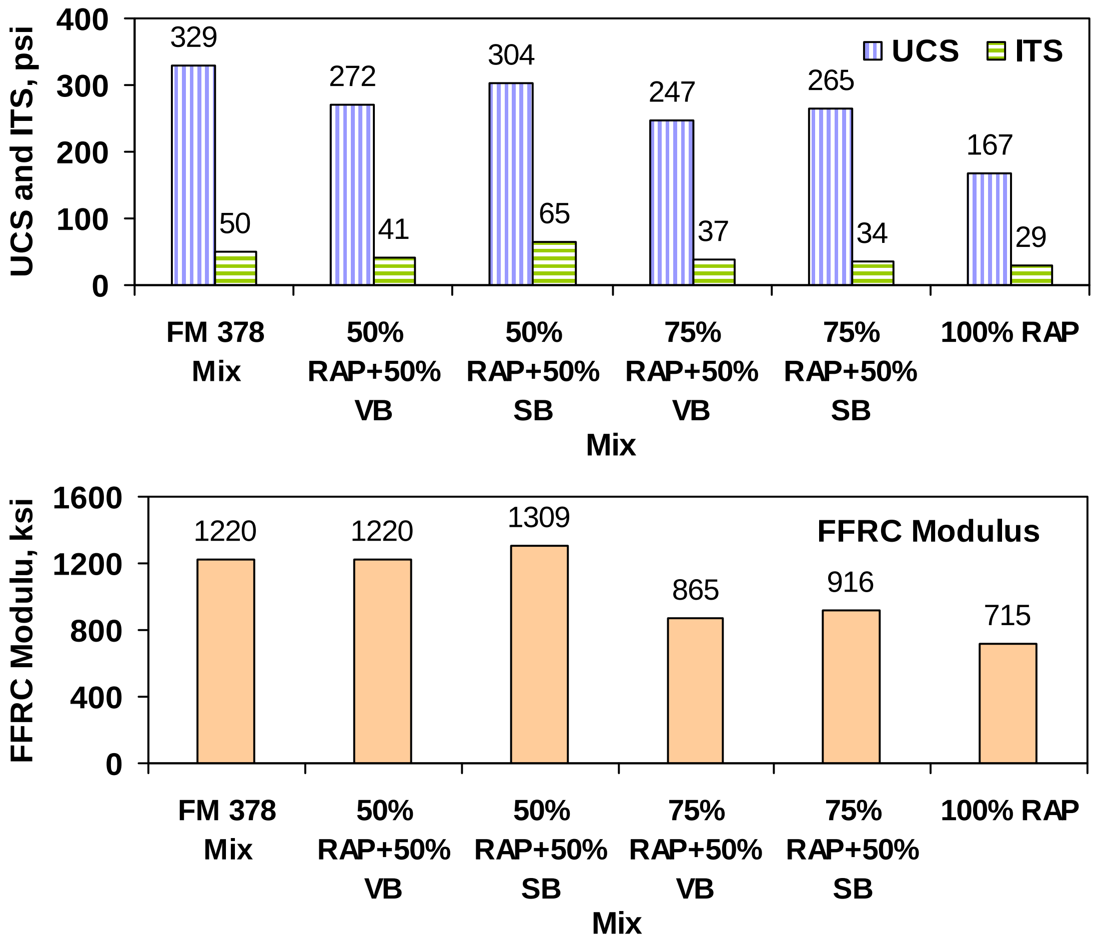


Figure 6.5 – Comparison of Strength/Modulus of Mixes of Different RAP Contents and Different Granular Materials Treated with 2% Cement

The Lubbock District Lab had compared the compressive strengths of two untreated mixes before the field work started. One mix consisted of 12.5% RAP, 25% savage aggregates and 62.5% virgin aggregates. Another, as used in the field project contained 25% RAP, 25% salvage aggregates and 50% virgin aggregates. Both unconfined and confined compressive strengths of the mix containing 25% RAP were higher than those of the mix containing 12.5% RAP; typically, 40 psi vs. 32 psi at zero lateral pressure and 116 psi vs. 101 psi at 15 psi of lateral pressure.

Results from Field Tests

Field tests with the PSPA and LWD were performed in all three cement-treated sections and part of the untreated section after 3 to 5 days of construction. Average moduli obtained from these tests are summarized in Figure 6.6. The average modulus from the PSPA testing in the section treated with 2% cement is lower as compared with that from the laboratory FFRC testing on the specimen treated with 2% cement. According to the average laboratory modulus (1220 ksi, see Figure 6.5) and Equation 6.1 with a Poisson’s ratio of 0.22 and an adjustment factor of 0.87 for curing age, the field modulus should be about 1060 ksi. The difference can largely be attributed to the differences in compaction, mixing and curing conditions as well measurement error. The LWD provided very low moduli for the cement-treated base courses. This is explained due to the device having a capacity to measure a range of deflection from 0.2 mm to 30 mm, and at many points in the cement-treated sections (particularly, in 2% and 1.7% sections), the measured deflections were close to 0.2 mm.

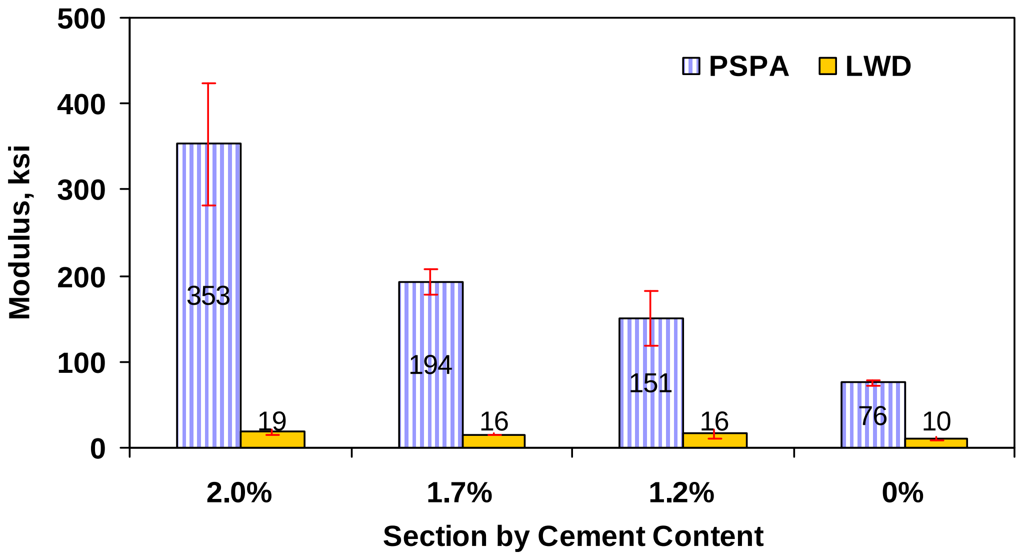


Figure 6.6 – Moduli Measured with PSPA and LWD on the New Base of FM 378

Rehabilitation Project in Yoakum District

This rehabilitation project was located on FM 448 in Fayette County of Yoakum District as shown in Figure 6.7. The procedure for base course construction of this project included pulverizing the existing surface layer and base down to 5 in., spreading the materials to widen the road bed, adding 4-in. thick hauled RAP, and then cement-treating (3%) the mix down to 8 in. The average RAP content in the new base course was estimated to be more than 60%.

