

EXPERIMENTAL AND FIELD STUDIES ON RECYCLED MATERIALS AS
PAVEMENT BASES

by

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ABSTRACT

EXPERIMENTAL AND FIELD STUDIES ON RECYCLED MATERIALS AS PAVEMENT BASES

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Natural aggregates derived from a variety of source rocks have been used as a road base material. But the extraction of natural aggregates resources is increasingly being constrained by urbanization, increased costs and environmental concerns. Thus, increased amounts of reclaimed materials are being used to supplement natural aggregates in road construction. Recycled Asphalt Pavement (RAP) material is one of the important recycled materials used in the present geotechnical applications. Many agencies are constantly seeking to reap the benefits of utilizing RAP. Main advantages of utilizing RAP include the preservation of the existing profile, conservation of asphalt and aggregate resources, conservation of energy, and reduction

in life-cycle cost. Therefore, it is no surprise that state highway agencies have been moving toward increasing the percentages of RAP in their HMA pavements. The 1993 EPA report mentioned that approximately 73 million tons of asphalt pavement material was recycled annually, which amounts to about 80% of the asphalt removed from pavements each year.

Quarry by-products are another important recycled materials showing good performance in many geotechnical applications. These are generally obtained from crushed natural stone. One of the fines obtained from limestone stone quarries are becoming popular. These fines when they are stabilized with some cementing materials can be used in any geotechnical applications. About 159 million metric tons (175 million ton) produced annually is thought to be used in many geotechnical applications. In a recent survey, three states (Arizona, Illinois , and Missouri) indicated that quarry by-products have been used as an embankment material and three other states (Florida, Georgia, and Vermont) indicated some use of quarry by-products in base or subbase for the pavement applications. These are also used as mineral filler in asphalt paving.

In this present research, a comprehensive experimental program was performed on two recycled materials which include RAP and Cemented Quarry Fines (CQF) which were used as a pavement base material.

All the tests provided repeatable and reliable results. Unconfined Compressive Strength (UCS) tests showed a peak stress of 1200 kPa for the CQF which was 12 times more than the untreated sample. UCS for the RAP material showed a strength of 340 kPa which was expected for the RAP materials. Peak values for the

resilient modulus for RAP and CQF were 330 MPa and 370 MPa respectively. These samples required more number of cycles to know the actual resilient modulus. Untreated sample showed a peak value of 220 MPa. Values for the swell tests was zero for the CQF whereas for the untreated sample was around 6%. RAP showed a less strain of 0.7% which is negligible for these materials. Consolidation Indices for these recycled materials showed values less than 0.001. Field monitoring data showed that the settlements and pressures were in permissible limits.

Results from the experimental program along with field monitoring data showed that these recycled materials are best suited as a pavement base material. Based on these results these recycled materials can be used for future research projects.

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CHAPTER 1

INTRODUCTION

1.1 Aggregate Bases

A pavement could be defined as a hard surface constructed over the natural soil for the purpose of providing a stable, safe and smooth transportation medium for the vehicles. A rigid pavement mainly consists of cement concrete at the surface followed by base and subbase courses (Khanna and Justo 1984). Base course is a medium to transfer the wheel loads from the surface to the layers underneath the base course. The quality of the base course material affects the rate of load transfer (Teller and Sutherland 1943), hence it is important to make sure that the base layer has enough capacity and strength to transfer the load from the vehicle to the layers below without causing any shear failure (Yoder and Witezak, 1975). Traditionally stones, bricks or aggregates have been used as a base material for the pavements. But due to the fast urbanization and increased costs and environmental concerns extraction of these natural aggregates are becoming difficult. To replace these natural aggregates a variety of recycled materials (waste glass, scrap tires, bottom ash etc.) are used as base courses. The Illinois Department of Transportation utilizes millions of tons of recycled materials; their annual usage is well over 1.5 million tons (Illinois Department of Transportation, report No. 142).

About thirteen recycled materials are being used and tested by Northeast Recycling Council (NERC) and different state Departments of Transportation (DOTs). The most commonly used materials are reclaimed paving materials, glass, rubber tires, and coal fly ash. According to the EPA report (1993) approximately 73 million tons of asphalt pavement material is recycled each year, which amounts to about 80% of the asphalt removed from pavements each year. The use of reclaimed pavement materials in road construction could serve the purpose of reducing the amount of construction debris disposed of in landfills which reduces environmental disturbance and the rate of natural resource depletion. In Brawley, California, the use of recycled materials in pavement construction reduced the cost of material per ton from \$40 to \$16 (Ayers, 1992).

Another such material which could be used as an alternative to the traditional base materials is lime stone quarry fines. According to Collins and Ciesielski (1994) expanding the markets for limestone quarry fines by relaxing specifications and standards in construction industry, will improve the chances of the lime stone quarry fines as a primary aggregate. Quarry waste is being generated, at a rate about 175 million tons per year (Collins and Ciesielski 1994). The material properties of this waste vary with the source, but are relatively constant at a particular site. A survey in 1994 showed that six states have used quarry waste in pavement applications (Collins and Ciesielski 1994). The research study conducted by Kumar and Hudson (1993) showed potential uses of quarry by-products in cement-treated sub-base/flowable fill, mineral filler in hot-mix asphalt and as a slurry seal aggregate. Another study by Lee and Nicholson (1997) found that combining 10% quarry tailings with a mixture of

municipal solid waste ash would provide an effective landfill cover material. Fraser and McBride (2002) presented a study of the case-specific geotechnical properties of quarry fines when used as embankment material in a limestone quarry.

Two kinds of recycled materials are used in this research study, Recycled Asphalt Pavement (RAP) Material and Cemented Quarry Fines (CQF). The main advantage of using RAP aggregate in place of the local soil was to increase strength modulus and minimize potential vertical rise due to swelling in the presence of water or cracking in the absence of water. Cemented quarry fines are obtained by stabilizing Limestone Quarry Fines (LQF) with cement which improves their engineering properties and thus make it more stable as a base material. This has a similar advantage as RAP material over the local soil. A series of laboratory tests which include Unconfined Compressive Strength test (UCS), 1-Dimensional free Swell test, 1-Dimensional Consolidation test, and Resilient Modulus test were conducted on the two selected materials.

1.2 Research Objectives

The main objective of this research is to evaluate the applications of RAP aggregate and CQF as potential base materials. To ascertain their use as a possible base material strength, swell potential, resilient modulus and consolidation properties of the materials were studied. The following tasks were performed to complete the present research:

- To review the available literature on recycled aggregate bases and their engineering properties, and a brief overview on the recycled materials in the present research and their engineering properties.
- To perform laboratory experiments to know the engineering and stiffness properties of these recycled materials, which include unconfined compressive strength tests, swell tests, consolidation tests and repeated load triaxial tests.
- To perform environmental assessment tests on the leachate generated from these recycled materials.
- To monitor the movements and the pressures induced by the traffic on these recycled materials.

1.3 Thesis Organization

Chapter 1 introduces the recycled aggregate materials used for this research. It also describes various chapters and their contents.

Chapter 2 presents an overview of literature review on recycled aggregates, and various case studies in which these recycled materials were used.

Chapter 3 describes the experimental program, research variables studied, sample preparation, laboratory test equipment including repeated load triaxial test, data acquisition procedures, and the details of the test procedures.

Chapter 4 presents the summary of all the test results conducted on the two materials.

Chapter 5 presents the field monitoring results; various plots are presented which were collected from all the field instruments that were installed.

Chapter 6 describes the summary and conclusions from the current study and also provides some important research directions in using these recycled materials.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter a brief overview on some recycled materials used in the pavement application is presented and different types of instruments and their applications in the geotechnical field are explained.

2.2 Recycled Materials in Pavement Application

The safe disposal of waste materials is an increasingly economic and environmental concern in the United states (Ahmed and Lovell, 1992). The volume of waste materials generated continues to increase even though the importance of recycling is being acknowledged. (Collins and Ciesielski, 1993 and Ciesielski, 1995). Between 1980 and 1988 the annual amount of waste recycled grew by 9 million tons: however, the amount of waste produced in the U.S. reached 4,500 million tons per year (Shelburne and DeGroot, 1998). Clean up of these waste materials have become a major issue as the existing disposal facilities are reaching their maximum capacity, and the approval for additional facilities such as landfills and incinerators are becoming more difficult to obtain.

Many of these wastes produced will remain in the environment for hundreds, perhaps thousands, of years. The production of non-degradable waste materials, combined with a growing consumer population, has resulted in a waste disposal crisis.

One solution to this crisis lies in the recycling of the waste materials into useful by-products. The beginning of the twentieth century has seen a tremendous growth in the Nation's infrastructure (Wilburn and Goonan, 1998). Much of the infrastructure consisted of pavements, bridges and other geotechnical structures constructed during the 1950's, 1960's and 1970's. These structures have now been deteriorated and need to be repaired or replaced. The areas with high population needs new infrastructure to meet these requirements. Infrastructure includes construction materials in general, and aggregates are the important components. Development and extraction of natural aggregate resources (primarily crushed stone and sand and gravel) are increasingly being constrained by urbanization, zoning regulations, increased costs, and environmental concerns, while use of recycled materials from roads and buildings is growing as a supplement to natural aggregates in road construction. Recycling represents one way to convert a waste product into a resource. It has the potential to (1) extend the life of natural resources by supplementing resource supply, (2) reduce environmental disturbance around construction sites, and (3) enhance sustainable development of our natural resources.

For the last five decades, states department of transportation (DOT) have been participating in evaluating and implementing these recycled materials in highway construction. Various tests have been conducted on these materials for the use in highway construction, and developing specifications for these materials. State DOTs contribute to the demand necessary to sustain and expand the secondary materials infrastructure. About thirteen recycled materials are currently being used by Northeast

Recycling Council (NERC) state DOTs. The most commonly used materials are reclaimed paving materials, glass, rubber tires, and coal fly ash. Eighty percent of the NERC states use glass and reclaimed paving materials; 50% use coal fly-ash. The majority of these materials are used as additives to wearing and base courses (the top and second layer, respectively, in a road), with reclaimed paving materials also being used as a base course. A number of states have experimented with the use of rubber tires, largely as an additive to wearing and base courses.

In the United States, the recycling process stream is estimated to be between 352 million tons (320 million metric tons) and 859 million tons (780 million metric 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 other geotechnical constructions (Holtz and Eighmy, 2000).

The annual usage of recycled materials in Illinois Department of Transportation in highway application is over 1.5 million tons. The educated use of recycled materials can result in reduced cost potentials and may enhance performance. Eleven recycled materials that the department has found to perform favorably as valuable supplements or substitutes for conventional materials include: air-cooled blast furnace slag, byproduct lime, fly ash, glass beads, granulated blast furnace slag, micro silica, reclaimed asphalt pavement recycled concrete pavement, steel reinforcement, steel slag, and wet-bottom boiler slag. Five additional materials experimented with by other states

but are currently not viable resources in Illinois highways, for economic or technical reasons are the following: bottom ash, crumb rubber, glass aggregate, waste foundry sand, and roofing shingles.

Asphalt paving materials are recovered from demolished roads. These are valuable, both for the asphalt binder and for the aggregates. More than 100 million tons of worn-out asphalt pavements are recovered annually. About 80 percent of the recovered material is currently recycled, and the remaining 20 percent reports to landfills. Two-thirds of the recycled material is used as aggregates for road base. The remaining one-third of recycled material is reused as aggregates for new asphalt hot mixes (Kelly, 1998). The Texas Department of Transportation (TxDOT) initiated a program in 1994 to encourage the use of recycled materials in Texas road construction and maintenance projects. TxDOT has learned a great deal from its five-year initiative to use more recycled materials. Using recycled materials in road construction offers opportunities to use huge quantities of recycled materials while extending the supply of traditional construction materials and ensuring good-quality roads. The United States Geological Survey (USGS) calculates that even though the use of recycled crushed concrete aggregates increased by 170 percent between 1994 and 1996, it still constituted only 0.4 percent of the total aggregates consumed in 1995.

2.2.1 Recycled Materials

Several recycled materials have been identified and a brief review on their occurrence, properties and their applications has been presented.

2.2.1.1 Crop and Animal waste

The U.S agricultural industry produces more than 400 million tons of crop wastes annually (Collins and Ciesielski, 1994). Currently, the majority of this material is being used as animal feed. There have been two reported uses of crop waste material for pavement construction. The first was an investigation of the potential use of rice husk ash as a supplemental cementing material for the replacement of Portland cement in PCC mixtures. The replacement of cement up to 20% with an equal amount of the rice husk ash contributed with an initial (1 to 3 days) increase in compressive strength, but as time passed the strength was reduced due to effect of alkali aggregate reactivity (Mehta, 1992). The second investigation involved converting cellulosic wastes (including crop residues, animal manure, and wood wastes) into binder materials. These materials could be converted into oil that could serve as an asphalt extender (Collins and Ciesielski, 1994 and Mehta, 1992).

