LONG-TERM DURABILITY STUDIES ON CHEMICALLY TREATED RECLAIMED ASPHALT PAVEMENT (RAP) MATERIALS

by

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ABSTRACT

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Reclaimed Asphalt Pavement (RAP) is being used as a construction material in Hot Mix Asphalt (HMA) to reduce material costs and stabilizing the pavements for several years. It has been reported that out of 45 million tons of RAP produced every year in US, only 33% is being used in HMA. It is clear that a large amount of RAP produced is disposed off as a waste material in landfills. Hence, in order to utilize the maximum percentage of RAP and reduce the disposal amounts, stabilized RAP can be used as a base layer. The use of RAP in pavement construction not only reduces the project costs but also helps in conserving the naturally occurring aggregates.

Recent studies have demonstrated that the RAP can be effectively used in base layers when blended with aggregate base materials and stabilized with chemical additives. However, the studies reported in the literature related to the use of RAP in base layers were based on only strength and stiffness parameters. But achievement of the specified strength does not always ensure durability. Therefore, in this research, durability tests were conducted to determine the long-term performance of the RAP mixtures. In order to accomplish this task, a comprehensive series of basic and engineering tests were conducted on various blended RAP mixtures at the UTA geotechnical and geo-environmental engineering laboratories. The RAP materials from three different locations in Texas were studied to account for the source variability. The basic tests conducted include the gradation, specific gravity and standard proctor compaction tests. These RAP mixtures were designed based on minimum unconfined compression strength (UCS) achieved at the end of 7-day curing period. This required UCS strength for treated samples is achieved by adding different dosage levels of chemical stabilizers such as Portland cement or Class C fly ash.

Long-term durability tests were conducted on both untreated and stabilized specimens by conducting wetting/drying cycles to replicate the moisture fluctuations in the field due to seasonal variations. Also, the leachate studies were conducted to study the rainfall infiltration and leachability of the chemical stabilizer from stabilized RAP mixture. Additionally, mineralogical studies were carried out to ascertain the chemical stabilization of RAP mixtures as well as any changes occurred during durability studies.

The results obtained from the engineering tests were compared among different RAP mixtures to identify the best performing mix. Results from wet/dry cycles showed a very low volumetric change and good retaining strength at the end of 3, 7 and 14 cycles. In addition, the leachate tests proved that leaching of chemical stabilizer from RAP mixes cannot be termed as a concern for long-term performance. The mineralogical tests involving X-ray diffraction (XRD) and Scanning Electron Microscope (SEM) studies confirmed that the necessary pozzalonic compounds were formed due to chemical stabilization. Out of several RAP mixtures studied from all three regions, the mixture composed of 75% RAP mixed with 25% base material with 4% cement was identified as a best performing mixture. It has been concluded from this study that to promote the usage of higher percentage of recycled materials and achieve good results, 75% RAP mixture has been proposed to use it as a base layer in pavement construction.

TABLE OF CONTENTS

APPENDIX

LIST OF ILLUSTRATIONS

Figure Page

LIST OF TABLES

Table Page

CHAPTER 1

INTRODUCTION

1.1 Introduction

Flexible pavements experience distress over a time period due to traffic and environmental factors. Typically, after three to five years of construction reflective cracking on the pavement surface, one of the primary forms of distress in hot-mix asphalt (HMA) overlays of flexible pavements may be observed (Myers et, al., 1998). The penetration of water through these reflected cracks accelerates the deterioration of the pavements by forming soft base layer underneath the roadway. Therefore, an appropriate rehabilitation technique needs to be adopted by the highway agencies in order to bring this asphalt pavement to the acceptable level of serviceability.

Previous studies have shown that transverse and longitudinal cracks in asphalt pavements overlaid with one or two inches of HMA had reflected back into the overlay within two to four years (Mckeen et, al., 1997). In addition, the cost of conventional base materials used in the highway engineering is also increasing due to many reasons such as depletion of natural resources, rising cost of mining and high transportation costs (Chen et. al., 2007). To encounter this problem the use of recycled materials are being investigated by the highway construction industry from several years (Chen, 2006). Reclaimed asphalt pavement (RAP) is one of the resources that have been used in HMA in recent years. The 1993 EPA report mentioned that approximately 73 million tons of asphalt pavement material was recycled each year, which amounts to about 80% of the asphalt removed from pavements each year (FHWA, 1993).

RAP is produced when old, damaged pavements are milled and crushed for addition as a component to new mixtures placed in the pavement layers. This utilization of RAP in the base layer was also done under full depth reclamation (FDR) processes. As a result of decreasing supplies of locally available quality aggregate in many regions around the world, growing concern over waste disposal, and the rising cost of bitumen binder led to a greater use of reclaimed asphalt pavement (RAP) for road construction. Also, previous experience had indicated that the recycling of asphalt pavements is a beneficial approach from technical, economical, and environmental perspectives (Epps, 1990).

The pavement reconstruction generally consists of removal and replacement of the existing surface layer or all of the underlying soils to enhance the performance of roadway. The use of RAP in road base and sub-base was evaluated in New Jersey (Maher and Popp, 1997). This study indicated that RAP has a slightly higher resilient modulus and field elastic modulus than the dense-graded aggregate used by the state of New Jersey. Also, in another study conducted in Florida the results showed that RAP is a well-graded material and its maximum dry density is comparable to those of conventional granular materials (Sayed, Pulsifier and Schmitt, 1993). RAP base potential was also evaluated in the construction of Lincoln Avenue project in Urbana, Illinois. This study concluded that RAP can be successfully used as a conventional base material by comparing it with a crushed stone base (Garg and Thompson, 1996).

When a higher percentage of RAP is used in base layer applications, it must be ensured that the minimum standards set by AASTHO has to be satisfied and these standards are for gradation (AASHTO M43), moisture-density relations (AASHTO T-180) and resilient modulus (AASHTO T274). Most of the RAP mixtures do not often meet the minimum requirements set by AASHTO. In such cases, stabilization with cement or fly ash allows the use of these low quality reclaimed asphalt pavement materials with the minimum required strength characteristics.

The materials tested in this study include RAP and local base materials from three districts (El Paso, Fort Worth and Childress) in the state of Texas. Various trial mixes were blended with different percentages of RAP and base materials and then stabilized with Type I/II Portland cement for designing the mixes. These mixes were proposed based on the minimum UCS strength of 300 psi given in Item 276 of current TxDOT procedures for mix design. Initially, for the El Paso RAP a total of eight stabilized RAP mixes were studied to achieve the required strength and to understand the behavior of blending process between RAP and base materials. Based on the knowledge gained from the results of El Paso RAP, only three mixes were studied with varying percentages of cement dosages for the Fort Worth and Childress RAP materials. The major objective of this research and the thesis organization are presented clearly in the following sections.

1.2 Research Objectives

The main objective of this research is to study the long-term performance of the design RAP mixes by conducting durability studies. The secondary objective of this study is to conduct mineralogical tests to examine the chemical stabilization occurring within the blended RAP mixtures. The following tasks are performed to carry out the present research:

- To collect the literature available on recycled materials, stabilization of recycled asphalt pavement and durability tests on RAP materials.
- To conduct basic engineering tests to determine the gradation to classify the materials and moisture content – dry density relationships to determine the compaction characteristics of the materials.
- To perform durability tests which included wetting/drying studies for 14 cycles and leachate studies for 14 cycles.
- To conduct unconfined compression strength tests at various stages of durability studies to understand the percentage of retained strength.

- To compare the results obtained for the design RAP mixes and identify the best long-term performing mix.

1.3 Thesis Organization

Chapter 1 introduces the problems associated with flexible pavements, the problem statement and the materials involved. It describes the purpose of various chapters and their contents.

Chapter 2 reviews the literature available on the recycled materials used in highway engineering, types of recycling processes for RAP, properties of recycled asphalt pavement, chemical stabilization of RAP and durability studies conducted by previous researchers on RAP.

Chapter 3 describes the details of various test procedures involved in this study. Procedure followed to prepare samples for both untreated and treated samples is also included. The procedures to conduct mineralogical tests were also explained in this chapter.

Chapter 4 summarizes the results obtained from El Paso district RAP materials. These test results include gradation for RAP and base materials, optimum moisture content and maximum dry density values for different RAP mixes using standard Proctor compaction test, wetting/drying studies, leachate studies and strength tests. After summarizing all the results the best performing mix is identified among the several mixes designed for this site.

Chapter 5 provides the results obtained from basic and engineering tests on Fort Worth district RAP aggregates. The best mix is recognized for this site as well using the results obtained from durability tests.

Chapter 6 summarizes the test results of RAP and base materials obtained from Childress district. The long-term durability studies are conducted on the designed RAP mixes for this site to figure out the best performing mix.

Chapter 7 addresses the summary and conclusions from this research study and also provides some future research recommendations to perform in order to implement the results from this study.

A list of references is included at the end of this report to support the current research work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Reclaimed asphalt pavement (RAP) is produced in huge quantities due to pavement repairs and rehabilitation processes (Taha, et al., 2002). This recycled asphalt can be used in hot mix asphalt (HMA) as well as in the base layers under full-depth reclamation technique. According to Taylor (1987), the idea of asphalt recycling was documented as far back as 1915, but it could not gain much popularity until mid-1970. In this chapter, a review of recycling materials in highway applications, asphalt pavement recycling methods, properties of RAP, chemical stabilization of RAP and long-term durability studies conducted on recycled asphalt pavement will be discussed. The information presented in this chapter was collected from journals, books, conference proceedings and other research project reports.

2.2 Recycled Materials in Pavement Construction

At present, there is a substantial emphasis on waste management at National, State, and local level government agencies. The government at various levels had passed the legislation for mandating the recycling of waste materials (FHWA, 1996). The volume of waste materials being produced continued to increase even though the importance of recycling is being acknowledged (Collins and Ciesielski, 1993; Ciesielski, 1995). In United States, the amount of solid waste from pavement materials going to landfills is estimated to be nearly 4.5 billion tons (Padgett and Stanley, 1996). Recycling of the waste for applications such as road and infrastructure construction seems to be a viable solution to address this problem.

Recycled materials have been used in all layers of the pavement, from the surface down to the unbound supporting layers. The most commonly used recycling materials tested by many state department of transportation's (DOT's) are reclaimed paving materials, glass, rubber tires, and coal fly ash. Therefore, recycling of the construction debris for a new construction or rehabilitation technique helps in reducing waste disposal sent to area landfills and also extends the life of natural resources by supplementing resource supply (Wilburn and Goonan, 1998).

In the United States, the recycling process stream is estimated to be between 352 million tons and 859 million tons per year. Among the recycled materials used, blast furnace slag, coal bottom ash, coal fly ash, and RAP materials are generally used as a stabilizer or a base in the pavement construction. It is estimated that out of 41 million tons produced, 33 million tons (nearly 80%) are used effectively in the pavement and in other geotechnical constructions (Holtz and Eighmy, 2000).

The United States Congress passed Solid Waste Disposal Act (SWDA) in 1965 which studied the importance of recovery and disposal of solid waste. In 1970, this Act was modified by the Resources Recovery Act (RCA) which urged to encourage the use of products with recycled material content and thereby eliminate the requirement to use only virgin materials in construction process (Rana, 2004). But in early 1970’s three pieces of Federal legislation which includes National Environmental Policy Act (NEPA) of 1969, Resource Conservation and Recovery Act (RCRA) of 1976 and the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) of 1980 altered the RCA act and made fundamental changes in management of waste and by-product materials (FHWA, 1998). After this period there has been a lot of research going on to use this recycling materials for various infrastructure projects.

2.2.1 Recycled Materials

Use of waste materials in highway construction is being practiced by many state DOT’s. These materials disposal became a problem for the manufacturers who produces them. Hence, their use as a construction material is becoming popular in order to reduce the disposal problem. The following section is a brief review of properties, annual production, uses and highway applications of some of these materials.

2.2.1.1 Bottom Ash

Coal bottom ash is the by-product of burnt coal collected from the bottom of the blast furnace which has coarse, granular and incombustible properties (FHWA, 1998). It is porous in nature and dark gray in color with a grain size similar to sand particles (Figure 2.1). When pulverized coal is burned in a boiler, about 80% of the unburned material is entrained in the flue gas and captured as fly ash. The remaining 20% of the ash is dry bottom ash which is collected in a water-filled hopper at the bottom of the furnace. Bottom ash is generally a well-graded material, variations in particle size distribution may occur in ash samples taken at different times from the same power plant. It mostly consists of silica, alumina and iron, with low percentages of magnesium, sulfates and potassium (FHWA, 1998).

Figure 2.1 Bottom Coal Ash
(Source: http://www.caer.uky.edu/kyasheducation/images/ccbs/bottomash-scoop600.jpg)

Maximum dry density of bottom ash is usually 10-25% lower than those of naturally occurring granular materials. However, the typical OMC range for bottom ash is found to be 12 – 24% (Lovell et al., 1991). It has a friction angle of 38 to 42^0 which is similar to sand and has a CBR of 40-70% (Majizadeh et al., 1979). Some of the applications of bottom ash in construction industry are as a fine aggregate in hot mix asphalt, granular material in stabilized base applications, structural fill materials in highway embankments, flowable fill and raw feed for production of Portland cement concrete (Rana, 2004). This bottom ash is screened or grinded before using it as granular base or sub-base when it consists of particles with size more than 19mm. The utility industry in United States generated 16.1 million tons of bottom ash in 1996 (FHWA, 1996).

2.2.1.2 Crushed Glass

In United States waste glass constitutes to 7 percent of municipal solid waste generated. The glass is considered to be the second largest recycling material next to paper throughout the world. When waste glass is crushed and screened from the municipal and industrial streams it produces recycled glass cullet. This glass cullet will be very useful as a fine aggregate material in areas where good quality traditional aggregates are high in demand and expensive.

Apart from using the recycled glass to produce new glass bottles it can also be used in construction industry for various purposes. The waste glass can be used as a fine aggregate in asphalt paving mixes and the resulting mixture is termed as glassphlat. This glass cullet is considered to be an excellent replacement for traditional aggregates in many construction projects (Figure 2.2). It is also used as an additive in clay because the recycled glass has low melting temperature than virgin glass and therefore, lowers the costs for producing tiles and bricks. Moreover, crushed glass can also be used as a substitute for granular soils, for roadway sub-base and added as a course aggregate in hot-mix asphalt.

When glass is fractionated to the size of fine aggregates it exhibits properties similar to the sandy material which includes high stability and frictional strength due to angular nature of crushed glass (Wartman et al., 2004). The other benefits in using recycled glass include low absorption, low specific gravity and low thermal conductivity, which in turn improve the property of heat retention in glass mixes. Also, the high frictional angle (approximately 50^0) of well crushed glass contributes to good lateral stability for pavement surfaces (Petrarca, 1988). Some of the important properties that should be considered while using crushed glass in granular bases are gradation, density, friction angle, and bearing capacity, durability, and drainage characteristics.

Figure 2.2 Recycled Glass Driveway
(Source: http://swamplot.com/wp-content/uploads/2009/01/filterpave-cordell.jpg)

2.2.1.3 Roofing Shingles

Every year approximately 11 million tons of waste asphalt roofing shingles are generated in US (TxDOT, 1997). These roofing shingles are mainly produced due to tear-offs from re-roofing jobs or demolition of old houses. Typically, shingles consist of 25% asphalt, 25% fiber glass and 50% granular/filler material (Brock, 1987). The asphalt roofing shingles have great potential for recycling because of their high availability in construction and demolition waste industries. The recycling of roofing shingles involves three basic steps:

1. Removing all the contaminants (wood sheathings, nails, and card boards) which interfere with the processing system. A magnet can typically remove all the metal pieces from the shingles.

2. Grinding shingles to a specified size depending upon the intended end use (Figure 2.3).
3. Using these processed shingles in pavement construction.

Figure 2.3 Graded 1/4 inch Roofing Shingles
(Source: http://www.asphaltmagazine.com/)

Asphalt pavement properties usually improve with the addition of Roofing shingles. Research shows that they improve rutting and cracking resistance and the organic fibers reinforce the pavement. Study conducted by Epps and Paulsen in 1986 at University of Nevada concluded that the use of roofing shingles in hot mix asphalt resulted in lower paving costs by investigating the technical and economical aspects. Previous studies involving recycling of roofing shingles reduced the cost of HMA by 2.79$ per ton (Brock and Shaw, 1989). In addition, incorporation of roofing shingles in hot mix asphalt improved the rutting resistance and stiffness of the mixture (Grzybowski, 1993, Ali et al., 1995 and Foo et al., 1999).

Other applications of roofing shingles in asphalt pavements are for cold patch works. Several states in US are using this technique since many years because it helps in minimizing the dust, loss of gravel and reduction of vehicle noise. It is also being used to construct temporary roads, driveways and parking lots. Roofing shingles blended with recycled asphalt pavement (RAP) is used in sub-base applications to reduce the compaction problems.

2.2.1.4 Waste Tires

Waste tires have been a disposal problem in the past and are continuing to accumulate throughout the U.S every day. Nearly 280 million tires are discarded annually of which 30 million are reused. About 85% of the discarded tires are automobile tires and the rest are truck tires (FHWA, 1998). Recent study from EPA showed that over 279 million waste tires are being added every year to the estimated 2 billion stockpiled tires across the country. This huge collection of tire scraps from both automobile industry and stockpiles has become a significant problem and imposing to find new solutions for using them as a construction material.

The scrap tires can be used in construction activities as whole tires, tire shreds and crumb rubber (Figure 2.4). In 1991 the federal government mandated the use of recycled rubber in all highway construction projects by passing the Intermodal Surface Transportation Efficiency Act (ISTEA) (Khatib and Bayomy, 1999). Using shredded waste tires as a lightweight fill material for road construction has proven to be another beneficial use of this waste product (Engstorm and Lamb, 1994). The shredded tires when used in road base or sub-base layer improved the drainage characteristics and extended the life of roadway. (Geisler et al., 1989). In addition, retaining walls can be constructed using whole tires by stacking one above the other and crumb rubber is used in hot mix asphalt by blending it with asphalt binder (Rana, 2004)

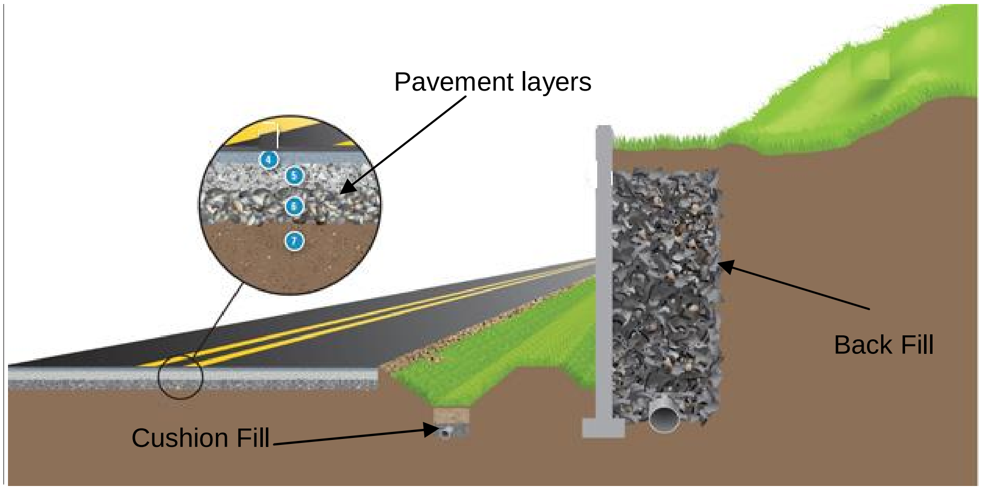


Figure 2.4 Scrap Tires in various applications
(Source: http://www.agc.org/galleries/enviroimages/roadways-toolkitimg.jpg)

2.2.1.5 Compost

Compost can be defined as the disinfected and stabilized product of the decomposition process which is sold for using as a soil amendment, artificial top soil or other similar uses. Composting is the technique of recycling the organic waste materials. In this process, the organic matter is converted to materials that could be effectively used in daily life applications like landscaping and soil erosion control (Puppala, 2005).

Compost can increase soil air space, drainage and moisture holding capacity. It also releases nutrients which helps in mitigating salt concentrations, buffer against heavy metals and soil pH changes, encourages earth warms and other beneficial insects and micro organisms.

The main purpose of compost in highways is as mulch, blended topsoil replacement, commercial fertilizer and soil amendments (Degroot et al., 1995). Ettlin and Stewart (1993) found that yard waste compost could be used for slope stabilization and erosion control on slopes up to 42%. A study conducted by the Connecticut Department of Transportation found composts and mulches reduced soil erosion ten-fold compared to bare soil surfaces on a 2:1 slope (Demars and Long, 1998). Furthermore, Demars and Long (1998) report that when compared to silt fences, compost is 99 percent more effective in keeping sediment out of nearby surface waters, and 38 percent more effective than hydro seeding. Glanville et al., (2001) reported runoff and interrill erosion rates were significantly lower on newly constructed highway embankments when using compost instead of imported topsoil. In addition, compost can be used in a variety of sectors like landscaping, land reclamation, erosion control, top dressing (for golf courses, park land), agriculture, residential gardening and nurseries (Diaz et al., 1993).

2.2.1.6 Recycled Asphalt Pavement (RAP)

Reclaimed asphalt pavement consists of removed and processed asphalt pavement materials containing both aged asphalt and aggregates. Every year, the US highway industry generates over 100 million tons of RAP through the rehabilitation and reconstruction of existing highways (Huang et al., 2005). Figure 2.5 shows the RAP stockpile from Lubbock, Texas. This

RAP can be used as granular base or sub-base material in virtually all pavement types, including paved and unpaved roadways, parking areas, bicycle paths, gravel road rehabilitation, shoulders, residential driveways, trench backfill, engineered fill, pipe bedding, and culvert backfill (Saeed, 2008).

In 1985 Asphalt Recycling and Reclaiming Association (ARRA) reported that nearly 13% of the total paving operations used recycled asphalt in United States (Franco, 1985). According to a 1994 survey of all state transportation agencies, at least 32 states have used or are using RAP in cold recycling of asphalt pavements (Collins et., al 1999). The Environmental Protection Agency (EPA) had reported that 80% of the asphalt removed is being recycled every year. However, this recycling is higher than those of aluminum cans (60%), newsprints (56%), plastic soft drink bottles (37%) and glass bottles (31%). The public could not recognize this high recycling rate of asphalt probably due to low publicity efforts by the asphalt pavement agencies (Potturi, 2006). Because of the better understanding of the RAP materials in recent years more uniform mixes are being produced which helps in reducing the cost of paving while saving the natural resources.

Figure 2.5 RAP stockpile in Lubbock Texas

2.3 Recycling Processes for RAP

Recycling of the existing pavement materials for rehabilitation is an old technique which gained popularity after 1975 based on the following facts (Chen, 2006).

- Increase in construction costs and reduced funding for transportation projects.
- A large number of asphalt roads needed to be rehabilitated which increased the opportunity for recycling.
- Many agencies feared about the depletion of locally available aggregates resulting in higher costs for extraction and hauling from other cities nearby.
- The use of RAP in pavement rehabilitation decreases the amount of waste to be dumped and helps in resolving the disposal problems in landfills.
- Even though the aged asphalt may have lost some of its original properties due to the factors like oxidation but when it is mixed with new asphalt it will automatically serve as an effective binder (Asphalt Institute, 1983). In this way the reuse of the aged asphalt may reduce the amount of new asphalt required for pavement construction.

Recycling of existing pavement materials for rehabilitation offered an effective solution to all the above problems. Related to asphalt pavement recycling, there are several methods available for each particular situation. Therefore, each project being considered for recycling must be carefully evaluated to determine the method most appropriate for recycling. The advantages and disadvantages of asphalt pavement recycling recognized by NCHRP report 54 is illustrated in Table 2.1.

Table 2.1 Advantages and Disadvantages of Recycling Methods (NCHRP, 58)

Recycling Categories	**Advantages**	**Disadvantages**
Surface	• Reduces reflection cracking • Promotes bond between old pavement and thin overlay • Provides a transition between new overlay and existing gutter, bridge, pavement etc. that is resistant to raveling (eliminates feathering) • Reduces localized roughness • Treats a variety of types of pavement distress (raveling, flushing, corrugations, rutting, oxidized pavement, faulting) at a reasonable cost • Improved skid resistance • Minimum disruption to traffic	• Limited structural improvement • Heater-scarification and heater planning have limited effectiveness on rough pavement without multiple passes of equipment • Limited repair of severely flushed or unstable pavements • Some air quality problems • Vegetation close to roadway may be damaged • Mixtures with maximum size aggregates greater than 1-in. cannot be treated with some equipment
In- place	• Significant structural improvements • Treats all types and degrees of pavement distress • Reflection cracking can be eliminated • Frost susceptibility may be improved • Improve ride quality	• Quality control not as good as central plant • Traffic disruption • Pulverization equipment repair requirement • Cost • Cannot be easily performed on PCC pavements
Central-plant	• Significant structural improvements • Good quality control • Treats all types and degrees of pavement distress • Reflection cracking can be eliminated • Improved skid resistance • Frost susceptibility may be improved • Geometrics can be more easily altered • Better control if additional binder aggregates are used	• Increased traffic disruption • May have air quality problems at plant site.

As recycling provided a wide variety of advantages many agencies like National Cooperative Highway Research Program (NCHRP), Federal Highway Administration (FHWA), Corps of Engineers (for the Air Force) and US Navy had sponsored several recycling projects and implementation studies. The Asphalt Recycling and Reclaiming Association (ARRA) recognized five types of asphalt pavement recycling. They are

1. Cold Planing
2. Hot recycling
3. Hot In-place recycling
4. Cold Recycling
5. Full Depth Reclamation

2.3.1 Cold Planing

The asphalt pavement is removed to a specified depth and the surface is restored to a desired grade and cross slope with free of humps, ruts and other surface imperfections. The depth of pavement removed is usually between one and two inches. This pavement removal or “milling” is completed with a self-propelled rotary drum cold planing machine (Figure 2.6). The reclaimed asphalt pavement (RAP) is transferred to trucks for removal and stockpiled for hot or cold recycling.

Figure 2.6 Cold Planing Machine
(Source: www.coughlincompany.com/rotomilling/)

2.3.2 Hot Recycling

RAP is combined with new aggregate and asphalt cement and/or recycling agent to produce hot mix asphalt (HMA). Although batch type hot mix plants are used, drum plants typically are used to produce the recycled mix. Most of the RAP in this process is taken from cold planing or can be produced from pavement removal and crushing at the site. The mix placement and compacting equipment and procedures are those typical of HMA construction.

2.3.3 Hot In-place recycling

The recycling is performed on-site, and the pavement typically is processed to a depth of 3/4 to 1-1/2 inch. The asphalt pavement is heated, softened and scarified to the depth specified. An asphalt emulsion or other recycling agent is added, and with one of the processes, new HMA is incorporated as required. The three hot in-place recycling methods are heater-scarification, repaving and remixing. A typical hot in- place recycling machine is shown in Figure 2.7.

Figure 2.7 Hot In-Place Recycling Machine
(Source: www.fhwa.dot.gov/pavement/recycling/98042/01.cfm)

2.3.4 Cold In-place recycling

Cold In-Place Recycling (CIR) is defined as a rehabilitation technique in which the pavement materials are reused in the same place (ARRA, 1992). For CIR, the existing asphalt pavement typically is processed to a depth of 2 - 4 inches. In this process the materials are mixed in-place without the application of heat (Figure 2.8). The pavement is pulverized and the reclaimed material is mixed with an asphalt emulsion or emulsified recycling agent, spread and compacted to produce a base course. Cold recycled bases require a new asphalt surface. The lower traffic pavement may use an asphalt emulsion surface treatment while a higher traffic pavement uses a modified emulsion surface treatment or an HMA surface.

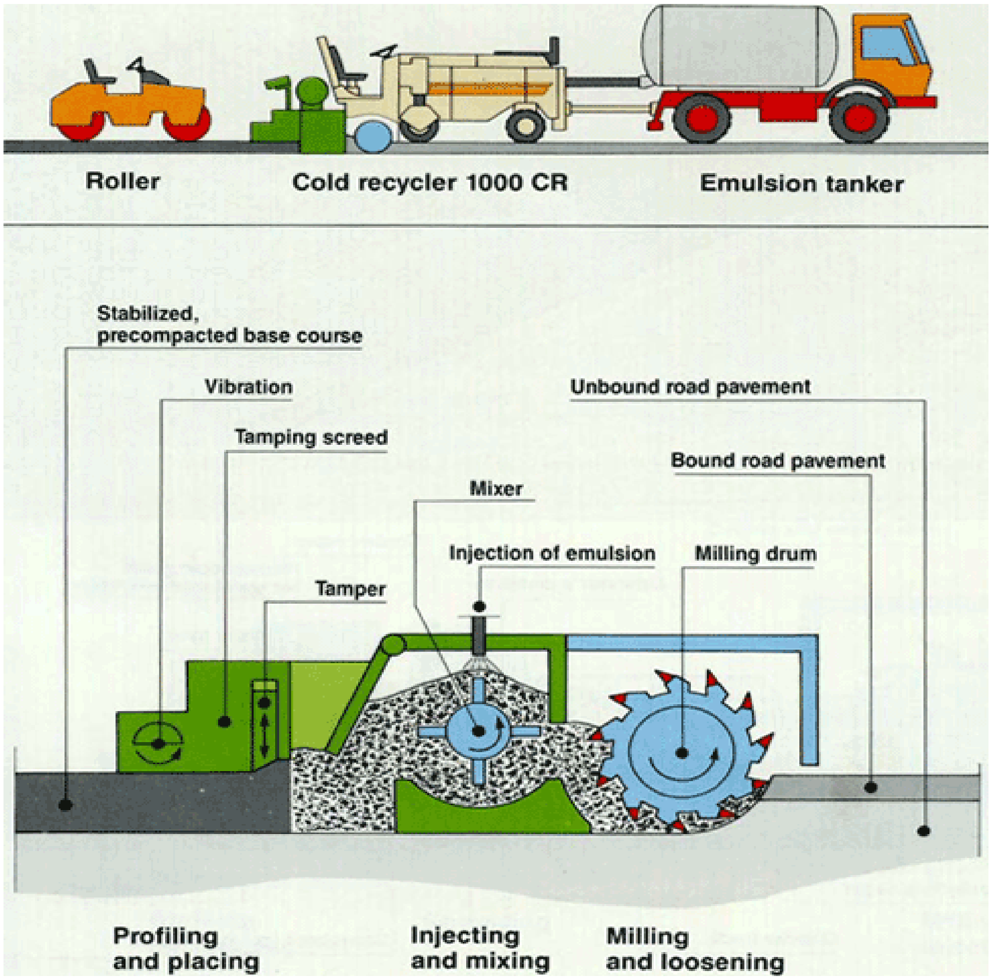


Figure 2.8 Cold In-Place Recycling Process
(Source: www.fhwa.dot.gov/pavement/recycling/98042/13.cfm)

2.3.5 Full-Depth Reclamation (FDR)

Deteriorating roads are a constant problem for cities and counties. That's why engineers and public works officials are turning to a process called full-depth reclamation (FDR) with cement. It is an in-situ process that grinds up the existing asphalt pavement and aggregate base course and mixes both together and replaces it back on the subgrade soil (Figure 2.9). With FDR, all of the pavement section and in some cases a predetermined amount of underlying material, are mixed with asphalt emulsion to produce a stabilized base course. Base problems can be corrected with this construction.

Full depth reclamation consists of six basic steps: pulverization, additive and/or emulsion incorporation, spreading, compacting, shaping, and placement of new asphalt surface. There's no need to haul in aggregate or haul out old material for disposal. Truck traffic is reduced, and there is little or no waste. The use of FDR is appropriate when certain types of pavement failures are present, including deep rutting, alligator cracking, longitudinal cracking in the wheel path, edge cracking, block cracking, transverse cracking, maintenance patching, depressions or high spots, and weak base or subgrade materials (Taha et., al, 1999).

Figure 2.9 Full Depth Reclamation Process
(Source: http://www.asphaltzipper.com/img/full_depth_reclamation3.jpg)

2.4 Recycled Asphalt Pavement Properties

Reclaimed asphalt pavement (RAP) is the term given to removed or reprocessed pavement materials containing asphalt and aggregates. RAP consists of high-quality, well-graded aggregates coated by asphalt cement once it is well crushed and screened. The properties of the RAP mainly depend upon the constituent materials and the type of asphalt concrete mix. A summary of physical, chemical and mechanical properties affecting the Pavement Performance is presented in the Table 2.2.

Table 2.2 Properties influencing pavement performance (NCHRP, 598)

Physical Properties	**Chemical Properties**	**Mechanical Properties**
• Particle gradation and shape (max/min sizes) • Particle surface texture • Pore structure, absorption, porosity • Permeability (hydraulic properties) • Specific gravity • Thermal Properties • Volume change (in wetting & drying) • Freezing/ Thawing resistance • Deleterious substances	• Solubility • Base exchange • Surface charge • Chemical reactivity (resistance to attack by chemicals, chemical compound reactivity, oxidation and hydration reactivity, organic material reactivity Chloride content)	• Particle strength • Particle stiffness • Wear Resistance • Resistance to degradation

2.4.1 Physical Properties

The major physical properties considered for recycled asphalt pavement are gradation, unit weight, moisture content and asphalt content. And these properties of RAP are largely dependent on the properties of the constituent materials and the type of asphalt concrete mix (wearing surface, binder course, and other materials).

Both milling and crushing can cause some aggregate degradation. The gradation of milled RAP is finer and denser than that of the virgin aggregates. On the other hand, crushing does not cause as much degradation as milling. Also, the particle size distribution of milled or crushed RAP may vary to some extent, depending on the type of equipment used to produce the RAP, the type of aggregate in the pavement and whether any underlying base or sub-base aggregate has been mixed in with the RAP material during the pavement removal (Saeed, 2008).

During processing, virtually all RAP produced is milled or crushed down to 38 mm (1.5 in.) or less, with a maximum allowable top size of either 51 mm (2 in.) or 63 mm (2.5 in.). Table 2.3 lists the typical range of particle size distribution that normally results from the milling or crushing of RAP. Usually, milled RAP is always finer than crushed RAP. Most of the RAP sources are well-graded coarse aggregate, comparable to, or perhaps slightly finer and more variable than, crushed natural aggregates.