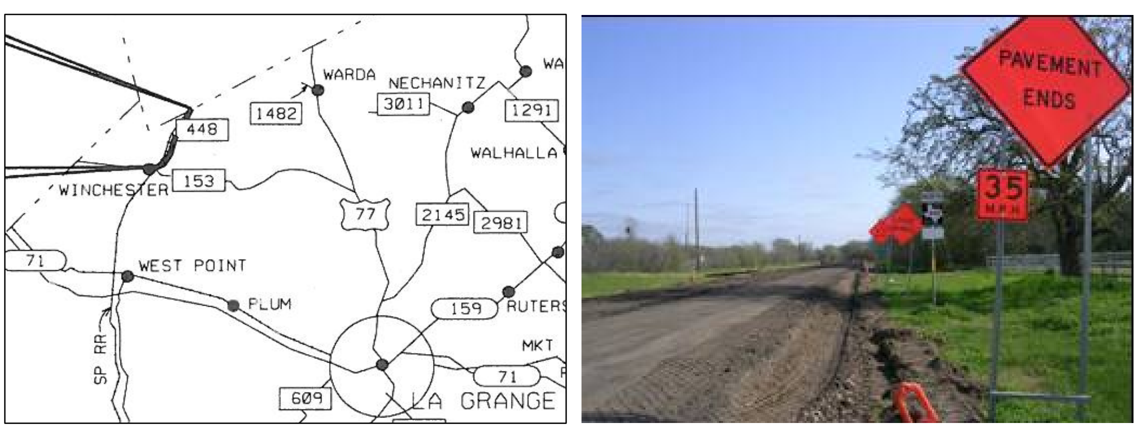


Figure 6.7 - Location of the Rehabilitation Project on FM 448

Results from Laboratory Tests

Road mix was sampled at five stations along the project during construction just before water and cement were applied. Figure 6.8 shows the particle size distribution of the mix sampled from each of the five stations. None of the gradations met TxDOT Specification Item 247 requirements for Grade 1 base materials. The average fines content in the mix is a little bit more than 1%. These characteristics are very similar to those of 100% RAP as reported in Chapter 3.

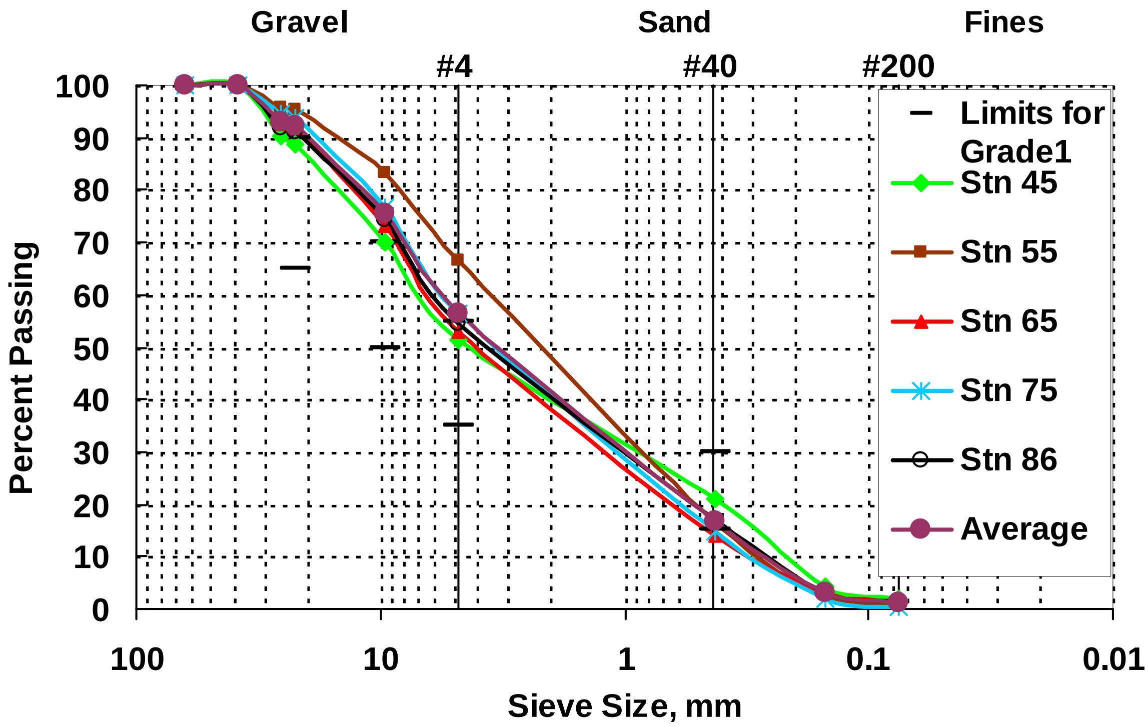


Figure 6.8 - Gradation of the Mix Used in the FM 448 Project

The optimum moisture content (OMC) and maximum dry density (MDD) of the mix without treatment were 7.2% and 124.0 pcf, respectively. For the mix treated with 3% cement, the OMC was 8.2% and the MDD was 125.8 pcf.

Figure 6.9 shows the 7-day UCS, ITS and FFRC modulus of the road mix sampled from each station. The average UCS, ITS and FFRC modulus were 298 psi, 40 psi and 1060 ksi, respectively, which all fit the model for mixes of 75% RAP (300 ksi for UCS, 40 psi for ITS and 1000 ksi for FFRC Modulus) provided in Chapter 4..

The retained UCS, ITS and FFRC modulus were obtained from a procedure similar to the tube suction test (draft TxDOT Test Procedure Tex-144-E) and the average values of the three parameters are 126%, 104% and 88%, respectively.

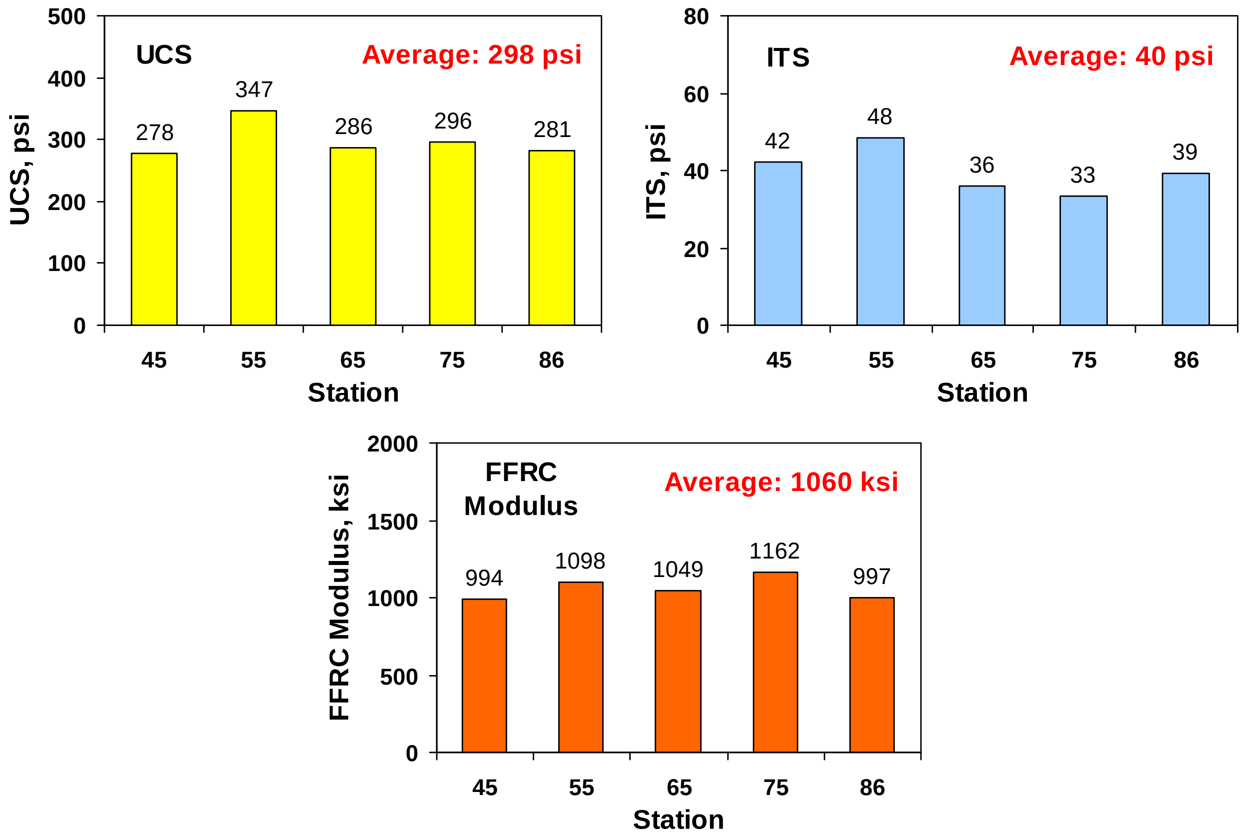


Figure 6.9 – Strengths and Modulus of 3% Cement-Treated Mix Used in the FM 448 Project

Results from Field Tests

Field tests with the PSPA and FWD were performed on the new base course in a 3000-ft section along the project. At the time of testing, the base in this section had been cured for 24 hours after initial compaction. In addition, a 500 ft section just next to the 3000-ft section was also tested. This short section had an age of 4 weeks.