2.2.1.2 Compost

Compost is a relatively stable end product resulting from a biological process of decomposition of organic wastes. These wastes can include a wide range of materials including: crop wastes, sewage sludge, yard wastes, paper mill sludge, and food wastes (Collins and Ciesielski, 1994). Although, some concerns with possible leachate problems, odors, worker health and safety, and public acceptance hinder the use of this material in many areas, compost has been used in several highway and airport shoulders. (Ahmed, 1991 and Thoresen, 1993).

2.2.1.3 Cement and Lime Kiln Dusts

Cement kiln dust is produced in high temperature kilns where raw materials are used to produce a cement clinker. Dust collected during this operation consists of fine powdery materials, the exact components of which depend upon the raw materials added to the kiln (Collins and Ciesielski, 1994). As of 1992, more than 3.5 million metric tons of cement kiln dust were generated each year (Todres et al., 1992). Lime kiln dusts are physically similar to cement kiln dusts, but differ in chemical make up. As of 1994, about 2 to 4 million metric tons of lime kiln dust was generated in commercial lime plants (Collins and Ciesielski, 1994).

Kiln dusts have had some usage as mineral fillers in hot-mix asphalt, stabilizers for base courses, and as stabilizers for sewage sludge. Only a few states have used kiln dusts for pavement applications and the results of these have not always been successful (Collins and Ciesielski, 1994). One study using cement kiln dust found that the material could be used to reduce the incidence of wetting-induced failure or collapse of highway embankments (Miller et al., 1997). In the study conducted by Lin and Zhang, 1992 which involved the stabilization of a roadway test section base course with cement kiln dust and fly-ash were successfully used as a replacement for either lime or Portland cement. During construction it was found that delaying placement of the mixture for 8 hours after wetting resulted in substantial increases in strength.

2.2.1.4 Construction and Demolition Waste

It was estimated that anywhere from 20 to 30 million tons of construction and demolition (C & D) would be generated every year in the U.S (Collins and Ciesielski

1994). A large percentage of this material, specifically wood and plaster is not suitable for most pavement applications. The remaining materials include: glass, metal, concrete, brick, asphalt concrete, shingles, plastic and other miscellaneous materials. When the quantity of any of these individual materials is sufficient, they can be used individually in pavement construction. All organic material or any other hazardous material such as asbestos should be kept separate from the C&D wastes.

Several states have investigated the use of C&D waste materials, as an embankment material, base course material and aggregate in asphalt concrete pavements. Other factors influencing the use of C&D include the cost of treating the waste to make it environmentally acceptable and the relative cost of local aggregates (Ahmed 1991).

2.2.1.5 Roofing Shingles

In 1995, the yearly U.S. production of waste roofing shingles was estimated at 12 million tons (Ali et al. 1995). Roofing shingle waste generated from manufacturing operations is suitable for use in either hot-mix or cold-patch materials. Roofing Shingles obtained from demolition contractors are generally too contaminated to be used as paving material without extensive processing (Paulsen et al. 1987).

In 1994, three state DOTs indicated that they had used roofing shingles in asphalt mixtures. One application, in Illinois, involved using the shingles as aggregate in a cold-patch material. Another study evaluating the use of shingles in asphalt paving mixtures found roofing shingles could be satisfactorily placed in both dense and SMA mixtures (Newcomb et al. 1993). In 1993, a Minnesota DOT pavement containing 5 to

7 percent shingles, by weight, reported good performance after two years (FHWA, 1993). A laboratory study in Canada found that satisfactory hot-mix asphalt mixtures could be made with up to 25 percent by weight of the mixture being roofing shingles (Ali et al. 1995).

In this current research two recycled materials were used as a pavement base which includes Recycled Asphalt Pavement Material (RAP), Cemented Quarry Fines (CQF). A brief review on these recycled materials and their occurrence, properties and their highway applications has been presented in the following sections.

2.2.2 Recycled Asphalt Pavement Material

Reclaimed asphalt pavement is the pavement material that is removed and/or reprocessed. The final product known as RAP contains both asphalt and aggregates. The Environmental Protection Agency (EPA) reported that 80% of the asphalt that is removed in each year is recycled. This recycling rate is higher than those of aluminum cans (60%), newspapers (56%), plastic soft drink bottles (37%) and glass bottles (31%). Despite these high recycling rates, the public still regard asphalt recycling efforts as the lowest among other solid waste products, probably due to low publicity efforts by the asphalt pavement groups. The 1993 EPA report also mentioned that approximately 73 million tons of asphalt pavement was recycled, which was considerably higher than the remainder of industrial waste products that were recycled.

2.2.3 Recycling Processes

Typically the asphalt pavement is either removed by milling of upper surfaces or full depth removal of the entire pavement section itself. A milling machine is used

remove top 2 in. of the surface with a single pass whereas a rhino horn on a bulldozer is used for full depth removal of the entire pavement in several broken pieces. These pieces are subjected to crushing, screening, conveying and stacking in stockpiles. Typically, this processing is performed at a central processing plant.

Another form of RAP material can be produced by in situ recycling of the old pavements by pulverizing them first and then incorporating them into base courses with or without additives. These processes are referred in the literature as cold in-place and hot in-place recycling methods, with hot process requires the heating of the upper asphalt

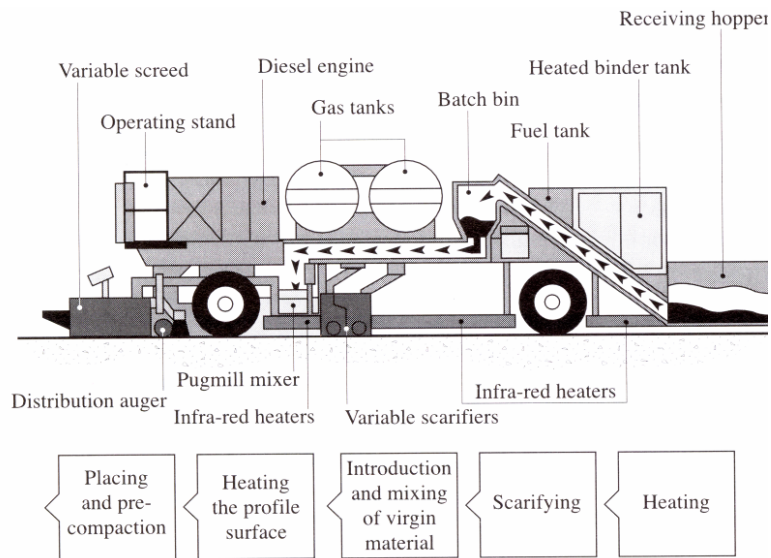


Figure 2.1 Schematic of Hot-In Place Recycling Machine (from Sherwood, 1995)

surface layers of typically 2 in. using a hot recycling machine shown in Figure 2.1. Cold in-place mixing can be carried out to different depths and a schematic showing this process of in-place mixing can be seen in Figure 2.2.

It should be noted that the RAP materials produced from both central processing facility and in situ recycling methods can be used in the following applications: asphalt concrete aggregate, asphalt cement binder, granular base aggregate, stabilized base aggregate and embankment or fill material. Utilizing in these applications result in several benefits, which includes lower costs, lower utilization of virgin materials which are becoming scarce, reduced land-filling, reduced energy consumptions by eliminating fuel consumptions required for land-filling trips, and faster construction if in-place recycling methods are employed.

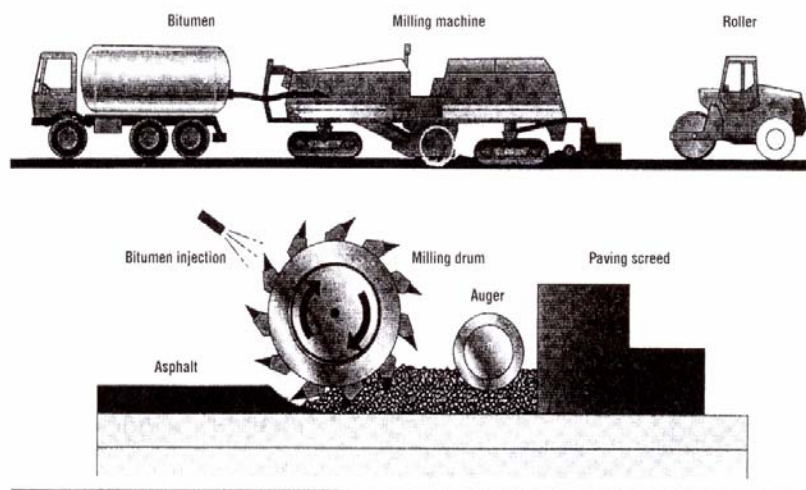


Figure 2.2 Schematic of Cold-In Place Recycling Machine (from Sherwood, 1995)

2.2.4 Typical Properties of RAP Materials

In this section, physical, chemical and engineering properties are discussed. Table 1 presents both physical and mechanical properties of the RAP materials. It should be noted that the unit weight of RAP varies between 19.4 and 23.0 kN/m³ whereas the moisture content varied between 5 to 8%. Compaction unit weights ranged

between 16.2 and 20.0 kN/m³ and the California Bearing Ratio values ranged from 20 to 25. Chemically, a small percent of RAP material (6%) contain hardened asphalt binder and the rest is predominantly composed of natural aggregates. The asphalt binder can be of hardened type due to oxidation process during service period of asphalt pavements.

Table 2.1 Physical and Mechanical Properties of RAP Materials

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

2.2.5 Limestone Quarry Fines

2.2.5.1 Origin

Quarry fines which can be used as a construction aggregate are obtained during the process of crushing stones. This process involves blasting, primary and secondary crushing, washing, screening, and stockpiling operations. Quarry fine are obtained as a by-product during crushing and washing operations. Generally from these operations three types of quarry by-products are obtained which include screenings, pond fines,

and baghouse fines (Tepordei and Valentin 1992). In this review of literature the by-products from screenings are explained in detail.

2.2.5.2 Screenings

Screenings are the finer fractions that are separated on a 4.75 mm (No. 4) sieve which are obtained after crushing and separation operations. Physical properties, size distribution, particle shape can be different from one quarry location to another, depending on the geological source of the rock quarried, the crushing equipment used, and the method used for coarse aggregate separation. Screenings generally contain freshly fractured faces and have a fairly uniform gradation, and do not usually contain large quantities of plastic fines (Kalcheff and Machemehl 1980)

2.2.6 *Current Management Options*

2.2.6.1 Recycling

About 159 million metric tons (175 million ton) produced annually is used especially the pond fines. In a recent survey, three states (Arizona, Illinois, and Missouri) indicated that quarry by-products have been used as an embankment material and three other states (Florida, Georgia, and Vermont) indicated use of quarry by-products in base or subbase applications. In some areas limestone screenings are used as agricultural limestone, and baghouse fines from the limestone quarries are used as mineral fill in asphalt paving (Sandra and Charles 1980).

2.2.6.2 Market Sources

Quarry by-products are available at over 3,000 stone quarry operations located in every state except Delaware. Screenings are readily available at most quarries,

especially limestone quarries. Although large quantities of pond fines are produced, they must be reclaimed from the ponds and adequately dewatered before they can be considered suitable for use. Baghouse fines are only produced at dry processing plants in areas where there is a lack of market for washed aggregate products. These areas are usually in the more arid regions of the country in the western states (Collins and Ciesielski 1993)

2.2.7 Highway uses and processing requirements

Screenings have properties that are suitable for use as an aggregate substitute in Portland cement concrete, flowable fill, and asphalt paving applications. Baghouse fines and/or pond fines could potentially replace much of the fines in flowable fill mixes, depending on strength requirements. Screenings can be used in granular base courses.

2.2.8 Material Properties

2.2.8.1 Physical Properties

Screenings are a uniformly sized, fine, sandy material with some silt particles. Screenings commonly range in particle size from 3.2 mm (1/8 in) down to finer than 0.075 mm (No. 200 sieve). Normally, the percentage of particle sizes finer than 0.075 mm (No. 200 sieve) is 10 percent or less by weight. Stockpiles of screenings may contain some particles up to 4.75 mm (No. 4 sieve) in size, which is usually the screen size used for separation. Some weathered rock or overburden material may be present in the screenings from certain processing operations.