Table 2.3 Typical range of particle size distribution for RAP (Kallas,1984)

Screen Size (mm)	Percent Finer After Processing or Milling (%)
25	95 - 100
19	84 - 100
12.5	70 - 100
9.5	58 - 95
75	38 - 75
2.36	25 - 60
1.18	17 - 40
0.60	10 - 35
0.30	5 - 25
0.15	3 - 20
0.075	2 - 15

The unit weight of milled or processed RAP depends on the type of aggregate in the reclaimed pavement and the moisture content of the stockpiled material. Although available literature on RAP contains limited data pertaining to unit weight, the unit weight of processed RAP has been found to be slightly lower than natural aggregates which range from 19.4 to 23 kN/m^3.

The amount of information available about the moisture content of RAP stockpiles is limited. It has been reported in literature that crushed or milled RAP can pick up a considerable amount of water if exposed to rain. Moisture contents up to 5 percent or higher have been observed for RAP stored in a stock pile (Smith and Richard, 1980). According to Decker and

Young (1996) during periods of extensive precipitation, the moisture content of some RAP stockpiles increase from 7 to 8 percent.

The asphalt cement content in RAP typically ranges between 3 and 7 percent by dry weight. The asphalt content present in the RAP sticks very low with the aggregate due to exposure of the old pavement to atmospheric oxygen (oxidation) during their use and weathering. The degree of hardening depends on several factors, including the intrinsic properties of the asphalt cement, the mixing temperature and time, the degree of asphalt concrete compaction , asphalt cement air voids content, and its design life.

The recovered asphalt from RAP usually exhibits low penetration and relatively high viscosity values, depending on the amount of time the original pavement has been in service. Penetration values at 25℃ (77℉) are likely to ran ge from 10 to 80 while the absolute viscosity values at 60℃ (140℉) may range from as low as 2,0 00 poises up to as high as 50,000 poises. Epps et al., (1977) indicates that depending on the extent of aging normally viscosity ranges from 4,000 to 25,000 poises.

2.4.2 Mechanical Properties

When RAP is added to asphalt mixture for laying a new pavement it changes the mechanical properties (like strength and durability) of the mixture and inhibits the performance of the pavement (Lachance, 2006). Generally, the mechanical properties of the RAP rely essentially on original asphalt pavement type and the methods used to recover the material. The compacted unit weight of RAP ranges from 16.2 kN/m^3 (100 lb/ft^3) to 20.0 kN/m^3 (125 lb/ft^3) (Senior et al., 1994). California Bearing Ratio (CBR) values for RAP material containing rock aggregate have been reported in the 20 to 25 percent range. When RAP is blended with natural aggregates for use in granular base, the asphalt cement in the RAP has a significant strengthening effect over time, such that the specimens containing 40 percent RAP have produced CBR values exceeding 150 after 1 week (Hanks and Magni, 1989). As most of the RAP produced is recycled back into pavement construction there is limited data available on the mechanical properties of the RAP in various other applications. Table 2.4 shows the important physical and mechanical properties of RAP considered for both laboratory and field testing.

Table 2.4 Physical and Mechanical Properties of RAP Materials (Potturi, 2006)

Property	**Typical Range**
Unit Weight	19.4 to 23 kN/m^3 (120 to 140 pcf)
Moisture Content	5 to 8%
Asphalt Content	3 to 7 %
Asphalt Penetration	10 to 80 at 25^{0}C
Absolute Viscosity	4,000 to 25,000 poise at 60^{0}C
Compacted Unit Weight	16 to 20 kN/ m^3 (100 to 125 pcf)
California Bearing Ratio (CBR)	20 to 25% for 100%RAP

2.4.3 Chemical Properties

The chemical properties influencing the strength of the recycled asphalt pavement are chemical reactivity, solubility, pH, chloride content and surface charge. The chemical composition of RAP is essentially similar to that of the naturally occurring aggregate which is its principal constituent. In RAP the major constituent (93-97%) are mineral aggregates involving mainly high molecular weight aliphatic hydrocarbon compounds. However, the minor percentage of RAP consists of other materials such as sulfur, nitrogen, and polycyclic hydrocarbons (aromatic and/or naphthenic) of very low chemical reactivity (Noureldin, 1989).

2.5 Chemical Stabilization of RAP

Reclaimed asphalt pavement (RAP) has been widely used in the US since the 1970s. The use of RAP allows for lower material costs, elimination of RAP disposal costs, removal of a waste product from landfills, conservation of aggregate resources and reduction in life-cycle cost. In Texas, 3.2 million tons of RAP was produced in 2006. According to TxDOT, RAP is a salvaged, milled, pulverized, broken or crushed asphalt pavement with 100% of the particles passing the 2- in. sieve.

Most of the studies that deal with the use of stabilized RAP are in conjunction with in-place recycling dealing with full-depth reclamation. The RAP is usually stabilized with calcium-based chemicals like cement or lime or other additives such as fly ash, cement kiln dust and asphalt emulsion. Based on extensive review of literature, the number of studies performed on stabilized RAP being used as base is rather limited.

The initial studies of characterizing base and sub-base materials including stabilized RAP materials was undertaken by Lofti and Witczak (1985). In this research resilient moduli of five cement-treated base materials used by the Maryland State Highway Administration were determined and evaluated. Specific values of layer coefficients based on the moduli were estimated for using in the design of flexible pavement.

MacGregor et al. (1999) found that, for aggregate specimens compacted to at least 95 percent of the standard Proctor's maximum dry unit weight and tested at OMC, an increase in RAP content increased the resilient modulus of the recycled layer, which effectively increased the structural number (SN) of the layer. This study concluded that, because of the increased SN, RAP was a beneficial additive to the base material tested. They also found that the addition of up to 50 percent RAP had little effect on the hydraulic conductivity of the material.

Taha et al. (2002) prepared various blends of RAP and a virgin aggregate using 0, 3, 5, and 7% Type I Portland cement by dry weight of the aggregate with 100/0, 90/10, 80/20, 70/30, and 0/100% RAP to virgin aggregates. Compaction and Unconfined compression strength (UCS) tests were conducted on both treated and untreated aggregates. The modulus values were arrived from the UCS results using correlations between resilient modulus (M_r) and UCS. No resilient modulus tests were conducted in the laboratory environment. The unconfined compressive strength test results from the samples cured for 3, 7, and 28 days indicated that as virgin aggregate and cement contents in the blend increased, the strength and modulus increased. They concluded that RAP aggregate seems to be a viable alternative to aggregate bases used in road base and sub-base construction. However, for all RAP-virgin aggregate mixtures stabilized with cement, a higher base thickness would be needed if more RAP percentage is used. They also showed some concern with the permeability of the 100% RAP mixtures.

Taha (2003) repeated the same study but with the cement kiln dust (CKD). But in this case both the materials used were by-products which help in preventing environment and conservation of natural resources. They found the same trends in gain in strength and stiffness with the CKD as those with cement. In this study they concluded that about 15% CKD is needed for an optimum design.

Gnanendran and Woodburn (2003) conducted a series of resilient modulus, CBR and UCS tests on cement, lime and fly ash stabilized RAP materials in Australia. These tests provided typical resilient moduli of these aggregates, and enhancements in moduli values with respect to each of the chemical treatments.

In his research work Ordonez (2006) stabilized the RAP with different dosages of cement and polyethylene fibers in UTA. The engineering tests conducted on the stabilized RAP materials include permeability, leaching (COD, pH, TSS, TDS and Turbidity), unconfined compression, and small-strain shear modulus tests. The test results obtained were compared with previous studies and concluded that RAP is a sound alternative to use it as base/sub-base materials.

Potturi et al. (2007) at UT-Arlington utilized a locally produced reclaimed asphalt pavement material from Dallas area as a control/untreated base material. This material was then subjected to stabilization with cement and cement-fibers. A resilient modulus based experimental program was then designed and followed to test untreated, cement treated and cement-fiber treated RAP base materials. Type1 Portland cement and fibrillated polypropylene fibers were used as additives for stabilization. The modulus of the RAP steadily increased from about 30 ksi for untreated RAP to 50 ksi with 6% cement. No strength tests were carried out as a part of this study.

In a case study reported by Li et al. (2007), the stabilization of recycled pavement material (RPM) with class C fly ash was evaluated. The blending of asphaltic recycled material with fly ash was used as a base course for 0.31 mile (0.5 km) section in Waseca, Minnesota. California bearing ratio (CBR) and resilient modulus (Mr) tests were conducted on the RPM alone and fly-ash stabilized RPM (SRPM) mixed in the field and laboratory to evaluate how addition of fly ash improved the strength and stiffness. The fly ash stabilization of RPM had significantly improved CBR and Mr which is beneficial in terms of increasing pavement capacity and service life. Falling Weight Deflectometer (FWD) tests were also conducted in field to evaluate the effect of freeze thaw cycles after one winter season.

Guthrie et al. (2007) studied the effects of reclaimed asphalt pavement (RAP) content and cement content on the strength and durability of a recycled aggregate base material typical of Utah. Their laboratory work was based on a full-factorial experimental design, including five RAP contents, five cement contents, and three replicate specimens of each possible treatment. Measurements of unconfined compressive strength (UCS) and final dielectric value in the tube suction test (TST) were used to assess material strength and durability, respectively. The UCS decreased from 425 psi to 208 psi as RAP content increased from 0% to 100% and increased from 63 psi to 564 psi as cement content increases from 0% to 2%. Similarly, the final dielectric value decreased from 15 to 6 as RAP content increased from 0% to 100% and decreased from 14 to 6 as cement content increases from 0% to 2%. Increasing RAP contents generally correspond to decreasing dry densities. With design criteria requiring 7-day UCS values between 300 psi and 400 psi and final dielectric values less than 10 in the TST, the results of Guthrie et al. (2007) research suggested the use of RAP contents in the range of 50% to 75% and a cement content of 1% to 2%.

A study by Baugh and Edil (2008) evaluated the effects of cement kiln dust (CKD) treatment on RAP and Recycled Pavement Material (RPM) consisting of milled asphalt and limestone base course. Blends were prepared at CKD contents of 5, 10, 15, and 20% by dry weight of the aggregate and cured for 7, 28, and 56 days. Standard Proctor compaction, California bearing ratio (CBR), resilient modulus, and unconfined compressive strength (UCS) tests were used to evaluate the materials as well as the effects of freeze-thaw cycling. Maximum dry unit weight decreased and optimum moisture content increased with increasing CKD content. The CBR of treated materials was 6 to 9 times that of untreated material after 7-days of curing. Resilient modulus increased 75 to 650% after 56 days of curing, but no trend was found with CKD content. Freeze-thaw cycling reduced the resilient modulus (maximum of about 50%) and UCS (maximum of about 30%). The unconfined compression strength values increase about 1.5 to 2 times than the after 56-days of curing when compared with initial strength at the given CKD content. However, the moduli of the RAP and RPM mixes were quite similar. This study demonstrated the potential for using CKD as a stabilizer for RAP materials. Further testing, such as large scale model experiments simulating prototype pavement structure, field tests, comprehensive durability tests, and tests with higher CKD contents, were recommended by the authors.

In the report submitted by Locander (2009) to Colorado Department of Transportation (CDOT), usage of RAP as a base course material was evaluated. In this study a total of 10 samples from different stockpiles across the state and 10 Class 6 aggregate base course materials were tested to determine the potential of RAP as a base layer. The different tests conducted include Permeability, Plasticity Index (PI), specific gravity, optimum moisture content and asphalt content in RAP. It was reported from this study that RAP when compared with ABC Class 6 base aggregate showed similar engineering pavement design properties. Hence, it was concluded that Usage of RAP as an unbound aggregate base course is an appropriate alternative design and construction approach.

2.6 Durability Studies on RAP

The durability studies on reclaimed asphalt pavement include wetting and drying or freezing or thawing studies and leachate studies. The number of studies performed on the durability of recycled pavement is very rare and a few studies that are available in the literature will be discussed in this section. The most challenging issue for any stabilization technique is its durability or permanency of stabilization. If the leaching of the chemical stabilizer occurs through moisture movements in the base layer it will reflect in serious implications for durability and sustainability of the pavement. One form of moisture conditioning effects on chemically-treated soils is related to moisture fluctuations from seasonal changes and their impact on the performance of these soils. This aspect is often studied in soil stabilization projects as a part of the durability studies (Chittoori, 2008). The commonly used test for durability studies is ASTM D 559 or ASTM D 560 which measures the resistance to 12 cycles of wetting and drying or 12 cycles of freezing and thawing. In recent years many researchers have begun to use non-abrasion type (ASTM C 593-95) of durability studies which uses Vacuum Saturation Equipment to test the durability of stabilizer for strength (Imran et., al. 1999).

Many state agencies like TXDOT have reported problems regarding disappearing of stabilizers from the base layers after certain years. Most of the research done in the past report that these durability studies are not due to abrasion of the pavement but rather because of chemical reversal of the stabilization process. In most of the cases the reversal of stabilizers is associated with moisture absorption into the stabilized materials. Capillary rise of water in stabilized surface is highly detrimental and can induce secondary reactions (McCallister and Petry, 1990). Due to the metastable nature of many of the mineral phases in chemical stabilization the water movement makes the alkali and alkali earth metals to reach out and there by decreases the strength of the stabilized layer.

Another important objective of the stabilization technique is to address the permanency of chemical stabilizer, i.e. the ability of the chemical additive to hold the recycled asphalt pavement for longer time period. Leaching of a chemical stabilizer through moisture movements will have serious implications on the durability and sustainability of the chemical treatment. One of the detrimental effects that a chemically treated soil may experience is the loss of the chemical stabilizer through leaching. Previous studies report that the leaching through moisture flows in subgrade soils result in variations of pH and Calcium and Magnesium ratios, which can influence the permanency of the chemical modifiers (McCallister, 1990). Studies addressing leaching of chemical stabilizer for recycled asphalt pavement (RAP) materials have not been researched till now.

2.7 Summary

This chapter first covers the recycled materials used in highway construction with a brief description about important recycled materials being used in the infrastructure industry in recent years. Among all these recycled materials reclaimed asphalt pavement is identified to be the most common recycling material used in base layers for a pavement. Since the main objective of this research is to use RAP as an effective base material, the recycling processes and properties of RAP are discussed in the later portion of the chapter. Finally, a few studies on chemical stabilization of RAP and durability studies related to recycled asphalt pavement are described at the end of the chapter.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 Introduction

The main objective of this research is to study the long-term performance of the chemically treated recycled asphalt pavement by aggregate materials conducting durability studies. In order to accomplish this task, wetting/drying studies, leachate analysis and unconfined compression strength tests were carried out on RAP and conventional aggregates with different percentages of cement and fly ash contents for various mix designs. For accounting the variability in RAP three different locations were chosen in Texas from which RAP materials were collected and used in this research. These are El Paso, Fort Worth and Childress districts. Finally, mineralogical studies which includes XRD and SEM tests with capabilities to conduct EDS studies were performed on each designed mix to identify the minerals formed due to chemical reaction between recycled asphalt, aggregate and Portland cement (Type I).

3.2 Selection of test materials

The selection of RAP materials has been decided based on a survey sent to 25 districts in the state of Texas. Some of the items included in this questionnaire are

- the extent of the availability of the RAP material
- whether and why the district use RAP in bases
- typical aggregate types, sources and gradations and binder grades expected in their RAP
- how the districts utilize the use of stabilized RAP in their projects and
- the districts which believe they can benefit from the outcome of this study.

Upon receiving responses from all the districts, six districts have shown positive response and accepted to cooperate with this study. These six sites include El Paso, Fort Worth, Childress, Lubbock, Waco and Pharr districts. But in this study materials from El Paso, Fort Worth and Childress districts are only included because of the time constraint. The RAP materials collected from all the three districts are shown in Figures 3.1, 3.2 and 3.3 below. Apart from RAP the local base material used by the district in their pavement construction is also collected from each district in order to determine the best mix. Also, the chemical stabilizers used for stabilizing RAP are Portland cement (Type I/II) and fly ash (Class C).

Figure 3.1 RAP from El Paso District

Figure 3.2 RAP from Fort Worth District

Figure 3.3 RAP from Childress District

3.3 Properties of the test materials

The main focus of this study is to develop a mix design procedure and guidelines for using stabilized RAP as a base material in flexible pavements. In this research the major part of the work involving design of the mix, determination of basic properties of the designed mix i.e., sieve analysis, optimum moisture content (OMC) and maximum dry density were determined. This mix design is mainly dependent upon the TxDOT procedure Item 276 which requires UCS strength of 300 psi for a one day cured specimen. Based on the mix design, the durability and leachability studies along with strength tests were conducted. This research project is a joint collaboration between University of Texas at El Paso (UTEP) and University of Texas at Arlington (UTA).

The UTEP team performed the mix design studies and UTA has performed a few experimental studies for validating the mix designs. Sieve analysis for both RAP and traditional base materials was carried out as per the TxDOT procedure, Tex-110E.method. Soil Compaction tests were conducted on the RAP and base materials to establish the optimum moisture content and dry unit weight relationships. These tests were also conducted as per the TxDOT procedure (Tex-114-E) for determining the laboratory compaction characteristics and moisture-density relationship. This procedure requires a compactive effort of 32.5 ft-lb/in^3. Based on this requirement, for a 4.54 kg (10 lb) weight of hammer and a height of drop of 0.46 m (1.5 ft), it was determined to compact the specimen in three layers with 50 blows per layer for a specimen size of 6 in. diameter and 4.5 in. height. The results of these tests for El Paso, Fort Worth and Childress RAP are presented in the chapters 4, 5 and 6.

Apart from these basic engineering tests specific gravity of the RAP material is also found using Tex-227F. This test gives theoretical maximum specific gravity of bituminous mixes. In this a known amount of sample depending upon the gradation will be taken in a glass pycnometer. It is then filled with adequate amount of water and agitated for 15 to 30 seconds while the vacuum is being applied. This process is done for 15 to 20 minutes until all the air bubbles are removed from the RAP material. Once this procedure is finished the pycnometer along with water and aggregate will be measured again. A schematic of whole set up for conducting this test is shown in Figure 3.1. The formula for calculating the specific gravity is given as

$$G_r = \frac{A}{A+D-E}$$

Where G_r = theoretical maximum specific gravity

A = weight of dry sample in air (g)

D = weight of calibrated pycnometer with water (g)

E = weight of pycnometer containing sample and filled with water to calibration level (g)

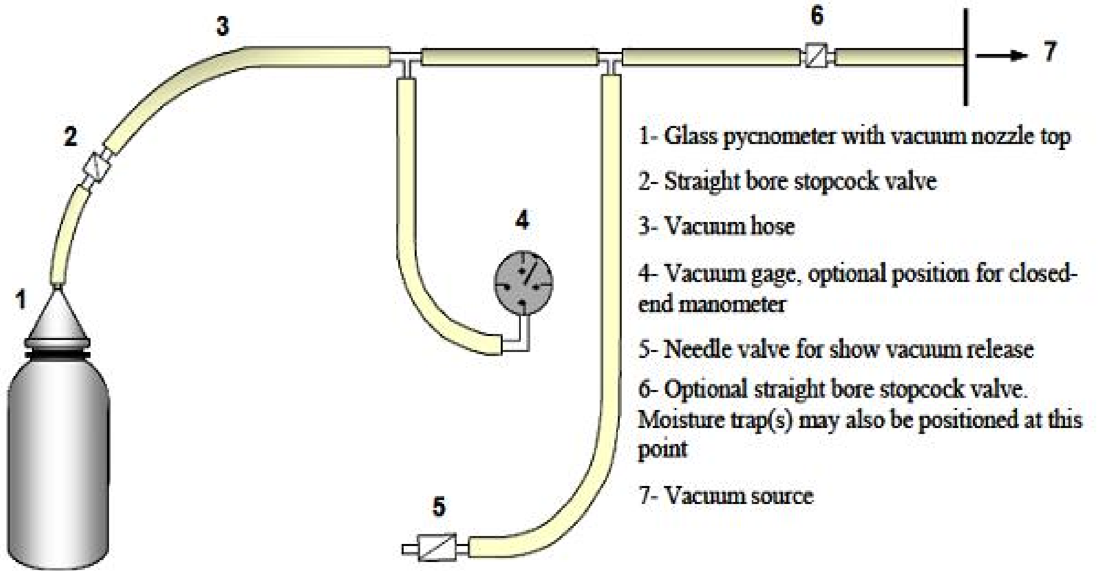


Figure 3.4 Specific Gravity Test Setup (TxDOT, Tex-227F)

3.4 Durability Studies

When the recycled asphalt pavement is stabilized with chemical additives like cement or fly ash their permanency of the stabilization has to be checked. In other words the duration for which the cement additive holds on to the RAP particles to provide the desired strength and stiffness. The permanency of the additive is affected by the leaching of the chemical stabilizer through moisture movements, which have serious implications on the durability and sustainability of the chemical treatment. One of the detrimental effects that a chemically-treated RAP may experience is the loss of the chemical stabilizer through leaching process. Previous studies reported that the leaching through moisture flow in soils result in changes in pH and the Calcium and Magnesium ions ratios, which can influence the permanency of the chemical modifiers (McCallister, 1990).

An important test to address the durability of a chemically treated recycled material in arid environments is by exposing the treated specimens to various cycles of wetting and drying processes. The high permeability of the RAP mixes is responsible for moisture damage due to seasonal variations by stripping the binder from the aggregates in RAP. The following sections details the procedures followed to conduct these durability studies. The test procedures followed by Chittoori (2008) at UTA for conducting durability and leachate studies were used in this research.

3.4.1 Specimen Preparation

The samples for conducting the durability tests are prepared using dynamic compaction because it is very difficult to compact the base materials using static method. An automatic proctor tamper (Figure 3.5) is used to prepare the samples by using Tex-114E test procedure. The steps involved are:

1. The RAP and base materials collected from district offices are sieved according to the required gradation. This gradation is found out while doing preliminary tests.
2. A total of 12 lbs of both RAP and base or only RAP material is taken in a pan by considering fractional weights from each individual pan as shown in Table 3.1.
3. This material is mixed with the proposed chemical stabilizer percentage.
4. Now the exact amount of material required to prepare the sample is calculated using volume of the mold, dry density and moisture content.

5. The prepared mixture is left for half an hour for the cement to take place the hydration process.
6. This material is filled into the mold in three layers by giving 50 blows for each layer.
7. At the end the specimen is extruded from the mold by using a hydraulic jack.

Figure 3.5 Automatic Proctor Compactor

Table 3.1 Gradation of 75%RAP+25% Base mix 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	

3.4.2 Wetting and Drying Studies

The procedure outlined by ASTM D 559 method was closely followed, which simulates both wet and dry cycle conditions close to local conditions in a reasonably short time period. The specimens were allowed to swell and shrink in both lateral and vertical directions. Prior studies by Punthutaecha et al. (2006) noted that the volumetric swell/shrink strains obtained by allowing lateral movement along with vertical movements are in close agreement with the field measured volume changes than those obtained by restraining the lateral movement.

According to the ASTM D 559 method, the specimens should be prepared and cured then submerged in water for 5 hrs for wetting cycle and then oven dried at 160ºF for 48 hours for drying cycle. Each wet-dry cycle consists of submerging the sample in water for 5 hours and then placing them in a 70℃ oven for 42 hours. After removal from the oven, the specimen is subjected to volume change and moisture content measurements. One cycle in this process is termed as complete saturation of sample for 48 hours to both wetting and drying.

The test was continued until 14 wet-dry cycles were completed or until the sample failed. The test setup used in this research can be seen in Figure 3.6. During wetting and drying periods, the changes in specimen sizes were measured in all the three directions. The Vertical movement was measured with the help of a dial gauge and the radial movements were measured using a “pi tape”. After 3, 7, and 14, the specimens were subjected to UCS tests. The test results obtained provide adequate information whether the cement treated RAP materials are durable or fail prematurely.


a) b)

Figure 3.6 Test set up for Wetting/Drying Process a) Wetting b) Drying

3.4.3 Leachate studies

A new test protocol is developed by McCallister (1990) at University of Texas at Arlington to address the permanency of the chemical stabilization from moisture flows during rainfall events. This test utilizes a flexible wall mold housing the compacted and stabilized aggregate specimen. Figure 3.7 illustrates a schematic of the test setup used in this research. This setup is similar to the one used by McCallister (1990) and Chittoori (2008) for leachate studies conducted at UTA with the exception of a modification in the size of the soil specimen (6 in. diameter instead of 8 in. diameter).

The specimens were prepared with optimum moisture content and maximum dry densities using the procedure outlined in section 3.4.1. 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 flow such that one pore volume per day was obtained. 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. The formulae involved in the calculation of specimen void volume are given in Figure 3.8. In this figure typical calculations for 60%RAP+40% Base of El Paso RAP mix sample are given.

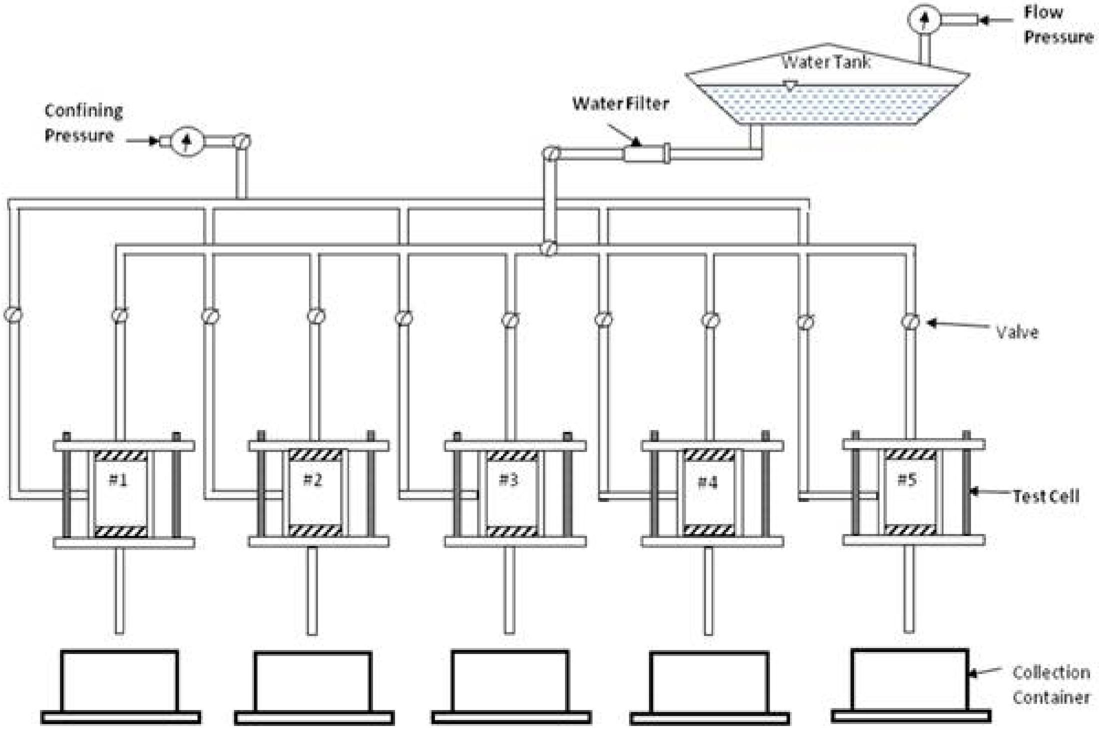


Figure 3.7 Schematic of Leachate Process (Chittoori, 2008)

The cured specimens were kept inside the sample cell (refer to Figure 3.9) and the top plate was fastened in place using the fasteners shown in Figure 3.9. A confining pressure (5 psi) higher than the flow pressure was applied through the confining pressure inlet. Then 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 the picture 3.10.

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 on RAP mixes at the end of 14 cycles of leaching. Leachate specimens collected were tested for ‘pH’ changes and ‘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 is made to correlate leaching cycles with field moisture movements from rainfall events. All these results are presented in Chapters 4, 5 and 6.

Dry Unit weight		γ_d = 133 pcf
Unit weight of water		γ_w = 62.4 pcf
Specific Gravity		G_s = 2.449
Sample Diameter		d = 6.0 in.
Sample height		h = 4.5 in.
Total volume	$V = \frac{\pi * d^2}{4} h$	V = $2.085 X 10^3$ mL
Void Ratio	$e = \frac{\gamma_{w*G_S}}{\gamma_d}$ -1	e = 0.149
Volume of Solids	$V_s = \frac{1}{1+e} V$	V_s = 1814.62 mL
Pore Volume	**$V_v = V - V_s$**	**V_V = 270.37 mL**

Figure 3.8 Pore volume Calculation for 60%RAP+40%Base mix of El Paso District

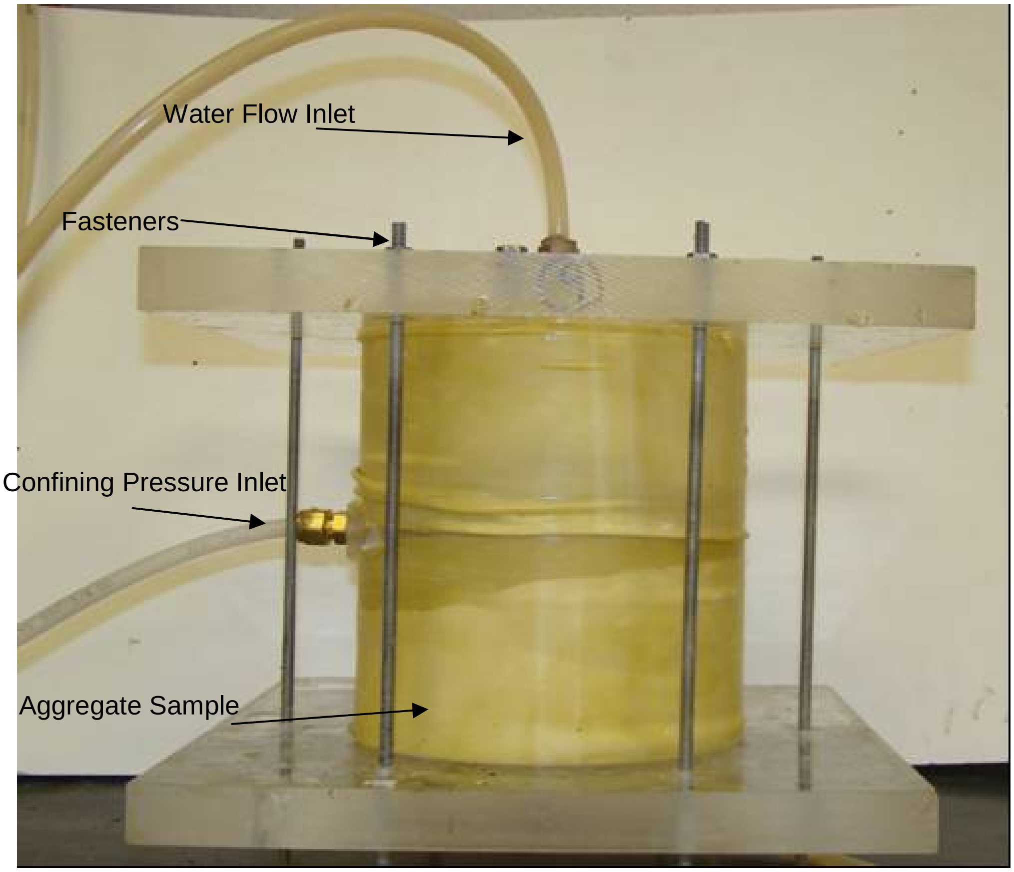


Figure 3.9 Leachate Cell

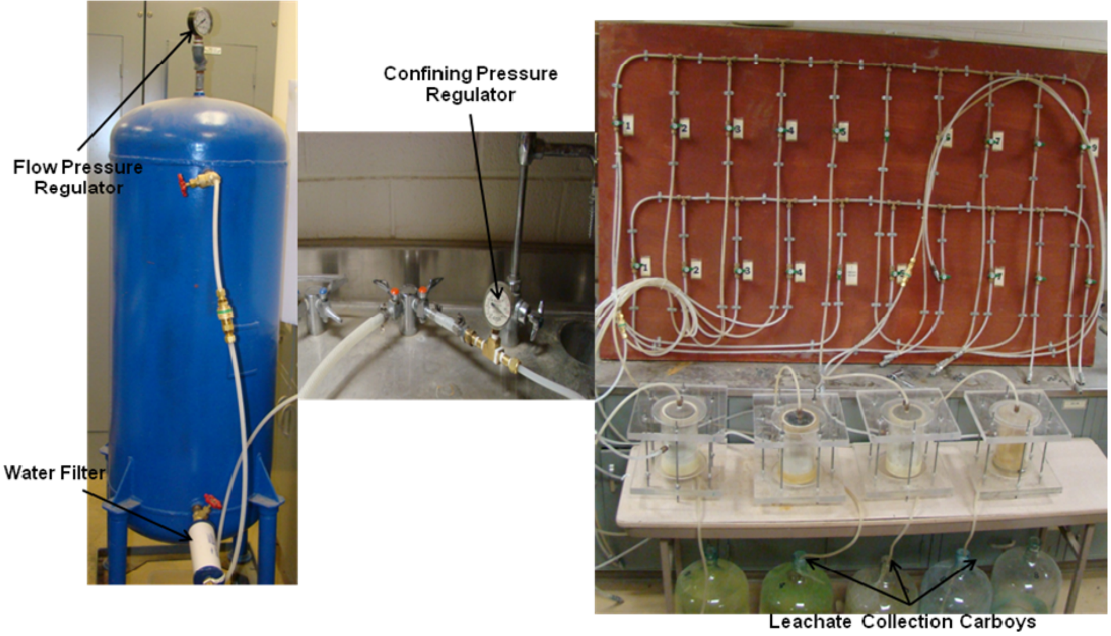


Figure 3.10 Apparatus for Leachate studies (Chittoori, 2008)

3.4.3 Unconfined Compression Strength Tests

Unconfined compression strength tests are performed on the samples after durability studies to know the ultimate load taken by the specimens. The samples are subjected to UCS tests after 0, 3, 7 and 14 cycles of wetting/drying studies and at the end of 14 leachate cycles. These UCS test results will be analyzed to address any potential loss of strength in the cement stabilized RAP after different cycles of durability studies. The equipment used for UCS testing of RAP mixes is shown in Figure 3.11.