Figure 6.10 shows the moduli measured with the PSPA and backcalculated from the FWD deflection measurements. Approximately, the average modulus from the PSPA tests is 2.5 times of that from the FWD tests both for the section cured 24 hours and for the section cured 4 weeks.

After conversion and adjustment, the predicted field modulus for the 24-hr cured section should be about 600 ksi. This value is much greater than the average (315 ksi) from the actual PSPA measurements. The same reasons for the difference between the laboratory and field moduli for the FM 378 project can also be applied to this case.

For the section of 4-week age, the average measured modulus is 901 ksi which is very close to the predicted value (920 ksi).

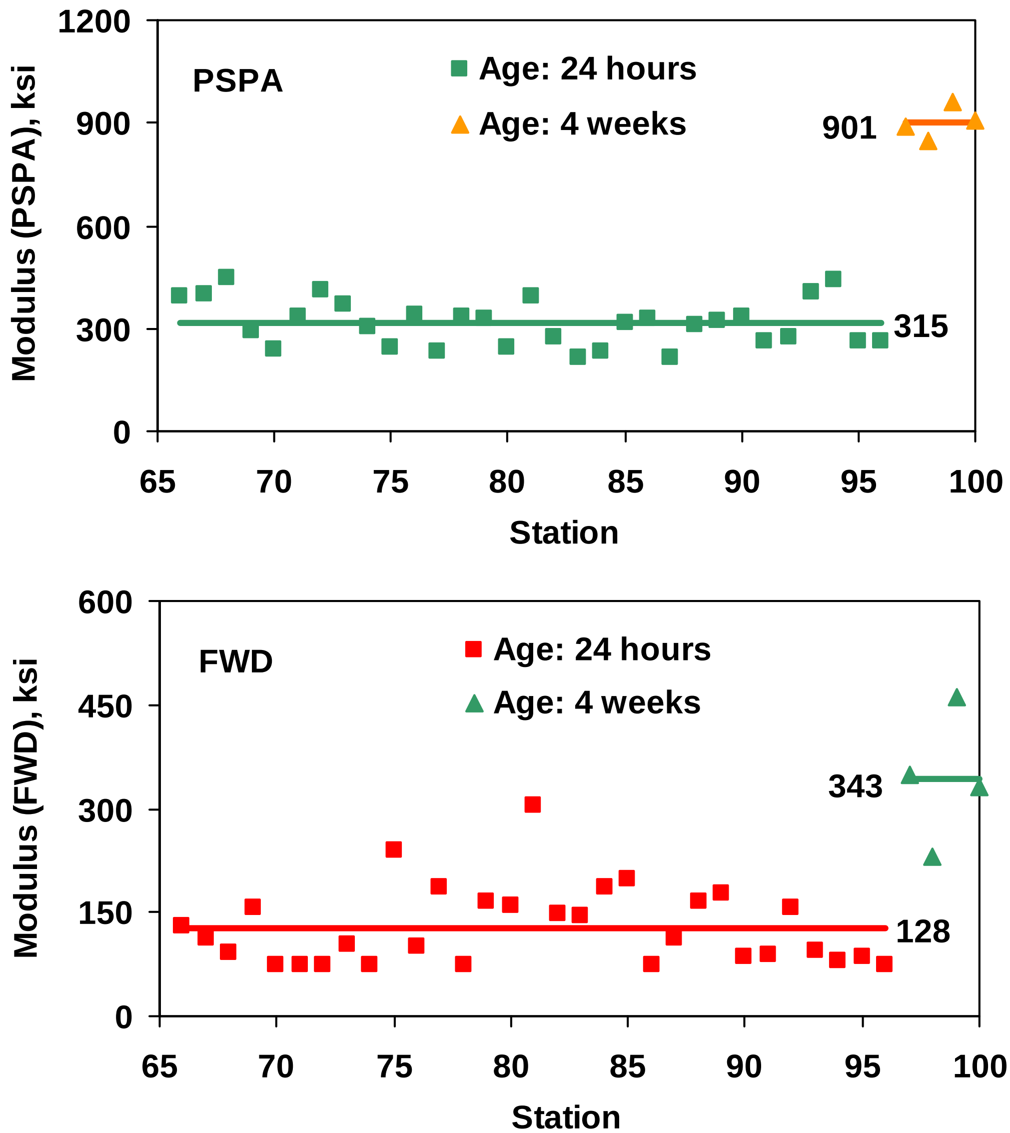


Figure 6.10 – Moduli from PSPA and FWD Tests on the New Base of the FM 448 Project

The NDG testing in the 3000-ft long section provided an average dry density of 120.1 pcf and an average moisture content of 11.0% which are considerably different from those (MDD of 125.8 pcf and OMC of 8.2%) obtained from the laboratory testing. The reasons for the differences are unknown. Laboratory specimens prepared with 11% moisture content yielded 191 psi for UCS, 24 psi for ITS and 680 ksi for FFRC modulus, which are much less than those values shown in Figure 6.9.

Rehabilitation Project in Fort Worth District

This rehabilitation project was located on FM 2415 in Johnson County of Fort Worth District as shown in Figure 6.11.

Figure 6.11 – Location of the Rehabilitation Project on FM 2415

The procedure for the base course construction of this project included:

- Pulverizing the existing surface layer and base down to 6 in. and hauling them to the plant,
- Mixing the pulverized material with additional RAP at a ratio of 6 to 4,
- Treating the mix with 4% cement and then mixing with water to reach a moisture content of 11.2% as per the mix design for the base course,
- Hauling the treated mix back to the site, and
- Spreading to widen pavement and form a 10-in. thick new base.

The average RAP content in the base course placed at this site is estimated to be 60% or more.

Results from Laboratory Tests

The plant mix was sampled at four locations from the stockpile before water and cement were applied. Figure 6.12 shows the particle size distributions of the four locations. The gradation of the mix used in this project is very similar to that used in the FM 448 project; that is, the coarse fraction is too fine and the fine fraction is too coarse. However, the average fines content in the mix was slightly more than 2.5% which is significantly higher than that of the mix used in the FM 448 project.

The OMC and MDD of the mix without treatment were 7.8% and 122.8 pcf, respectively. For the mix treated with 4% cement, the OMC was 8.8% and the MDD 124.7 pcf.

Figure 6.13 shows the 7-day UCS, ITS and FFRC modulus of the road mix sampled from each station. The average UCS, ITS and FFRC modulus are 507 psi, 53 psi and 1275 ksi, respectively. Both the individual and the average UCS values of the mix are greater than the minimum requirement by TxDOT Specification Item 276. As a result, the ITS and FFRC modulus of the mix are much higher than their corresponding values (40 psi and 1000 ksi) for a UCS of 300 psi. In such a sense, the mix used in this project was perhaps over-stabilized. The average retained UCS, ITS and FFRC modulus of the mix are 104%, 92% and 85%, respectively.