Table 2 compares the particle size distribution of the fines fraction (finer than No. 4 sieve) of screenings from several different aggregate sources. Different types of

crushers were used to produce these screenings. Despite differences in rock types and crushing machinery, the gradings of the resultant screenings are quite similar.

2.2.9 Chemical Properties

There is very little difference in the chemistry or mineralogy of screenings and pond fines from the same quarry or rock source, and also very little difference in the chemistry within the size fractions of the pond fines.

Table 2.2 Average particle size distribution of screenings from processing of different quarry fines

QUARRY FINES						
	Flint	Trachyte	Limestone	Diabase	Granite	Quartzite
SIEVE SIZE	PERCENT PASSING					
3.18 mm	100	100	100	100	100	100
2.36 mm	83	82	85	87	86	88
1.18 mm	51	52	54	61	60	71
0.600 mm	31	33	34	41	42	57
0.300 mm	18	22	23	27	28	33
0.150 mm	10	13	15	17	19	15
0.075 mm	6	8	7	9	12	7

2.2.10 Mechanical Properties

Published data on the mechanical properties (unit weight, compacted density, California Bearing Ratio (CBR), shear strength, etc.) of either screenings, settling pond fines, or baghouse fines are not readily available. The mechanical properties of quarry by-products can be expected to vary according to the type of rock from which the by-products were derived.

2.3 Inclinometers

The main objective of this section is to present a brief review on the importance of instrumentation and different types of instruments used in the geotechnical field. It explains about the inclinometers and how these inclinometer readings are used in calculating the settlements and deformations in the field.

Instrumentation is necessary to assist in the evaluation of the safety of the structure and is an integral part of the geotechnical design. Every structure is constructed with the earth and rock materials available in nature. These materials have to be suitable for the construction of a structure. As these are available in natural processes, they are unlike the materials such as steel and concrete whose properties are uniform. There is a considerable risk of failure of a structure after construction even though the geotechnical engineers consider every possible mode of failure. To overcome these failures visual observations supported by quantitative measurements obtained from the instrumentation can provide engineers with the information and checking the design assumptions (EM 1110-2-19908, 30 June).

2.3.1 Characteristics and Instrumentation objectives

Monitoring of the field instruments is the most vital part in a project after the construction of a site. Therefore a geotechnical engineer must have a thorough knowledge how to operate these instruments. A good geotechnical engineer has to know where he has to place and what type of instrument he has to choose for the project requirement. Instruments cannot give good readings unless they are placed in the right location (EM 1110-2-19908, 30 June).

The main objectives of instrumentation are divided into four categories, analytical assessment, prediction for the future performance, legal evaluation, and development and verification of future designs (EM 1110-2-19908, 30 June).

1) Analytical assessment

Analysis of the data obtained from the field instruments will enable us to verify the design parameters that were used during the construction of the structure. The field data obtained after construction helps to determine the efficiency of the innovative technology and materials that were used. It also helps us to analyze adverse events that may occur due to heavy future traffic loads and various natural phenomenon such as seismic forces, heavy rainfall, etc.

2) Prediction of future performance.

The readings from the field instruments should be analyzed carefully so as to predict the future behavior of the structure. The readings have to be monitored before and after the rainfall, where the water has a high potential of penetrating the structure. These intermediate readings can be used for the future predictions.

3) Legal evaluation

Valid instrumentation data is important for potential litigation related to construction claims. Precise interpretation of the data from the field instruments after construction can lead to determining the exact cause of failure of the structure if any. This type of investigation prevents any kind of fraudulent law suit being filed against the contractor.

4) Development and verification of future designs.

The instrumentation data collected after the construction of the site can be evaluated and assessed as how the site is responding to the design adopted. If this information is valid these design parameters can be used for other future projects.

2.3.2 Instrumentation Concepts

A well experienced engineer who knows the project design and the instruments has to determine effectively the number, type and location of the instruments. These instruments have to be handled very carefully because a lot of them have very sensitive parts and can be damaged easily. The engineer who performs the installation of these instruments should have the fundamental physics and mechanics involved, and should place the instruments where there are critical movements in the site (EM 1110-2-19908, 30 June).

2.3.3 Different types of instruments used in the field monitoring

After the construction of the structure the engineer has to know how the design is suited for the given conditions. So the engineer has to monitor the changes in the soil sub surface. There are various field instruments to measure soil movements, settlements, deformations, pore pressures in the soil, strains etc, they also warn us how the design assumptions are suited for the given field conditions (EM 1110-2-19908, 30 June).

Some of the instruments used in the geotechnical field are as follows (www.slopeindicator.com):

1. Extensometers.

2. Inclinometers.
3. Piezometers.
4. Soil Strain meter.
5. Pressure cells.
6. Settlement cells.
7. Goodman jack.

2.3.4 Inclinometers

There are two types of inclinometers that are available and used in the field;

- 1) Vertical inclinometers.
- 2) Horizontal inclinometers.

2.3.4.1 Horizontal Inclinometers

The major applications of horizontal inclinometers in geotechnical applications include, monitoring the settlements, providing settlement profiles of embankments, foundations, and monitoring deformation of the concrete face of a dam.



Figure 2.3 Inclinator with probe and accessories (www.slopeindicator.com)

2.3.5 Principles of Inclinometers

The horizontal inclinometers are used to measure the deformation and settlements under the structures. The main principle of horizontal inclinometer is it measures tilt in the plane of its wheels. These readings are recorded in a data mate. It is then downloaded into a soft ware. Here the software converts the tilt measurement to a linear measure in inches or mm. The basic principle used in the tilt measurement involves the sine function, an angle, and the hypotenuse of a right triangle (EM 1110-2-19908, 30 June).

2.4 Summary

This chapter first covers the importance of using recycled materials, followed by a brief description of some of the recycled materials used in pavement applications. This is followed by a brief description of the two recycle materials (RAP & CQF) which were used in the present research study. Description of all these materials includes the physical and mechanical properties. Among the recycled materials, the reclaimed asphalt pavement is considered one of the promising materials to be used as a base material. In USA quarry fines are highly produced and are used economically in various geotechnical applications. In the last section it explains about the importance of instrumentation in geotechnical engineering applications. Three horizontal inclinometers were installed in the present research site and there principles are also explained.

CHAPTER 3
EXPERIMENTAL STUDIES

3.1 Introduction

The objective of this chapter is to determine the geotechnical and resilient properties of RAP and Cemented Quarry Fines. For better understanding of these recycled materials local subgrade material was also studied. Laboratory tests namely, Optimum Moisture Content (OMC), Unconfined Compressive strength (UCS), Resilient Modulus (M_r), Swell, and Consolidation. To study the leachate behavior of these recycled aggregates chemical tests were performed. The following sections describe the tests performed, test equipments used and the test procedures followed. Table 3.1 shows the tests performed on recycled material aggregates.

Table 3.1 Engineering Test Program and Number of Specimens Tested

Test	RAP	CQF	QF	Local
UCS	3	3	3	3
Swell	1	1	1	1
Consolidation	1	1	1	1
Resilient modulus	3	3	3	3

3.2 Sieve Analysis

Sieve analysis was performed as per ASTM D422. An oven dry sample of 1.11pounds passing through No # 4 sieve was taken. Soils retained on various sieves were calculated and a particle distribution was obtained. Since the soil had less than 5% fines, wet sieve analysis was not done. Figure 3.2 and 3.3 shows the particle distribution curve for the recycled materials.

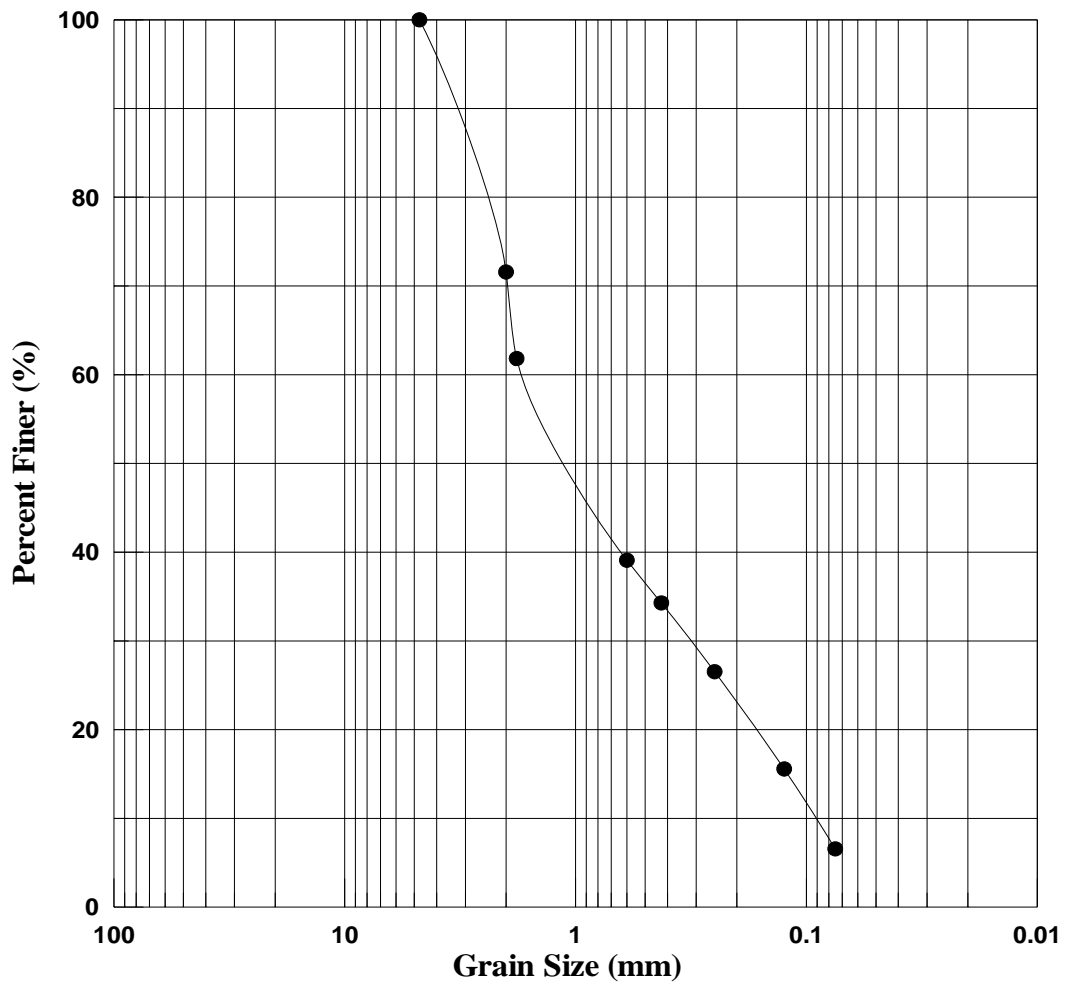


Figure 3.1 Particle size distribution (local subgrade soil)