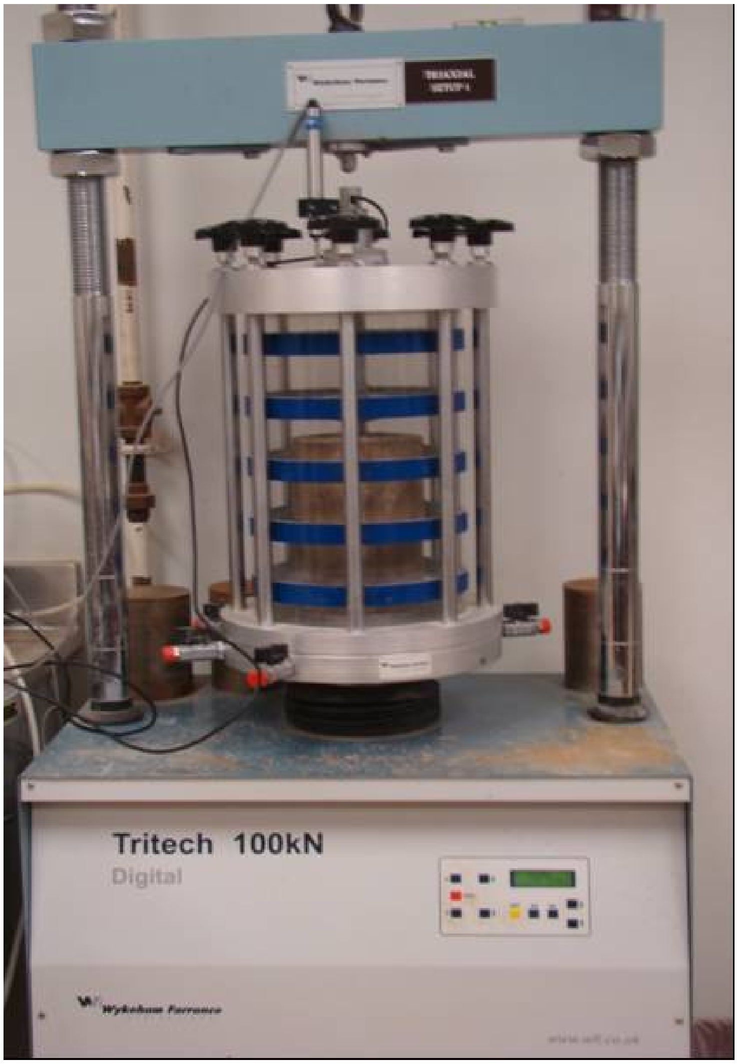


Figure 3.11 Unconfined Compression Strength Testing Machine

3.5 Mineralogical Studies

3.5.1 X-ray diffraction Studies

X-ray diffraction screening study was conducted on all the designed mixes for El Paso, Fort Worth and Childress sites to qualitatively identify the minerals formed during the blending of RAP, aggregate and cement mixture. 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 is measured this distance is called d-spacing. These d-spacing are compared with the 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 the X-ray diffraction test, the RAP mixes were air dried and hand crushed such that most of the material passes through No.200 sieve. Oven drying and pulverizing are not preferred as they may modify the mineralogical structure inside the sample and 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 3.12 and X-ray diffraction studies were carried out using a D-500 X-ray Diffractometer (Figure 3.13) 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 0.03^0 of 2-theta angle and a dwell time of 2s were selected. When the step scan is finished it gives certain peaks according to the intensities. These peaks are analyzed by identifying the minerals from software called JADE where the peaks obtained are matched with the minerals present in the software. There are no previous studies performed till now on these RAP mixes to identify the predetermined minerals formed due to chemical reaction between RAP, aggregates and cement. The test results of this X-ray diffraction analysis are presented in the following chapters.

Figure 3.12 Sample holder with powdered RAP mix

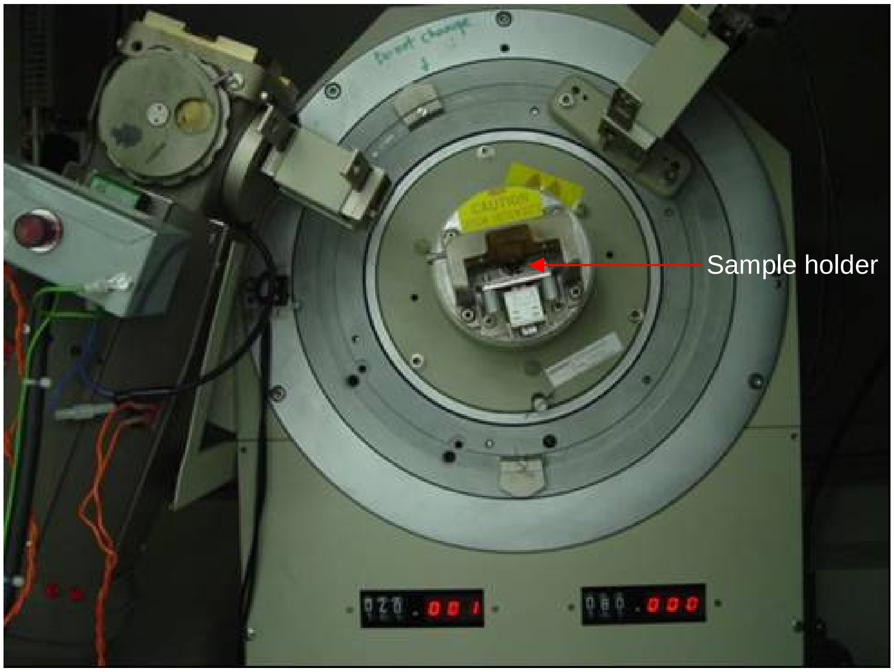


Figure 3.13 D- 500 X-ray Diffractometer

3.5.2 Scanning Electron Microscope (SEM studies)

The scanning electron microscope 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 the components in the RAP mixes. The magnifications and voltages in the test setup are altered to get a clear digital image. Also, 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 3.0 nm resolution at high vacuum and 4.0 nm resolution at low vacuum. There are particular instances when a low-vacuum or high vacuum modes can be used, but these instruments necessarily trade off resolution to be able to work with gas in the sample chamber. It is a computer controlled system for ultimate ease of use. A typical set up of the Scanning Electron microscope is shown in Figure 3.14.

Scanning electron microscopy 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 3.15) 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. Some of the pictures taken for the designed RAP mixes are shown in Chapters 4, 5 and 6. 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.

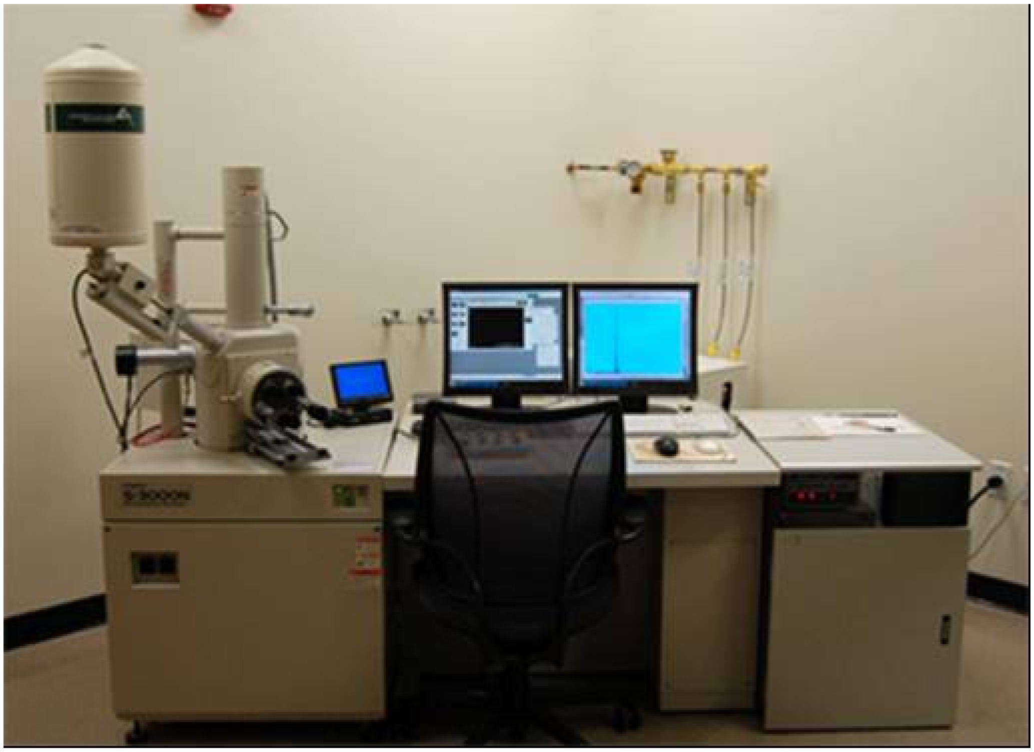


Figure 3.14 Scanning Electron Microscope (SEM) Test Setup

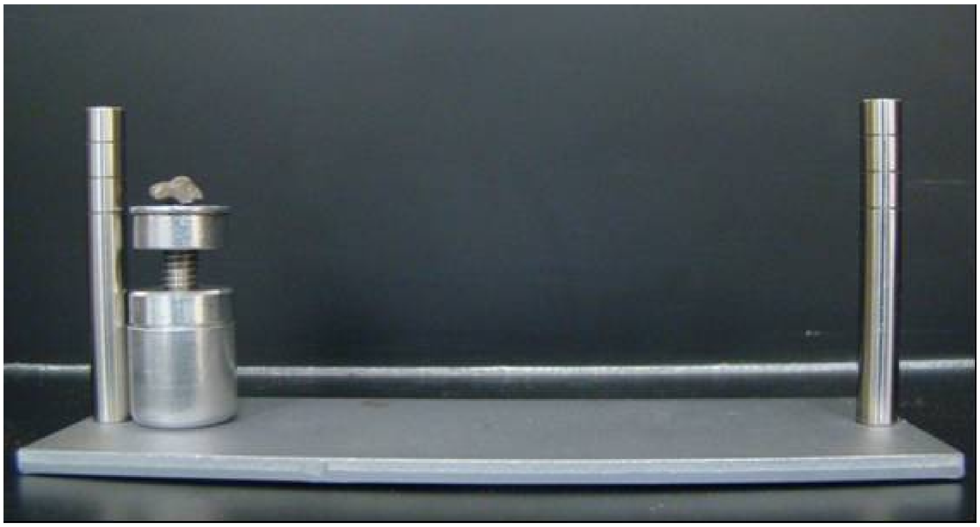


Figure 3.15 Sample holder For SEM analysis

3.6 Summary

In this chapter various test procedures adopted to determine the engineering properties of the RAP and base materials is discussed in detail. After that durability test procedures followed to replicate moisture fluctuations in the field during summer and rainy seasons is described and leachate studies following the simulation of moisture infiltration from rain fall events are presented. Mineralogical studies conducted on the RAP mixes to know the minerals formed due to blending of RAP and base materials are explained at the end. In the following chapters test results obtained from all the above mentioned tests will be presented.

CHAPTER 4

DURABILITY STUDIES ON ELPASO RAP

4.1 Introduction

This chapter presents test results for stabilized recycled asphalt pavement (RAP) and local aggregate base materials. Samples were collected from three districts, El Paso, Fort Worth and Childress in the state of Texas. A series of tests were performed first to classify the samples and then the durability studies were conducted to study the long-term performance of chemically stabilized RAP and aggregate mixtures. These tests included sieve analysis, proctor compaction, specific gravity, unconfined compression strength tests, wetting/drying studies, leachate studies and mineralogical tests. In this chapter the results pertaining to only El Paso RAP will be discussed in detail and in the following chapters results from Fort Worth and Childress RAP mixes are presented.

4.2 Basic properties of El Paso RAP

Reclaimed asphalt pavement (RAP) was collected from different locations in a stockpile from El Paso district to account for variability and brought to the laboratory for determining basic engineering properties. This RAP was blended with different percentages of locally available aggregate base in order to design the best performing mix to be used in the field conditions. This blended RAP and base mixes were stabilized with Type I Portland Cement and Class C Fly ash to achieve the minimum strength requirements by Item 276 of current TxDOT procedures which requires 300 psi of unconfined compression strength.

Determination of basic properties includes gradation for RAP and base, specific gravity, maximum dry density and optimum moisture content. The particle size distribution was determined using TxDOT sieve analysis procedure Tex-110E. Table 4.1 presents the particle size distribution for both RAP and base materials. Figure 4.1 shows the typical gradation curve for both these materials. Based on this data according to American Association of State Highway and Transportation Officials (AASHTO) the RAP material was classified as A-1-a and the base material was classified as A-1-b respectively.

Table 4.1 Particle size distribution for El Paso RAP and Base

Sieve Size	**Percent Passing (%)**	
	RAP	**Base**
1 3/4"	100.0	100.0
1"	100.0	100.0
7/8"	96.0	69.2
3/8"	53.4	69.2
#4	28.8	69.2
#40	4.5	50.2
#100	1.3	34.1
#200	0.4	17.9
Pan(-200)	0.00	0.00

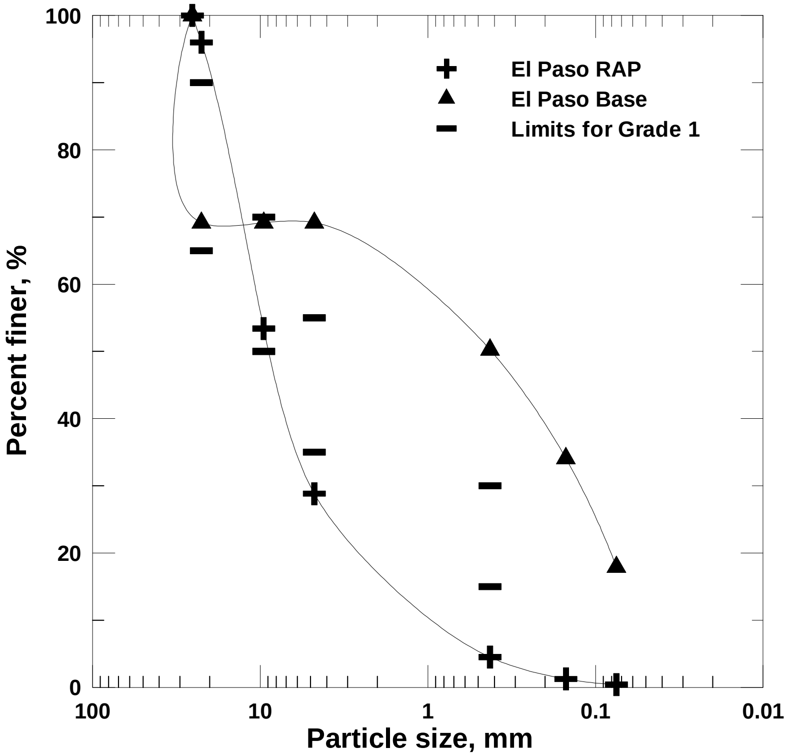


Figure 4.1 Particle size distribution for RAP and Base materials

The specific gravity for RAP material was found to be 2.449 using the test procedure outlined in section 3.4. Specific gravity of the aggregate base material was not determined in these studies. A threshold/target value of UCS (300 psi) was used to standardize various mixes designed by blending RAP and base materials with different percentages of additives. The mixtures studied for El Paso district are listed in Table 4.2 along with their notations.

Table 4.2 Details of mixes studied for El Paso RAP

Mix Type	Notation
100% RAP (0%Cement)	100R_0C
100% RAP (6%Cement)	100R_6C
100% RAP (7%Fly ash)	100R_0F
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

The optimum moisture content (OMC) and maximum dry density (MDD) values were determined using the TxDOT procedure (Tex-114 E method). The compaction test was performed using the compaction testing procedure Tex-114 E method. The mold dimensions were 6.0 in. in diameter and 4.5 in. in height. The weight of the hammer used was 10 pounds with a free-fall height of 18 in. A typical moisture content – dry density curve obtained from compaction test for 60%RAP+40%Base is shown in Figure 4.3.

The variations of OMC with RAP content for untreated and treated samples are presented in Table 4.3 and are illustrated in Figures 4.3 and 4.4 respectively. For both treated and untreated samples, the optimum moisture content percentage is reduced as the RAP content increased because less water is absorbed by the particles coated with asphalt.

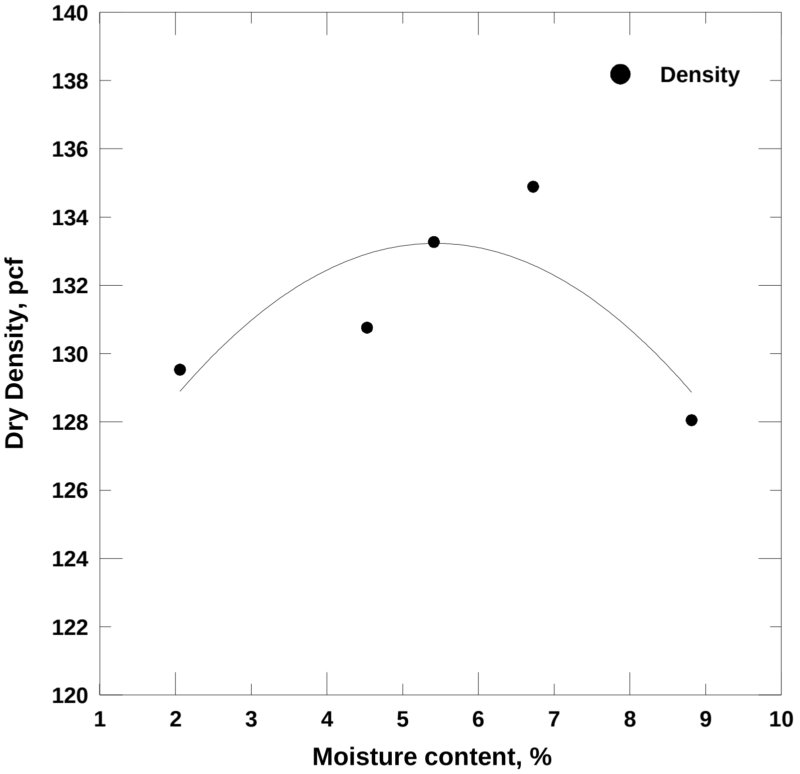


Figure 4.2 Typical Moisture Density curve for 60%RAP+40%Base mix

Table 4.3 Effect of RAP content on OMC

RAP Content	OMC (%)		
	Untreated	Cement	Fly Ash
50	6.1	6.5	NT
60	5.4	6.2	6.1
75	5.8	6.3	NT
100	5.3	5.2	5.4

Note: NT-Not Tested

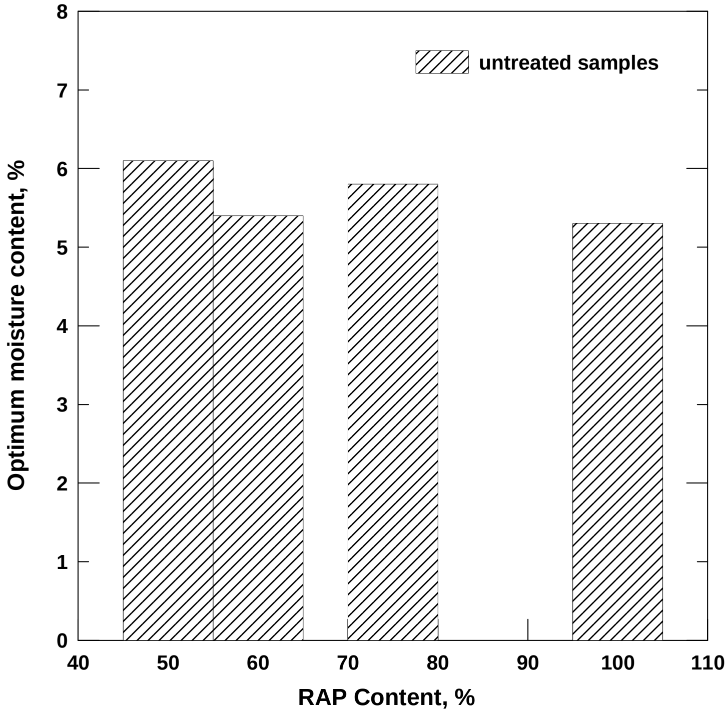


Figure 4.3 Effect of RAP content on OMC

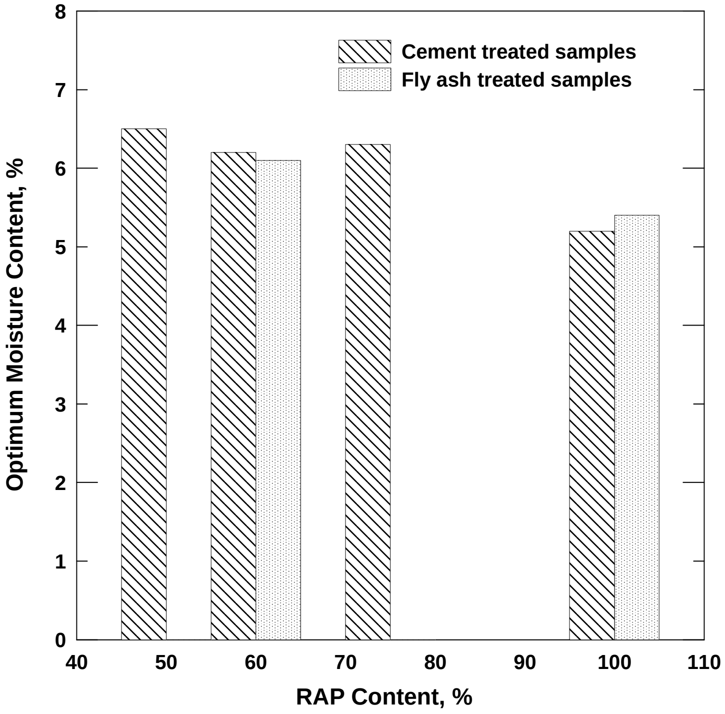


Figure 4.4 Variation of OMC for treated samples

The MDD values associated with RAP-base blend mixes were presented in Table 4.4 and graphically illustrated in Figures 4.5 and 4.6 respectively. The reduction of MDD with an increase in RAP content might be due to lower specific gravity of RAP material when compared to natural aggregate base.

Table 4.4 Variation of Dry Density with RAP content

RAP Content	**MDD (pcf)**		
	Untreated	**Cement**	**Fly Ash**
50	131.8	131.8	NT
60	133	133	134
75	125.5	127.5	NT
100	116	118	118

Note: NT-Not Tested

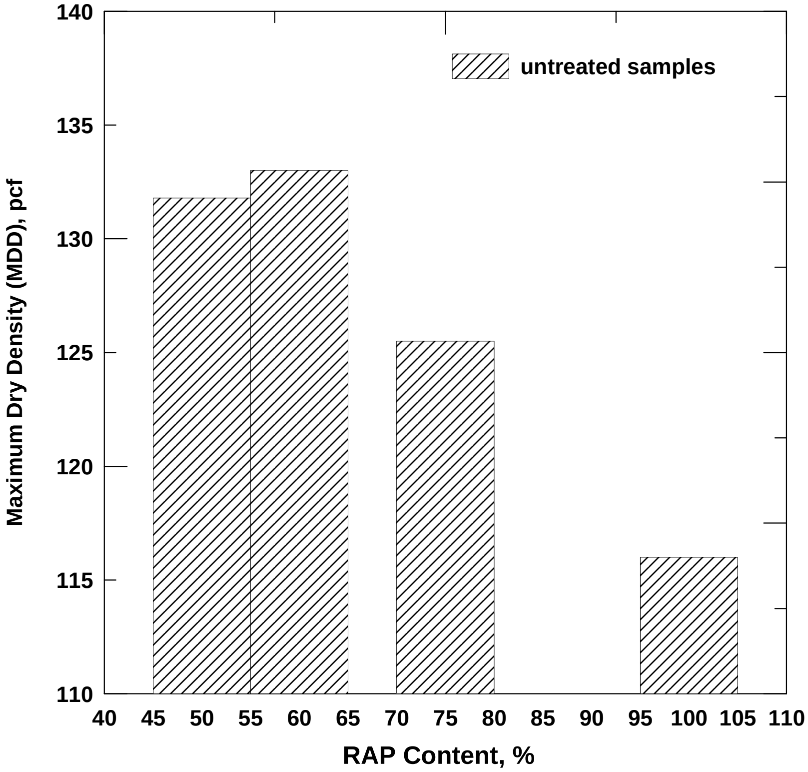


Figure 4.5 Effect of RAP content on MDD

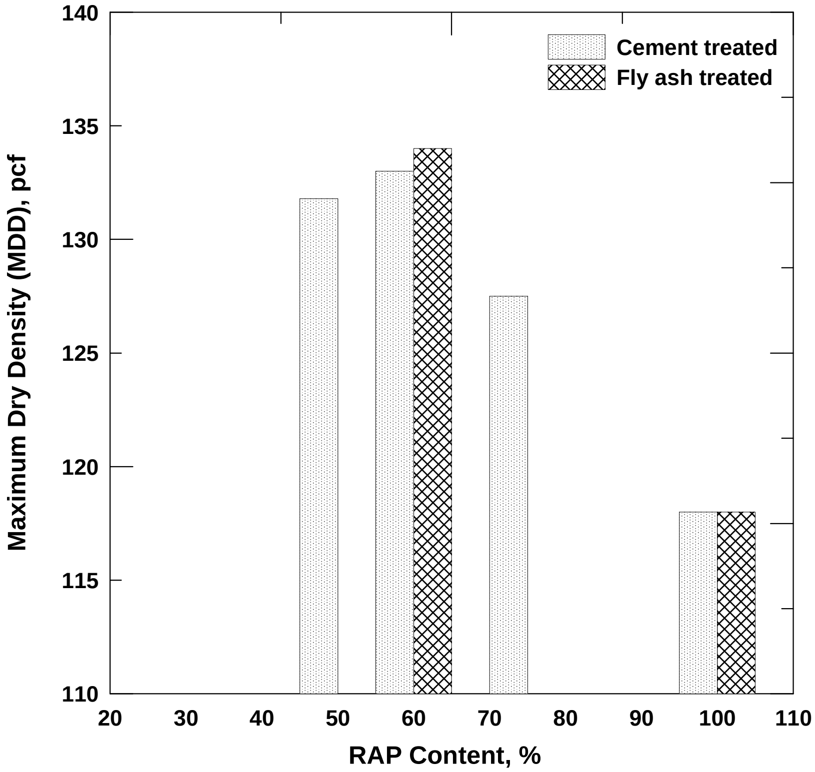


Figure 4.6 Variation of MDD for treated samples

4.3 Engineering Properties of El Paso RAP

The engineering properties for RAP mixes can be studied by performing strength and durability studies. The unconfined compression strength test helps in designing a mix by meeting the minimum strength requirement criteria as discussed in section 4.2 while durability studies gives an idea about the long-term performance of the chemical stabilization. The durability studies consist of conducting wetting/drying studies for 14 cycles and leachate analysis for 14 cycles. The results obtained from each mix were compared with one another to determine the best performing mix based on the final strength and durability of chemical additive.

4.3.1 Unconfined Compression Strength (UCS) Tests for Blended RAP mixes

For using recycled asphalt pavement (RAP) as base material and minimize the use of natural aggregates, different combinations of RAP and base blended mixes were designed. The

RAP and base mix proportion (RAP: Base) considered here in this research are 50:50, 60:40, 75:25 and 100:0 respectively. This utilization of reclaimed asphalt pavement to a maximum percentage can be achieved if it is stabilized with chemical additives like cement or fly ash to get the targeted strength. In recent years TxDOT has been using RAP up to 80% in base mixes (US 287 in Amarillo District with 6% fly ash) even though the typical percentage to be used is only 30%. This increasing percentage of RAP when stabilized with cement or fly ash will not only reduce the cost of the materials but also helps in saving naturally occurring materials. Hence, an attempt is made in this research to design a mix which uses maximum percentage of RAP with low stabilizer content by considering both strength and durability criteria.

The samples were prepared according to the procedure given in section 3.4.1 for both untreated and treated specimens. The prepared samples were cured for seven days in a moisture room before subjecting them to UCS test. The results of the UCS tests for both untreated and treated mixes were shown in Table 4.5. It can be observed from the data that untreated samples are very weak and have low strengths due to the lack of bonding between the asphalt and aggregate base particles. However, when the RAP mixtures are cement treated, their strengths increased by 23%, 5% and 12% for 50%RAP, 60%RAP and 75%RAP, respectively. The strength variation for untreated and treated samples versus different RAP contents is shown in Figure 4.7.

Table 4.5 Unconfined Compression Strength Test Data

RAP Content	**Unconfined Compression Strength (psi)**		
	Untreated	**Cement**	**Fly Ash**
50	12	290	NT
60	45	305	30
75	14	185	NT
100	0	210	0

Note: NT-Not Tested

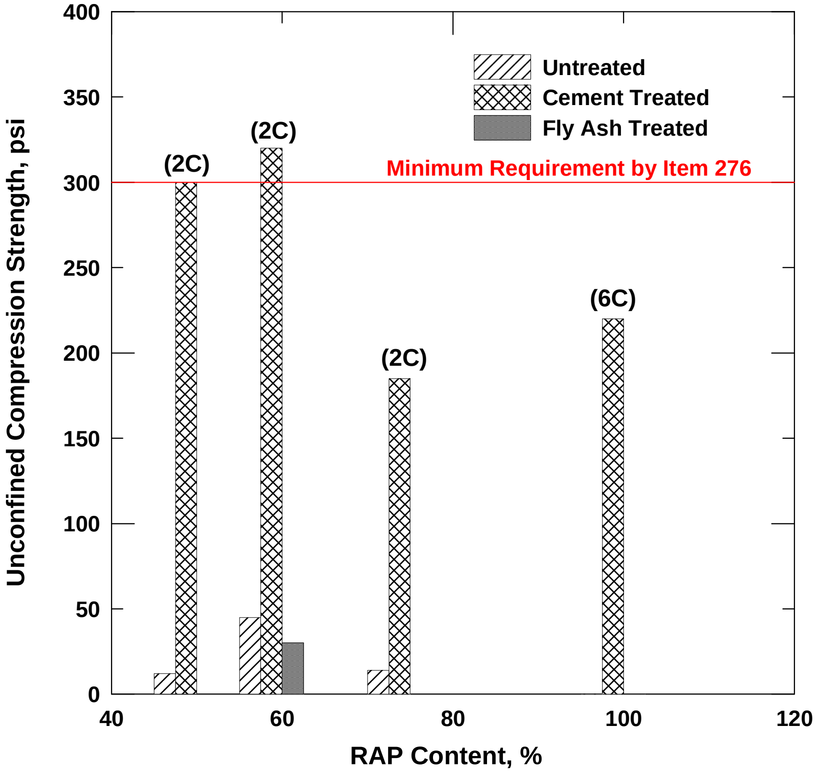


Figure 4.7 UCS Data for untreated and treated samples

4.3.2 Durability Studies

The durability tests are mainly conducted to assess the impact of moisture fluctuations and ingress on the performance of base and subgrade materials in terms of stiffness and strength property variations. In order to evaluate the long-term durability using the strength aspects as explained above, both wetting/drying and leachate studies are conducted on each mixture by performing UCS tests at select cycles. These tests simulate the performance of a stabilizer after certain years of stabilization process by correlating the number of cycles with the seasonal changes in the field.

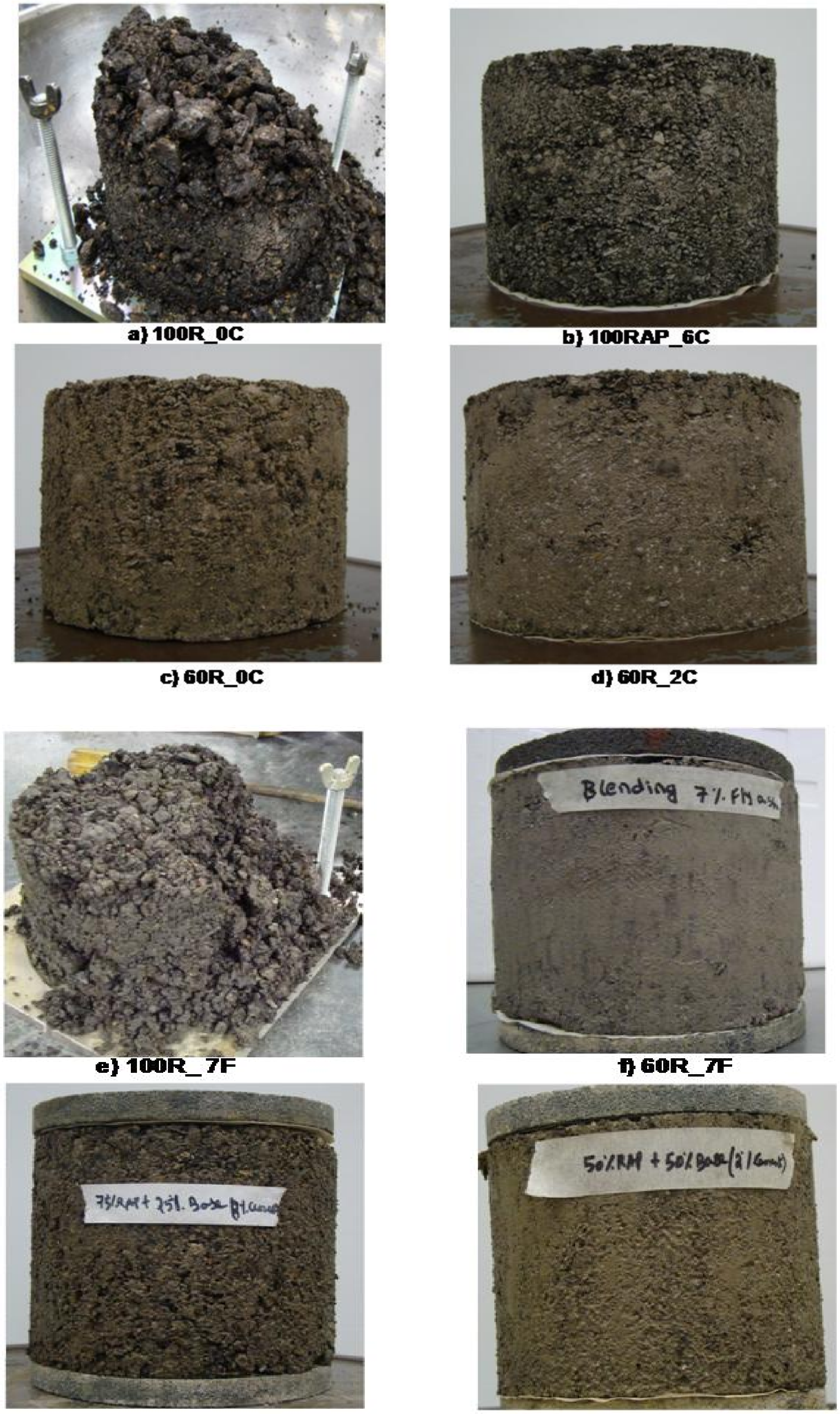
4.3.2.1 Wetting/Drying Studies

The main purpose of conducting wetting/drying studies was to simulate the seasonal moisture fluctuations that might have taken place during summer and winter seasons.