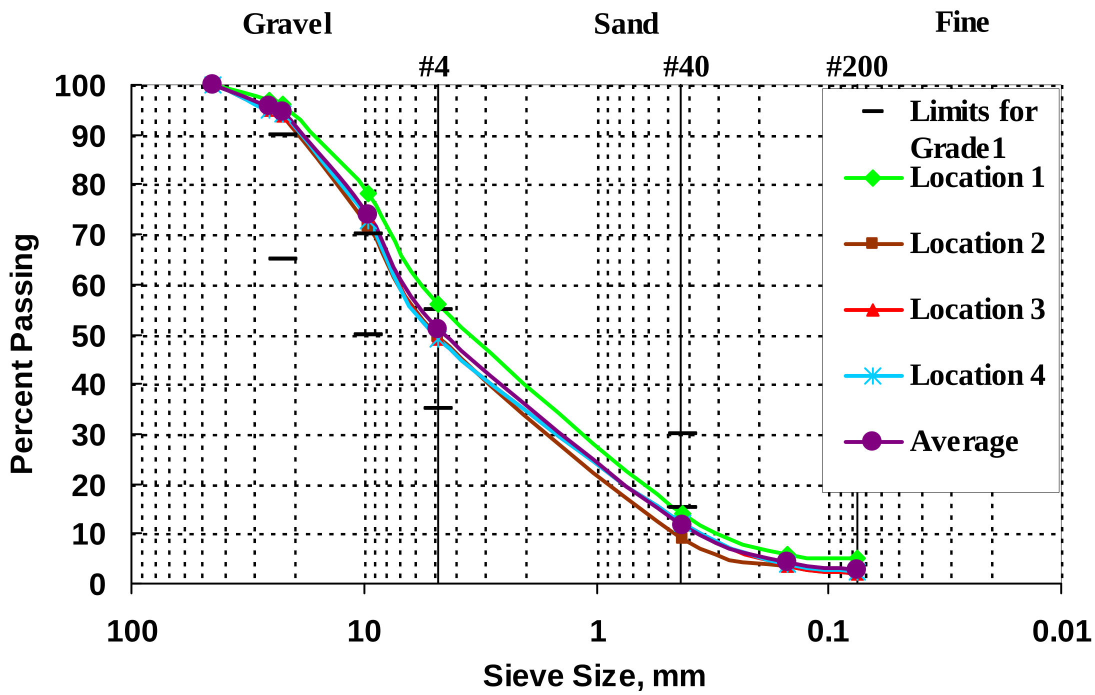


Figure 6.12 - Gradation of the Mix Used in the FM 2415 Project

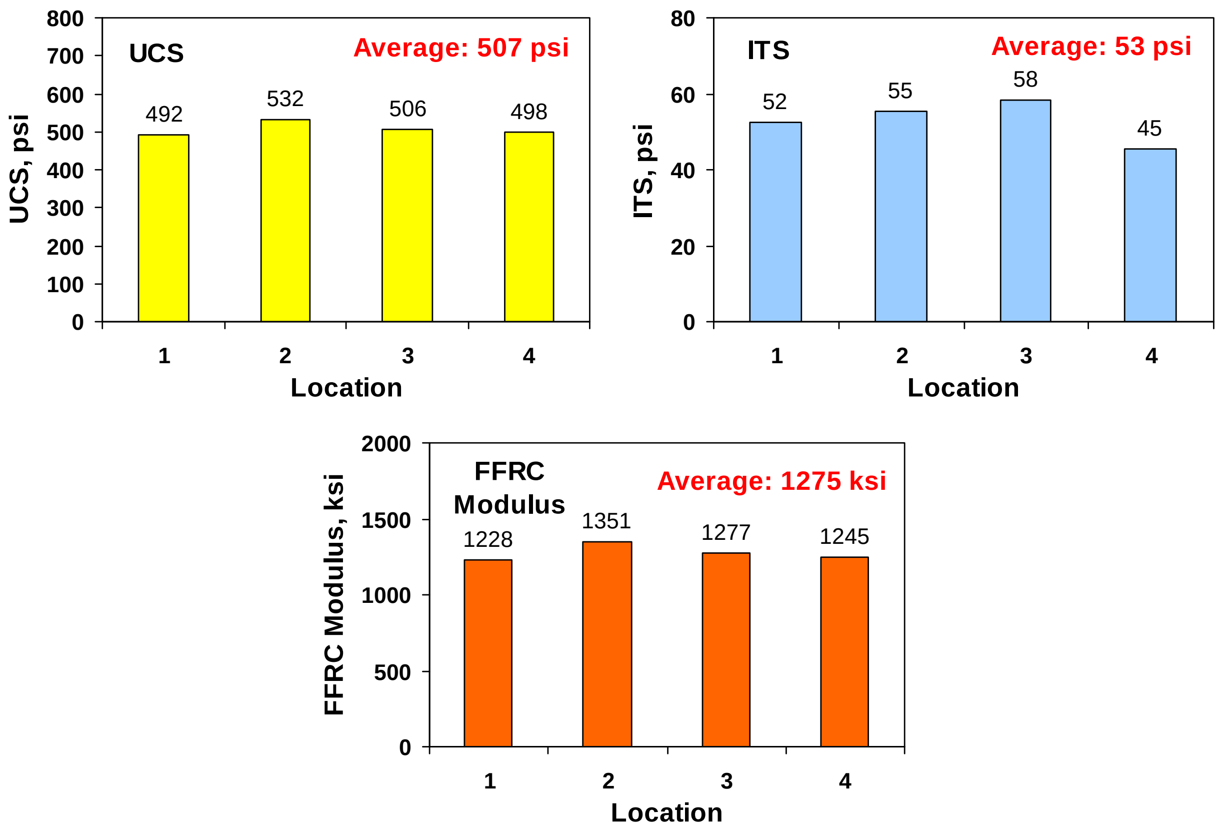


Figure 6.13 – Strengths and Modulus of 4% Cement-Treated Mix Used in the FM 2415 Project

Results from Field Tests

Field tests with PSPA were performed on the new base course in two 1400 ft-long sections along the project. At the time of testing, the first section had been cured for 24 hours, and the second one had an age of one week. FWD testing was scheduled for the two sections at the same time. However, the testing was actually performed a week late due to a mechanical problem with the FWD. Results from these tests are shown in Figure 6.14. The back-calculated moduli from FWD deflection data manifest a large variation due to the variability in the raw deflection data. The average moduli (580 ksi and 949 ksi) from PSPA tests on the new base in the two sections were slightly lower than the predicted ones (720 ksi and 1100 ksi) for the project with plant mixing.

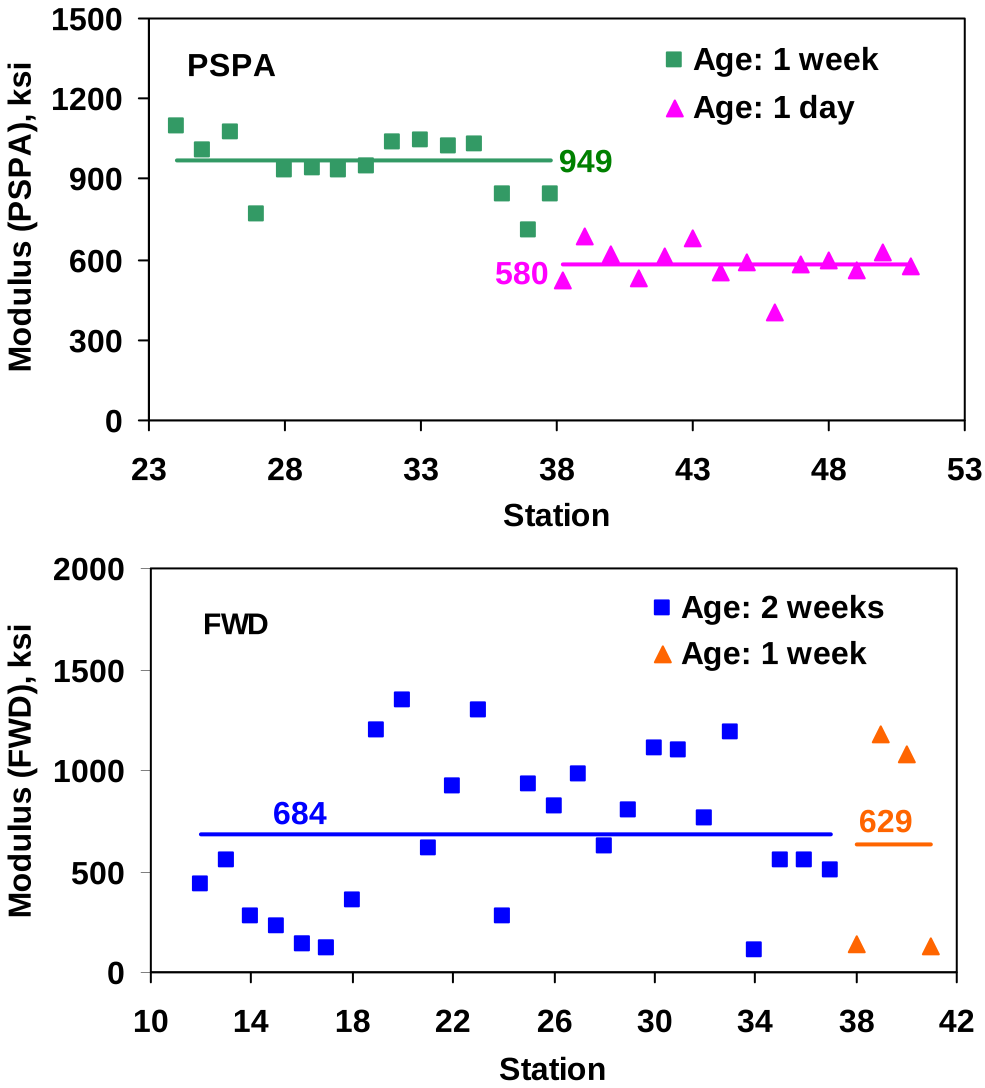


Figure 6.14 – Moduli from PSPA and FWD Tests on the New Base of the FM 2415 Project