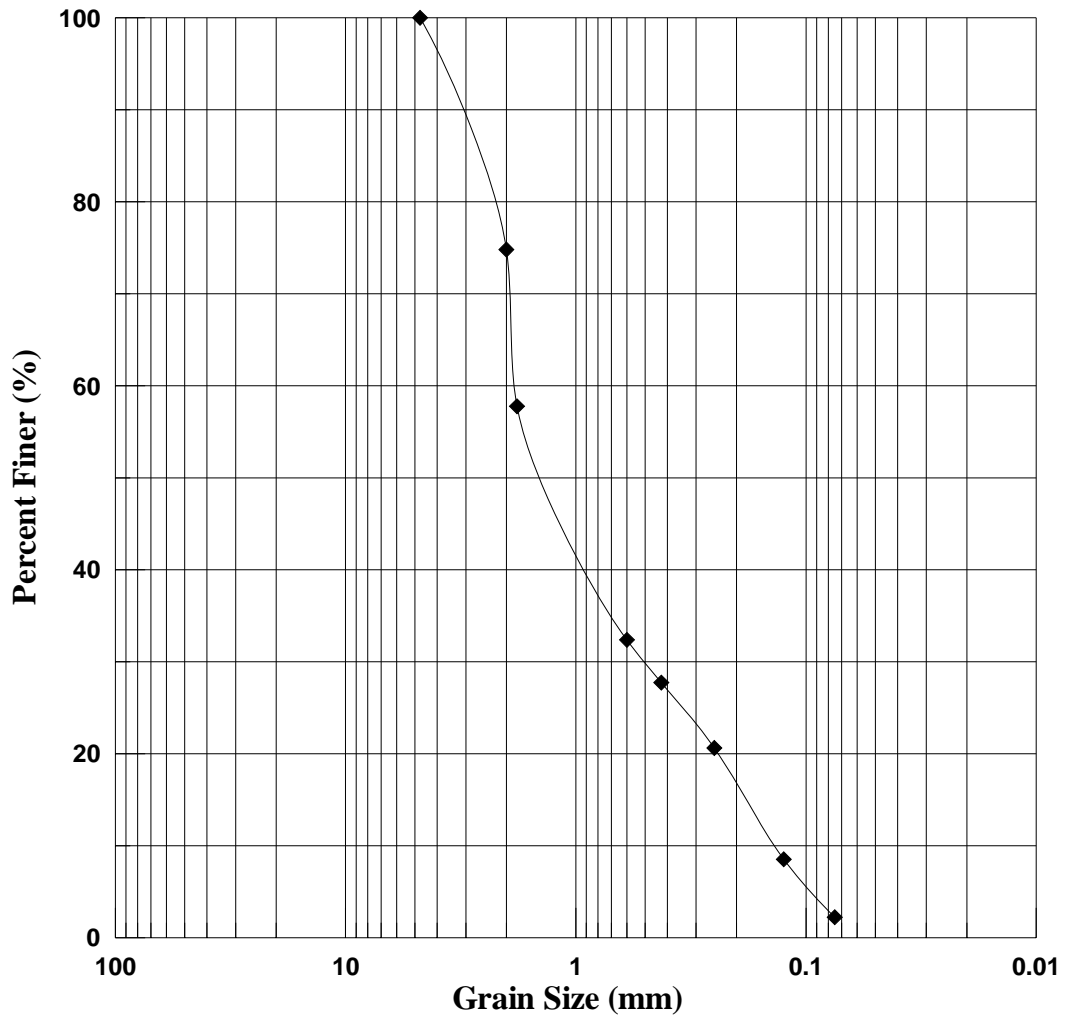


Figure 3.2 Particle size distribution (quarry fines)

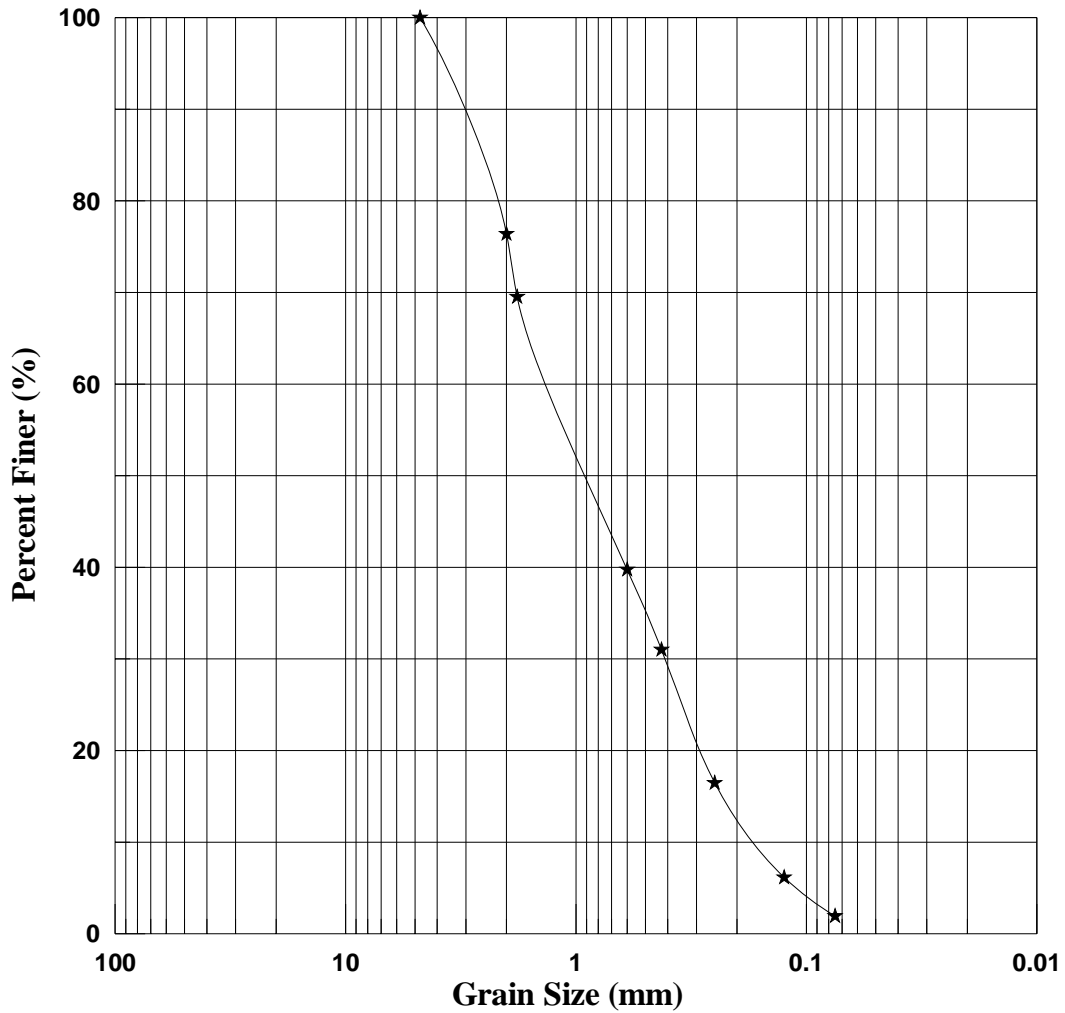


Figure 3.3 Particle size distribution (RAP)

3.3 Compaction Characteristics

Compaction characteristics were determined according to ASTM D698 (Standard Procter Test). For each sample the required amount of sample was mixed dry, and then a proper amount of water was added to the dry mix to obtain the desired moisture content. Then the sample was evenly distributed in the Standard Procter mould and compacted in approximately 3 equal layers, with 25 blows per layer. Figure 3.4 shows the optimum moisture content and dry densities for the recycled materials.

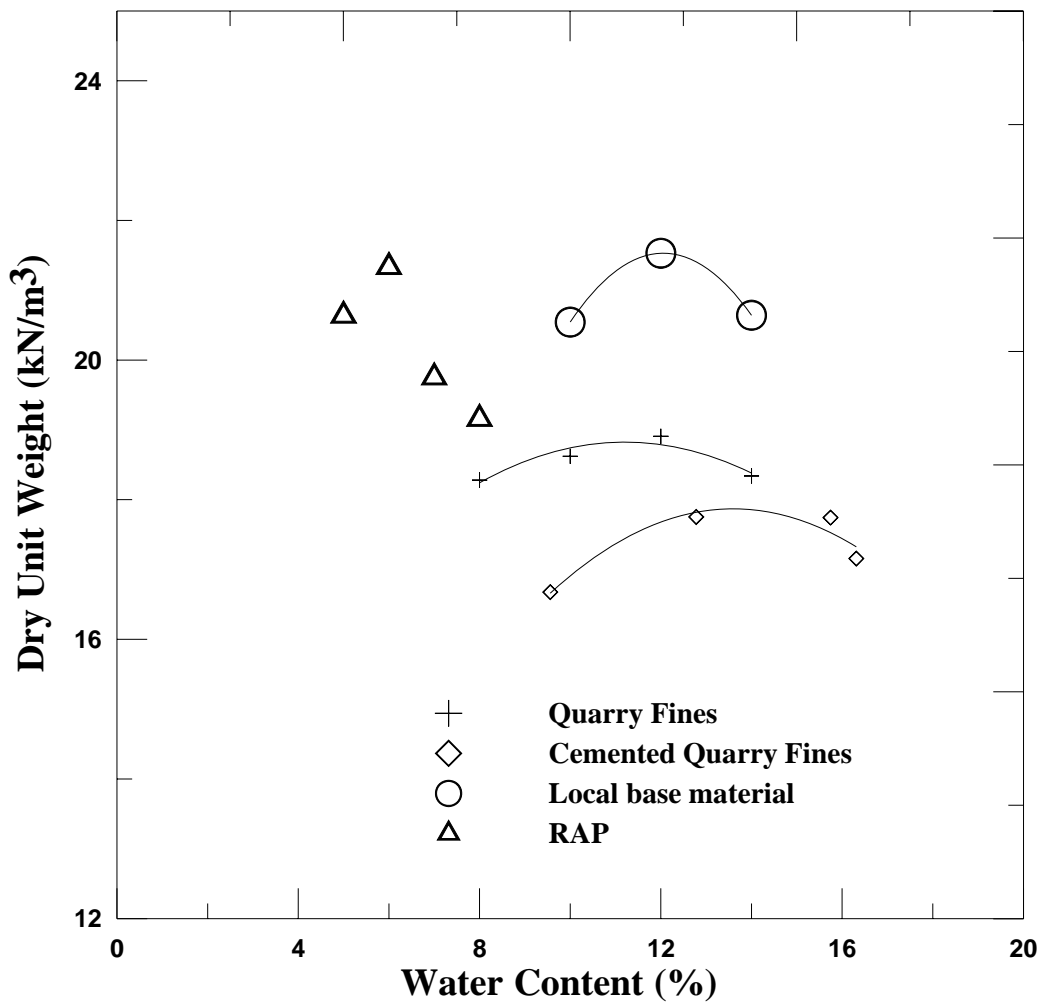


Figure 3.4 Compaction Curve for all materials

3.4 Unconfined Compressive Strength test

The unconfined compression test is a special form of a triaxial test in which the confining pressure is zero. Test was performed as per ASTM-D2166. In this test, a cylindrical specimen with dimensions 2.8 inch in diameter and 5.6 inch in height was prepared. Then it was placed in a triaxial cell and is sheared.

The main features of a triaxial test apparatus are shown below in figure 3.5. It consists of a circular base that has a central pedestal. A triaxial cell is fitted to the top

of the base plate with the help of 3 wing nuts. The triaxial cell is a perspex cylinder which is permanently fixed to the top cap and the bottom brass collar. There are three tie rods

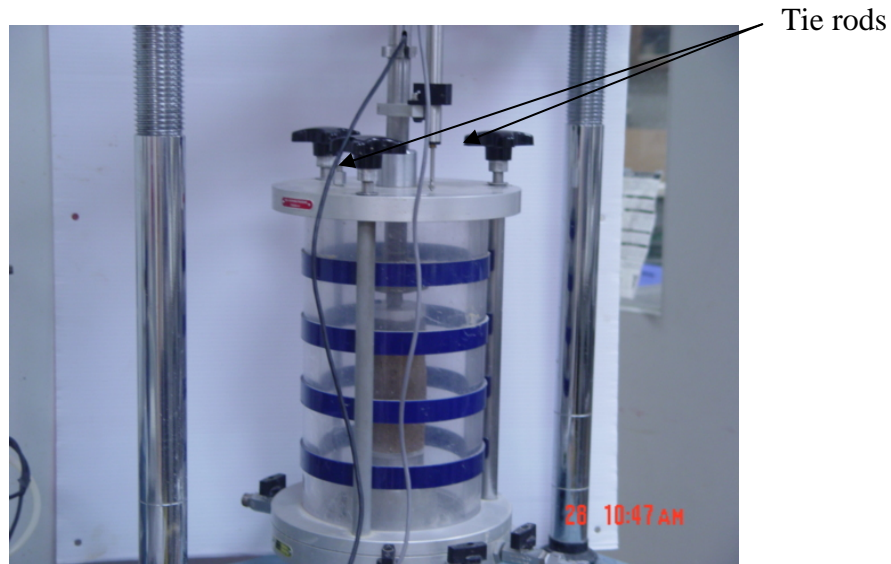


Figure 3.5 Triaxial cell for UCS

that supports the cell. The specimen is covered with a latex membrane. After the specimen is placed inside the cell soil sample is sheared with the help of a loading ram.

A graph is obtained between load and deformation from the computer software. A graph is plotted between stress Vs strain corresponding to the values of load and deformation. Stress is obtained by dividing the load by the area of the sample placed. Strain is obtained by dividing deformation by the original height of the sample.

3.5 Consolidation test

Consolidation tests on the recycled aggregate material were performed to address the compressibility nature of this recycled material. The test for conducted according to ASTM D2435. Sample was prepared in a 2.5 inch mould and was then placed for testing in an oedometer. An initial setting pressure of 40 kPa was applied on the sample. The initial setting pressure was chosen such that there was no swelling. The load was allowed to stand till there was no change in the dial gauge reading. Dial gauge reading was noted under initial setting pressure. The first increment of the load 40 kPa was applied and the readings were recorded at certain time intervals for 24 hours. The loading was doubled and hence successive pressures of 80, 160, 320 and 640 kPa were applied during loading. After that, the final load was unloaded from 160 kPa to 40 kPa. Figure 3.5 shows the set up for consolidation test.