Numerous studies have reported the results of wet-dry cycle related tests on soil samples to address the moisture fluctuations. In this research, similar test procedures were followed for recycled aggregate material to study its long-term performance as a base layer.

The standard ASTM D 559 method was followed to perform wetting/drying studies on each design mix. For completing one cycle, a total of 48 hours is required as each sample is soaked under water for 5 hours (wetting) and kept in the oven at 160^0F for another 42 hours (drying). In this study, a total of 14 wetting/drying cycles were performed which requires a total of 28 days to complete the testing on each specimen. At each cycle, volumetric changes taken place in all the three directions were measured. The vertical movements were measured using vernier calipers and the radial movements were measured with a pi tape. Based on the final volumetric change and retained strength after 3, 7 and 14 cycles of wet/dry cycles ranking was given for every mix in Table 4.6 to recognize the best performing mix.

The various blended RAP base mixes prepared before subjecting them to wetting/drying studies is shown in Figure 4.8. It can be seen from this figure that no representative sample could be made from 100% RAP and 100% RAP with 7% Fly ash.



a) 100R_0C

b) 100RAP_6C

c) 60R_0C

d) 60R_2C

e) 100R_7F

f) 60R_7F

g) 75R_2C

h) 50 R_2C

Figure 4.8 Different RAP mixes at Initial conditions (0 cycles)

After preparing the sample using the procedure explained in section 3.4.1, the sample was cured for seven days in a moisture room before subjecting them to wet/dry cycles. 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.

The volumetric strain versus 3 cycles of wetting/drying plots for the mixes 60R_0C, 60R_2C, 50R_2C, 75R_2C, 100R_6C and 60R_7F are shown in Figures 4.9 and 4.10. It can be noted from these graphs that the volumetric change for 60R_2C is very low when compared with the other mixes. Also, the strength tests conducted after 3 cycles were compared with initial strengths (at zero cycles) to know the percentage of retained strength. This variation of strength can be seen in Figure 4.11. The conditions of specimens after 3 cycles can be seen in Figure 4.12.

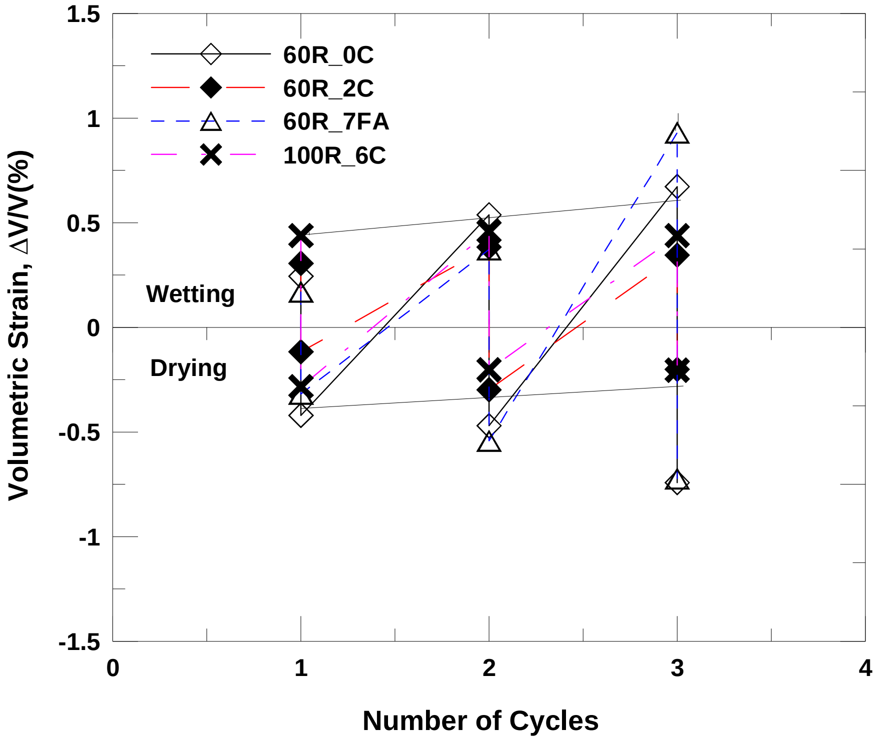


Figure 4.9 Volumetric changes with 3 W/D for different RAP mixes

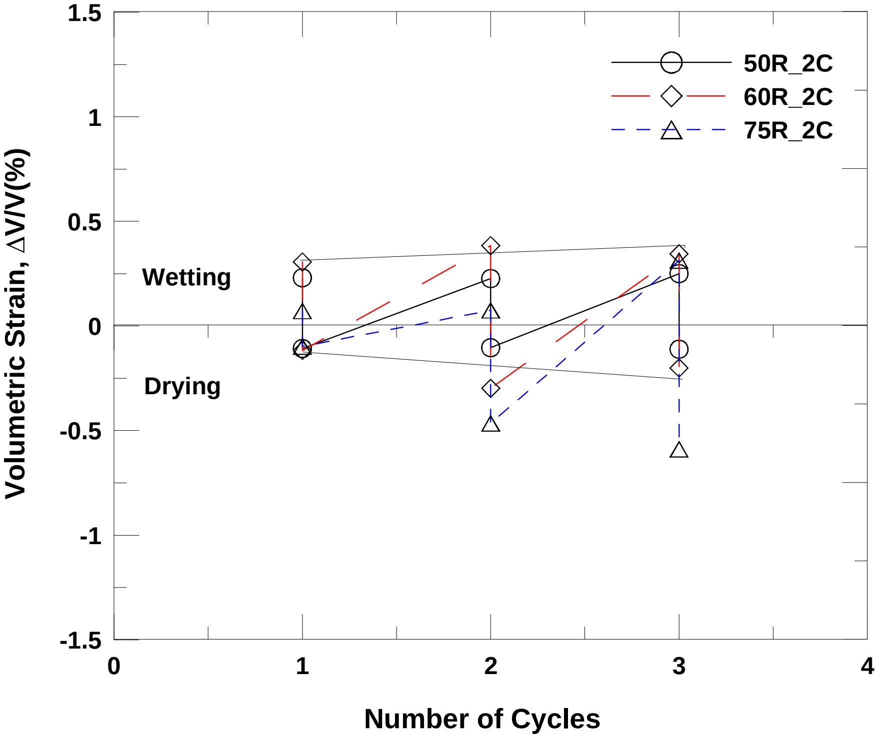


Figure 4.10 Volumetric changes with 3 W/D cycles for various blended RAP mixes

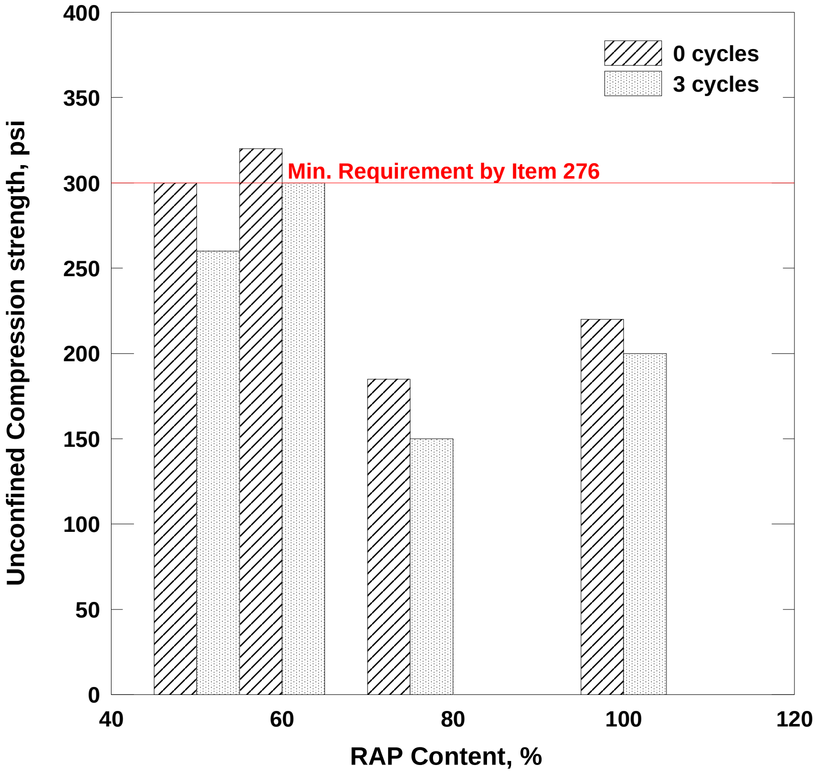
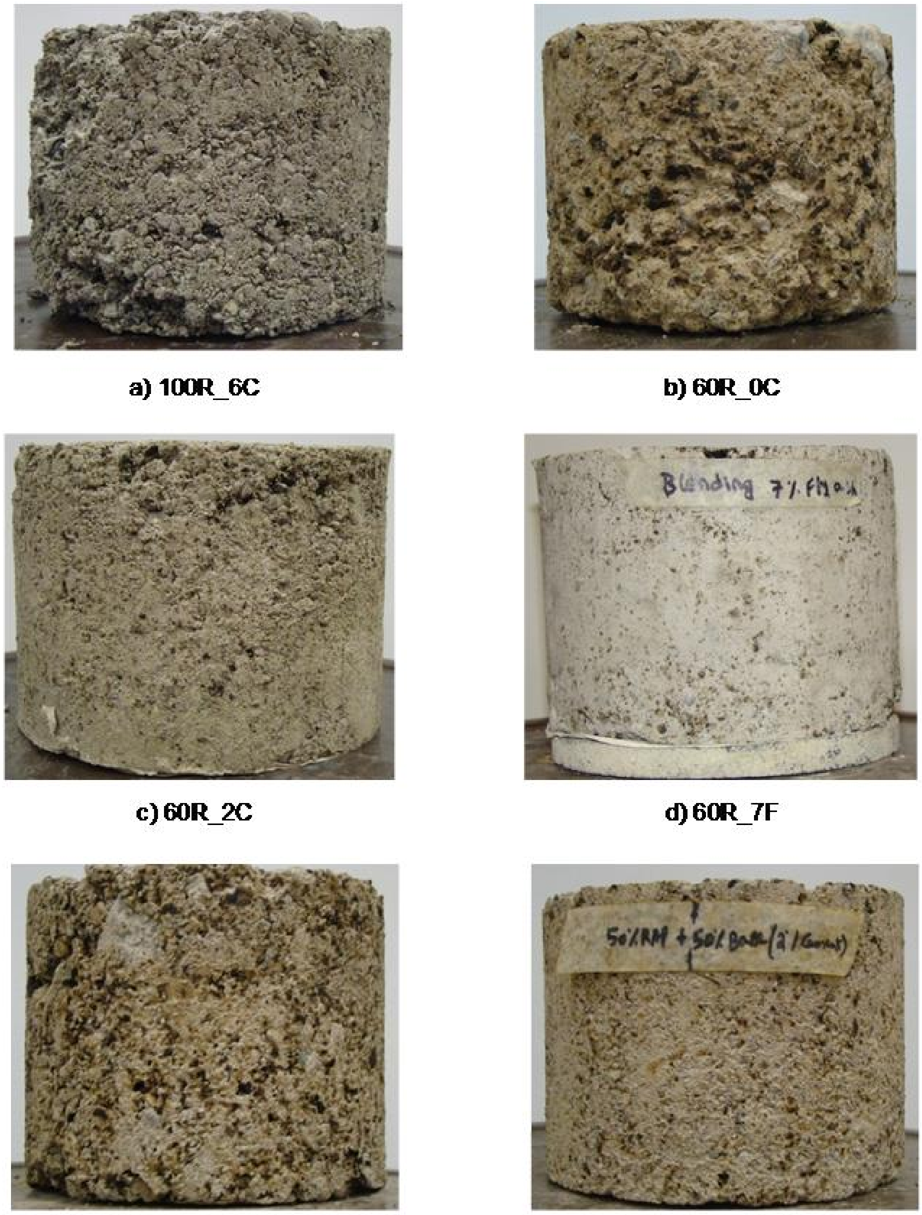


Figure 4.11 Comparison of UCS strengths with 0 and 3 W/D cycles

Similarly the wetting/drying studies were performed for 7 and 14 cycles to study the effects of moisture fluctuations on long-term performance of a mix. The aggregate samples were subjected to alternate wetting and drying studies to a maximum of 14 cycles because this laboratory saturation can be related to performance of the design mix for a longer period in the field. During the test, the volumetric change was measured after each cycle to identify swell-shrink potential and strength tests were conducted at the end of 7 and 14 cycles to know the percentage of strength retained. Since the material is an aggregate base material, very low changes in volumetric strains were observed for each wet/dry cycle, this is drastically different from the responses noted on subgrade soils.



a) 100R_6C b) 60R_0C

c) 60R_2C d) 60R_7F

e) 75R_2C f) 50R_2C

Figure 4.12 RAP mixes after 3 W/D cycles

The plots in Figures 4.13 and 4.14 depict the comparison of change in volumetric strain versus number of cycles for 7 and 14 wet/dry tests. From the figures, it can be observed that 60% RAP treated with 2% cement shows a very low change in volumetric strain when compared to 100% RAP mix stabilized with 6% cement. The other mix designs show a slightly higher percentage of volumetric strains which are in the range of 1% to1.25%. In Figure 4.15, it can also be noted that the 60R_2C mix is showing consistent amount of retained strength even after 14 cycles of wetting/drying studies. The chemical stabilization with fly ash did not work for the present RAP mixes because of the exhibition of low strength and high volumetric change after 7 cycles. The Table 4.6 provided at the end of this section summarizes the results obtained from wet/dry cycles for all the mixes studied. The pictures taken for all the mixes studied after 7 and 14 cycles of W/D studies are shown in Figures 4.16 and 4.17.

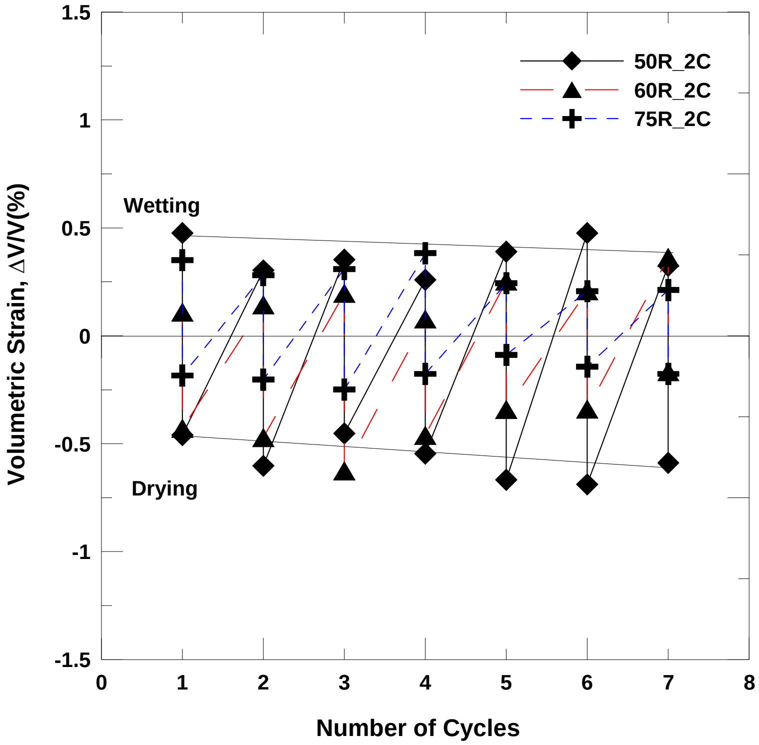


Figure 4.13 Volumetric changes with 7 W/D cycles for different RAP contents

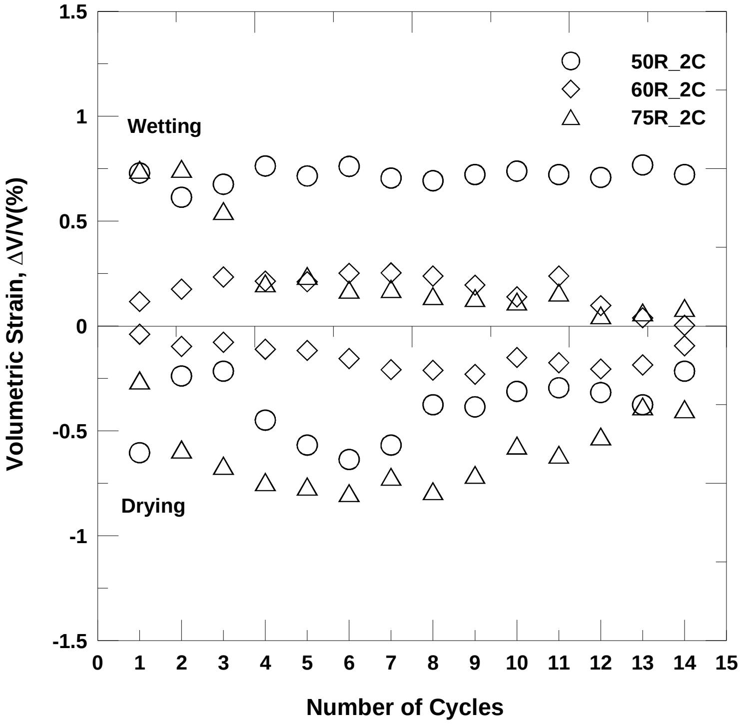


Figure 4.14 Volumetric changes with 14 W/D cycles for different RAP contents

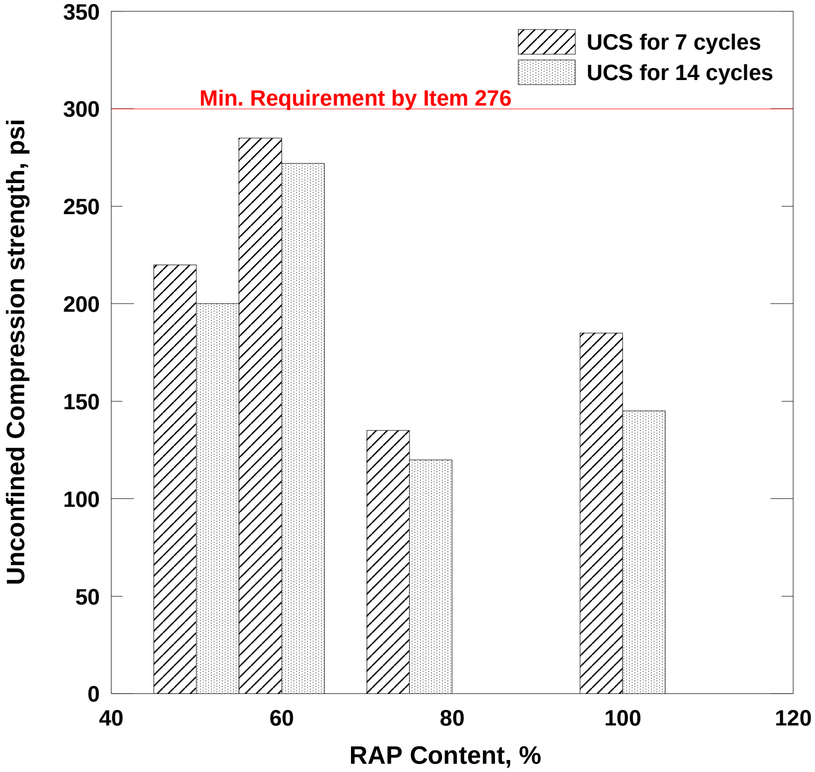


Figure 4.15 UCS strength variations with 7 and 14 W/D cycles

a) 100R_6C

b) 60R_0C

c) 60R_2C

d) 60R_7F

e) 75R_2C

f) 50R_2C

Figure 4.16 RAP mixes after 7 W/D cycles

a) 100R_6C

b) 60R_0C

c) 60R_2C

d) 75R_2C

e) 50R_2C

Figure 4.17 RAP mixes after 14 W/D cycles

Based on the information given in Table 4.6 it can be observed that 60%RAP blended with 40%Base and treated with 2% cement performs satisfactorily. This mix shows a very low volumetric change after 3, 7 and 14 wet/dry cycles and has a consistent retained strength even after 14 cycles of wetting/drying studies. The other mix which can be considered to be well in match with 60R_2C is 75R_2C because it also has a very low volumetric strain change and standard decrease in strength for all the cycles studied. The fly ash treated sample is very weak in its strength and got crumbled after 7 wetting/drying cycles. While 100R_6C have very low volumetric change but its strength got reduced well below the required standard after 14 cycles. Another important reason for not considering this mix is that it may become uneconomical to use 6% cement in base layer stabilization. The other RAP mix 50R_2C has also shown some steady retained strength with a little change in volumetric strain during 7 and 14 cycles of wetting/drying cycles. The reason for not selecting this mix is to utilize maximum percentage of RAP in a mix with the best results obtained.

Table 4.6 Summary of Wet/Dry studies on RAP mixes

Mix Type	**# of cycles**	**Total Volumetric change (%)**	**Retained UCS (psi)**	**# of 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		

Note: # of cycle's tested-14

4.3.2.2 Leachate Studies

Leachate studies were performed on the blended RAP mixes to study the permanency of cement stabilization. Due to rainfall infiltration the calcium present in the cement gets washed away by the process of leaching. When the loss of this chemical additive occurs it results in reduction of durability and sustainability of chemical stabilization. The main factors contributing to the leaching of this chemical additive are rainfall infiltration and moisture fluctuations in ground water table due to seasonal variations underneath the pavement. Hence, this test is also carried out as one of the durability studies on the designed RAP mixes to study the leaching of stabilizer over a longer time period.

A detailed procedure for conducting this test is outlined in the section 3.4.3. The leachate studies conducted by McCallister (1990) and Chittoori (2008) on soil samples reported that the leachate collected at 3, 5, 7, 11 and 14 cycles showed variations in pH and calcium ions. The test setup used to conduct the leachate studies in this research is shown in Figure 3.10. This test setup is similar to the one used by McCallister (1990) and Chittoori (2008) at UTA; however the specimen sizes are different. In their study, the specimen dimensions were 8.0 X 6.0 inches and 4.0 X 6.0 inches, respectively.

In this test, water is forced into the specimen at a certain pressure (5 psi) from the top and a confining pressure of 5 psi was applied at the middle of the flexible mold as shown in Figure 3.9. The pressurized water through the sample was collected at the bottom of the test setup after a certain number of leachate cycles. One leachate cycle is defined as the amount of leachate close to total voids present in the compacted specimen. A total of 14 leachate cycles were conducted on each aggregate specimen and this leachate was studied for pH and calcium changes. At the end of 14 leachate cycles the sample was subjected to UCS strength to determine the percentage of retained strength. The results obtained in these tests are presented in the following sections.

All the treated and untreated design mixes were subjected to leachate studies to study the loss of calcium ions and pH changes. Figures 4.18 through 4.22 present the comparison of calcium ion concentration and pH changes with number of leachate cycles. It can be observed from the Figure 4.17 that for 100R_0C mix the loss of calcium ion concentration is decreasing with increase in number of cycles due to poor holding capacity of recycled asphalt. It is to be noted here that the untreated/unblended RAP (100R_0C) has calcium concentration even before treatment with calcium based additives. The calcium concentration present in the virgin RAP could be attributed to the mixing of stabilized base with RAP during milling operations. On the other hand, when this mix is stabilized with 6% cement the trend observed is similar to untreated sample except that at 14 cycles the loss of calcium was reduced by 70% which proves that the cement is holding on to the asphalt particles to provide some strength. When the cement stabilization is carried out for different percentages of RAP content as shown in Figure 4.18 a similar pattern of decrease in concentration of calcium ions have taken place. The more loss of calcium concentration in 50R_2C can be attributed due to additional calcium concentration present in limestone base material. The loss of calcium ions in base material can be observed in 60R_0C mix as it is not stabilized with any cement.

Figures 4.20 and 4.21 shows the typical variation of pH for different RAP mixes blended with the base material. The pH of untreated RAP mixtures ranged from 7.8 to 8.5 for 14 leachate cycles whereas for treated soil mixtures, it ranged from 7.8 to 10.8 for the same number of leachate cycles. For 60R_2C the variation of pH was between 8.5 and 7.7 which is the range measured for the normal tap water. This trend indicated that the loss of calcium ions in this mixture was almost negligible.

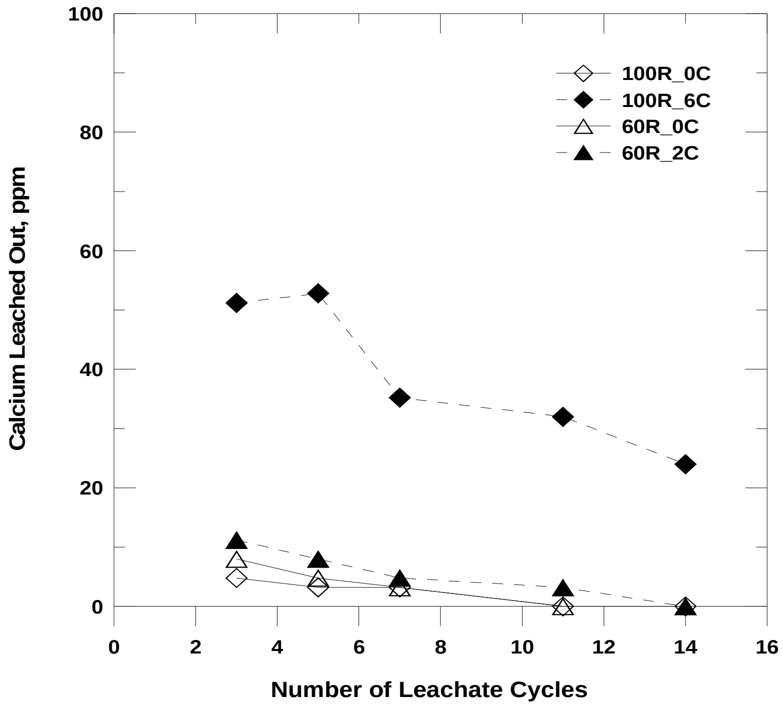


Figure 4.18 Comparison of Calcium leached out for untreated and treated RAP mixes

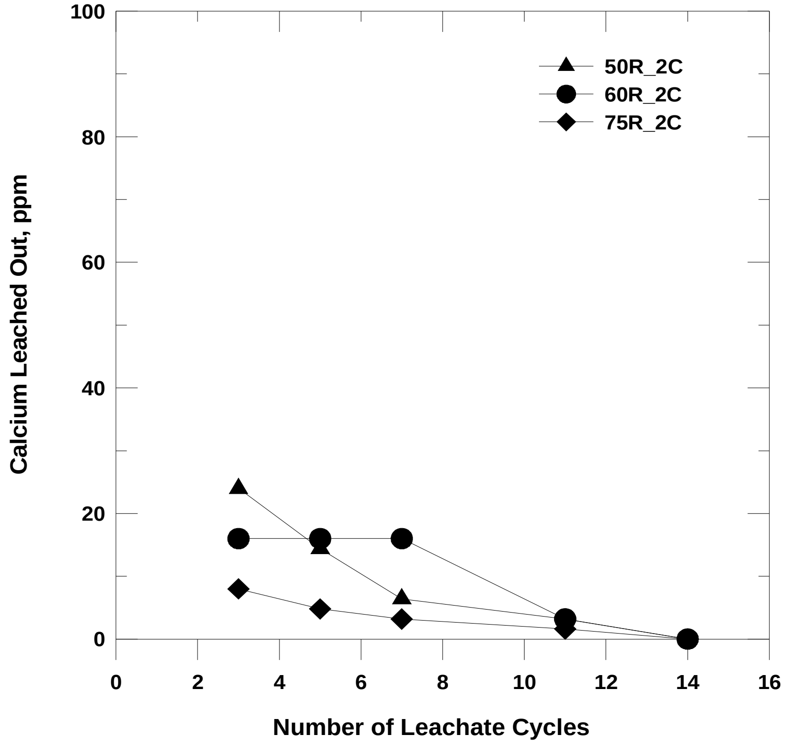


Figure 4.19 Comparison of Calcium leached out for various RAP contents

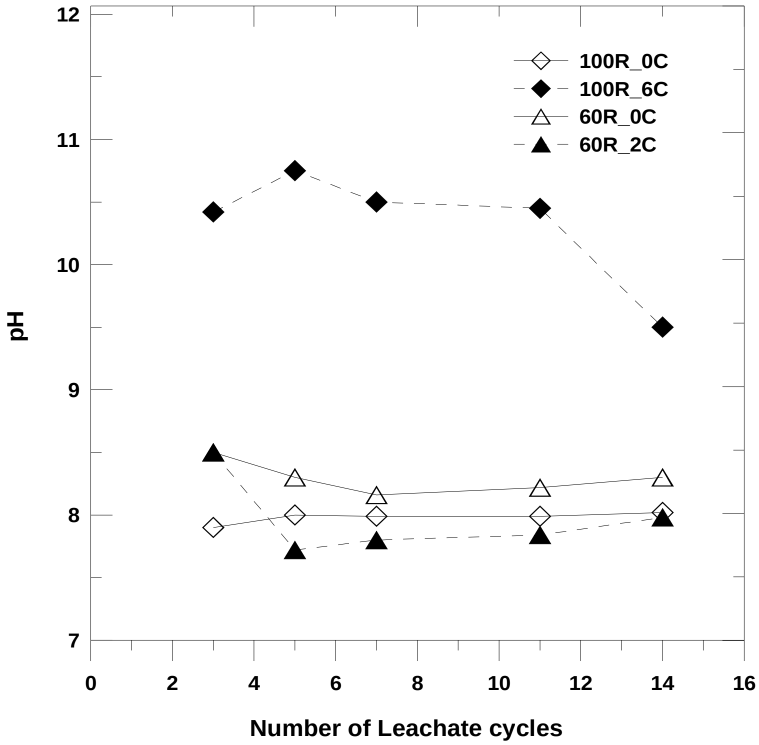


Figure 4.20 Variation of pH with cement stabilization

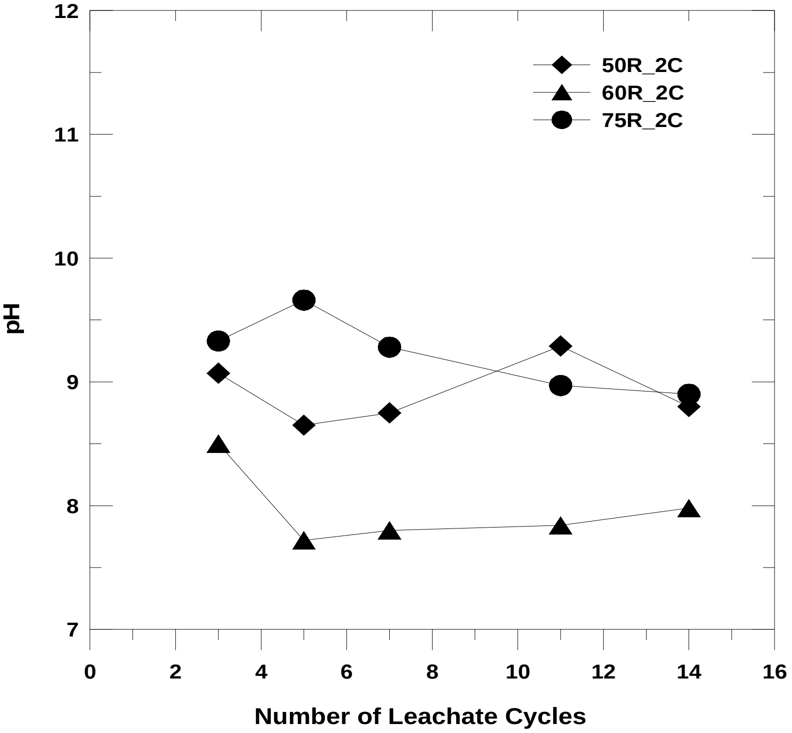


Figure 4.21 Variation of pH with different RAP contents

Unconfined compression strength tests were conducted on all the soil samples subjected to leaching of 14 cycles to understand the percentage of retained strength variation. The percentage of retained strength with different RAP contents is shown in Figure 4.22. From this figure, it is clear that the percentage of retained strength after 14 cycles of leaching is highest for 60R_2C because of its high holding capacity for calcium ions as explained in the above sections. Nevertheless, all other specimens provided similar findings such as high retained strength. The percentage retained strengths for various blended RAP contents is shown in Table 4.7.