The NDG testing along the two sections provided an average dry density of 115.2 pcf and an average moisture content of 13.3% which are different than those obtained from the laboratory tests (MDD of 124.7 pcf and OMC of 8.8%). Again, the reasons for the differences are unknown.

The laboratory specimens prepared with 11.2% moisture content and with 4% cement yield 245 psi for UCS, 29 psi for ITS and 977 ksi for FFRC modulus which are much less than those values shown in Figure 6.13.

Five cores were retrieved at five different locations after the new base had been cured for about 2 months. The results from the strength and modulus tests performed on these cores are shown in Figure 6.15. In consideration of the long curing age of these cores, the UCS and FFRC modulus values reflected in Figure 6.14 are consistent with those from the laboratory tests on the 7-day cured specimens. Actually, for cement-treated RAP mixes, an increase of 15% in UCS from 7-day cure to 28-day cure has been reported by Taha at al. (2002). Finally, as shown in Figure 6.16, no cracks were observed on the cores from the 4% cement-treated base course.

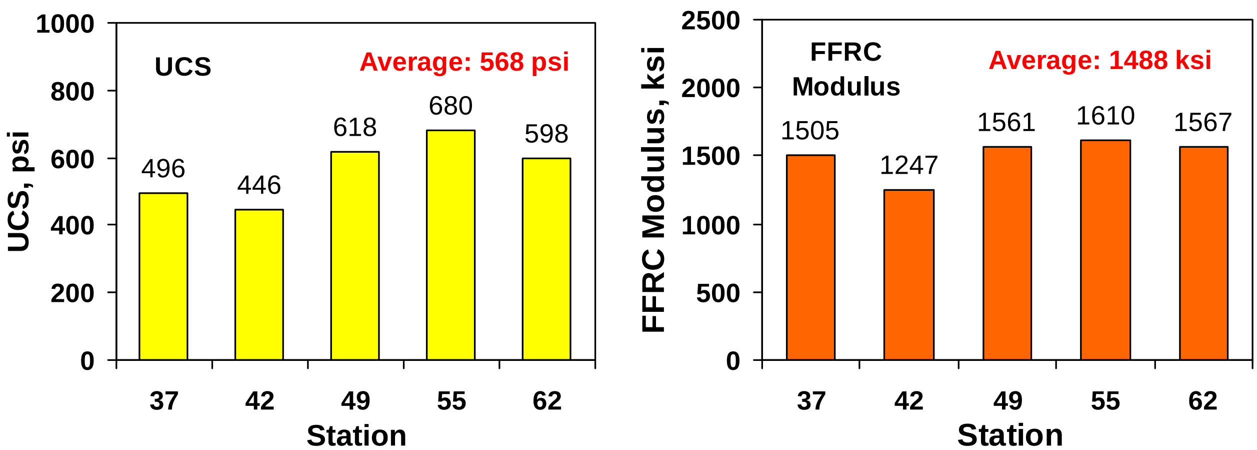


Figure 6.15 – UCS and FFRC Modulus of Cores from the New Base of the FM 2415 Project

Figure 6.16 – Cores Retrieved from New Base of the FM 2415 Project

Summary

Initial field trials were conducted for three construction projects with cement-treated RAP mixes as their base courses. The results from these trials indicate the following:

- In terms of UCS, ITS and FFRC modulus, the mix design model developed from the laboratory experiments for cement-treated RAP mixes can be applied to the mix design for construction.
- Combining the FFRC modulus and PSPA-type modulus measurements has potential in developing a QA/QC procedure for construction of cement-treated base courses.
- The design optimum moisture contents of the mixes used in the FM 448 and FM 2415 projects were significantly (approximately 3%) lower than those measured by NDG in the field. This matter needs further investigation.

Chapter 7

Conclusions and Recommendations

Conclusions

Based on the laboratory results from this research project, the following conclusions can be made:

- The gradations of unfractionated RAP from different stockpiles are quite similar. Lack of finer aggregates is a common characteristic of the RAP materials in Texas.
- According to the UCS requirement for cement-treated base materials by TxDOT specifications, the use of cement-treated mix of high RAP content as base material for roadway rehabilitation construction is feasible.
- RAP content and cement content in a RAP mix has a strong impact on the properties of the mix.
- For a 300-psi UCS, the statistical optimum cement contents are about 4%, 3% and 2% for mixes of 100% RAP, 75% RAP and 50% RAP, respectively.
- The results from UCS, ITS, FFRC modulus and resilient modulus tests are consistent. Corresponding to a 300-psi UCS, the ITS, FFRC modulus and resilient modulus are about 40 psi, 1000 ksi, and 250 ksi, respectively.
- RAP blended with granular base materials of relatively higher finer aggregate, particularly fines content, can improve the quality of a RAP mix.
- The use of salvage base as opposed to transporting the virgin aggregate can be a cost effective way to build the new base courses of cement-treated RAP mixes.
- Asphalt content in RAP does not seem to have a considerable impact on strength and modulus of RAP mixes.
- For the mixes that meet the 300-psi UCS requirement, permanent strains up to1000 cycles are less than 50 micro-strains.
- For the mixes that meet the 300-psi UCS requirement, the average retained UCS, ITS and FFRC modulus from tube suction tests meet or closely meet the recommended value of 80% (draft TxDOT Test Procedure Tex-144-E), and the average retained UCS values from wet-dry testing are similar.

- All dielectric values for cement-treated RAP mixes are much smaller than 10 (recommended by draft TxDOT Test Procedure Tex-144-E). Thus, dielectric constant measurement seems to have less meaning for cement-treated materials.
- Results from initial field tests confirmed the mix design model developed in the laboratory.
- A modulus-based QA/QC procedure seems to be feasible for cement-treated base courses containing high RAP content.
- The applicability and effectiveness of density-based QA/QC procedures for cement-treated base courses containing high RAP content need to be further investigated.

Recommendations

Most of the researches regarding RAP as a base course material has been laboratory testing. Many questions still exist as to how construction process, traffic loading and environmental factor will affect the performance.

During the period of the research project, field trials were applied to one maintenance (roadway widening) project with low RAP content (25%) and two rehabilitation projects with high RAP content (more than 50%). However, these trials were done with limited field activities, and only the initial date was collected from each project due to the time frame of the research project. For a systematic validation procedure that should include mix design, construction practice, QA/QC, and relatively long-term performance monitoring, an implementation project is needed. The long-term performance monitoring should include the following concerns:

- Degradation of RAP aggregate due to repeated truck traffic loading and the environment
- Strength and modulus decrease duo to asphalt viscosity in RAP at high temperature
- Long-term moisture susceptibility
- Gradation requirement for RAP used as base course material

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Appendix A

Modified Tex-120-E

Test Procedure for

RAP-CEMENT TESTING

TxDOT Designation: Tex-120-C

Effective Date: For Review

1. SCOPE

1.1 This method consists of two parts.

1.1.1 'Part I, Compressive Strength Test Methods (Laboratory Mixed) determines the unconfined compressive strength of compacted recycled asphalt pavement (RAP)-cement specimens after seven days curing (10 lb. hammer, 18-inch drop, 50 blows/layer using 6 x 8 in. mold).