Figure 3.6 Consolidation test setup

3.6 One-Dimensional Free Swell Test

The One-Dimensional Free Swell Test (ASTM D4546) measures the amount of heave in the vertical direction of a laterally confined specimen in a rigid ring. The set up is shown below in figure. Readings were taken for 24 hours and the swell strain was calculated. Readings were taken for 24 hours and the swell strain was calculated.



Figure 3.7 Free vertical swell test setup

3.7 Resilient Modulus Test

3.7.1 Resilient Modulus Test Procedure

The Resilient Modulus Test using the Cyclic Triaxial test equipment is designed to simulate the traffic wheel loading on the in situ soils by applying a sequence of repeated or cyclic loading on the sample specimens. In this thesis research, the standard

method of testing for determining the resilient modulus of soils and aggregate materials – AASHTO Designation T 307-99 has been employed. The stress levels used for testing the specimens are based upon the location of the specimen within the pavement structure as standardized by AASHTO for Base/Subbase materials.

Table 3.2 below presents the testing sequence employed in the test procedure. The confining pressure typically represents overburden pressure of the specimen location in the subgrade. The axial deviatoric stress is composed of two components, cyclic stress, which is the applied deviatoric stress and a constant stress, typically represents a seating load on the soil specimen. It should be noted that the constant stress is typically equivalent to 10% of overall maximum axial stress.

A haversine-shaped wave load pulse with a frequency of 10 Hz was applied as the traffic wheel loading on the soil. A loading period of 0.1 sec and a relaxation period of 0.9 sec were used in the testing. These loading features are in accordance with the resilient modulus test procedure outlined in AASHTO T 307-99 procedure. The selection of haversine load is recommended in AASHTO procedures based on the road test research performed in the USA.

Tests were conducted on the RAP and CQF test specimens and were compacted at the optimum moisture content. Quarry fines have less strength in natural state so these were stabilized with cement (2.3%).

3.7.2 Soil Specimen Preparation Procedure

RAP base specimens for the resilient modulus tests have been compacted at the optimum moisture content and the maximum dry unit weight. The samples were

compacted in three layers, with 25 drops per layer in a 10 cm in diameter by 11.6 cm in height mold. After compaction, the specimens have been extruded and testing was done immediately. The cemented quarry fines sample was kept for curing for 7 days. The cylindrical specimens were then subjected to testing immediately after the curing period.

3.7.3 Equipment Employed for the Resilient Modulus Testing

The RMT was conducted using the UTM-5P dynamic triaxial system. The UTM-5P is a closed loop, servo control, materials testing machine and is designed to facilitate a wide range of triaxial testing. The major components of UTM-5P system are loading frame, controller and data acquisition system.

3.7.3.1 Loading Frame

The loading frame consists of a heavy flat base plate, supported on four leveling screws. Two threaded rods support the crosshead beam and provide height adjustment. The frame is of heavy construction to limit deflection and vibrations that could influence the accuracy of measurements during dynamic repeated loading tests. The loading forces are applied through the shaft of a pneumatic actuator mounted in the centre of the crosshead. Sensitive, low friction displacement transducers attached to the crosshead enable measurement of the permanent and small resilient deflections of the specimen during loading. The loading frame is as shown in the figure 1 below.

Table 3.2 Resilient Modulus Testing Sequence

No.	Confining Pressure		Max. Axial Stress		Cyclic Stress		Constant Stress		No. of Load Cycles
	kPa	psi	kPa	Psi	kPa	Psi	kPa	Psi	
0	103.4	15	103.4	15	93.1	13.5	10.3	1.5	500-1000
1	20.7	3	20.7	3	18.6	2.7	2.1	0.3	100
2	20.7	3	41.4	6	37.3	5.4	4.1	0.6	100
3	20.7	3	62.1	9	55.9	8.1	6.2	0.9	100
4	34.5	5	34.5	5	31	4.5	3.5	0.5	100
5	34.5	5	68.9	10	62	9	6.9	1	100
6	34.5	5	103.4	15	93.1	13.5	10.3	1.5	100
7	68.9	10	68.9	10	62	9	6.9	1	100
8	68.9	10	137.9	20	124.1	18	13.8	2	100
9	68.9	10	206.8	30	186.1	27	20.7	3	100
10	103.4	15	68.9	10	62	9	6.9	1	100
11	103.4	15	103.4	15	93.1	13.5	10.3	1.5	100
12	103.4	15	206.8	30	186.1	27	20.7	3	100
13	137.9	20	103.4	15	93.1	13.5	10.3	1.5	100
14	137.9	20	137.9	20	124.1	18	13.8	2	100
15	137.9	20	275.8	40	248.2	36	27.6	4	100

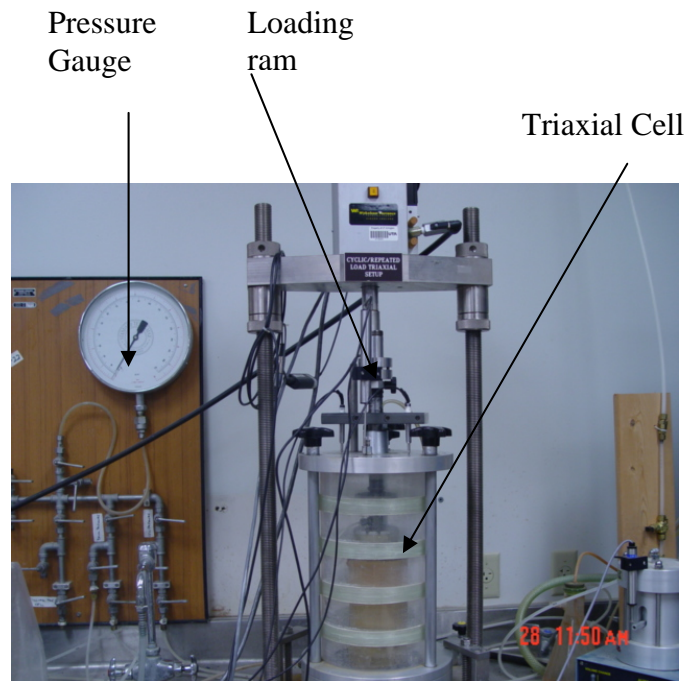


Figure 3.8 Loading frame and triaxial cell setup

3.7.3.2 The pneumatic loading system

The UTM pneumatic system is an air compressor controller unit used to control both load and pressures applied on soil specimens. For asphalt tests, only the vertical force pneumatics is required, while the unbound tests on soils require both confining and axial deviatoric pressure pneumatics. The system requires a filtered clear air supply at a minimum supply pressure of 800 kPa. Lower supply pressures will prevent the system from achieving the maximum specified stresses or forces, as selected by the operator. Figure 3.9 shows the Pneumatic system at the UTA geotechnical lab facility.



Figure 3.9 Pneumatic System

3.7.3.3 Triaxial Cell

The triaxial pressure cell used is suitable for testing specimens having dimensions of upto 200 mm height by 100 mm diameter. This unit is rated to a maximum confining pressure of 1700 kPa. To provide maximum visibility, the cell chambers are made of Lucite-type material. The cell is designed to contain pressurized liquid only and so the use of any compressible gas as a confining medium is dangerous.

3.7.3.4 Control and Data Acquisition System

The UTM Control and Data Acquisition System (CDAS) is a compact, self contained unit that provides all critical control, timing and data acquisition

functions for the testing frame and transducers. The CDAS consists of an Acquisition module (analog input/output) and a Feedback Control module (analog input/output). The Acquisition module has eight normalized transducer input channels that are digitized by high speed 12 bit Analog to Digital (A/D) converters for data analysis and presentation. In addition two 14 bit Digital to Analog (D/A) converters are available to provide computer control of the voltage to pressure converters. The air pressure is controllable over the range 0 – 700 kPa. There are two output channels provided for applying confining pressures. The SOL1 is used as the trigger input to the feedback control module that creates and controls the waveform. The SOL2 output is used for the digital control signal from computer to control the confining pressure solenoid for triaxial tests.

The Feedback Control module has three normalized input channel controls. These channels are dedicated to the actuator position, actuator force and general purpose input (Aux) for on-specimen transducers. This module has a dedicated communication interface of its own that provides for an uninterrupted, simultaneous communication with the PC enabling increased speed of operation and flexibility. The figure 3.10 below shows the control and data acquisition system.

3.7.3.5 Linear Variable Displacement Transducers (LVDTs)

Based on the AASHTO testing procedure T 307-99, high resolution LVDTs are needed to measure the soil displacements. Two LVDTs are used to record the vertical displacements. This external displacement transducer is easy to install and provides a simplified procedure to reset the initial zero reading. The LVDTs are placed

on the top cover of the cell and fitted to the load shaft. The maximum scale stroke for these two LVDTs is ± 5 mm, with a resolution of 0.001 mm accuracy. The output from each LVDT is monitored independently and compared to the output of the other LVDTs. Figure 3.11 shows the external transducer assembly employed in this project.

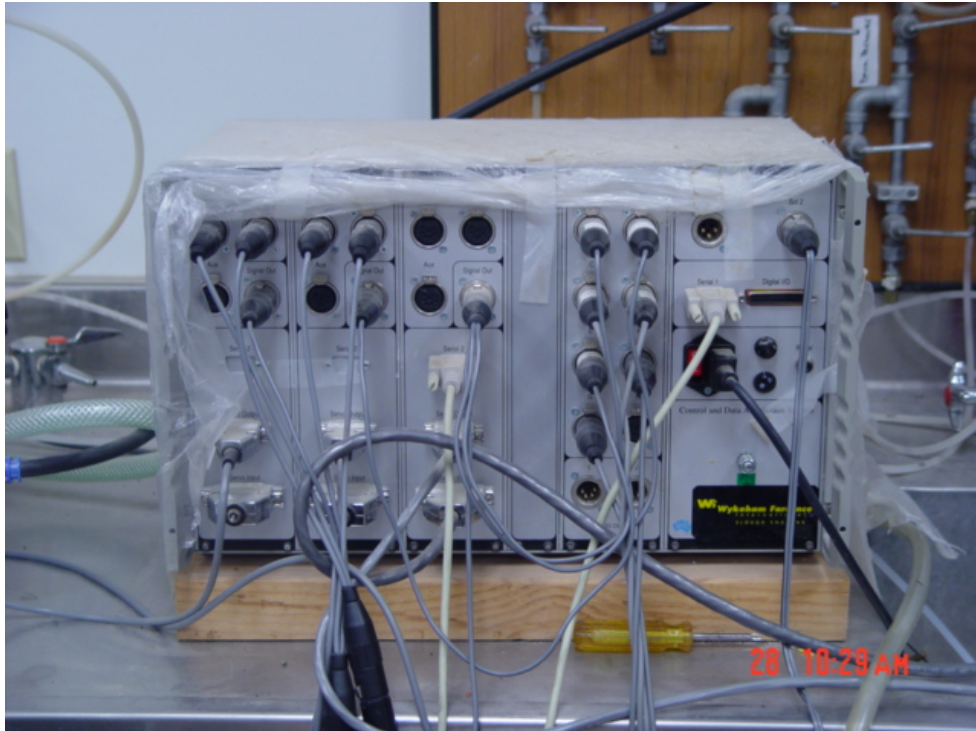


Figure 3.10 Control and Data Acquisition System

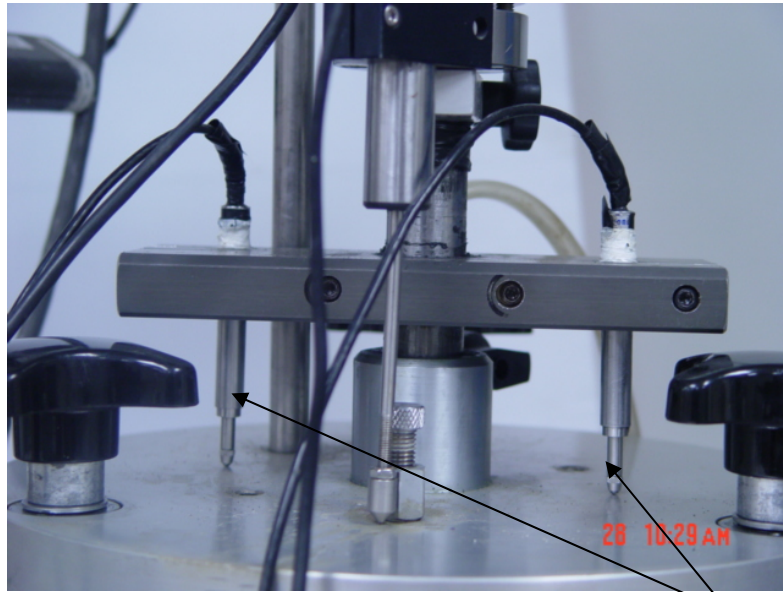


Figure 3.11 External LVDTs Assembly

LVDTs

3.7.3.6 Software

The UTM software is used for equipment control and data acquisition operations. In this software, there are programs available for several test procedures, which include unconfined compressive strength test, resilient modulus test, unconsolidated undrained test, consolidated undrained test, consolidated drained test and a provision for user defined programs. The user program is a program that is provided for operators to create their own testing methods and protocols. In this Research, the AASHTO T 307-99 program for the determination of resilient modulus of aggregate base materials has been used. The figure 3.12 below shows a sample test data window during the test.