Table 4.7 Variation of strength versus RAP content

RAP content	**UCS strengths (psi)**		**% retained strength after 14 leachate cycles**
	0 cycles	**14 cycles**	
50	300	254	85
60	320	289	90
75	185	162	88
100	220	185	84

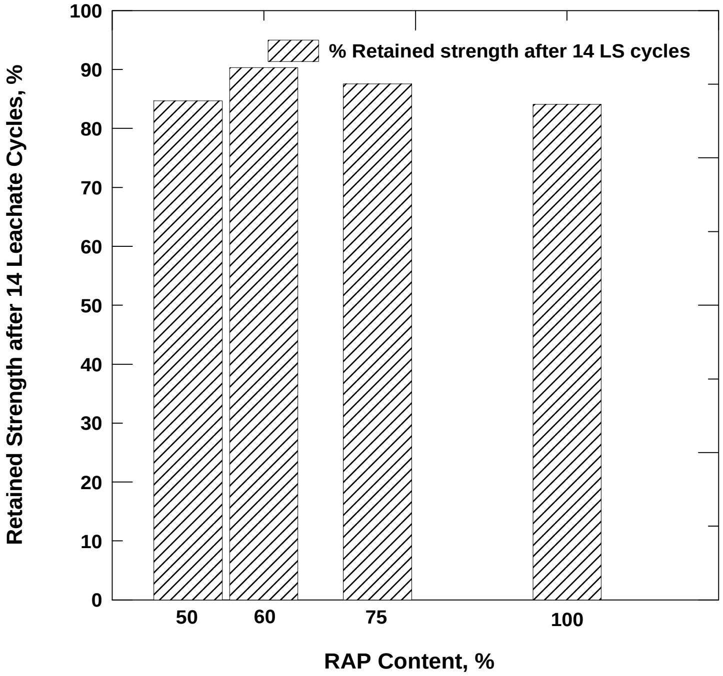


Figure 4.22 Comparison of retained strength versus RAP content after leachate studies

An attempt is made here to correlate the laboratory leachate studies with rainfall infiltration in the field to know the number of years the pavement is expected to performing well. Again this is a preliminary type analysis, nevertheless, it will provide input on whether leaching should be termed as a concern or not. It is assumed in this analysis that water table is at a considerable depth below the road surface. For this purpose a similar analysis conducted by Chittoori, 2008 was followed. The total rainfall data was taken as 30 inches per year as per the Texas precipitation records. The infiltration rate was taken as 41% (Range 33-50%) of the total rainfall in a year for asphalt pavement (Cedergren et al. 1973). The detailed procedure for calculating the number of years replicated in the field is displayed in Figure 4.22. Table 4.8 depicts the number of years of field corresponds to the number of cycles represented in the laboratory.

Field Infiltration:

Average Annual Rainfall in Texas (AAR) = 30 in. (Texas Precipitation Records)

Approximate Percentage of Infiltration (%I) = 41% (Cedergren et al. 1973)

Rainfall infiltered per year (I_{field}) = AAR*%I = 12.3 in.

Laboratory Infiltration:

Diameter of laboratory sample (D) = 6.0 in.

Cross sectional area (A) = $A = \frac{\pi D^2}{4} = 182.41 \text{ cm}^2$

Volume of water infiltrated for 1 pore volume I_L = 270.37 ml

Volume of water infiltrated for 14 pore volumes $I_{14} = I_L*14 = 3785.18 \text{ cm}^3$

Converting volume to head of water $I_{Lab} = I_{14}/A$ = 20.75 in.

# of years replicated in the lab n = I_{Lab}/ I_{field} = 1.68 years

Figure 4.23 Procedure to correlate laboratory leachate studies to field infiltration

Table 4.8 Number of years replicated in field for various RAP mixes

Mix Type	**% retained strength after 14 leachate cycles**	**# of years replicated in field**
50R_2C	84	1.79
60R_0C	71	2.13
60R_2C	90	1.68
75R_2C	88	2.15
100R_6C	85	2.96

4.3.3 Mineralogical tests

The mineralogical tests were conducted on all RAP mixes to study the minerals formed during the blending of RAP and base materials. Also, they were used to investigate whether any pozzolanic compounds were formed during the chemical stabilization of RAP mixes. The mineralogical tests conducted involve X-ray diffraction analysis and Scanning Electron Microscope studies with Electron Dispersive System (EDS). The procedures for carrying out these tests were clearly explained in sections 3.5.1 and 3.5.2 respectively.

4.3.3.1 X-Ray Diffraction Analysis

In XRD, the powdered sample was placed in a sample holder as shown in Figure 3.12 and inserted into X-ray difrractometer to scan the elements with an input voltage of 40 kV and a current of 30 mA. A step scan mode was selected with a step size of 0.02^0 of 2-theta angle and a dwell time of 2 sec were applied. The plot drawn between 2-theta angle and number of counts gives some peaks between the selected scan ranges indicating the presence of specific minerals (refer Figure 4.24). These peaks were matched with the powder diffraction files (PDF) of thousands of minerals in software called JADE 5 to determine the minerals.

Unfortunately, there were no XRD studies conducted till now on recycled asphalt pavement materials to identify the presence of predetermined minerals. Several groups of minerals like polymers, zeolites, cementitious compounds and others were searched in the software to match the peaks of the minerals present in each group with the peaks of required RAP mix. The minerals determined using this process were considered to be found only in traces in the mixes because the intensities with which these peaks matched were less than 30% of the original peaks. Some of the important compounds formed during the cement and fly ash stabilization of RAP mixes were Aluminum oxide (Al_2O_3), Aluminum Calcium (Al_4Ca), Silicon oxide (SiO_2), Calcium Aluminum Borate ($CaAl_2B_2O_7$) and other several minerals which show partial nature of cementing compounds.

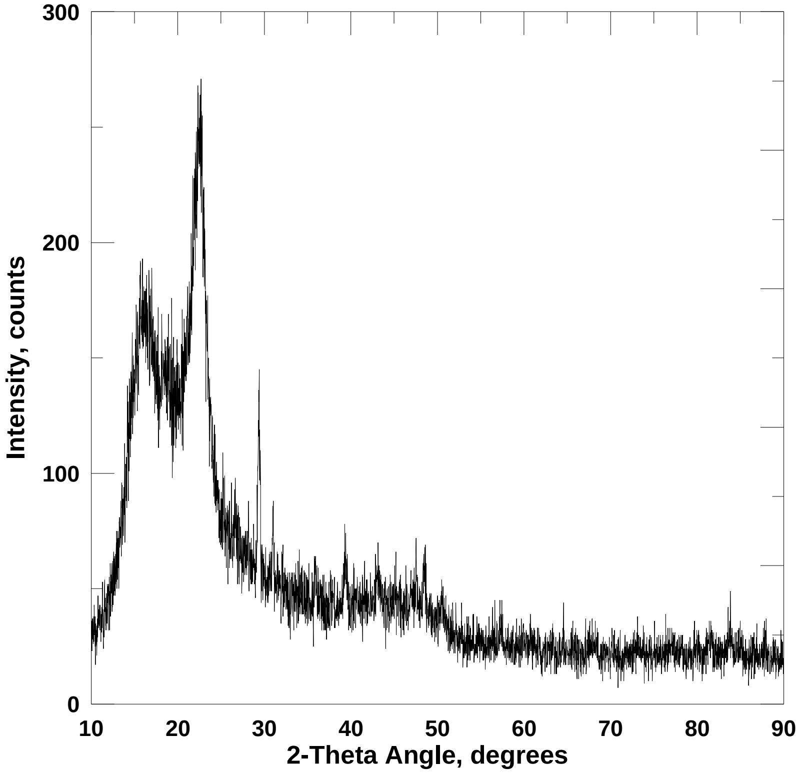


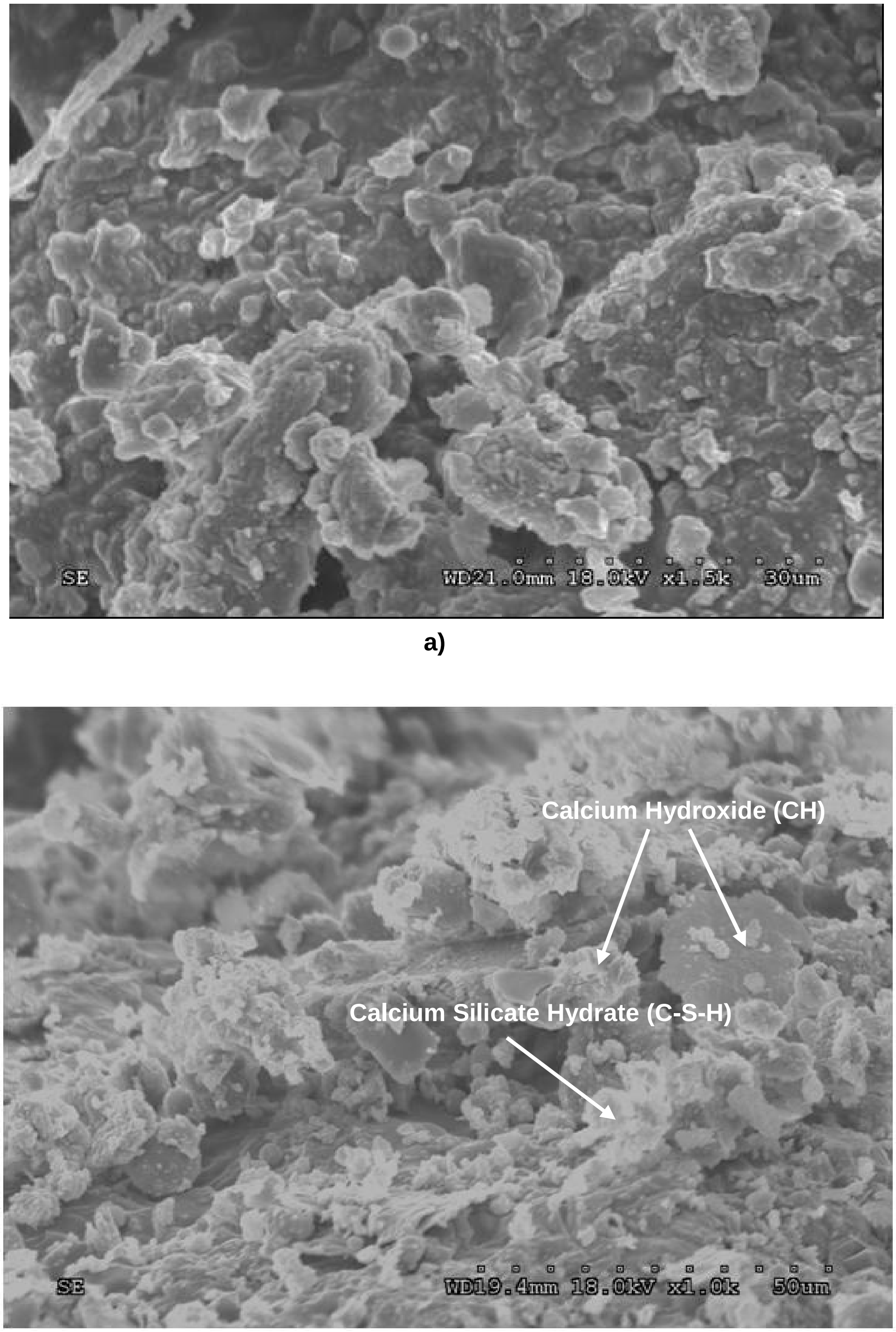
Figure 4.24 Typical XRD plot for 60R_2C RAP mix

4.3.3.2 Scanning Electron Microscope studies (SEM)

The other type of mineralogical tests conducted in this research was scanning electron microscope with the capability to conduct Electron dispersive system (EDS). The main purpose of conducting SEM is to observe the different patterns formed due to chemical stabilization in blended RAP mixes. While EDS provides the quantitative spot chemical composition for the particular area selected in the SEM pattern. The EDS analysis is performed in the similar pattern as in XRD studies because in this test also a high range of X-ray beam was made to fall on the selected area in the SEM picture to scan the sample and corresponding peaks were obtained. These peaks were then matched with peaks of elements present in the periodic table in the computer software (Revolution) to identify the presence of particular element. A detailed procedure along with pictures showing test set up and sample holder was explained in chapter 3 (section 3.5.2).

A tiny sample taken from the powdered RAP mixes was coated with silver before carrying out SEM because of its low conductivity. 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 set up were altered until a more refined picture is observed. The SEM pictures for all the RAP mixes considered are shown in Figures 4.25 to 4.28.

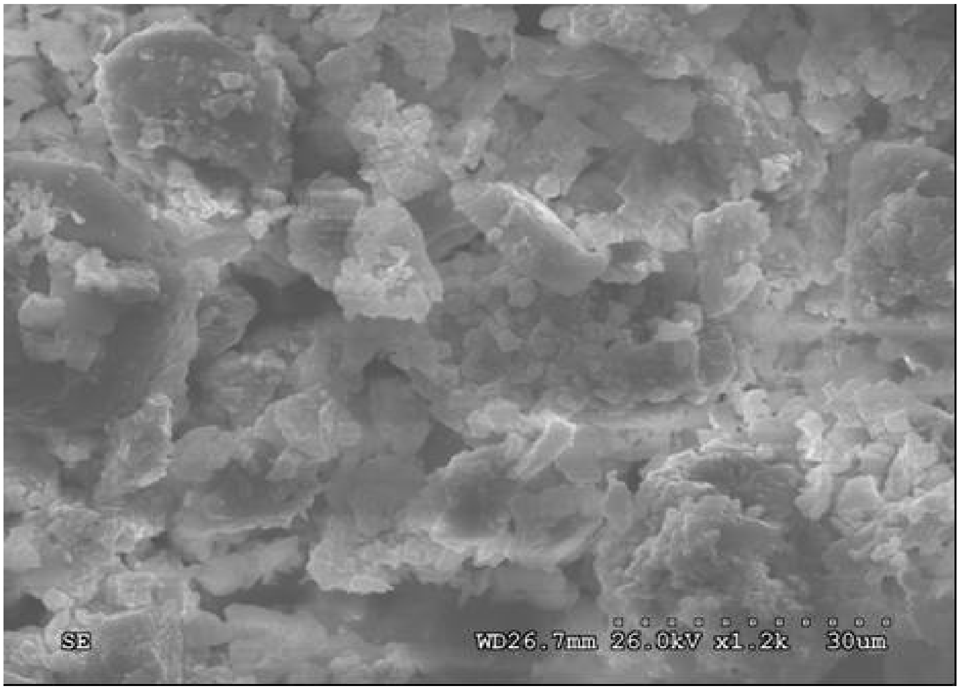
The cementing compounds detected around the aggregate samples include fibrous and long needle shaped compounds known as ettringite minerals. The other cementing compounds observed were calcium silicate hydrate gel (C-S-H) which is in bundles and calcium hydroxide (CH) crystals. These cementing compounds formed due to stabilization of RAP mixtures indicate the strength enhancements as per chemical treatments (Stutzman, 2001). Also, the EDS analysis performed on untreated and treated 100%RAP are shown in Figures 4.29 and 4.30 respectively. It should be noted from these figures that the percentage of calcium increased after the chemical treatment. In addition, the presence of oxygen, silicon and aluminum elements in traces proved that the pozzalonic reactions are occurring between the asphalt and cement particles.



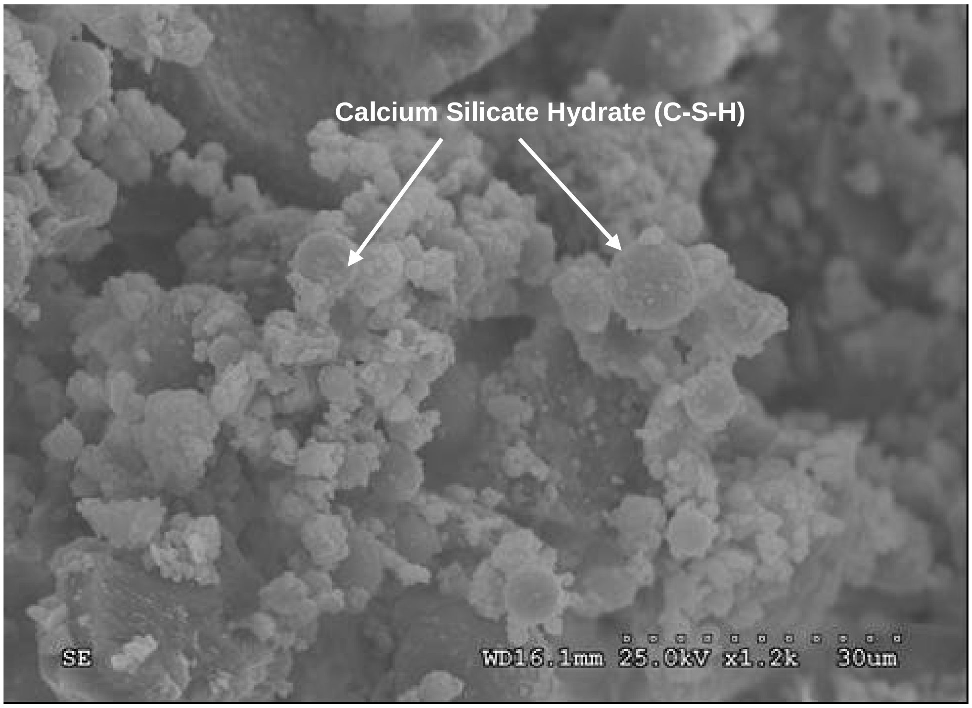
a)

b)

Figure 25 SEM pictures of a) 100R_0C b) 100R_6C

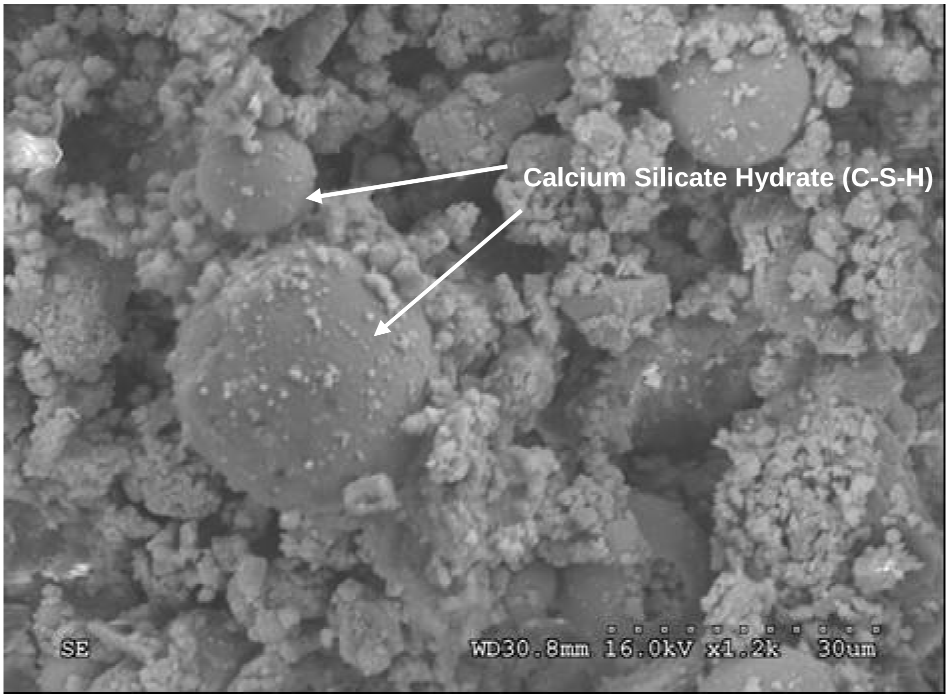


a)

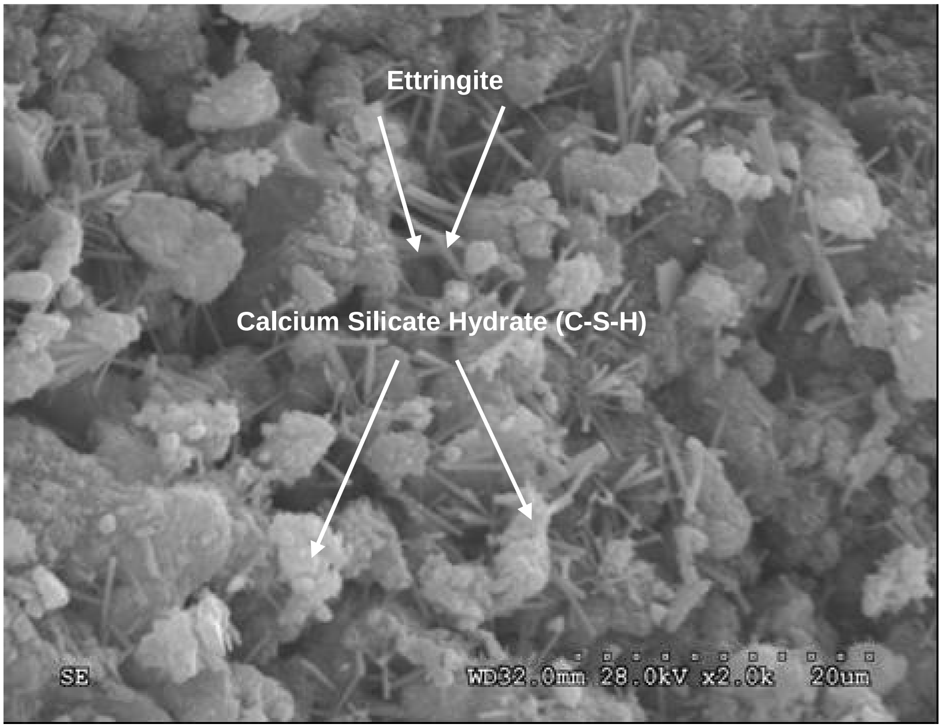


b)

Figure 26 SEM pictures of a) 60R_0C b) 60R_2C



a)



b)

Figure 27 SEM pictures of a) 60R_7F b) 75R_2C

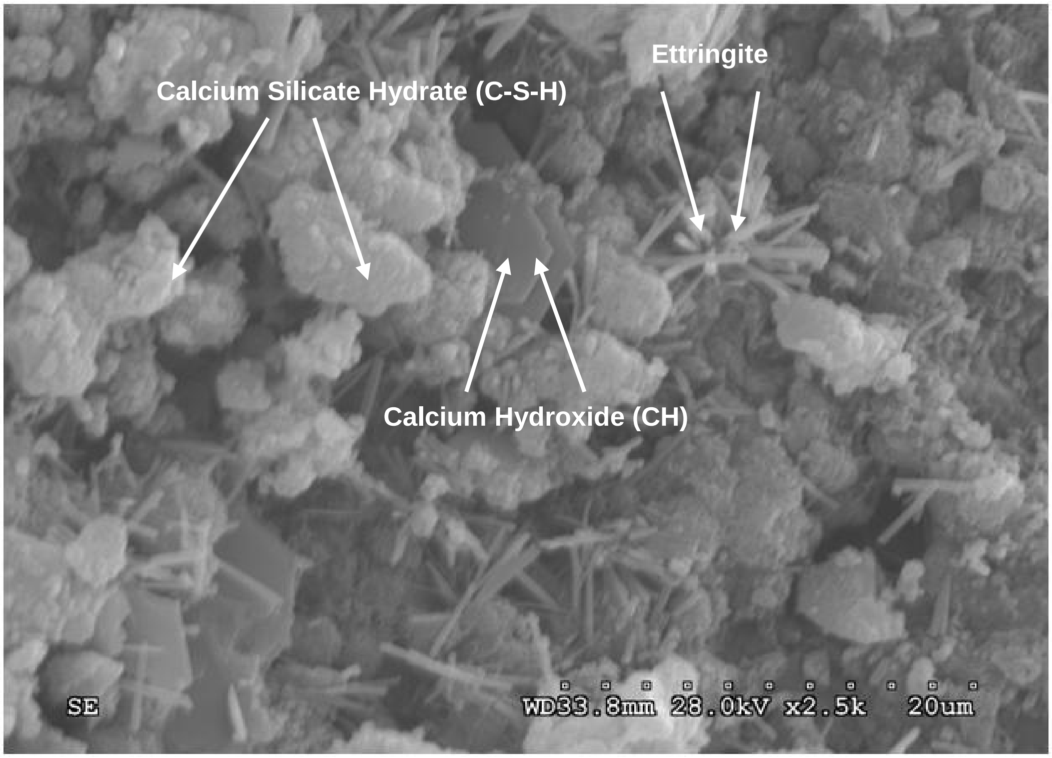


Figure 4.28 SEM picture of 50R_2C RAP mix

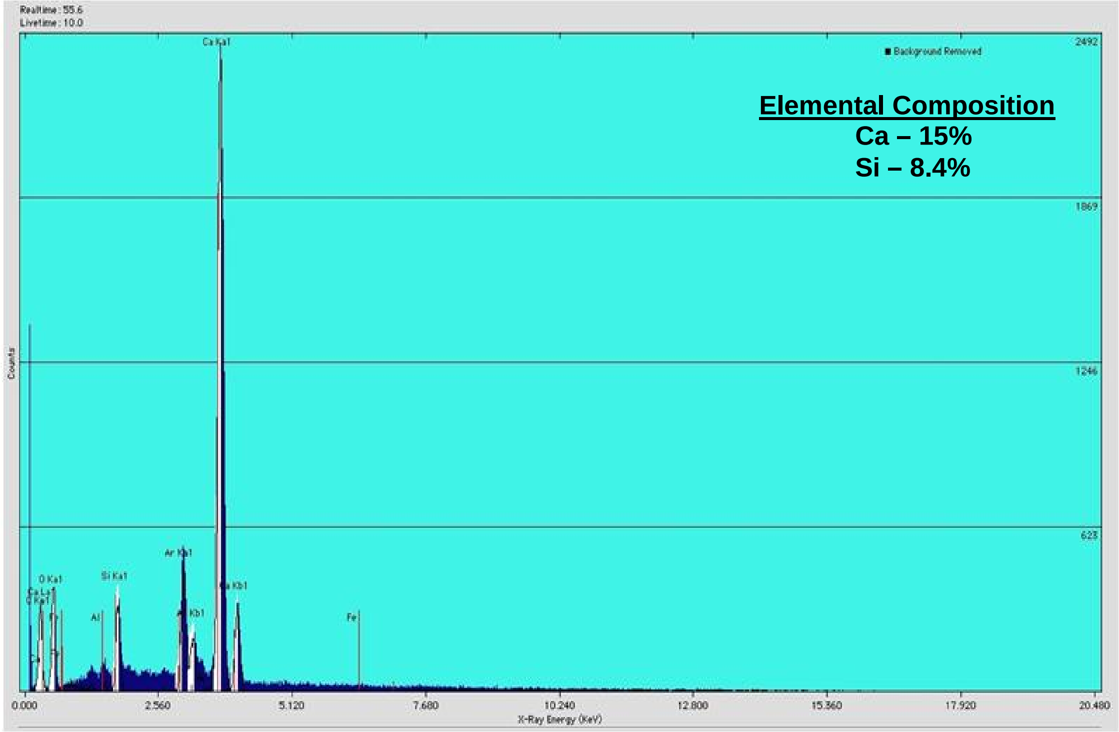


Figure 29 EDS picture of 100R_0C

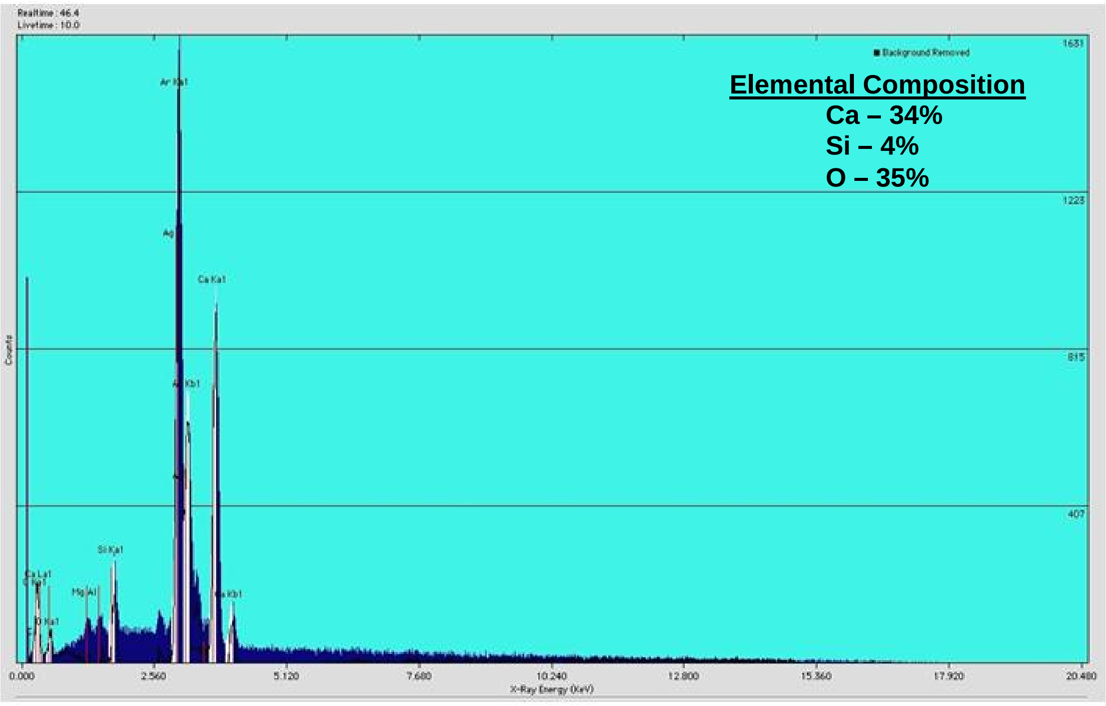


Figure 4.30 EDS picture of 100R_6C

4.4 Summary

In this chapter, the basic properties of the RAP mixes are presented for both treated and untreated samples with respect to different RAP contents. The blended RAP mixes were designed using the UCS strength as criterion and these mixes were subjected to durability studies for studying the long-term performance of each mix. The durability studies conducted were wetting/drying and leachate studies for 14 cycles. The results are analyzed and the best performing mix was selected based on best performance. Mineralogical tests consisting of X-ray diffraction and scanning electron microscope analysis were performed to identify the minerals formed.

CHAPTER 5

DURABILTIY STUDIES ON FORT WORTH RAP

5.1 Introduction

In this chapter the test results obtained for Fort Worth RAP mixes are presented in detail. The tests conducted include basic engineering tests and durability studies along with mineralogical tests. The durability studies were performed to study the behavior of stabilized RAP mixes in the long run by subjecting them to diverse weather conditions occurring in north Texas. In addition, rainfall infiltration was replicated in the laboratory by using leachate studies. Mineralogical tests were also performed to identify the minerals formed in the stabilized RAP specimens and examine the morphology in the blended mix along with chemical compositions. Based on the information from the test results obtained on several trial mixes of El Paso RAP (outlined in Chapter 4), only three mixes with different RAP/Base compositions were considered and studied for Fort Worth RAP to identify the best performing mix in the long run.

5.2 Fundamental Properties of the test materials

The main purpose of performing basic engineering tests was to understand the material characterization and its behavior. The RAP and base materials obtained from Fort Worth district were first subjected to basic tests to classify them and then determine the optimum moisture content and maximum dry density values from compaction tests. Primarily, RAP was blended with conventional base aggregate to design the mixes which are later studied in durability tests. This design of a mix was based on ‘Item 276’ of TxDOT procedure require a UCS strength of 300 psi after seven days of curing for the samples treated with cement.

The sieve analysis was performed using Tex-110E procedure on both RAP and base materials. The gradation obtained for both RAP and base is shown in Table 5.1 and the gradation curves are shown in Figure 5.1. Based on this data using American Association of

State Highway and Transportation Officials (AASHTO) classification both RAP and the base material were classified as A-1-a and are termed as granular materials with less than 30% passing number 40 sieve.

Table 5.1 Gradation for Fort Worth RAP and Base materials

Sieve Size	Percent Passing (%)	
	RAP	Base
1 3/4"	98.48	100.00
1"	92.10	87.47
7/8"	88.54	79.53
3/8"	69.80	52.28
#4	38.37	36.39
#40	7.10	10.76
#100	1.13	6.13
#200	0.58	3.68
Pan(-200)	0.00	0.00

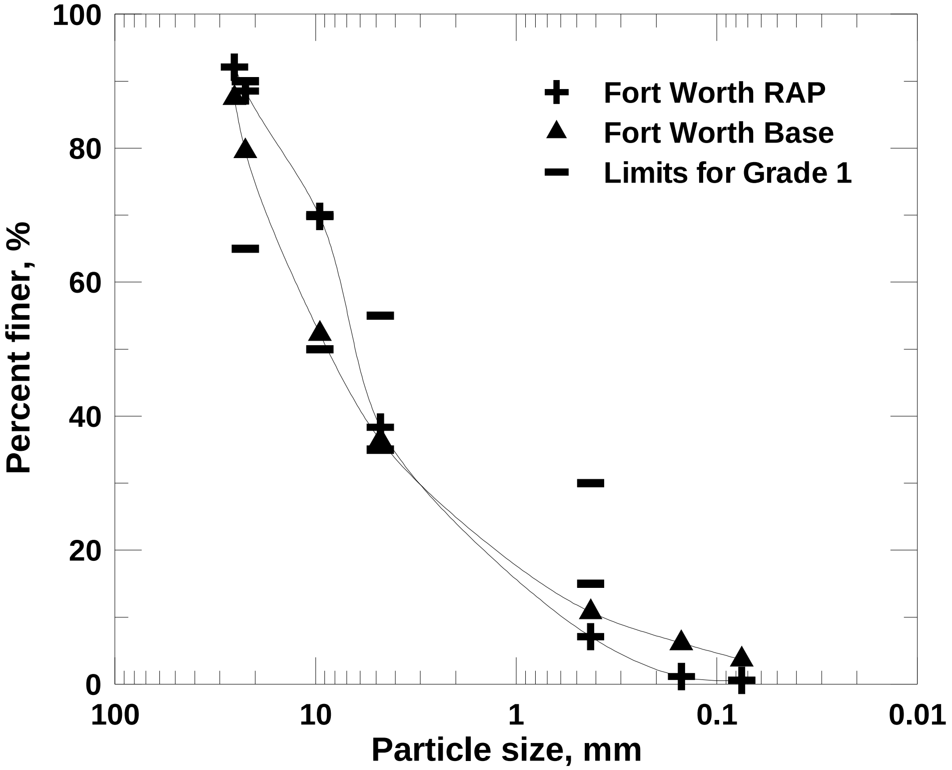


Figure 5.1 Particle size distribution for Fort Worth RAP and Base

The specific gravity for the RAP material was determined to be 2.374 using the procedure TxDOT procedure Tex 227-F. The procedure for performing this test was explained in chapter 3. Depending upon the minimum UCS strength criteria the RAP mixes were designed and these mixes for Fort Worth RAP are listed in Table 5.2 along with their respective notations.