1.1.2 'Part II, Compaction Testing of Road Mixed Material applies to cement treated RAP sampled from the roadway during construction.

1.2 The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

2. APPARATUS

2.1 As outlined in test methods:

- Tex-101-E
- Tex-113-E
- Tex-117-E

2.2 *Compression testing machine*, with capacity of 60,000 lb (270 kN), meeting requirements of ASTM D 1633.

2.3 *Triaxial screw jack press* (Tex-117-E), used when anticipated strengths are not in excess of 400 psi (2758 kPa).

3. MATERIALS

3.1 *Hydraulic (Portland) cement.*

3.2 *Tap water.*

4. PREPARING SAMPLE

4.1 Select approximately 200 lb (90 kg) of material treat with cement according to Part II of Tex-101-E.

PART I, COMPRESSIVE STRENGTH TEST METHODS (LABORATORY MIXED)

5. PROCEDURE

5.1 Determine the optimum moisture content and maximum dry density for a RAP-cement mixture containing 3%[1] cement, using Tex-113-E. The amount of cement added is a percentage based on the dry mass of the RAP mixture.

If desired, wrap the specimens prepared for MD curves in cellophane and let stand for 24 hours on the counter top. Obtain the specimens' unconfined compressive strengths as per Tex-117-E and/or moduli as per Draft Tex-148-E. These values can be used to estimate whether the cement is compatible with the RAP mixture.

5.2 Recombine the sizes prepared according to Part II of Tex-101-E to make three individual samples and add the optimum moisture content, from Tex-113-E to each sample. Mix thoroughly.

5.2.1 Cover the mixture (without additive) to prevent loss of moisture by evaporation. Allow the wetted mixtures to stand for at least 12 hours before compaction. When the PI is less than 12, the standing time may be reduced to not less than three hours. Split or referee samples should stand the full term.

5.2.2 Prior to compaction, replace any evaporated water and thoroughly mix each specimen.

5.2.3 Add cement uniformly and mix thoroughly.

5.3 Compact the specimen in four layers using Tex-113-E compactive effort.

5.3.1 Alter the percent molding water slightly as the percent cement is increased or decreased. Do this in order to mold nearer optimum moisture without running a new M/D curve for each percentage of cement.

Note 1—A new M/D curve for each percentage of cement may be performed, if desired.

5.3.2 Use the following rule to vary the molding water:

- % molding water = % optimum moisture from M/D curve + 0.25 (% cement increase), where

[1] Changed from 6% to 3% since most projects require 2% to 4% cement

- % cement increase = difference in cement content between curve and other cement contents.

5.4 Using the moisture contents outlined above, mold three specimens for each cement content using 2, 3, and 4% [2]cement for mixture containing up to 75% RAP and 3, 4 and 5% cement for mixture of 100% RAP to complete the full set.

5.4.1 After the top surface of each specimen has been leveled and the specimen measured, carefully center over porous stone and remove specimen from mold by means of small press.

5.4.2 Place a card on each specimen showing the laboratory identification number and the percent of cement.

Note 2—In calculating the actual dry density of laboratory mixed RAP-cement specimens, the dry mass of material is the total mass of oven dry RAP mixture in the specimen plus the mass of cement. The amount of moisture should be the mass of hygroscopic moisture in the RAP mixture plus the amount of water added based on the dry mass of the RAP mixture plus cement. Road mixed and wetted materials and RAP-cement cores shall have moisture and density determined from the oven dry masses.

5.5 Store test specimens the same day they are molded, with top and bottom porous stones, in the damp room for seven days. Do not subject specimen to capillary wetting or a surcharge. A triaxial cell is not used. A pan may be placed on top of the top porous stone to protect the specimen from dripping water.

Remove test specimens from the damp room and use a cloth to remove any free water on surface of specimen. The specimens are now ready for compressive strength test as per Tex-117-E. A compression testing machine of adequate range and sensitivity shall be used.

5.6 The moduli of the specimens can be obtained nondestructively as per Draft Tex-148-E just before compression tests.

5.7 If the second specimen tests within ten percent of the first, the engineer may elect to test the third specimen in indirect tension.

6. TEST REPORTS

6.1 Molding moisture to the nearest 0.1%

6.2 Dry density to the nearest 0.1 pcf (1 kg/m^3)

6.3 Unconfined compressive strength to the nearest whole psi (kPa) for each cement content tested

[2] Reduced to fit our observation

6.4 Modulus to the nearest whole ksi (MPa) for each cement content tested (if available)

6.5 Recommended cement content to the nearest 0.5 percent

Note 3—Store cement in airtight container or use fresh supply from the project, if possible.

Note 4—When comparing laboratory strengths with roadway strength, use the H/D correction factors in Table 1 of Tex-118-E on both laboratory and roadway specimens.

PART II, COMPACTION TESTING OF ROAD MIXED MATERIAL

7. PROCEDURE

7.1 Samples for moisture/density curve should be obtained just prior to the start of compaction operations on the roadway.

7.2 Cement stabilized materials taken from the roadway during construction should be screened over a 1/4 in. (6.3 mm) sieve at field moisture content, without drying.

7.2.1 Mix each of these two sizes, plus 1/4 in. (6.3 mm) and minus 1/4 in. (6.3 mm), for uniformity and weigh.

7.2.2 Cover each size fraction to maintain field moisture.

7.3 Recombine and mold one specimen at the field moisture condition and estimated mass to produce specimen compacted using Tex-113-E compactive effort. Molding should be accomplished using the same equipment and compactive effort as in Part I.

7.3.1 Adjust mass, if necessary, and weigh out not less than two additional specimens at the field moisture content for compaction. Molding moisture can be adjusted in each specimen by adding or removing moisture uniformly as needed.

7.3.2 Compact cement stabilized material in the laboratory in approximately the same timeframe as on the road. Compacted sample of cement-treated RAP from the road mix should not be prepared by oven drying.

Wrap the specimens prepared for MD curves in cellophane and let stand for 24 hours on the counter top. Obtain the specimens' unconfined compressive strengths as per Tex-117-E and/or moduli as per Draft Tex-148-E. These values can be used to estimate the quality of the cement-treated RAP.

Note 5—To determine moisture-density relationship of fine-grained materials with less than 20% retained on the 1/4 in. (6.3 mm) sieve and 100% passing the 3/8 in. (9.5 mm) sieve, the engineer may elect to use a mold with approximate dimensions of 4.0 in. (102 mm) in diameter by 6.0 in (152 mm) in height. The number of blows must be calculated when changing mold size to maintain a compactive effort of 13.26 ft-lb/in^3 (1100 kN-m /m^3).

Note 6—The contractor should be provided an initial optimum moisture based on preliminary laboratory tests.

8. TEST REPORT

8.1 Report density to nearest 0.1 pcf (1 kg/m^3).

8.2 Report moisture content to nearest 0.1 %.

8.3 Unconfined compressive strength to the nearest whole psi (kPa) for each specimen tested (if available)

8.4 Modulus to the nearest whole ksi (MPa) for each specimen tested (if available)

9. GENERAL NOTES

9.1 *Testing Notes*

9.1.1 Store cement in an airtight container to ensure a fresh supply.

9.1.2 Wetted stabilized materials taken from the roadway during construction should be prepared for testing without drying back.

9.1.2.1 The desired intent is to have the capability of weighing identical samples for strength and density control specifications.

9.1.2.2 The sample may have moisture added and remixed or removed with a fan while stirring for developing compaction curves.

9.1.2.3 The district laboratory should develop design strength data for these and other conditioning procedures.

9.2 *Design Notes*

9.2.1 When water, cement, and material have been brought together during construction, the mixture should receive final mixing and compaction during that same working day.

9.2.2 Cement contents less than 2.0% are not recommended due to difficulty in uniform distribution under construction conditions.

9.2.3 Cement stabilized RAP will perform as semi-rigid pavement. The engineer should not specify this type of pavement design on a soft foundation where relatively large deflections are likely to occur.

9.2.4 A density control specification is recommended for this type of stabilization. Field density control should be based on testing road mixed samples according to Tex-113-E. A minimum of 98% of the maximum density should be obtained for cement treated RAP.