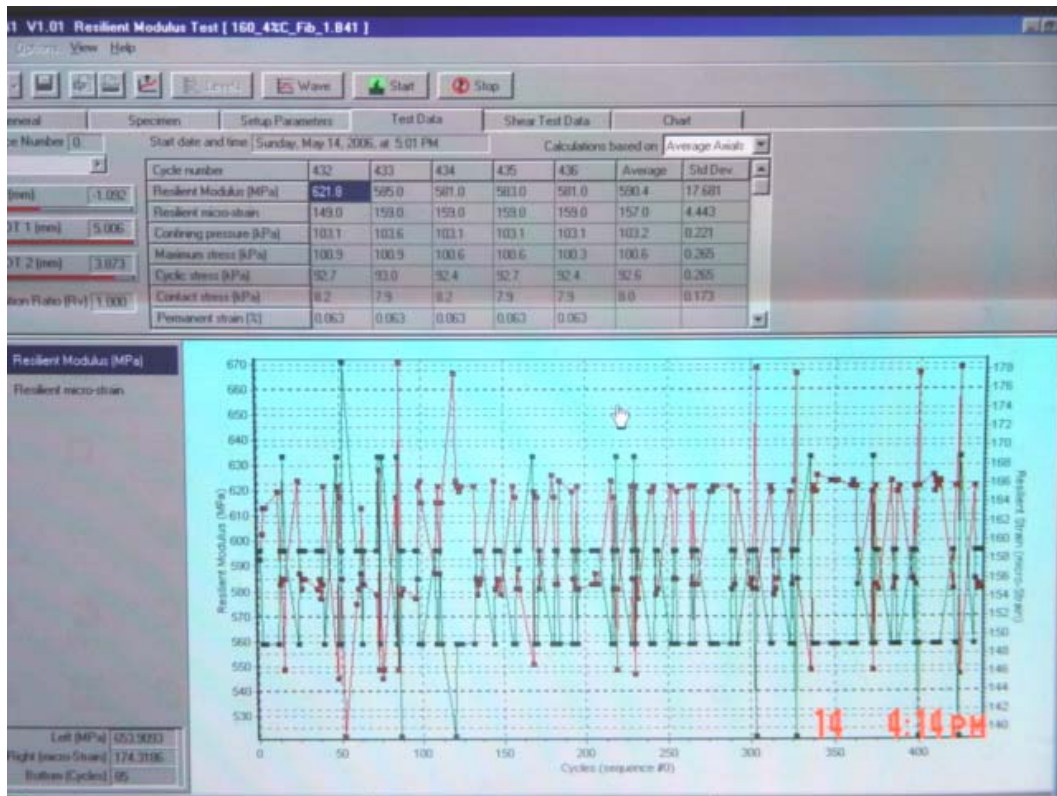


Figure 3.12 Software Windows Showing the Test Data

3.8 Environmental Assessments

Environmental tests consist of some physical and chemical tests performed on the samples collected from column studies. Leached samples were collected from all the recycled materials (ECS, RAP and QF) and from local soil. Recycled materials were compacted at OMC and the local soil was placed in its natural state in a cylindrical container. Water was sent from the top plate and was collected from the bottom. Figure () shows the setup.

Leached tests include pH (Std. Methods 4500-H⁺ B (pH meter)), turbidity (Std. Methods 2130 B, Turbidimeter), total suspended solids (Std. Methods 2540 D), Volatile

Suspended Solids (Std. Methods 2540 E), Total Dissolved Solids (Std. Methods 2540 C), Volatile Dissolved Solids (Std. Methods 2540 E), Biochemical Oxygen Demand (Std. Methods 5210 B).

3.8.1 pH

pH is a measure of the acidity or alkalinity a solution. Solutions with a pH less than seven are considered acidic, while those with a pH greater than seven are considered basic (alkaline). pH 7 is considered neutral because it is the accepted pH of pure water at 25 °C. pH is formally dependent upon the activity of hydrogen (H^+). Practically every phase of water supply and wastewater treatment such as acid-base neutrality, water softening, precipitation, coagulation, disinfection and corrosion are pH dependent. pH suitable for existence of most biological life is typically in the range of 6 to 9.



Figure 3.13 pH meter

3.8.2 Turbidity

Turbidity is cloudiness or opacity in the appearance of a liquid caused by solids, particles and other pollutants. Turbidity measurement provides an indication of the clarity of water and water quality. High turbidity values are due to the presence of clay, silt, silica, organic, detritus and micro-organisms. Nephelometric turbidity unit (NTU) is the common unit to express the turbidity.



Figure 3.14 Turbidimeter

3.8.3 Solids

Solids refer to matter suspended or dissolved in water. Total suspended solids (TSS) are the solids retained over a 1.5 μm filter paper. Solids passing through 1.5 μm filter paper are known as dissolved solids. Suspended solids eventually settle to the bottom of the natural body of water, causing formation of a sludge blanket. This may change the bottom condition affecting the growth and development of benthic organisms. Total dissolved solids (TDS) can change the salinity of water. Volatile suspended solids (VSS) and volatile dissolved solids (VDS) are determined by igniting the sample in a muffle furnace at 550°C. Volatile solids (VS) signify the amount of organic matter present in the sample.

3.8.4 Biological Oxygen Demand (BOD)

BOD is defined as the amount of oxygen required by micro-organisms to stabilize decomposable organic matter under aerobic conditions. The standard BOD test is conducted over a 5-day period at 20° C. BOD₅ test is useful in determining the extent of organic pollution in natural waters. Clean waters have BOD₅ of less than one (1) mg/L. Medium to strongly polluted waters have BOD₅ of 1-3 and above 3 mg/L, respectively.



Figure 3.15 BOD setup

3.9 Summary

This section provides a summary of experimental methods (OMC, Sieve Analysis, UCS, Swell, Consolidation, and Resilient Modulus), test procedures and equipment used in this research. The water quality parameters analyzed were: pH, turbidity, total suspended solids, volatile suspended solids, total dissolved solids, volatile dissolved

solids, and BOD. All these experimental and environmental tests were carried on the recycled materials and the local soil. Tests results are presented in chapter 4.

CHAPTER 4

ANALYSIS OF THE TEST RESULTS

4.1 Introduction

This chapter mainly discusses all the test results on the recycled aggregate base materials and the local subgrade material. Test results include unconfined compressive strength tests, swell tests, consolidation and resilient modulus tests. Environmental assessment results which explain about the leached behavior of the recycled materials are also discussed. These results will provide valuable insight potential of recycled materials as a pavement base material. All the tests were performed at UTA geotechnical and geo-environmental laboratories, which is fully equipped with all the experimental setups.

4.2 Unconfined Compressive Strength

Unconfined Compressive Strength (UCS) tests were performed on the recycled base materials at optimum moisture content. Samples were compacted in a 2.8 x 5.6 in. (diameter × height) mould. The treated samples were tested after a curing period of 7 days in a controlled environment. Figure 4.1 shows the unconfined compressive strength test results for the untreated and treated quarry fines. Untreated samples showed a low strength close to 100 kPa. The cemented QF material showed a peak UCS value close to 1200 kPa, which was 12 times more than the strength of the untreated QF material. When these recycled materials treated with cement the particle to particle bonding increase and the strength required for failure becomes very high. Thus the high strength in CQF could

be attributed to cementing reactions of the cement materials used for the stabilization of QF material. Figure 4.2 shows the unconfined compressive strength test results for the local subgrade material and RAP material. From the graph it can be observed that the local subgrade is having a very less compressive strength (≈ 110 kPa). It may be due to high moisture content in the natural state and may be due to high plastic characteristics of the soil. RAP material showed a peak stress of 340 kPa which was expected for these kind of recycled materials.

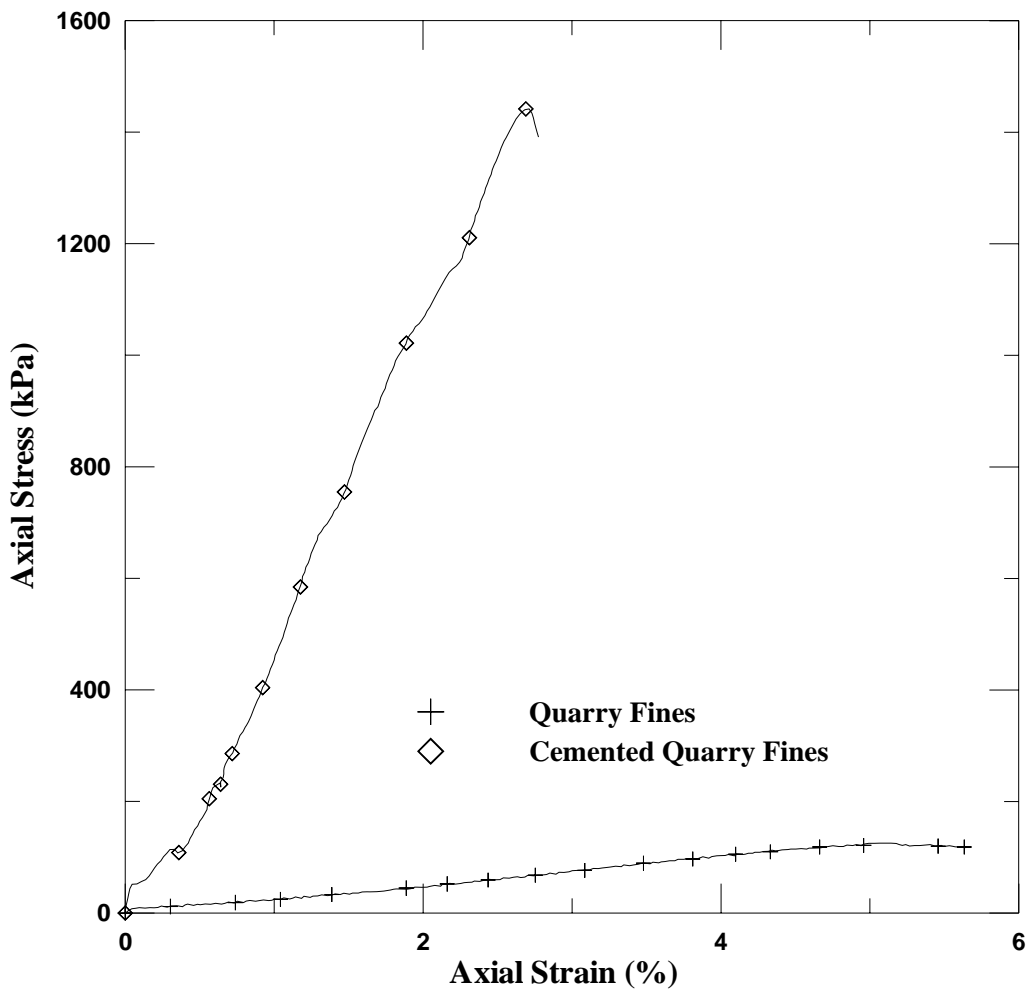


Figure 4.1 Unconfined Compressive Strength for treated and untreated quarry fines specimens