Table 5.2 Design mixes for Fort Worth RAP

Mix Type	**Notation**
100% RAP (4%Cement)	100R_4C
75% RAP+25% Base (4%Cement)	75R_4C
50%RAP+ 50% Base (2%Cement)	50R_ 2C

The optimum moisture content (OMC) and maximum dry density values for both untreated and treated samples were determined using Tex 114-E procedure. The only difference which was made in this procedure was instead of 25 blows a total of 50 blows per layer was required to compact the specimen uniformly. Because of the enough percentage of fines in the RAP and base materials, the OMC values increased with increase in RAP content for both untreated and treated samples. A typical moisture density curve for 100R_4C is shown in Figure 5.2. A table showing these changes is presented in Table 5.3 and shown graphically in Figure 5.3.

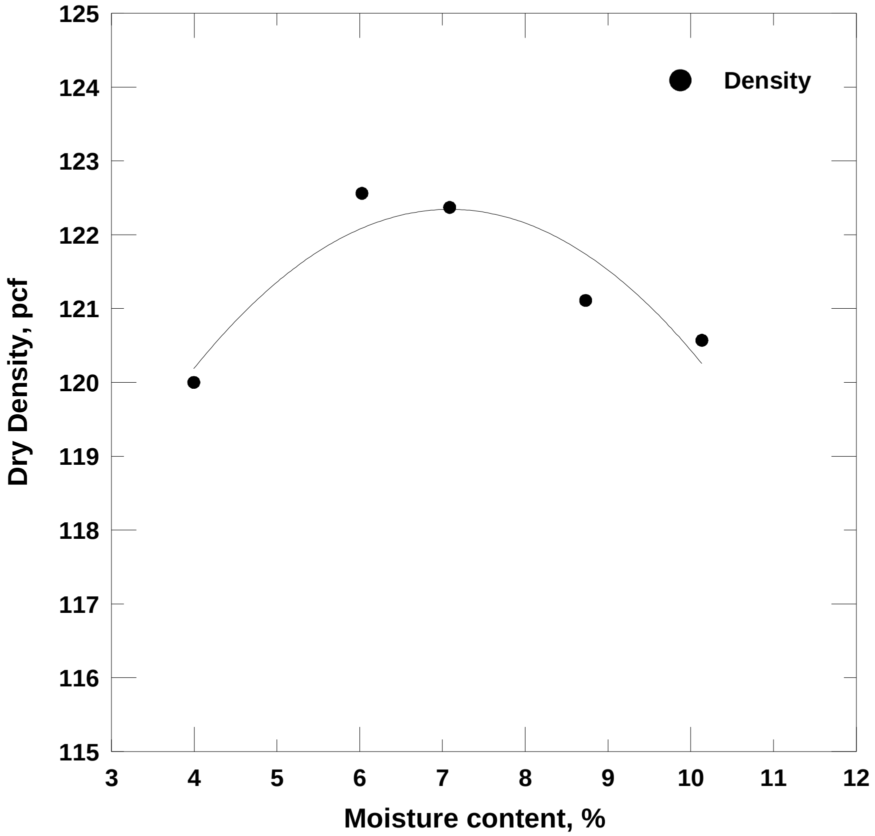


Figure 5.2 Moisture Density Curve for 100R_4C

Table 5.3 Effect of RAP content on OMC

RAP Content	**OMC (%)**	
	Untreated	**Cement**
50	4.8	5.5
75	5.2	6.2
100	6	6.7

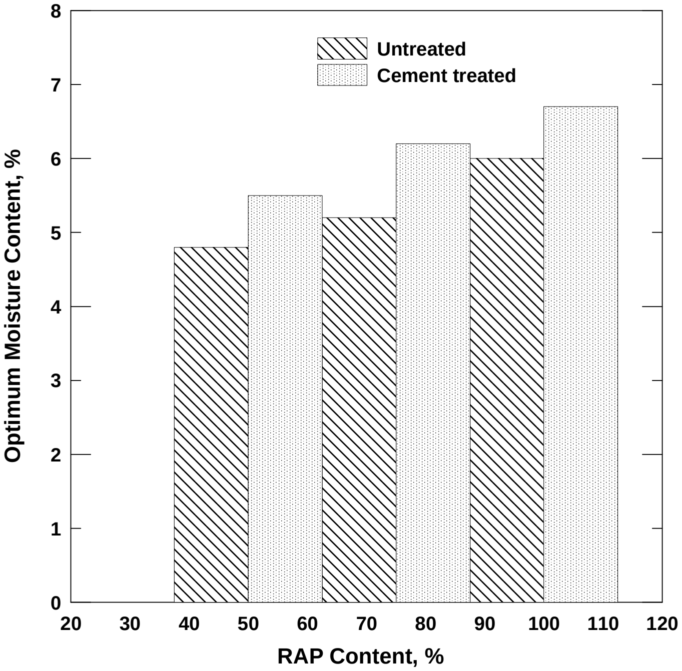


Figure 5.3 OMC for Untreated and Treated RAP mixes

The modified compaction test on blended RAP base mixes yielded the following results shown in Table 5.4. The dry density values decreased with an increase in RAP content which is attributed to reduction in percentage of base aggregate. In addition, for both untreated and treated samples, the MDD values increased due to the addition of cement stabilizer. These changes of MDD values can be seen in Figure 5.4.

Table 5.4 Effect of RAP content on MDD

RAP Content	**MDD (pcf)**	
	Untreated	**Cement**
50	125.6	127.3
75	121.7	126.4
100	115.9	120.2

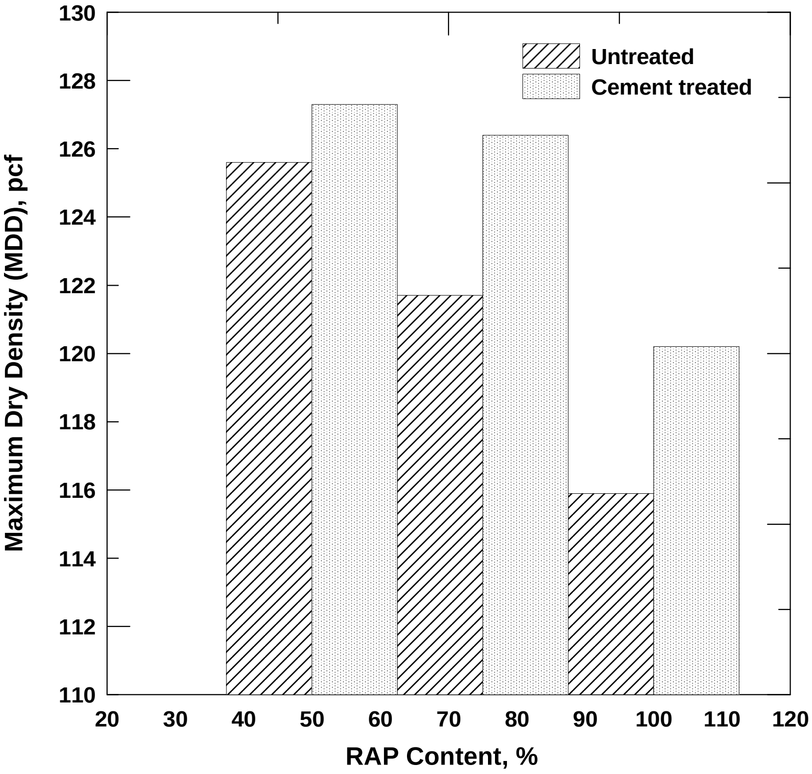


Figure 5.4 MDD for Untreated and Treated RAP mixes

5.3 Engineering Properties of Fort Worth RAP

Engineering properties studied includes unconfined compression strength and durability studies. The UCS strength is used to design a mix based on targeted strength after seven days of curing and durability studies gives an idea about the performance of the mix in the long run. Portland cement is the only stabilizer used for the RAP mixes because the fly ash stabilizer could not give enough strength to meet the minimum strength criteria set by the Item 276.

5.3.1 Unconfined Compression Strength (UCS) Tests for Untreated and Treated RAP mixes

As explained earlier, UCS is an important design parameter for adding sufficient amount of cement to obtain a target UCS of 300 psi. A combination of three RAP mixes with percentages varying from 50, 75 and 100% were used to design the mixes. These mixes were blended with corresponding base material and stabilized with different percentages of cement content to arrive at the target UCS strength.

The samples prepared as per Section 3.4.1 were cured for seven days in a moisture room before subjecting them to UCS test. The values obtained for both untreated and treated samples were listed in Table 5.5. The treated samples presented in this table were mixed with different percentages of cement to arrive the required strength. The treatment of 100R and 75R mixes was carried with 4% cement while 50R was mixed with only 2% cement. It can be clearly seen from the table that 100% RAP does not have any strength and hence a representative sample for untreated 100%RAP could not be prepared. On the other hand, when these mixes were treated with cement the strength increase significantly and reached the minimum strength criteria set by Item 276. The 100R_4C mix was considered for durability studies even though it did not meet the strength requirement because using 6% cement in the field becomes uneconomical. Also, another important point to be noted from the table is that the low strength for untreated samples can be due to fewer amounts of fine particles and lack of bonding between asphalt and base materials. The variation of strength for untreated and treated samples is presented in Figure 5.5.

Table 5.5 Variation of UCS with chemical treatment

RAP Content	**Unconfined Compression Strength (psi)**	
	Untreated	**Cement treated**
50	62	345
75	17	430
100	0	272

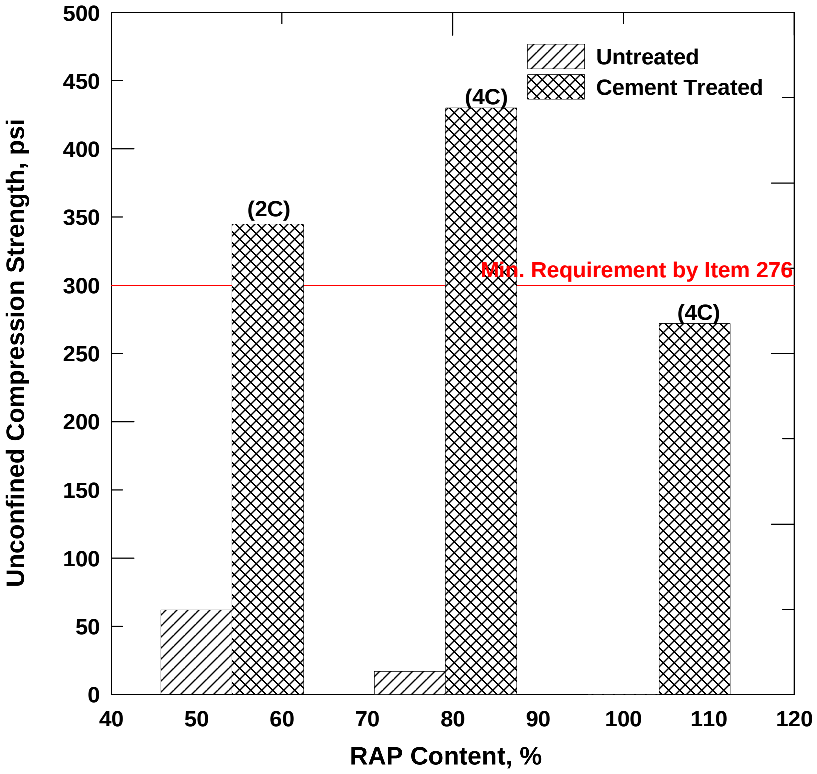


Figure 5.5 UCS for untreated and treated samples

5.3.2 Durability studies

The durability studies were conducted based on the procedure explained in Chapter 3. A total time of 48 hours was needed to complete one cycle of wetting/drying and hence 28 days were required to complete a total of 14 cycles on each RAP mix. The durability studies of RAP mixes also include leachate studies which checks for permanency of stabilizer after certain number of years of moisture leaching/movements in the field. 14 leachate cycles were conducted on RAP mixes to study the variation of calcium ion concentration with number of cycles. At the end of certain cycles of wetting/drying and 14 cycles of leachate cycles UCS tests were performed on RAP mixes to know the retained strength.

5.3.2.1 Wetting/Drying studies

The long-term durability studies of stabilized RAP was studied by conducting wetting/drying cycles to replicate the moisture fluctuations in field during summer and winter seasons. This process is carried out by following the standard ASTM D 559 method. The standard requires the specimen to be soaked in water for 5 hours initially and kept in an oven at 160^0F for 42 hours to complete one full cycle of wet/dry process. The volumetric strain changes taking place during this process was measured in all the three directions to understand the swelling and shrinking characteristics of the blended RAP mixes. After 3, 7 and 14 cycles of wet/dry tests, samples were taken out and subjected to UCS tests to determine the UCS strength with respect to initial UCS. The samples were prepared according to the procedure given in Section 3.4.1. The different types of mixes studied for Fort Worth site can been seen in Figure 5.6 at an initial condition of 0 cycles.

The plot for volumetric strain versus 3 cycles of wetting/drying studies is shown in Figure 5.7. The volumetric strain observed for 75R_4C is less when compared to other two mixes. This change was observed to be nearly 70% with respect to 100R_4C mix and 56% with 50_2C mix. Even though the amount of cement added was 2% more than the 50R_2C this mix shows more durable properties. Also, one more important reason to identify 75R_4C mix as best performing mix is that we can increase the percentage of RAP by 25% just by adding 2% cement more to get a good long-term performing mix. In addition, when it comes to strength criteria the percentage of retained strength for 3 wet/dry cycles were 81%, 96% and 94% corresponding to 100R_4C, 75R_4C and 50R_2C mixes. The comparison of UCS strengths between 0 and 3 wetting/drying cycles is shown in Figure 5.8. And the pictures of samples taken at the end of 3 cycles are shown in Figure 5.9.

a) 100R_4C

b) 75R_4C

c) 50R_2C

Figure 5.6 RAP mixes at initial conditions (0 cycles)

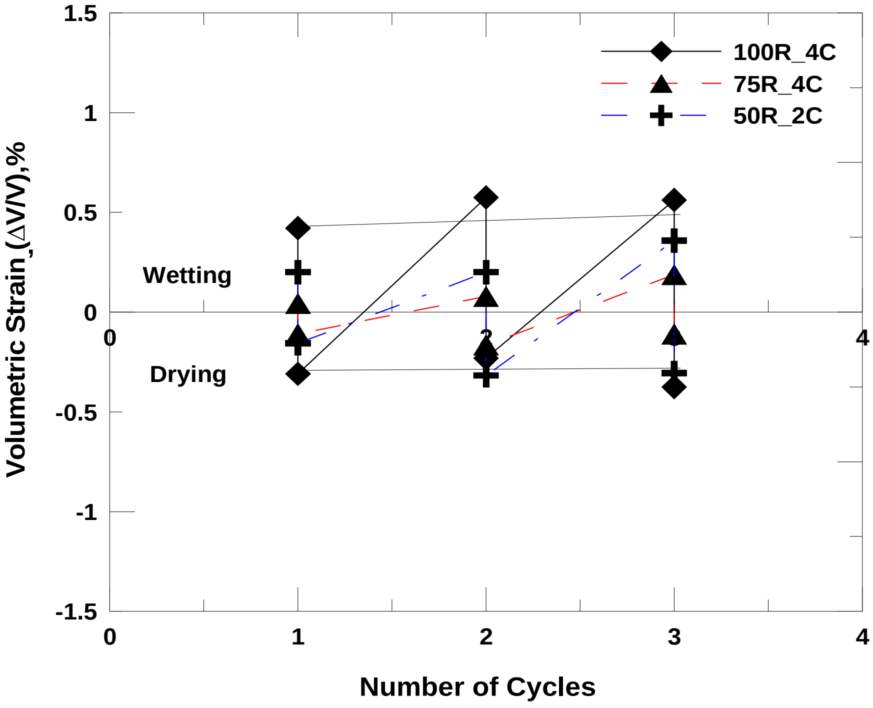


Figure 5.7 Volumetric changes for 3 W/D cycles

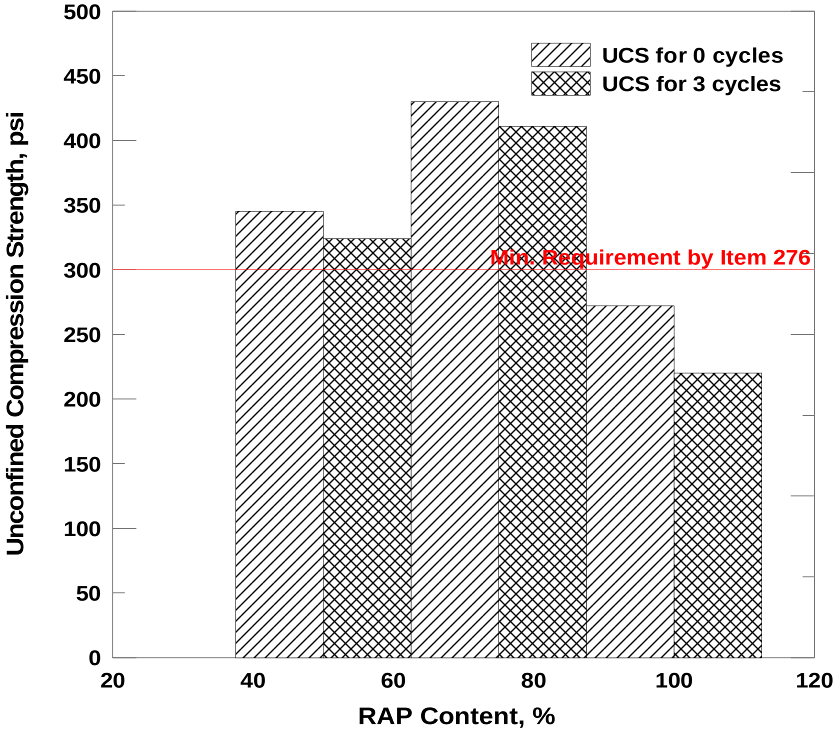
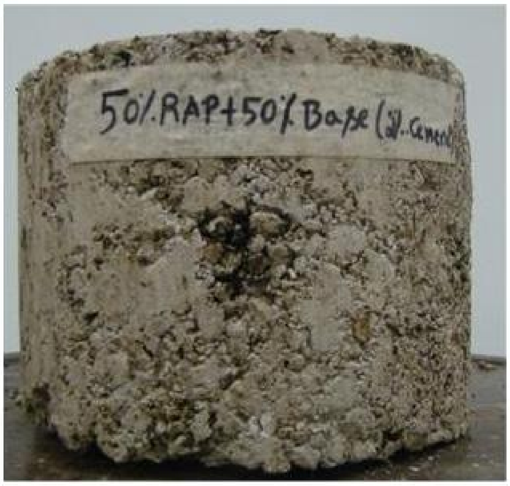


Figure 5.8 UCS values for 0 and 3 W/D cycles

a) 100R_4C

b) 75R_4C



c) 50R_2C

Figure 5.9 RAP mixes at the end of 3 W/D cycles

The blended RAP mixes were subjected to longer periods (7 and 14 cycles) of wetting/drying studies, to determine their performance as a base layer in the long run. By performing wetting/drying cycles for 7 and 14 cycles helps in understanding the volumetric changes taking place, and also deterioration of RAP mixes for extended periods. One more important point to be noted in these tests is that the samples were subjected to adverse climatic conditions which might occur in the region of north Texas. Hence, the behavior of samples in the laboratory can well be correlated with the field conditions. The results obtained for RAP mixes are shown in Figures 5.10 through 5.14 along with pictures taken at the end of 7 and 14 wet/dry cycles.

Figures 5.10 and 5.11 display the volumetric changes occurred during 7 and 14 cycles of wetting/drying studies. These plots clearly show that 75R_4C has the lowest volumetric change in both the cases. This volumetric change kept on reducing as the number of cycles increased because the sample neither absorbed moisture nor released it to swell or shrink. Also, the percentage of retained strength was very low which makes this mix unique from the other two mixes. On the other hand 50R_2C mix showed consistent low volumetric strains for both 7 and 14 cycles. Even though this mix performed well in the case of volumetric strain but when the strength aspect came into picture it decreased well below the required criteria at the end of 14 cycles. The mix 100R_4C had very low UCS strength since initial conditions and it got decreased by nearly 70% at the end of 7 and 14 wet/dry cycles. Hence, based on the findings explained above 75R_4C has been identified to be the best performing mix in the case of wetting/drying studies. A table showing the summary of results from all the wet/dry cycles and UCS tests were presented in Table 5.6.

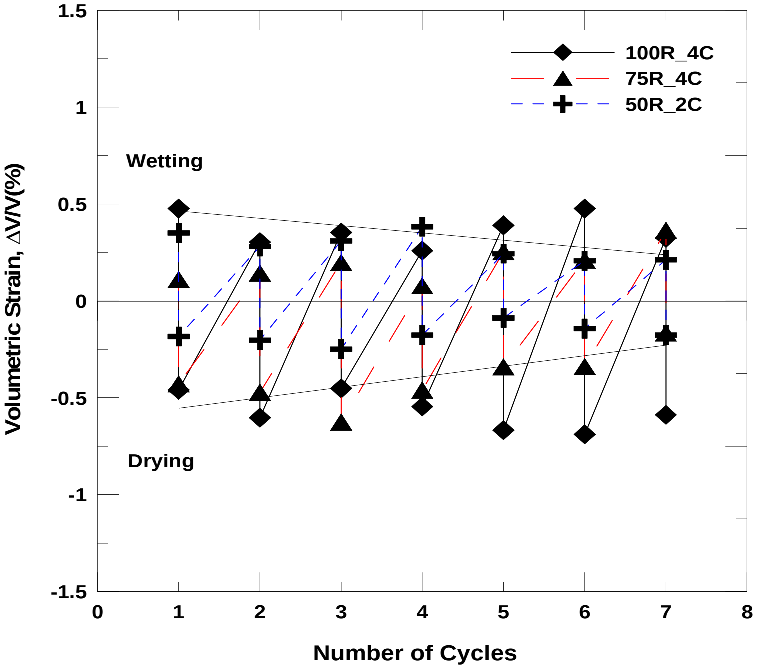


Figure 5.10 Volumetric changes for 7 W/D cycles

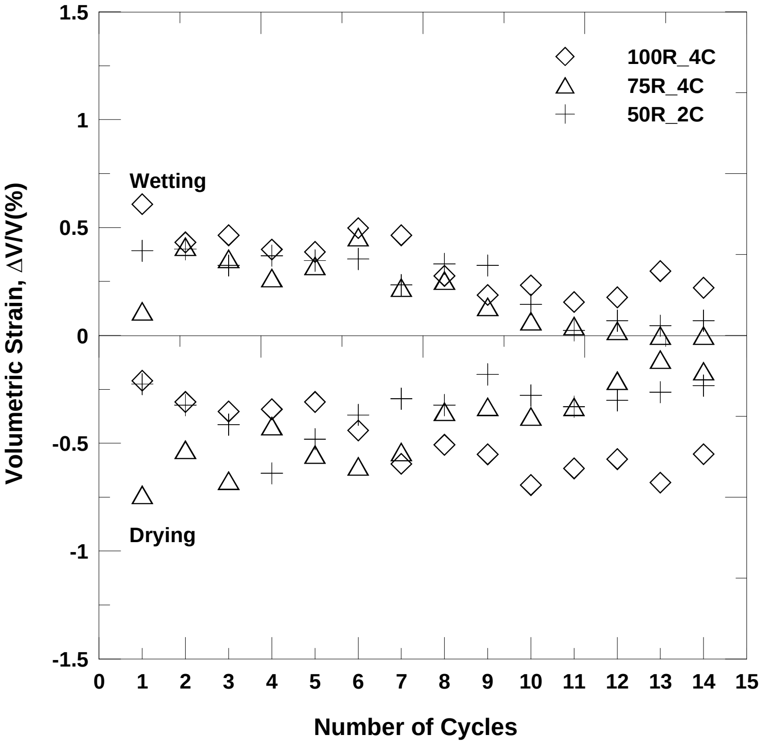


Figure 5.11 Volumetric changes for 14 W/D cycles

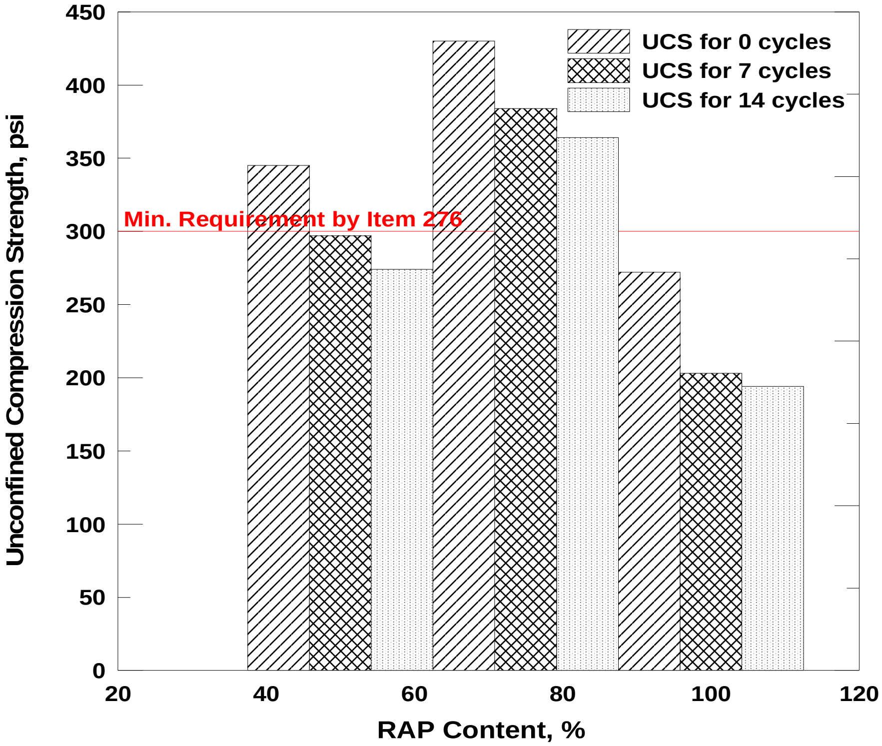


Figure 5.12 Retained UCS strengths after 7 and 14 W/D cycles

a) 100R_4C b) 75R_4C

c) 50R_2C

Figure 5.13 Samples at the end of 7 W/D cycles

a) 100R_4C

b) 75R_4C

c) 50R_2C

Figure 5.14 Samples at the end of 14 W/D cycles

Table 5.6 Summary of Wetting/Drying studies

Mix Type	**# of cycles**	**Total Volumetric change (%)**	**Retained strength (psi)**	**# of 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	0.3	274		

Note: # of cycle's tested-14

5.3.2.2 Leachate Studies

Another type of durability test which is used to study the long-term performance of a RAP mix is leachate studies. In this test the leaching out of chemical stabilizer through the rainfall infiltration or moisture fluctuations were studied. If this leaching process occurs for longer time then the blended RAP mix loses its strength and fails to carry the load coming on to it. The procedure for conducting this test was given in Section 3.4.3 along with a picture of the test set up.

The water sent with 5 psi pressure from the top of the sample is collected at the bottom of the test set up in carboys after certain number of leachate cycles. One leachate cycle is said to be completed when all the pores in the sample were filled with water. After 3, 5, 7, 11 and 14 leachate cycles the leachate collected was tested for changes in pH and calcium concentration. At the end of 14 cycles of leaching the sample was taken out and UCS test was conducted to determine the retained strength.

The test results obtained for leachate studies were presented in Figures 5.15 and 5.16. It can be noted from the Figure 5.15 that even though 75R_4C was stabilized with 4% cement the loss of calcium concentration was very low and this value reached zero at the end of the 14 leachate cycles. This high calcium holding capacity of 75R_4C has also resulted in a higher value of retained strength as shown in Figure 5.17. However, the 100R_4C has been losing considerable amount of calcium ion concentration with the corresponding number of cycles and became weak at the end of the test. This loss of calcium concentration can be attributed to poor bonding between the cement and RAP particles. This analogy can be best described in the mineralogical studies conducted which showed distinctive results for each RAP mix studied. The other blended RAP mix 50R_2C also leached low amount of calcium concentration but the percentage of retained strength was less than that of 75R_4C mix. The 100R_0C mix was studied in order to test check for calcium concentrations in 100% RAP material.

The Figure 5.16 shows the variation of pH in different RAP mixes varying with number of leachate cycles. The pH for 100R_4C mix ranged from 10.9 to 11.4 indicating the presence of calcium ion concentration in the leached water. While for 75R_4C and 50R_2C RAP mixes the pH range is 8.4 to 11 showing the decrease in loss of calcium due to leaching process. After 14 cycles of leachate studies, the samples were subjected to strength tests to determine the remaining strength after the loss of calcium stabilizer. The variation in percentage of retained strength with different RAP contents is displayed in Figure 5.18.

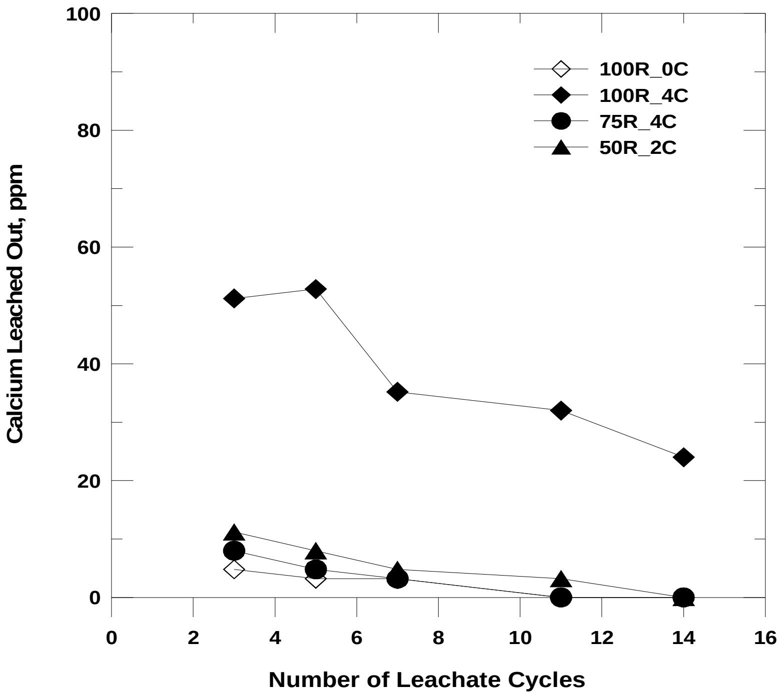


Figure 5.15 Calcium leached out versus number of leachate cycles

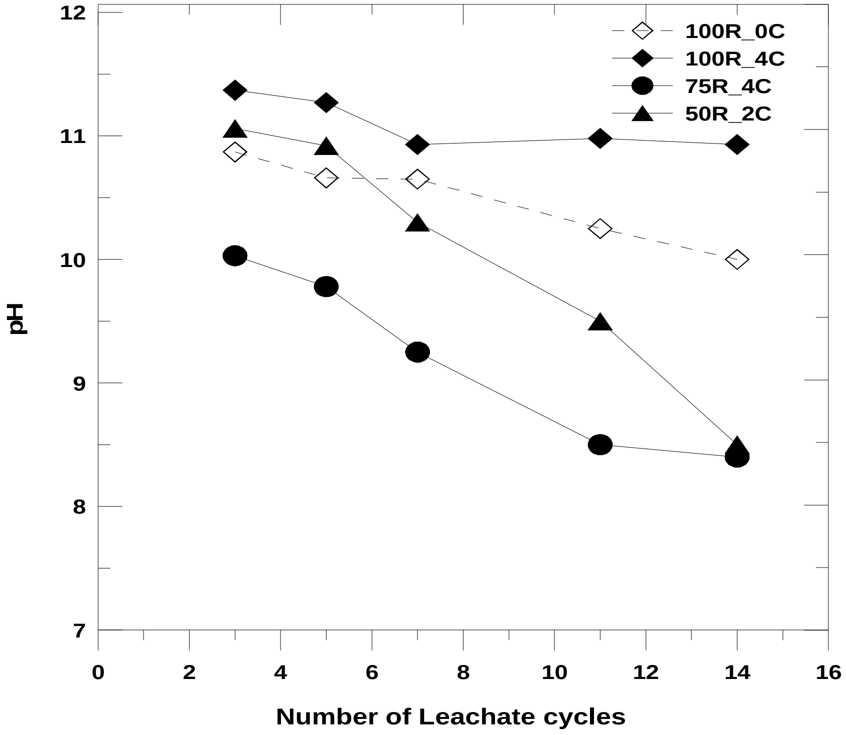


Figure 5.16 Variation of pH with leachate cycles

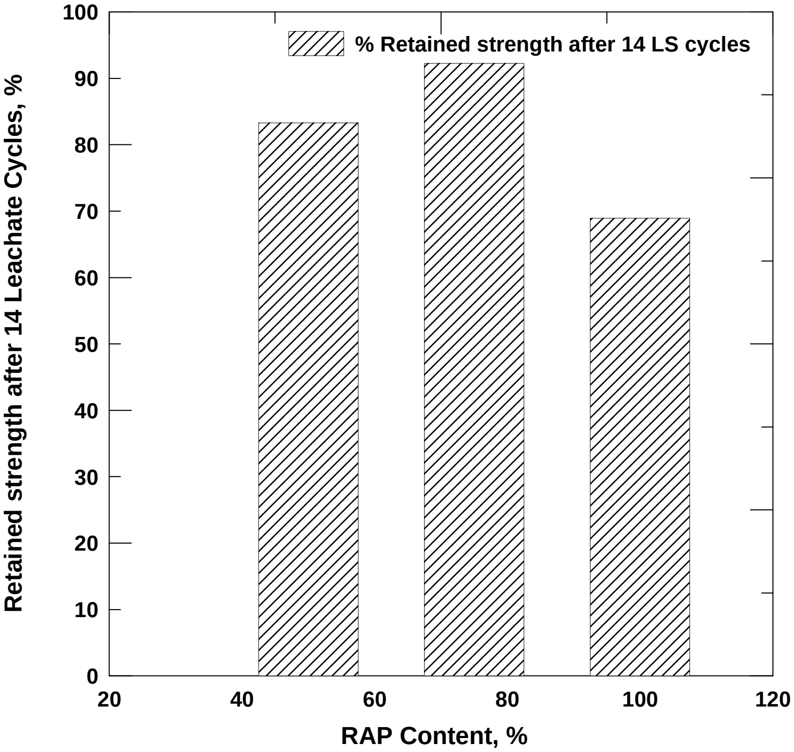


Figure 5.17 Retained strength versus different RAP contents after 14 LS cycles

The leachate cycles studied in the laboratory can be correlated to number of years the pavement is performing successfully in the field. A detailed procedure of calculations performed to get the number of years was explained in Chapter 4 (Figure 4.23). However, the values obtained were completely based on certain assumptions and gives an idea whether leaching should be termed as a problem or not in the field. Table 5.7 lists the number of years replicated in the field with percentage of retained strength for corresponding RAP mixes.