9.2.5 It is recommended that RAP stabilization receive an asphaltic surface course from base crown to base crown to reduce erosion along the pavement edge.

9.2.6 Cement characteristics vary widely with source. The engineer should perform strength tests with the cement to be used on the project.

Appendix B

Modified Item 276

ITEM 276 (Modified)

CEMENT TREATMENT OF HIGH CONTENT RAP LAYERS (PLANT-MIXED)

276.1. Description. Construct a base course composed of recycled asphalt pavement (RAP), salvaged base, and/or add rock, hydraulic cement, and water, mixed in an approved plant.

276.2. Materials. Furnish uncontaminated materials of uniform quality that meet the requirements of the plans and specifications. Notify the Engineer of proposed sources of materials and of changes in material sources. The Engineer will verify that the specification requirements are met before the sources can be used. The Engineer may sample and test project materials at any time before compaction. Use Tex-100-E for material definitions.

A. RAP. RAP is salvaged, milled, pulverized, broken, or crushed asphalt pavement. Crush or break RAP so that 100% of the particles pass the 2-in. sieve.

Use of Contractor-owned RAP including hot-mix asphalt (HMA) plant waste is permitted, unless otherwise shown on the plans. Department-owned RAP stockpiles are available for the Contractor's use when the stockpile locations are shown on the plans. If Department-owned RAP is available for the Contractor's use, the Contractors may use their own fractionated RAP and replace it with an equal quantity of Department-owned RAP. This allowance does not apply to Contractor's using non-fractionated RAP. Department-owned RAP generated through required work on the Contract is available for the Contractor's use when shown on the plans. Perform any necessary tests to ensure Contractor or Department-owned RAP is appropriate for use. Unless otherwise shown on the plans, the Department will not perform any tests or assume any liability for the quality of the Department-owned RAP. When shown on the plans, the contractor will retain ownership of RAP generated on the project.

Fractionated RAP is defined as having two or more RAP stockpiles, whereas the RAP is divided into coarse and fine fractions. The coarse RAP stockpile will contain only material retained by processing over a 3/8 in. screen or 1/2 in. screen, unless otherwise approved. The fine RAP stockpile will contain only material passing the 3/8 in. screen or 1/2 in. screen, unless otherwise approved. The Engineer may allow the Contractor to use an alternate to the 3/8 in. screen or 1/2 in. screen to fractionate the RAP. The maximum percentages of fractionated RAP may be comprised of coarse or fine fractionated RAP or the combination of both coarse and fine fractionated RAP.

Determine gradation of RAP stockpiles for mixture design purposes in accordance with Tex-236-F. Perform other tests on RAP when shown on the plans. Do not use Department or Contractor owned RAP contaminated with dirt or other objectionable materials. Do not use Department or Contractor owned RAP if the plasticity index is greater than 8. Determine the plasticity index in accordance with Tex-106-E if the decantation value exceeds 5%.

Do not intermingle Contractor-owned RAP stockpiles with Department-owned RAP stockpiles. Remove unused Contractor-owned RAP material from the project site upon completion of the project. Return unused Department-owned RAP to the designated stockpile location.

B. Cement. Furnish hydraulic cement that meets the requirements of DMS-4600, "Hydraulic Cement," and the Department's Hydraulic Cement Quality Monitoring Program (HCQMP). Sources not on the HCQMP will require testing and approval before use.

C. Salvage Base. When required, furnish salvage base that when proportionally added to the RAP meets the gradation requirements of Grade 1 Item 247, "Flexible Base," for the type and grade shown on the plans, before the addition of cement.

D. Add Rock. When required, furnish add rock that when proportionally added to the RAP and/or salvage base meets the gradation requirements of Grade 1 Item 247, "Flexible Base," for the type and grade shown on the plans, before the addition of cement. Alternatively, finer quarry aggregates can be added to the RAP so that the gradation would conform to Grade 1 Item247.

E. Water. Furnish water that is free of industrial waste and other objectionable material.

F. Asphalt. When permitted for curing purposes, furnish asphalt or emulsion that meets the requirements of Item 300, "Asphalts, Oils, and Emulsions," as shown on the plans or as directed.

G. Mix Design. Submit a mix design to the Engineer for approval before the start of the project. Include the optimum moisture content, maximum dry density, percent and gradation of RAP and add rock, percent salvage base, and optimum percent cement required to meet the mixture requirements in Table 1. Prepare specimens for all tests in accordance with Tex-113-E. The preliminary target cement contents of 4% with 100% RAP, 3% with 75% RAP and 2% with 50% RAP are recommended. Use Item 276 for RAP content of less than 50%. The use of the target contents without proper verification is strongly discouraged.

Table 1 - Laboratory Mixture Design Properties

Property	**Curing Method/Test Method**	**Criterion**
Unconfined Compressive Strength	Tex-120-C[1] Part 1/Tex-117-E	300 psi minimum
Seismic Modulus	Tex-120-C Part II/ Draft Tex-148-E[2]	Report
Retained Strength/Modulus Ratio	Draft Tex-144-E[3]	0.8 minimum

276.3. Equipment. Provide machinery, tools, and equipment necessary for proper execution of the work. Provide rollers in accordance with Item 210, "Rolling." Provide proof rollers in accordance with Item 216, "Proof Rolling," when required.

A. Cement Storage Facility. Store cement in closed, weatherproof containers.

B. Mixing Plant. Provide a stationary pugmill, weigh-batch, or continuous mixing plant as approved. Equip plants with automatic proportioning and metering devices that produce a uniform mixture of base material, cement, and water in the specified proportions.

C. Spreader Equipment. When shown on the plans, provide equipment that will spread the cement-treated mixture in a uniform layer in 1 pass. When shown on the plans, equip spreaders with electronic grade controls.

276.4. Construction. Construct each layer uniformly, free of loose or segregated areas and with the required density and moisture content. Provide a smooth surface that conforms to the typical sections, lines, and grades shown on the plans or established by the Engineer. Start placement operations only when the air temperature is at least 35°F and rising or is at least 40°F. The

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[1] Tex-120-C is a suggested modified version of Tex-120-E as enclosed in the subsequent appendix.
[2] Refers to the method for free-free resonant column tests
[3] Refers to the Tube Suction Test Method

temperature will be taken in the shade and away from artificial heat. Suspend operations when the Engineer determines that weather conditions are unsuitable.

A. Mixing. Thoroughly mix materials in the proportions designated on the mix design, in a mixing plant that meets the requirements of Section 276.3.B, “Mixing Plant.” Mix at optimum moisture content, unless otherwise directed, until a homogeneous mixture is obtained. Do not add water to the mixture after mixing is completed unless directed.

B. Placing. Place the cement-treated RAP mixture on a subgrade or base prepared in accordance with details shown on the plans. Bring the prepared roadway to the moisture content directed. Haul cement-treated RAP mixture to the roadway in clean trucks and begin placement immediately. Place cement-treated RAP mixture only on an area where compacting and finishing can be completed during the same working day. Spread and shape in a uniform layer with an approved spreader. Construct individual layers to the thickness shown on the plans. Maintain the shape of the course by blading. Correct or replace segregated areas as directed, at no additional expense to the Department.

Construct vertical joints between new cement-treated base and cement-treated base that has been in place 4 hr. or longer. The vertical face may be created by using a header or by cutting back the face to approximately vertical. Place successive base courses using the same methods as the first course. Offset construction joints by at least 6 in.

C. Compaction. Compact the mixture in one lift using density control unless otherwise shown on the plans. Complete compaction within 2 hours after the application of cement. Sprinkle or aerate the treated material in accordance with Item 204, “Sprinkling,” to adjust the moisture content during compaction. Determine the moisture content of the mixture at the beginning and during compaction in accordance with Tex-103-E to ensure that the moisture content is within ± 1% of the moisture content specified in the mix design. Tex-103-E Part III (microwave oven) can be used to expedite this activity[4].

Begin rolling longitudinally at the sides and proceed towards the center, overlapping on successive trips by at least one-half the width of the roller unit. On superelevated curves, begin rolling at the low side and progress toward the high side. Offset alternate trips of the roller. Operate rollers at a speed between 2 and 6 mph, as directed.