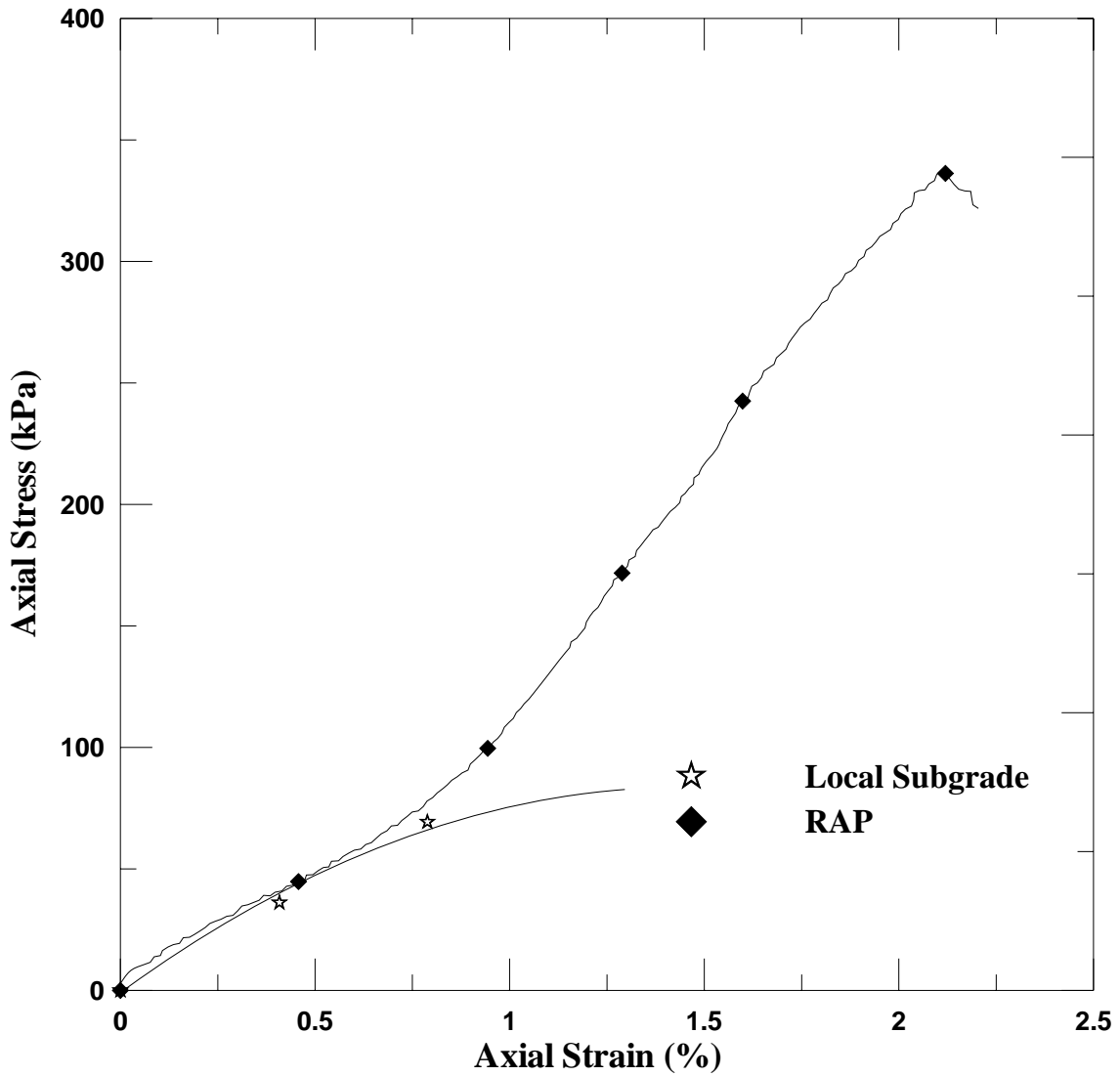


Figure 4.2 Unconfined Compressive Strength for local subgrade material and RAP material

Figure 4.3 shows the comparison for the RAP, local subgrade, and untreated and treated quarry fines. It can be clearly seen that the quarry fines material shows a higher compressive strength when treated with cement.

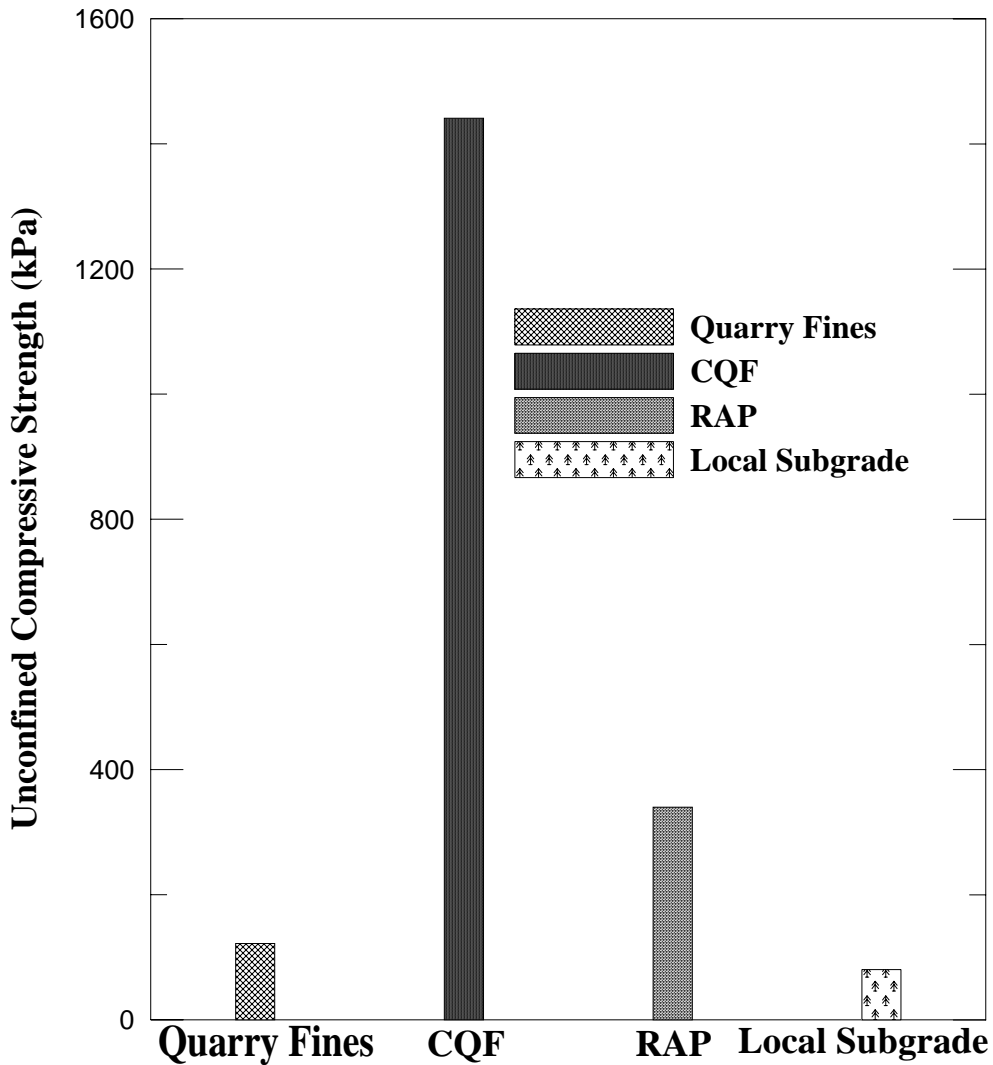


Figure 4.3 Comparison of Unconfined Compressive Strengths of all the materials tested

4.3 Free Vertical Swell

To understand swelling nature of all the materials, vertical free swell tests were conducted on both treated and untreated samples. These tests were performed on a 2.8 inch diameter samples as per ASTM D-4546 method. Treated sample was subjected to a curing period for 7 days under controlled environment. The samples (RAP, treated and untreated Quarry Fines) were compacted at optimum moisture content (OMC), and the local subgrade soil was compacted at its natural moisture content and was subjected to

testing. Figure 4.4 shows the swell strain (%) variation with respect to time (hours) on logarithmic scale. It can be observed that the magnitude of the vertical free vertical strain for the untreated quarry fines was close to 6%. For the cement treated quarry fines swell strain was close to 0%. This confirms that the QF is a moderately swelling material whereas the cemented quarry fine is a non-swelling material. The non-swelling behavior of CQF was attributed to cementing actions in the treated sample.

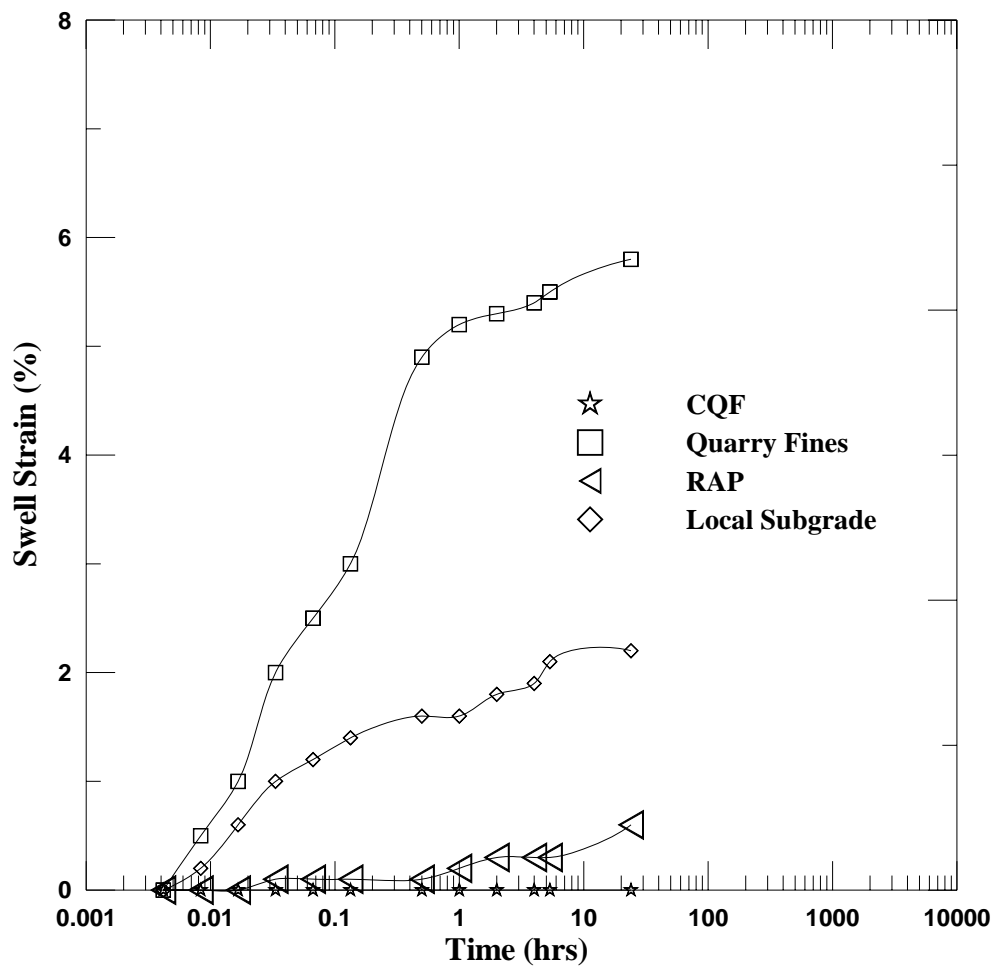


Figure 4.4 Variation of free vertical swell strain (%) with elapsed time (hrs)