Table 5.7 Summary of Leachate studies

Mix Type	**% retained strength after 14 leachate cycles**	**# of years replicated in field**
50R_2C	83	1.82
75R_4C	92	1.80
100R_4C	69	2.83

5.3.3 Mineralogical tests

Mineralogical tests conducted on RAP mixes include XRD and SEM studies. These tests were performed to examine the chemical bonding formed between RAP and base materials after stabilizing with cement. As these tests are micro analysis special training has to taken before performing these tests. Detailed procedures for conducting these tests were explained in Chapter 3.

5.3.3.1 X-Ray Diffraction Studies

A high range X-ray beam was made to fall on the powdered sample present in the holder initially and these rays were reflected back at certain angles called 2-theta. This reflection of rays were converted to digitized signals and plotted in computer software between 2-theta and intensity. The intensities with which the beams are reflected vary between each mineral found in the sample. Hence, these intensity peaks obtained were matched with predetermined powder diffraction files (PDF) of thousands of minerals in software called JADE 5 to identify the presence of particular mineral.

The main purpose of conducting X-ray diffraction analysis on RAP mixes is to check for the formation of any pozzolanic compounds due to cement stabilization. After searching several mineral data bases in the software, traces of Silicon oxide (SiO_2), Aluminum oxide (Al_2O_3), Calcium oxide (Cao) and other important mineral peaks were detected in all the treated RAP mixes. The presence of some chromium compounds were also observed in this test. All the minerals identified for the Fort Worth RAP mixes show partial nature of pozzolanic action. A typical plot of 2-theta versus intensity obtained for 75R_4C mix is shown in Figure 5.18.

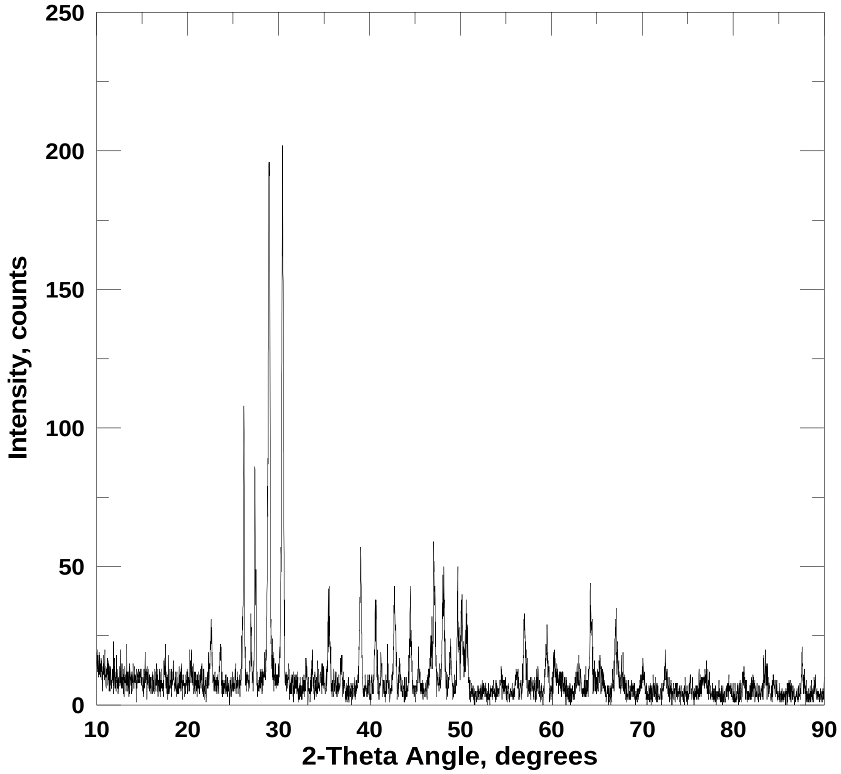


Figure 5.18 XRD plot for 75R_4C mix

5.3.3.2 Scanning Electron Microscope studies (SEM)

The scanning electron microscope 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 the components in the RAP mixes. The magnifications and voltages in the test setup are altered to get a clear digital image. The process for conducting this test was given in Section 3.5.2.

The SEM pictures taken for the RAP mixes shown in Figures 5.19, 5.20 and 5.21 clearly depicts the fibrous compounds and needle shaped compounds indicating the formation of cementing compounds. It was reported in the literature that if these kinds of shapes were observed in the SEM pictures then it signifies that chemical stabilization had occurred in the sample. Also, Energy Dispersive System (EDS) studies were conducted on the same sample on which SEM was performed to quantify the elemental composition at a particular area. The analysis of EDS gave some important elements indicating the stabilization process of blended RAP mixes. These elements include Chromium, Calcium, Beryllium, Aluminum, Silicon and Oxygen.

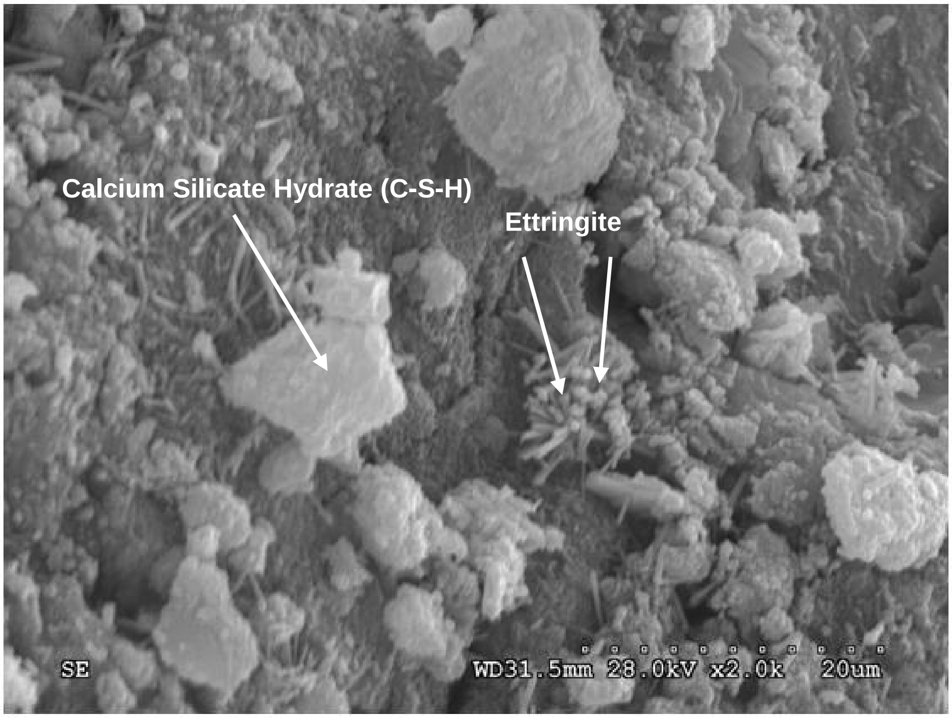


Figure 19 SEM picture of 100R_4C RAP mix

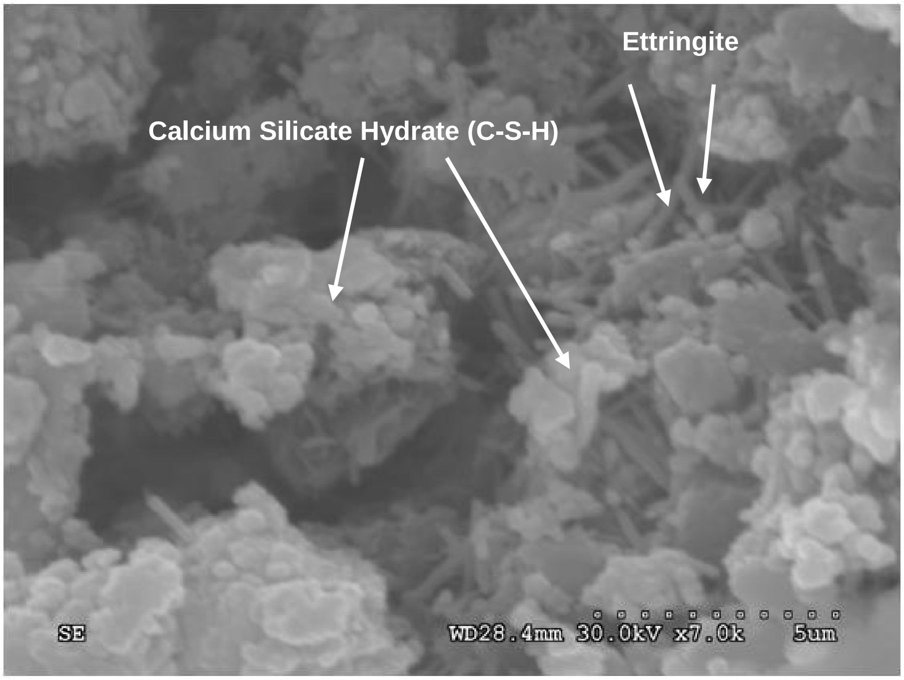


Figure 20 SEM picture of 75R_4C RAP mix

Figure 5.21 SEM picture of 50R_2C RAP mix

5.4 Summary

In this chapter the results obtained from basic tests conducted on Fort Worth RAP and base materials were presented. The design of RAP mixes were carried out based on the minimum UCS strength criteria. Then the analysis of both wetting/drying and leachate studies were carried out to study the long-term performance of the mixes. Based on the durability studies conducted on three types of RAP mixes the one with 75% RAP material stabilized with 4% cement was recognized to be the best long-term performing mix. At last mineralogical tests were presented to show that chemical stabilization of the RAP mixes was successful.

CHAPTER 6

DURABILTIY STUDIES ON CHILDRESS RAP

6.1 Introduction

In this chapter the results on the Reclaimed Asphalt Pavement (RAP) materials collected from Childress district of Texas are discussed in detail. The results obtained from both basic and engineering tests on blended RAP-base mixes were analyzed to propose an effective RAP mix to be implemented in the field conditions. In order to utilize the maximum percentage of RAP and achieve higher strength RAP is blended with locally available base material in Childress district and then stabilized with chemical stabilizers such as cement and fly ash. For this site, only three mixes were studied with varying percentages of RAP because a more polished idea was gained after studying the results from previous two chapters.

6.2 Materials Characterization

The material characterization includes determination of particle size distribution, specific gravity, optimum moisture content and maximum dry density values. After determining the basic properties for both RAP and base materials collected from Childress district each mix was designed by blending RAP with the base aggregates. The main objective of this research is to use the maximum percentage of RAP in the mix design and reduce the use of natural aggregates in the base layer. Hence, the mixes with less than 50%RAP was not considered in this study.

The particle size distribution was conducted based on Tex-110E procedure and the results were presented in Table 6.1 and depicted in Figure 6.1 visually for both RAP and base materials. Both RAP and base materials are classified as A-1-a granular materials according to AASHTO soil classification. Also, according to AASHTO standards these materials are rated to be excellent for using them in subgrade layers in pavement construction.

Table 6.1 Particle size distribution for Childress RAP and Childress base

Sieve Size	Percent Passing (%)	
	RAP	Base
1 3/4"	96.7	100.0
1"	90.9	99.6
7/8"	88.9	98.2
3/8"	68.5	46.6
#4	40.0	38.0
#40	11.1	15.5
#100	2.2	3.8
#200	0.3	1.0
Pan(-200)	0.00	0.00

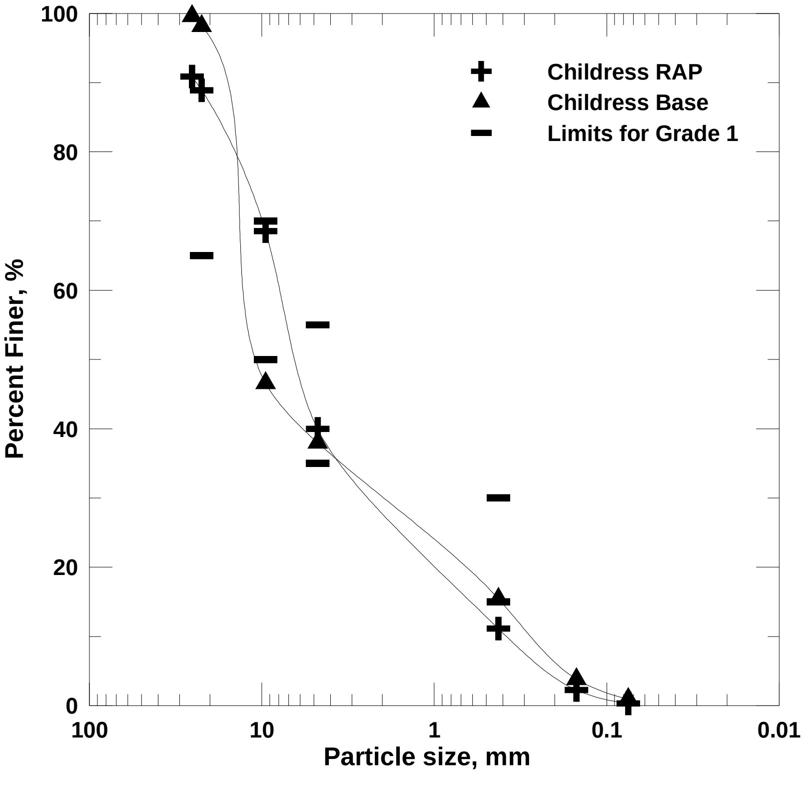


Figure 6.1 Gradation for Childress RAP and Childress Base

The procedure outlined in section 3.4 was closely followed to conduct the specific gravity test on the RAP material. The specific gravity value by this process was determined to be 2.27.

For designing the RAP mixes the blending process was carried out with different percentages of RAP and base materials added with various percentages of cement content to achieve the minimum UCS strength criteria (300 psi). The three reliable mixes found with this process were listed in Table 6.2.

Table 6.2 Design mixes for Childress RAP

Mix Type	**Notation**
100% RAP (4% Cement)	100R_4C
75% RAP+25% Base (4% Cement)	75R_4C
50%RAP+ 50% Base (4% Cement)	50R_ 4C

The OMC and MDD values associated with each RAP-base blend are presented in Table 6.3. Regarding OMC, less water is needed to achieve optimum moisture content at higher RAP percentages because a smaller amount of water is absorbed by the asphalt particles. This reduction of OMC is observed for both untreated and treated samples as shown in Figure 6.2. The reason for decrease of MDD values with increase in RAP can be due to the higher specific gravity of base material than RAP. Moreover, these MDD values decreased with increase in RAP content for samples treated with cement which validates the above statement. The variation of MDD values with different RAP contents for untreated and treated samples is presented in Figure 6.3.

Table 6.3 Moisture-Density data for untreated and treated samples

RAP Content	**OMC (%)**		**MDD (pcf)**	
	Untreated	**Cement**	**Untreated**	**Cement**
50	6.5	6.7	123.2	133.7
75	6.5	6.5	130	131.2
100	5.5	6.1	123.2	125.5

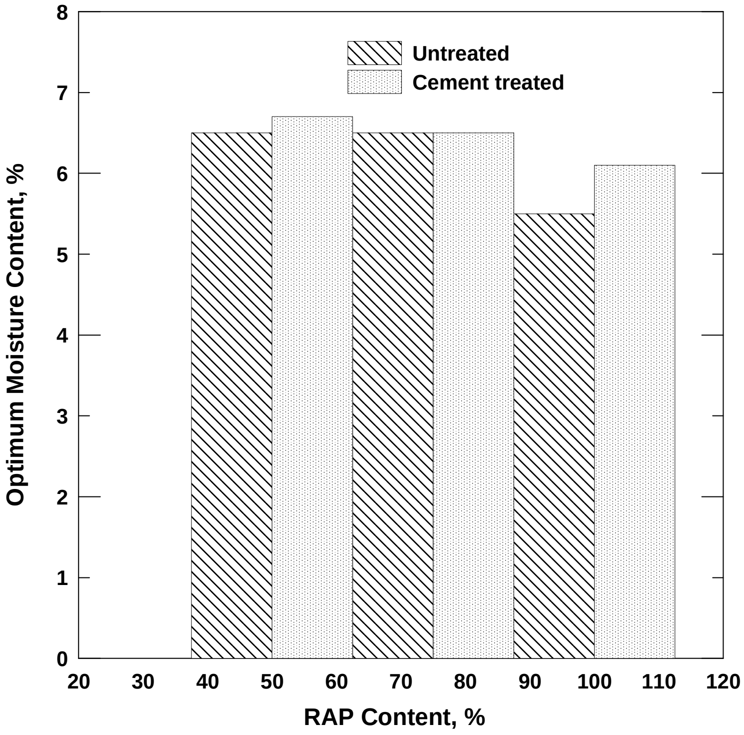


Figure 6.2 Variation of OMC for untreated and treated specimens

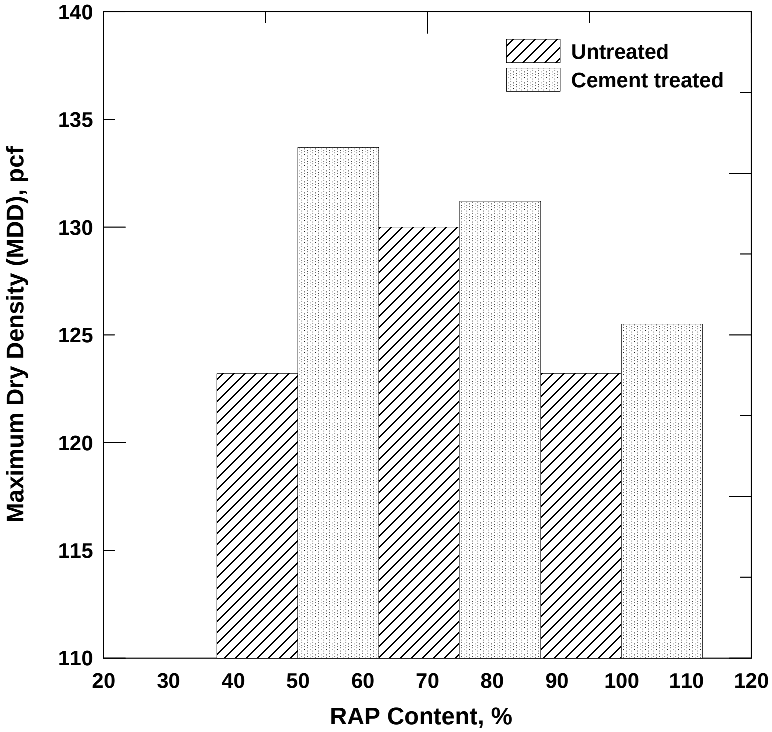


Figure 6.3 Variation of MDD for untreated and cement treated samples

6.3 Engineering Properties of Childress RAP

Engineering properties of RAP mixes consists of both strength and stiffness characteristics. The strength properties of the RAP-base blend was studied using the unconfined compression strength test and stiffness characteristics were studied using durability studies. The UCS test is used to design the mix using the targeted strength and durability studies give an idea about the performance of the mix in the long run. The durability studies conducted involves wetting/drying studies and leachate studies to replicate the moisture fluctuations due to seasonal changes. The RAP mixes were stabilized with Portland cement type I/II for to reach the required threshold strength.

6.3.1 UCS tests for untreated and treated RAP mixes

As per current TxDOT procedure a UCS value of 300 psi has to be achieved by the design mix in order to use it as a base layer in the pavement construction. For accomplishing this task, the RAP and base materials were mixed in different proportions with varying cement contents to prepare the samples. These prepared samples were cured for seven days and then tested for the targeted UCS value. The strength values obtained for both untreated and treated samples were presented in Table 6.4. It can be observed from this table that the untreated samples do not have any strength. But when these samples were treated with 4% cement their strength increased significantly. The Figure 6.4 shows this variation of UCS for both untreated and treated samples.

Table 6.4 UCS data for untreated and treated samples

RAP Content	**Unconfined Compression Strength (psi)**	
	Untreated	**Cement**
50	16	510
75	15	465
100	0	385

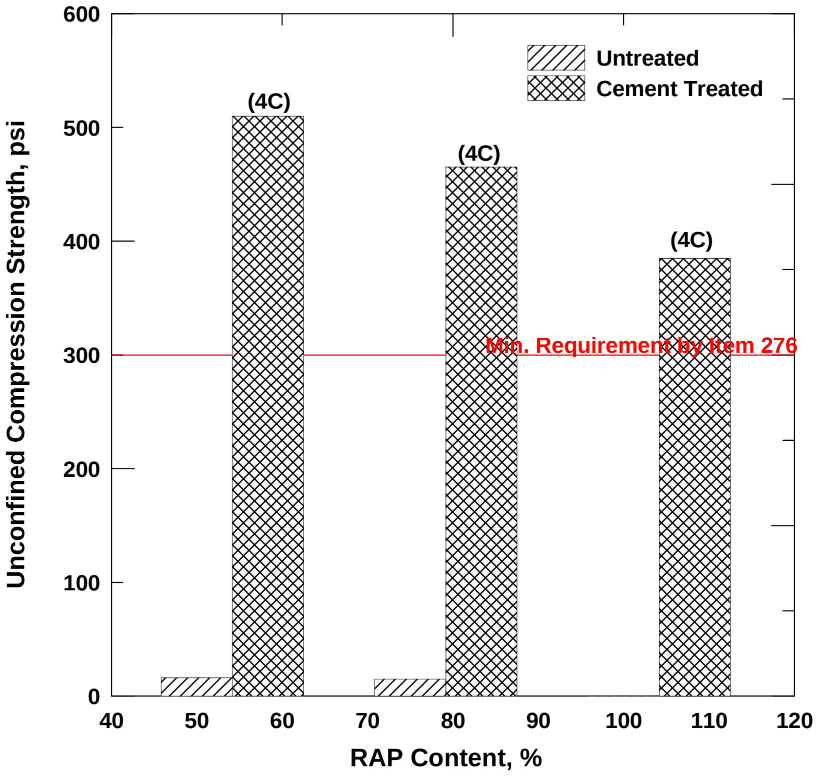


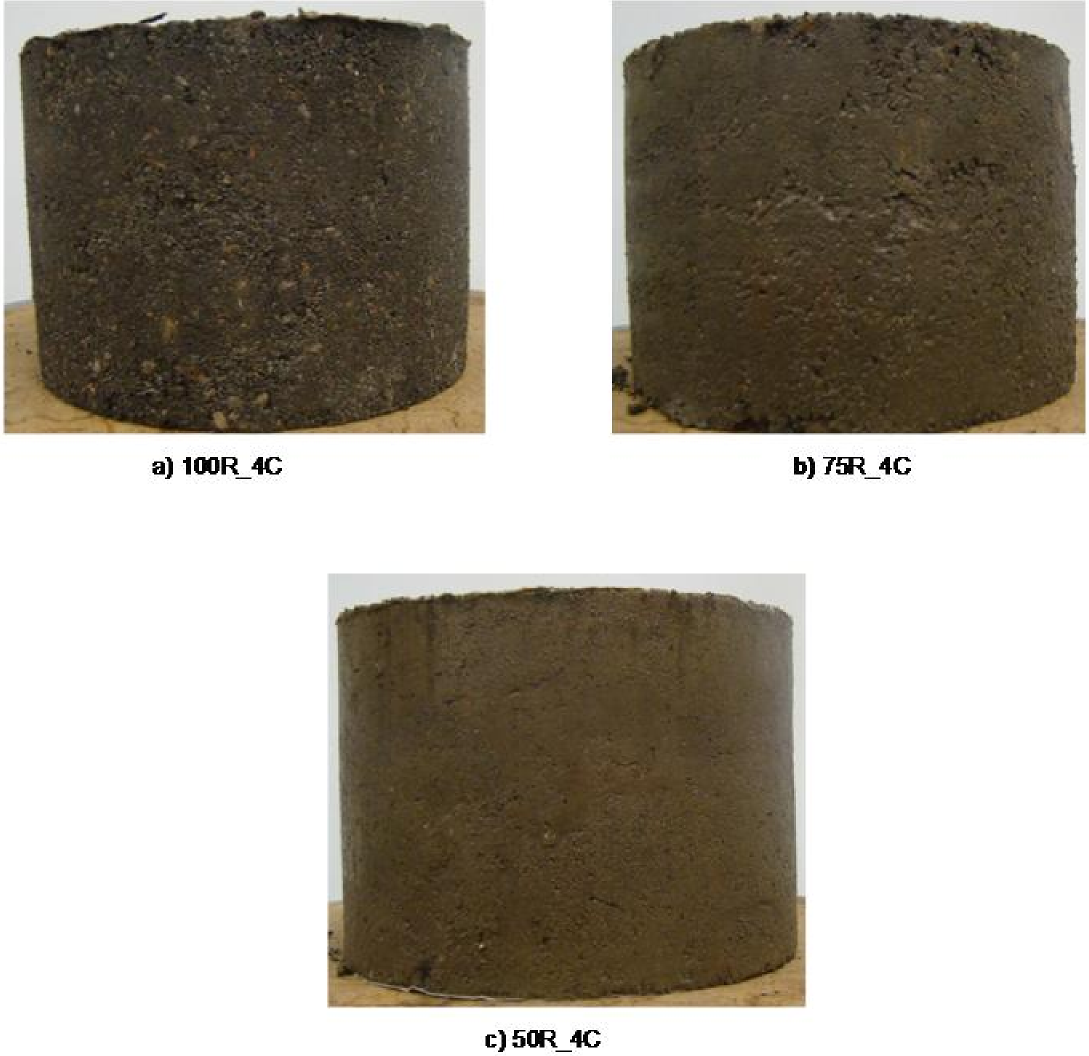
Figure 6.4 Variation of UCS with chemical stabilization

6.3.2 Durability studies

An appropriate stabilizer design practice such as the proposed cement treated RAP material should be thoroughly evaluated to address the permanency of cement stabilizer, i.e. the duration for which the cement additive holds on to the RAP particles to provide the desired strength and stiffness improvements. This permanency of cement is affected by the moisture movements and has serious implications on durability of the pavement. The durability studies on RAP mixes include 14 cycles of wetting/drying studies and 14 cycles of leachate studies.

6.3.2.1 Wetting/Drying studies

The standard ASTM D 559 method was used to conduct wetting/drying cycle investigations. The procedure involves in submerging the samples in water for 5 hours and then oven drying at 160^0F for another 42 hours. Hence, to complete one cycle of wetting/drying studies a total time of 48 hours is required. After removing sample from the oven volume changes and moisture content variations were recorded. During wetting and drying periods sample sizes will be measured in all the three dimensions. The vertical movements were measured with the help of vernier calipers and the radial movements were measured using a “pi tape”. At the end of 3, 7 and 14 cycles the samples were taken out and subjected to UCS tests. The designed RAP mixes at initial conditions are shown in Figure6.5.



a) 100R_4C

b) 75R_4C

c) 50R_4C

Figure 6.5 RAP mixes at 0 cycles

After the samples were prepared as per the Section 3.4.1 they were cured for seven days in a moisture room before subjecting them to 3, 7 and 14 wet/dry cycles. The volumetric changes taking place in 100R_4C, 75R_4C and 50R_4C for 3 wetting/drying cycles is presented in Figure 6.6. From this figure it can be observed that among all blended RAP mixes studied the lowest volumetric change is seen in 75R_4C. Also, 75R_4C mix did not undergo significant volumetric changes neither lost substantial amount of initial strength after 3 wet/dry cycles. When compared with the 100R_4C RAP mix the percentage of reduction in 75R_4C mix was nearly 84% and for 50R_4C this percentage reduction was observed to be 20%. In addition, 50R_4C RAP mix even though has higher amount of strength than 75R_4C mix, the volumetric changes in wet condition were observed to be of 75% higher for each cycle. For the 100R_4C, the volumetric change was high and the amount of strength lost during this wet/dry period is also examined to be high. The conditions of the RAP mixes at the end of 3 cycles are presented in Figure 6.7.

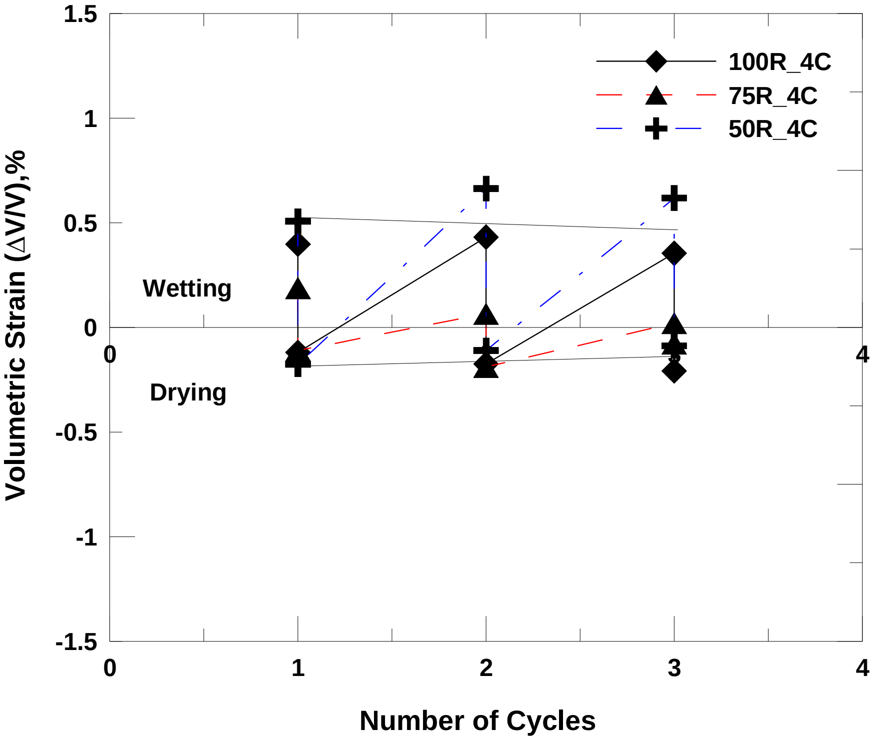


Figure 6.6 Volumetric changes for 3 W/D cycles

a) 100R_4C **b) 75R_4C**

c) 50R_4C

Figure 6.7 RAP mixes at the end of 3 W/D cycles

In the similar pattern wetting/drying studies were carried out until 7 cycles to study the performance of the mixes in the long run. For this site wet/dry cycles for 14 cycles were not included because the collection of materials was delayed. This alternate wetting and drying process of the RAP mixes replicates the moisture fluctuations in the field. The volumetric changes after each wet/dry process was recorded and plotted with number of cycles as shown in Figure 6.8. According to Figure 6.8 the 75R_4C mix shows the lowest values of volumetric change and was very stable with only 95% retained strength. The 50R_4C mix does have enough strength after 7 wet/dry cycles but the volumetric changes are 86% more when compared to 75R_4C mix and the sample displayed some deterioration at the end of 7 cycles. To have a clear idea about this performance the pictures of samples taken at the end of 7 wet/dry cycles were presented in Figure 6.9. The strength variation for different RAP mixes after 3 and 7 cycles was given in Figure 6.10 to know the retained strength.

Table 6.5 summarizes all the test results obtained from wetting/drying studies. Based upon the volumetric changes measured and the retained strengths at the end of 3 and 7 cycles ranking was also given for each mix studied to identify the best performing mix. It can be clearly noted from this table that 75R_4C is the best performing as per wetting/drying studies since this combination shows a lowest volumetric change when compared to the other mixes.