1. **Ordinary Compaction[5].** Roll with approved compaction equipment as directed. Correct irregularities, depressions, and weak spots immediately by scarifying the areas affected, adding or removing treated material as required, reshaping, and recompacting.
2. **Density Control[6].** Compact to at least 98%[7] of the maximum density determined in accordance with Tex-120-C. The Engineer will determine roadway density in accordance with Test Method Tex-115-E[8] and will verify strength in accordance with Tex-120-C. Remove material that does not meet density requirements. Remove areas that lose required stability, compaction, or finish. Replace with cement-treated mixture and compact and test in accordance with density control methods.

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[4] It is of utmost importance to enforce this item. This should be over-emphasized to the Area Engineers and Inspectors through education.

[5] Ordinary Compaction for bases should be more strongly discouraged.

[6] The use of alternate methods to NDG should be considered

[7] As shown in this research, the MD curve of stabilized material varies very little with moisture. It may be advisable to improve the density requirements.

[8] The need to calibrate the NDG to the mix should be strongly conveyed to the Area Engineers and Inspectors.

The Engineer may accept the section if no more than 1 of the 5 most recent density tests is below the specified density and the failing test is no more than 3 pcf below the specified density.

D. Finishing[9]. Immediately after completing compaction, clip, skin, or tight-blade the surface of the cement treated material with a maintainer or subgrade trimmer to a depth of approximately 1/4 in. Remove loosened material and dispose of it at an approved location. Seal the clipped surface immediately by rolling with a pneumatic-tire roller until a smooth surface is attained. Add small increments of water[10] as needed during rolling. Shape and maintain the course and surface in conformity with the typical sections, lines, and grades shown on the plans or as directed.

Finished grade tolerances for subgrade will be in accordance with Section 132.3.F.1, "Grade Tolerances." Finished grade tolerances for base will be in accordance with Section 247.4.D, "Finishing." Do not surface patch.

E. Curing. Cure for at least 3 days by maintaining in a thorough and continuously moist condition by sprinkling in accordance with Item 204, "Sprinkling." When permitted, cure with an asphalt material applied at a rate of 0.05 to 0.20 gal per square yard or as shown on the plans or directed. Maintain the moisture content during curing at no lower than 2 percentage points below optimum. Do not allow equipment on the finished course during curing except as required for sprinkling, unless otherwise approved. Continue curing until placing another course or opening the finished section to traffic.

276.5. Quality Control. The Contractor is responsible for quality control (QC) of the process and the completed base. The Engineer will provide sampling frequencies.

A. Moisture Content. Use Tex-103-E to check moisture content shortly before the addition of cement[11]. If rain has occurred after testing and before the addition of cement, recheck the moisture content. Adjust by moisture addition (water truck) or aeration if the average moisture content is not within 1% of the mix design recommendation. Recheck the moisture content if manipulation has occurred.

B. Cement Content. Apply the amount of cement recommended in the mix design. The Engineer must approve changes in the cement content or supplier[12].

C. Gradation. Obtain samples to the full depth before rolling. Check the gradation in accordance to Tex-103-E to ensure that the original gradation is met.

276.6. Measurement. Cement-treated base will be measured by the ton, cubic yard, or square yard as a composite mixture of cement, flexible base, and recycled materials.

Measurement by the cubic yard in final position and square yard is a plans quantity measurement. The quantity to be paid for is the quantity shown in the proposal unless modified by Article 9.2, "Plans Quantity Measurement." Additional measurements or calculations will be made if adjustments of quantities are required.

Measurement is further defined for payment as follows:

[9] The roller requirements may need better enforcement

[10] Area Engineers and Inspectors should be made aware of discouraging "slush rolling", instead of adding a small amount of water indicated in this item.

[11] Microwave method can be used to expedite

[12] A rapid way of estimating the cement content should be researched and added here.

A. Cubic Yard in Vehicles. Cement-treated base will be measured by the cubic yard in vehicles as delivered on the road.

B. Cubic Yard in Final Position. Cement-treated base will be measured by the cubic yard in its completed and accepted final position. The volume of each course will be computed in-place between the original subgrade surfaces and the lines, grades, and slopes of the accepted base course as shown on the plans, and calculated by the method of average end areas.

C. Square Yard. Cement-treated base will be measured by the square yard of surface area. The dimensions for determining the surface area are established by the dimensions shown on the plans.

D. Ton. Cement-treated base will be measured by the ton (dry weight) in vehicles as delivered on the road. The dry weight is determined by deducting the weight of the moisture in the material at the time of weighing from the gross weight of the material. The Engineer will determine the moisture content in the material in accordance with Tex-103-E from samples taken at the time of weighing.

When material is measured in trucks, the weight of the material will be determined on certified scales, or the Contractor must provide a set of standard platform truck scales at a location approved by the Engineer. Scales must conform to the requirements of Item 520, "Weighing and Measuring Equipment."

276.7. Payment. The work performed and materials furnished in accordance with this Item and measured as provided under "Measurement" will be paid for at the unit price bid for "Cement Treatment (Plant Mix)" of the class (strength), flexible base type, grade, and thickness (for square yard measurement) specified. For cubic yard measurement, "In Vehicle" or "In Final Position" will be specified. This price is full compensation for furnishing and disposing of materials (including cement and base); storing, mixing, hauling, placing, sprinkling, compacting, finishing, curing, and maintaining and reworking treated base; and equipment, labor, tools, and incidentals.

Sprinkling and rolling, except proof rolling, will not be paid for directly but will be subsidiary to this Item, unless otherwise shown on the plans. When proof rolling is shown on the plans or directed by the Engineer, it will be paid for in accordance with Item 216, "Proof Rolling."

Where subgrade or base courses are constructed under this Contract, correction of soft spots will be at the Contractor's expense. Where subgrade or base is not constructed under this Contract, correction of soft spots will be paid for in accordance with pertinent Items and Article 4.2, "Changes in the Work."

Asphalt used solely for curing will not be paid for directly but will be subsidiary to this Item. Asphalt placed for curing and priming will be paid for under Item 310, "Prime Coat."

Removal and disposal of existing asphalt concrete pavement will be paid for in accordance with pertinent Items or Article 4.2, "Changes in the Work."

A. Thickness Measurement for Cubic Yard in Final Position and Square Yard Payment Adjustment. Before final acceptance, the Engineer will select the locations of tests within each unit and measure the treated base depths in accordance with Tex-140-E.

1. Units for Payment Adjustment.

a. Roadways and Shoulders. Units for applying a payment adjustment for thickness to roadways and shoulders are defined as 1,000 linear ft. of treated base in each placement width. The last unit in each placement width will be 1,000 ft. plus the fractional part of 1,000 ft. remaining. Placement width is the width between longitudinal construction joints. For widening, the placement width is the average width placed of the widened section that is deficient in thickness.

b. **Ramps and Other Areas.** Units are defined as 2,000 sq. yd. or fraction thereof for establishing an adjusted unit price for ramps, intersections, irregular sections, crossovers, entrances, partially completed units, transitions to ramps, and other areas designated by the Engineer.

2. **Price Adjustments of Deficient Areas.**

a. **Thickness Deficiency ≤ 1.0 in.** Table 2 will govern the price adjustment for each unit with deficient areas ≤ 1.0 in.

Table 2
Measurements and Price Adjustment for Each Unit

Thickness Deficiency	Additional Measurements	Average Thickness Deficiency of 3 Measurements	Price Adjustment
≤ 0.5 in.	None	N/A	Full Payment
> 0.5 in.	2	≤ 0.5 in.	Full Payment
		> 0.5 in. ≤ 0.8 in.	75% Payment
		> 0.8 in. ≤ 1.0 in.	50% Payment
		> 1.0 in.	In accordance with Section 276.6.A.2.b.

b. **Thickness Deficiency ≥ 1.0 in.** Remove and replace areas of treated base found deficient in thickness by more than 1.0 in., unless otherwise approved. Take exploratory measurements at 50-ft. intervals parallel to the centerline in each direction from the deficient measurement until a measurement is not deficient by more than 1.0 in. The minimum limit of non-pay will be 100 ft.

B. **Excess Thickness and Width.** For cubic yard in final position and square yard measurement, no additional payment will be made for thickness or width exceeding that shown on the plans.