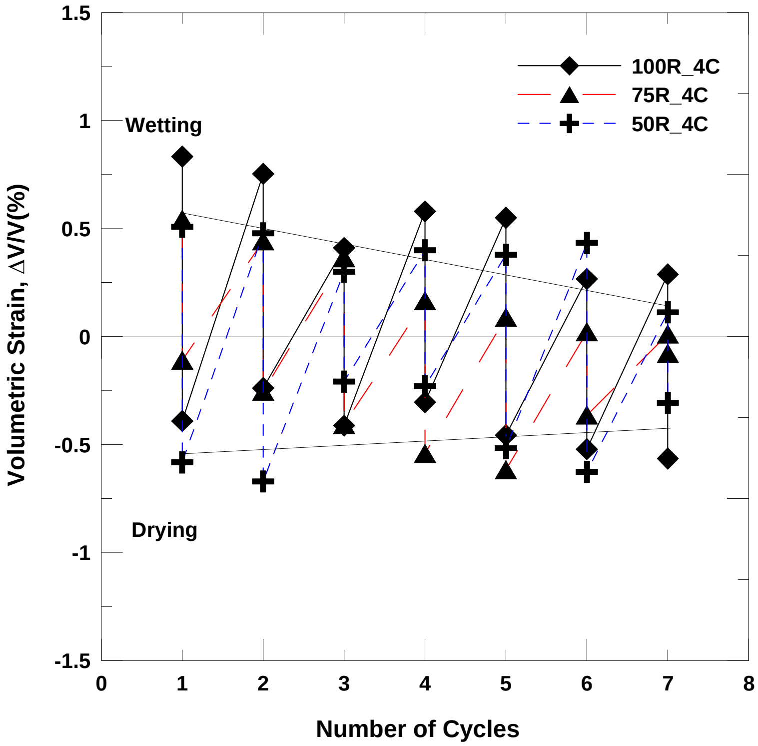
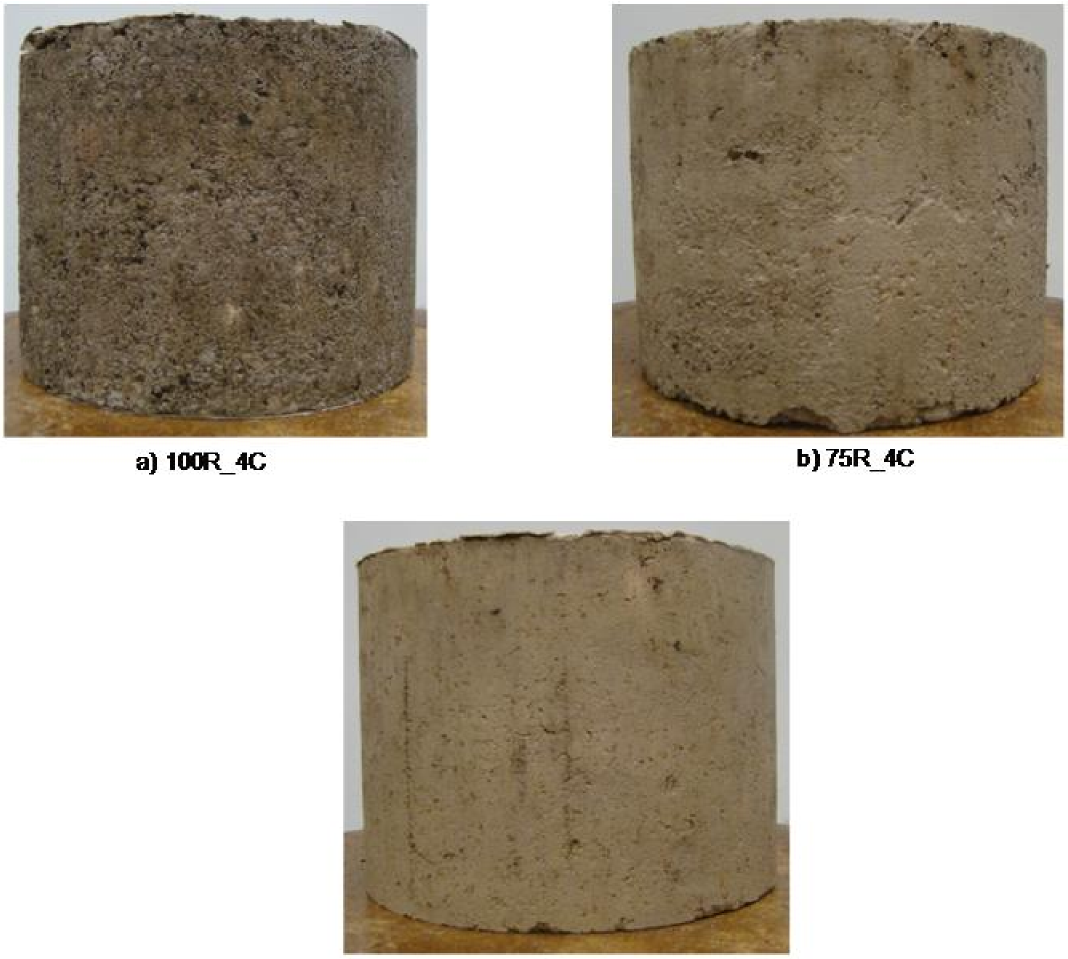


Figure 6.8 Volumetric changes for 7 W/D cycles



a) 100R_4C

b) 75R_4C

c) 50R_4C

Figure 6.9 RAP mixes at the end of 7 cycles

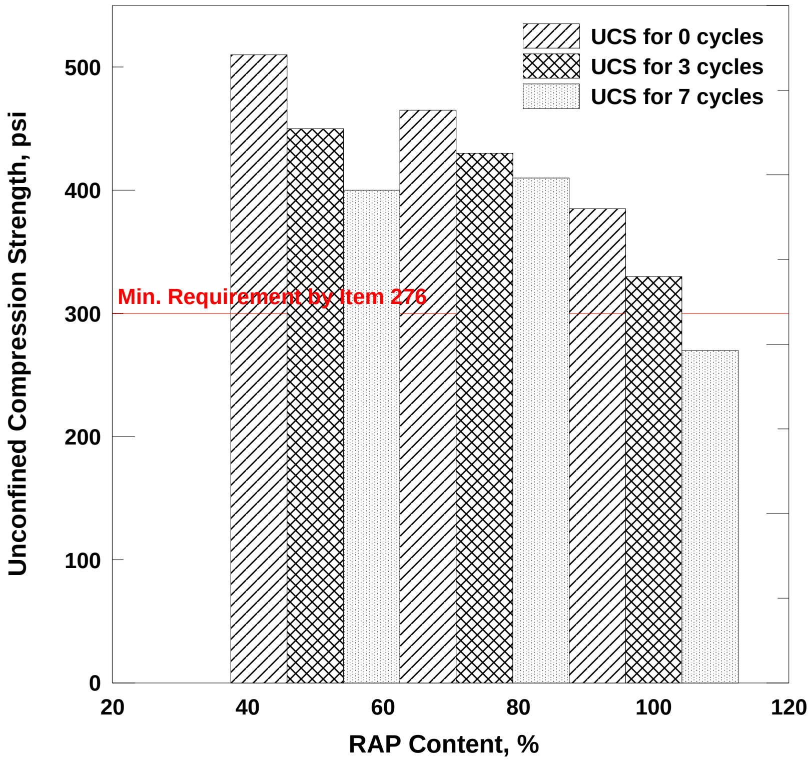


Figure 6.10 UCS strength after different wet/dry cycles

Table 6.5 Summary of Wetting/Drying studies

Mix Type	# of cycles	Total Volumetric change (%)	Retained strength (psi)	# of cycles sample survived	Rank
100R_ 4C	3	0.56	330	7	**III**
	7	0.85	270		
75R_ 4C	3	0.09	430	7	**I**
	7	0.08	410		
50R_ 2C	3	0.45	450	7	**II**
	7	0.575	400		

Note: # of cycle's tested - 7

6.3.2.2 Leachate Studies

Due to coarse nature of blended RAP mixes leachability tests can be easily conducted on these samples. The main intention for conducting leachate studies on RAP mixes is to address the leaching of chemical stabilizer through moisture movements that could reduce durability of the pavement. In the literature it has been reported that the leaching through moisture flows in soils result in variations in pH and calcium ion concentration which contributes to the loss of strength in the specimen.

The cured samples were kept inside the sample cell (refer to Figure 3.9) and the top plate was fastened in place using the fasteners shown in the figure. A confining pressure higher than the flow pressure is applied through the confining pressure inlet. Then the water was allowed to travel through the top cap under a constant flow pressure and the leachate was collected in 20 liter carboys shown in the Figure 3.10. The leachate samples collected after 3, 5, 7, 11 and 14 cycles of leaching were tested for calcium and pH changes. One complete leaching cycle can be defined here as the amount of leachate volume collected that is equivalent to its total void volume. At the end of 14 leachate cycles the RAP mixes were subjected to UCS test to measure the retained strength after leaching of the cement stabilizer.

The test results obtained from leachate cycles were presented in Figures 6.11 and 6.12. The variation of calcium concentration with number of leachate cycles for different RAP mixes is shown in Figure 6.11. It can be noted from this figure that although 75R_4C and 50R_4C mixes were stabilized with 4% cement the leaching of the calcium from these mixes was very low and it ranged from only 13 to 0 ppm for 14 leachate cycles. This represents that the blending of base with RAP material is holding the cement particles tight and also giving enough strength to perform well in the long run. However, when it comes to 100R_4C the loss of calcium concentration is ranging from 24 to 3 ppm showing poor holding capacity of RAP particles for cementitious compounds. The 100R_0C RAP mix was studied in this case to check for any presence of calcium in the 100% virgin RAP.

In Figure 6.12, the pH variation with number of leachate cycles for the designed RAP mixes was displayed. From this Figure, it can be observed that for the cement treated RAP mixes the variation of pH ranged from 11.8 to 8.5 indicating the loss of calcium ions from the sample. But in the case of untreated sample the pH changed between 9.2 and 8.0 showing some presence of calcium ion concentration. The percentage of retained strength after 14 leachate cycles for the RAP mixes is shown in Figure 6.13. The results from strength tests showed higher percentage of retained strength for 75R_4C mix signifying its high performance with blending and stabilization processes. Even though 50R_4C RAP mix displayed similar variation with respect to changes in calcium concentration and pH as of 75R_4C mix but its retained strength was a little lower at the end of 14 cycles. When it comes to 100R_4C mix the retained strength almost came down to 35% indicating considerable loss of stabilizer from the mix.

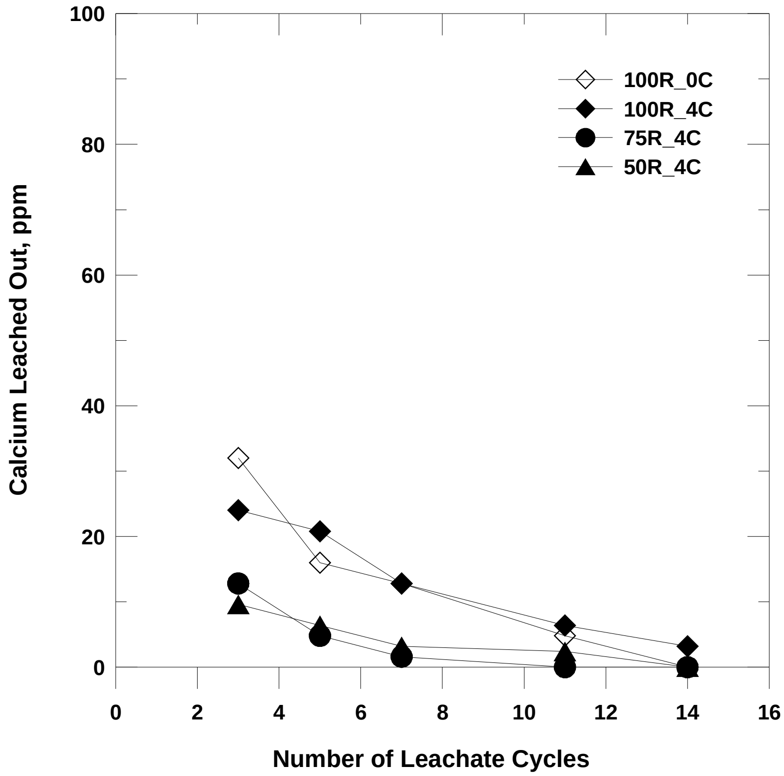


Figure 6.11 Variation of calcium ion concentration with leachate cycles

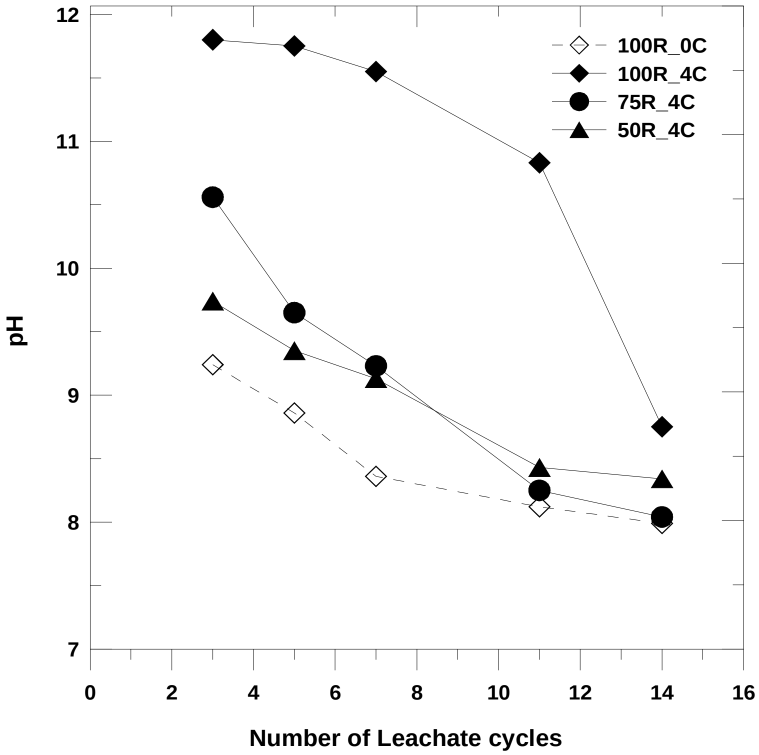


Figure 6.12 Comparison of pH for different RAP mixes

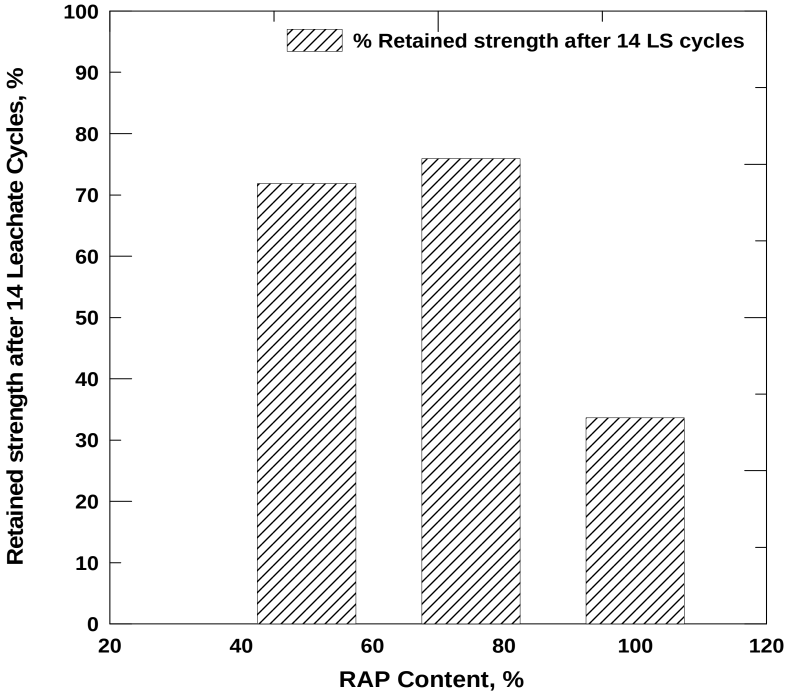


Figure 6.13 Percentage of retained strength for treated RAP mixes

From the above results, it can be noted that there was high retained strength after 14 cycles of leaching and a very low percentage of cement leaching for all the specimens studied. This low percentage of strength decrease and leaching of cement can be better understood if these leachate studies conducted in laboratory were correlated to field moisture infiltration using the calculations given in Figure 4.23. Based on these calculations the number of years replicated in the field were calculated and given in the Table 6.6 for each RAP mix. It can be recognized from this table that 75R_4C is the best performing mix considering all the factors studied in leachate analysis.

Table 6.6 Summary of leachate studies

Mix Type	**% retained strength after 14 leachate cycles**	**# of years replicated in field**
50R_2C	72	0.72
75R_4C	76	0.95
100R_4C	34	1.47

6.3.3 Mineralogical tests

The main purpose of conducting mineralogical tests is to understand the minerals and patterns formed during the stabilization process of blended RAP mixes. These mineralogical tests include X-ray diffraction studies for identifying the cementitious compounds and SEM studies with capability to conduct Electron dispersive System (EDS) for examining the different patterns and chemical compositions. The procedures for conducting these mineralogical tests were given in Sections 3.5.1 and 3.5.2.

6.3.3.1 X-Ray Diffraction Analysis

In X-ray diffraction studies the powdered sample is subjected to X-ray scanning to determine the minerals formed. There will be a variety of minerals formed due to the processes involving blending and stabilization of RAP mixes. These minerals were identified using the peaks given in the graph between 2-theta and intensity. The peaks with different intensities were formed during the scanning of the sample and these were matched with the Powder Diffraction Files (PDF) of several minerals in software called JADE 5 to identify the mineral formed.

In this analysis the main intention was to identify the presence of pozzolanic compounds formed in the RAP mixes due to the chemical stabilization. But after thorough analysis of all the groups like zeolites, synthetic compounds, cement compounds and others only traces of pozzolanic compounds consisting of Aluminum, Silicon, Calcium and Chromium were found. The minerals identified in this process consist of Silicon oxide (SiO_2), Aluminum oxide (Al_2O_3), calcium oxide (Cao), Boron Chromium, Calcium Borate and some synthetic compounds. A typical plot between 2-theta and intensity obtained from X-ray diffraction analysis for 75R_4C is shown in Figure 6.14.

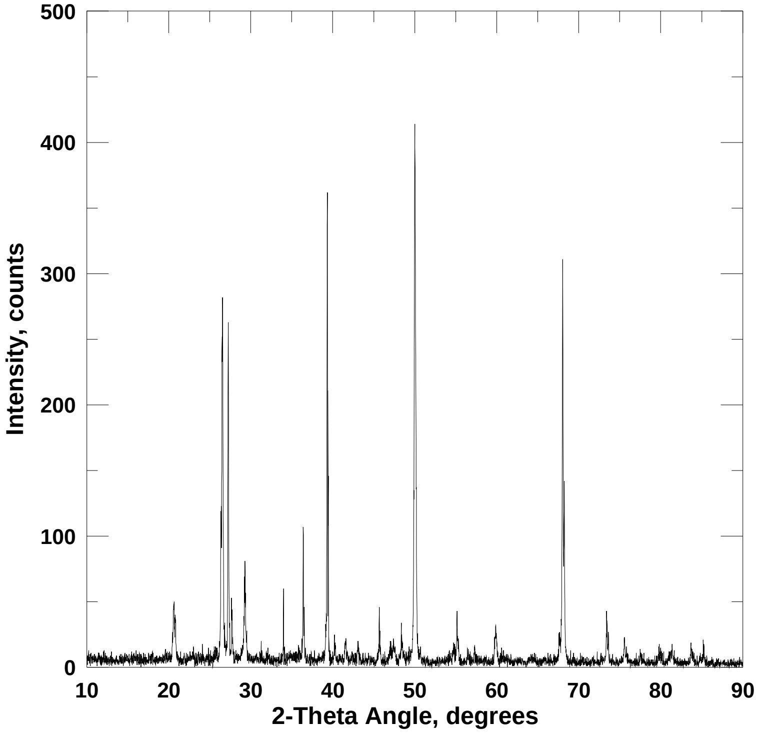


Figure 6.14 XRD Plot for 75R_4C

6.3.3.2 Scanning Electron Microscope studies (SEM)

The SEM pictures were taken to observe the fibrous and needle like patterns formed due to the cement stabilization of RAP mixes. The Electron Dispersive System (EDS) was conducted to know the chemical composition of the sample with in a particular area in the SEM picture. SEM image is formed when a high range of X-ray beam was made to fall on the sample which was subjected to a high vacuum mode. A high quality image was captured for all the design RAP mixes by altering the voltages and magnifications.

The pictures taken for the three RAP mixes of Childress district RAP are shown in Figures 6.15, 6.16 and 6.17. As all these samples were cement treated a needle like structures called ettringite compounds were clearly seen in the SEM pictures. Also, traces of calcium silicate hydrate gel (C-S-H) and calcium hydroxide (CH) compounds were found in traces. The analysis of EDS is done in a way similar to X-ray diffraction because EDS also gives certain peaks with different intensities. These peaks are then matched with the peaks found in the periodic table to identify the presence of certain element in the considered RAP mix. The elements found in Childress RAP mixes include Calcium, Beryllium, Boron, Oxygen and traces of other chemical elements.

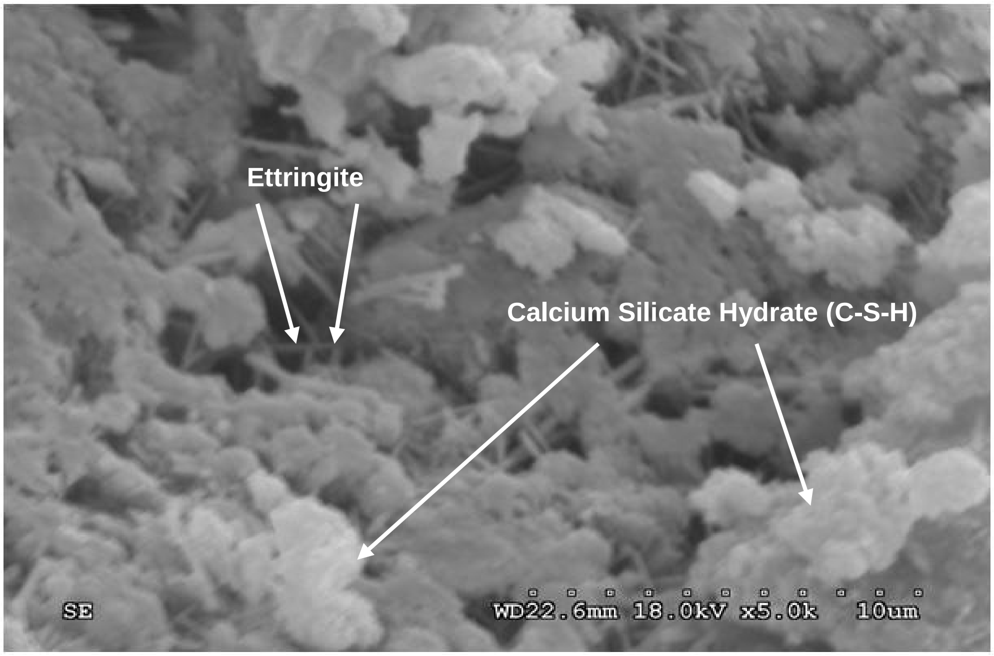


Figure 15 SEM picture of 100R_4C RAP mix

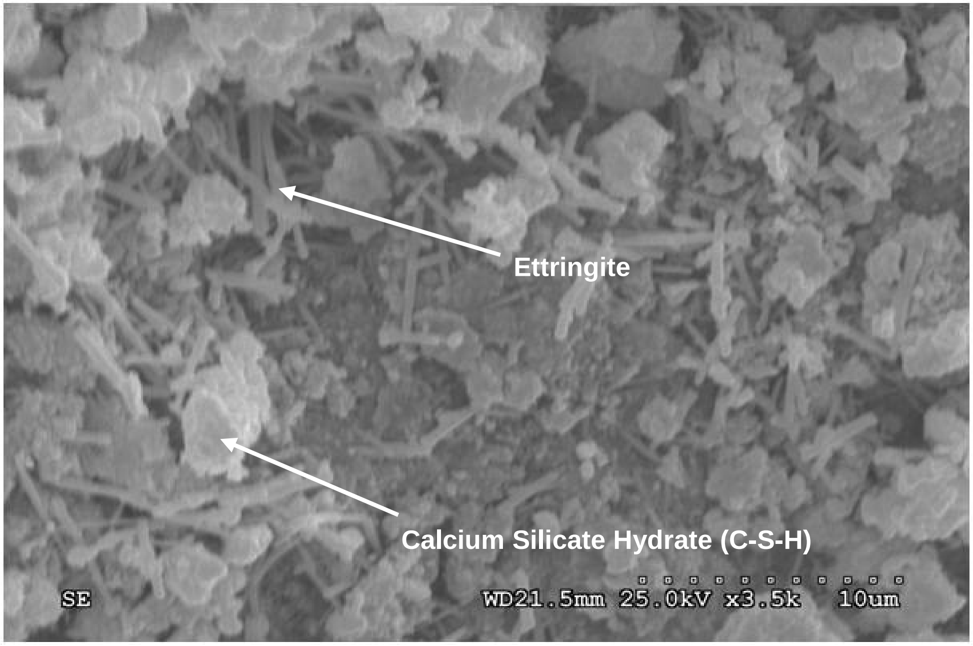


Figure 16 SEM picture of 75R_4C RAP mix

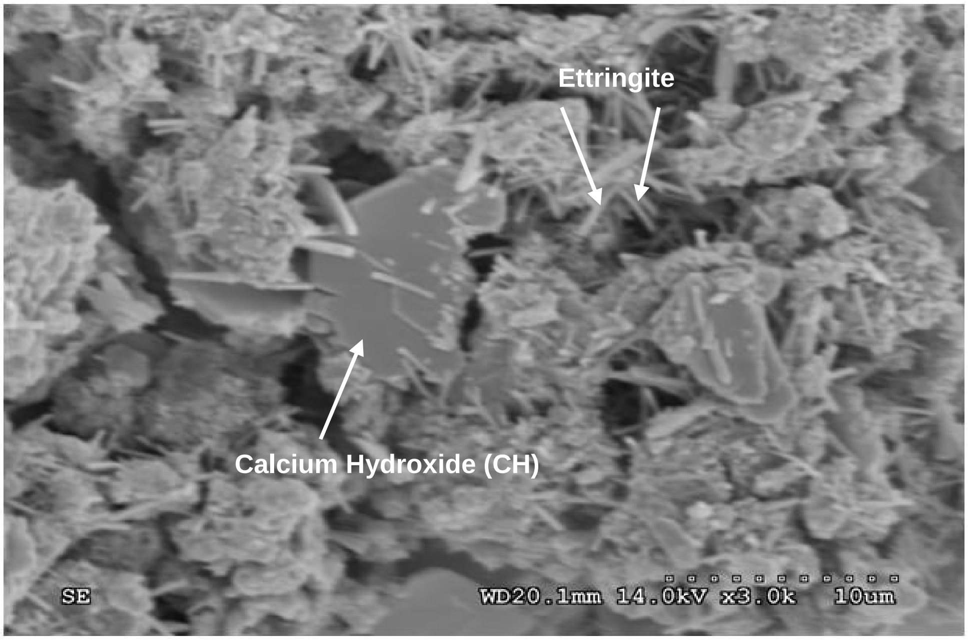


Figure 6.17 SEM picture of 50R_4C RAP mix

6.4Summary

In this chapter at first the results of basic engineering tests for both RAP and base materials from Childress district were discussed. After that the strength and stiffness properties were determined using UCS and durability tests. The UCS tests were used to design the blended RAP mixes based on minimum strength criteria. Then the designed RAP mixes were subjected to wetting/drying and leachate studies to study the long-term performance of each mix and identify the best performing mix among them. Finally, mineralogical tests were conducted to identify the pozzolanic compounds formed and also to monitor the different patterns created inside the sample during cement stabilization of RAP mixes.

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary and Conclusions

In the present research, the feasibility of using chemically stabilized reclaimed asphalt pavement (RAP) materials as base layer for a flexible pavement system is investigated. Reclaimed asphalt pavement (RAP) is produced when an old and damaged asphalt pavement is milled and crushed. This RAP material is used as an important recycling material in Hot Mix Asphalt (HMA) for several decades. Recent studies reported that RAP can be used in the base layer under full depth reclamation (FDR) process since large quantities of RAP are left unutilized and disposed of in the landfills (Taha, 2002). Hence, the use of these RAP materials in base or subbase layers allows for lower material costs, conservation of aggregate resources and elimination of disposal costs and removal of a waste product from landfills.

Based on an extensive review of literature, the studies performed on the stabilized RAP mixes were found to be rather limited. The studies conducted by Taha (2002), Potturi (2006) and Gutherie (2007) were only based on strength and stiffness properties of the stabilized RAP mixes. However, achievement of the specified strength and stiffness does not always ensure durability of these stabilized mixes. Therefore, in order to accomplish this task, the long-term performance of the chemically treated RAP-base blended mixes was studied in this research. These studies include wetting/drying studies, leachate studies and mineralogical tests on the designed RAP mixes.

The materials used to perform the durability studies were collected from El Paso, Fort Worth and Childress districts in the state of Texas. These materials include recycled asphalt pavement (RAP) and local base aggregate materials used by the respective districts in their conventional pavement construction. In the present work, various RAP mixes were designed by blending the RAP and base materials. Subsequently, these mixes were chemically stabilized with cement or fly ash to enhance its strength to meet the minimum standards set by the Item 276 of TxDOT specifications. The results obtained from the durability studies of RAP-base blend combinations were presented in detail in chapters 4, 5 and 6. Some of the important findings obtained from this research are summarized in the following sections.

Basic tests

1. The particle size distribution according to AASHTO for RAP and base materials was found to be A-1-a for all the samples from three sites considered. This classification of A-1-a was rated as an excellent to good material category for using the material as a base or sub-base layer by the AASHTO standards.
2. The specific gravity values of the RAP materials studied in this research varied between 2.27 to 2.45. These values are almost similar/lower to the natural aggregate materials having a specific gravity range of 2.4-2.9.This lower range of specific gravity obtained can be attributed to the lighter weight of the RAP than the natural occurring stone aggregates. The optimum moisture content (OMC) for both untreated and treated RAP-base blends varied from 5.3% to 7.1% which is similar to the typical range (5%-8%) of OMC for aggregate materials being used in the base layers. The OMC found to be decreased with increase in the RAP content in a mix. This decrease in trend with increase in RAP content can be attributed to the poor moisture holding capacity of the aggregate particles coated with asphalt.
3. The maximum dry density (MDD) values increased from116 to133.2 pcf with decrease in the RAP content for the blended mixes because of the higher specific gravity of the base aggregate than the RAP material. This increase in MDD values was observed for both untreated and cement treated samples.

Engineering tests

1. The UCS tests on untreated samples show that none of the mixes could meet the design criteria requiring a 7-day UCS value of 300 psi. In order to achieve the minimum strength requirement criteria of 300 psi, the cement dosages between 2% to 6% were added to different RAP mixes, which are ranging from 50% to 100% RAP contents. The long-term performance of the RAP mixes were studied using wetting/drying cycles to replicate the moisture fluctuations in the field due to seasonal temperature variations. The wetting/drying studies were conducted based on standard ASTM D 559 method which requires soaking of the sample in water for 5 hours and then kept in the oven at 160^0F for 42 hours to complete one full wet/dry cycle.
2. The change in volumetric strain after various wet/dry cycles (3, 7 and 14) was observed to be less than 1% for all the RAP mixes studied. This volumetric change is observed to be very small when compared to the natural soils subjected to the similar kind of wet/dry cycles with similar stabilization process. The volumetric change of nearly 30 to 50% was reported by Chittoori (2008) for natural soils.
3. Ranking analysis is performed to identify the best performing mix in terms of 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.
4. The mix with 75% RAP treated with 2 and 4% cement dosages was given rank one based on the criteria explained above followed by mix containing 50% RAP stabilized with 2 and 4% cement and 100% RAP mix with 4 and 6% cement contents for all the three sites considered in the research.
5. Leachate studies were also conducted on the designed RAP mixes to study the permanency of the cement stabilization. The variations in pH and calcium ion concentration were measured at the end of 3, 5, 7, 11 and 14 leachate cycles to understand the leaching of the stabilizer from the RAP mixes. The amount of calcium

ion concentration leached out from the treated mixes was detected to be less than 50 ppm for all the three samples studied. However, this calcium ion concentration leached out from lime/cement treated natural soils reported by Chittoori (2008) was between 250 to 700 ppm. This could be implied that the leaching of stabilizer may not be termed as a concern for the performance of RAP mix in the long run.

6. The UCS tests were conducted at the end of 14 leachate cycles to measure the retained strength with respect to the original strength of the mix due to leaching of the chemical stabilizer. The RAP-base combination showing the lowest variation in calcium ion concentration and the highest amount of retained strength was identified to be the best performing mix according to leachate analysis.
7. Based on the durability studies conducted on different RAP mixes studied for three districts, the mix with 75% RAP and 25% base with 2% cement has shown consistent results when compared with the other combinations. Even though, the mix with 60% RAP and 40% base with 2% cement has shown the best performance on El Paso RAP, this combination was not considered for the remaining two sites because of the mix 75%RAP with 2% cement gave almost similar results. In addition, the main intent of this research is to use the maximum percentage of RAP in the mix design to enhance the economical and environmental friendly approach.
8. Mineralogical studies conducted on all the RAP mixes have shown a partial presence of pozzalonic compounds contributing to the chemical stabilization in X-ray diffraction (XRD) analysis. The SEM pictures showing the fibrous and needle shaped compounds confirmed the cement stabilization of RAP mixes as per chemical treatments reported in the literature. Further studies are required to identify the type of pozzalonic compounds formed in these types of aggregate materials.
9. Overall, this research study leads to a conclusion that to promote high recycling efforts and to utilize huge quantities of recycled materials in pavement construction to develop

sustainable design of pavement structures, 75% RAP blended with 25% locally available base material with a minimum dosage of cement stabilization is recommended.

7.2 Future Recommendations

The following research recommendations can be used to study the performance of recycled asphalt pavement (RAP) in the long-term:

1. The field evaluation of the test sections prepared with various stabilized RAP mixes could yield more interesting results.
2. The effect of asphalt content in the RAP mix has to be studied in order to evaluate whether the asphalt content contributes to the strength of the mix.
3. Development of design charts by including modulus and stiffness properties of the stabilized RAP mixes to select certain base thickness based on traffic volume.
4. More mineralogical tests have to be conducted to know the particular type of cementitious compounds formed during the stabilization of blended RAP mixes.
5. It is also recommended to conduct non destructive tests such as cyclic triaxial tests on the RAP mixes at the end of wetting/drying and leachate cycles to know the strength and resilient modulus of the sample to obtain quality results and to save large amount of sample, time and labor.

APPENDIX

ABBREVATIONS USED IN THE THESIS

AAR – Average Annual Rainfall

AARA – Asphalt Recycling and Reclaiming Association

AASTHO – American Association of State Highway and Transportation Officials

ASTM – American Society for Testing and Materials

CBR – California Bearing Ratio

CERCLA – Comprehensive Environmental Response, Compensation and Liability Act

CIR – Cold In-place recycling

CKD – Cement Kiln Dust

COD – Chemical Oxygen Demand

EDS – Electron Dispersive System

EPA – Environmental Protection Agency

FDR – Full Depth Reclamation

FHWA – Federal Highway Administration

FWD – Falling Weight Deflectometer

HIR – Hot In-place recycling

HMA – Hot Mix Asphalt

ISTEA – Intermodal Surface Transportation Efficiency Act

MDD – Maximum Dry Density

NCHRP – National Cooperative Highway Research Program

NEPA – National Environmental Policy Act

OMC – Optimum Moisture Content

PDF – Powder Diffraction Files

PPM – Parts Per Million

RAP – Reclaimed Asphalt Pavement

RCA – Resources Recovery Act

RPM – Recycled Pavement Material

SEM – Scanning Electron Microscope

SWDA – Solid Waste Disposal Act

TDS – Total Dissolved Solids

TSS – Total Suspended Solids

TST – Tube Suction Test

TxDOT – Texas Department of Transportation

UCS – Unconfined Compression Strength

UTEP – University of Texas at El Paso

XRD – X- Ray Diffraction

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