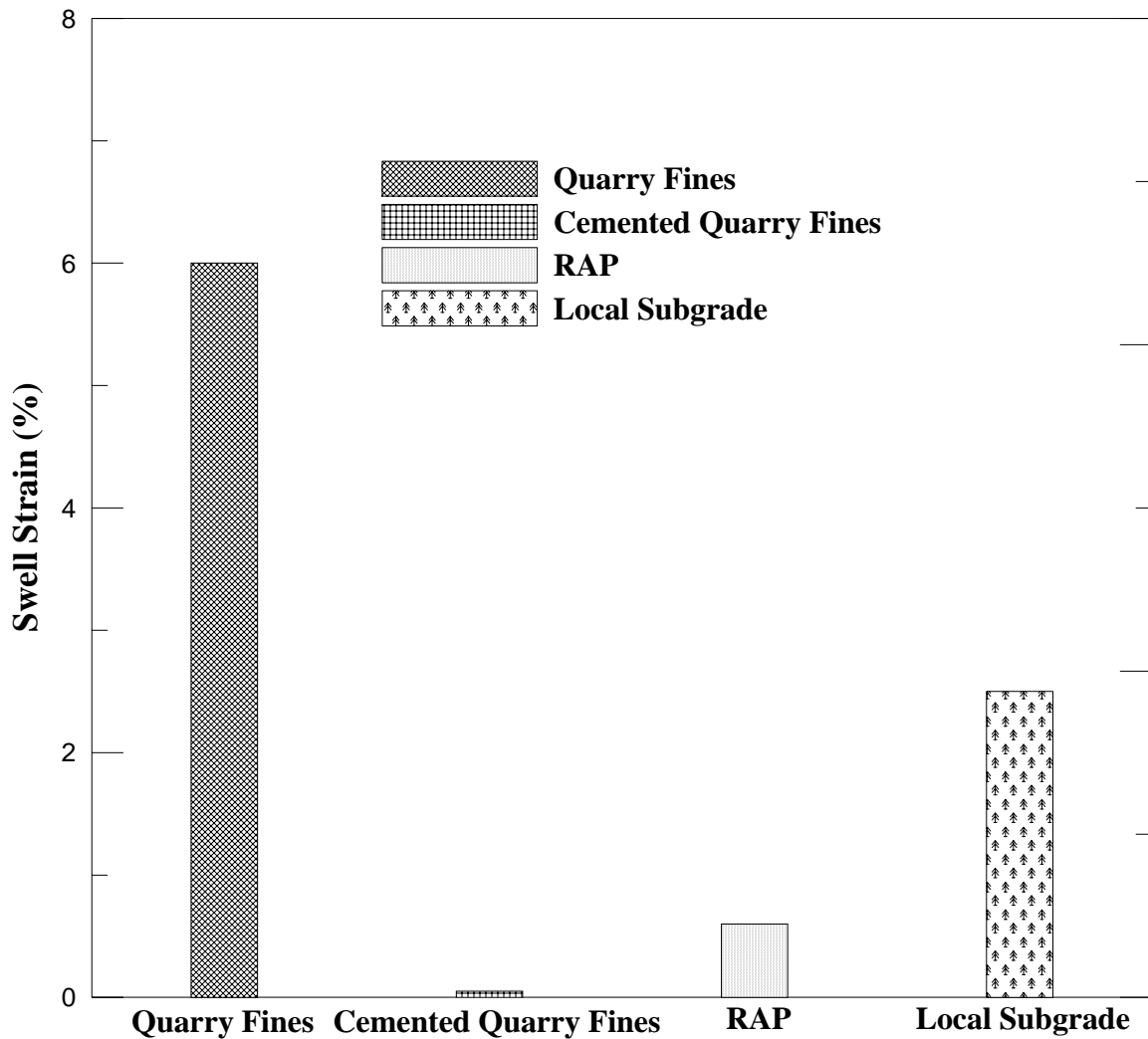


Figure 4.5 Swell Strains for recycled materials and local subgrade

Figure 4.5 give the bar graph for swell strains for the recycled materials and the local subgrade material. It was observed that local subgrade soil had a strain of 2.5 % which was high for the pavement subgrade material. This was attributed to the plastic characteristics of the local soil. RAP had a swell strain of 0.7 percent which was less compared to the local soil and such swell expected in the RAP materials.

4.4 Consolidation Tests

Consolidation tests on all the three materials (RAP, Quarry Fines and Local soil) were performed to address the compressibility nature of the recycled materials. The test was conducted according to ASTM D2435. Sample was prepared in a 2.5 inch diameter mould and was then placed for testing in an oedometer. An initial setting pressure of 40 kPa was applied on the sample. The initial setting pressure was chosen such that there was no swelling. The load was allowed to stand till there was no change in the dial gauge reading. Dial gauge reading was noted under initial setting pressure. The first increment of the load 40 kPa was applied and the readings were recorded at certain time intervals for 24 hours. The loading was doubled and hence successive pressures of 80, 160, 320 and 640 kPa were applied during loading. After that, the final load was unloaded to 160 kPa and finally to 40 kPa.

Figure 4.6 shows the graph between void ratio and logarithm of the pressure for the recycled materials and also for the local subgrade. Compression index C_c for the recycle materials was found to be 0.04; such number was expected for granular materials. Table 4.1 gives the values for the compression and recompression indices for the local subgrade and the recycled materials. C_c values generally vary from 0.3 to 0.1 for highly plastic clays and less than 0.075 for the low plastic clays (Terzaghi and Peck, 1943). From the table C_c values for the recycled materials indicate that they are less plastic and are less compressible. The local subgrade material has a C_c value of 0.135 which indicates that it is highly plastic soil and highly compressible which may result in high settlements on the pavement surface and can cause undulations.

Table 4.1 Compressibility Coefficients for recycled and local subgrade materials

Compressibility Coefficients	RAP	Quarry Fines	Local base Material
Compression index, C_c	0.044	0.0349	0.135
Recompression Index, C_r	0.007	0.007	0.017

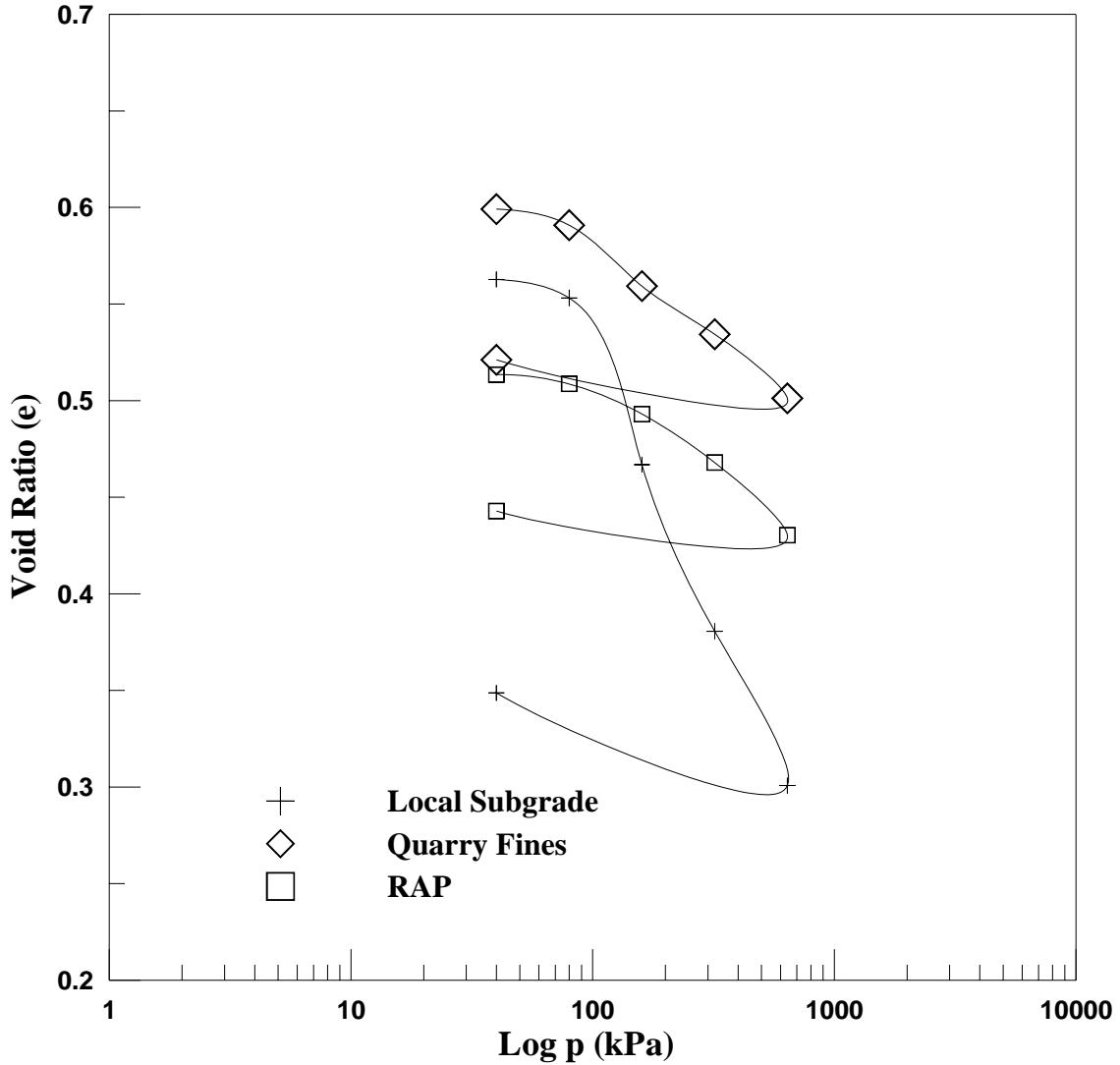


Figure 4.6 Variation of void ratio (e) with applied pressure (log p) for the recycled materials and local subgrade

4.5 Resilient Modulus

A repeated load triaxial test was followed to determine the resilient modulus for treated and untreated QF and RAP by following the AASHTO test procedure, T 307-99: 'Standard Method of test for Determining the Resilient Modulus of Soils and Aggregate Materials'. The test was conducted on compacted soil specimens that were prepared in accordance with the standard procedure.

The Resilient Modulus test applies test loads, which simulate the traffic wheel loads on the in situ soils by applying a sequence of repeated or cyclic loading on soil specimens. A haversine-shaped wave load pulse with a frequency of 10 Hz was applied as the traffic wheel loading on the soil. These loading features are in accordance with the resilient modulus test procedure outlined in AASHTO T 307-99. Both treated and untreated quarry fines samples were tested for the resilient modulus tests. Samples were compacted at the optimum moisture content in three layers. After compaction, the specimens have been extruded and the untreated sample was tested immediately after extrusion and the treated sample was tested after a curing period of 7 days.

Three test specimens were tested and the results were similar for all the three tests. Figures 4.7, 4.8, and 4.9 presents the average results of resilient modulus tests carried out on untreated quarry fines, cemented quarry fines and RAP material respectively. In untreated quarry fines as the deviatoric and confining stresses increases the resilient modulus increases and became constant and was decreasing after some cycles. In cemented quarry fines resilient modulus was increased with increased confining and deviatoric stress. This trend explains that the cement treated material behaves as a

granular material. In RAP material resilient modulus increased with deviatoric and confining pressure.

Figure 4.10 gives the comparison for the resilient modulus between the treated and untreated quarry fines. The graph shows higher M_R values for the cemented quarry fines and lower M_R values for the untreated quarry fines at the same axial and confining pressures. This is due to the soft nature of untreated samples which can produce high elastic strains. In untreated samples the peak resilient modulus was found to be around 240 MPa and further increase in the confining and axial stresses the value was decreased. In the cemented treated QF specimens, particle to particle bonding is very high and thus they deform very less under high confining and axial stresses.

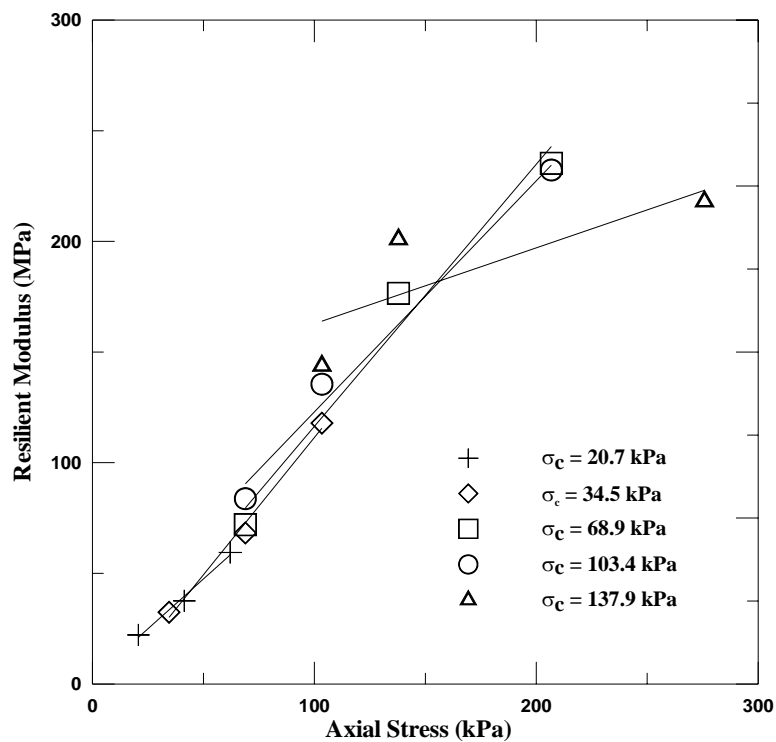


Figure 4.7 Variation of resilient modulus with axial stresses at different confining pressures for Untreated Quarry Fines

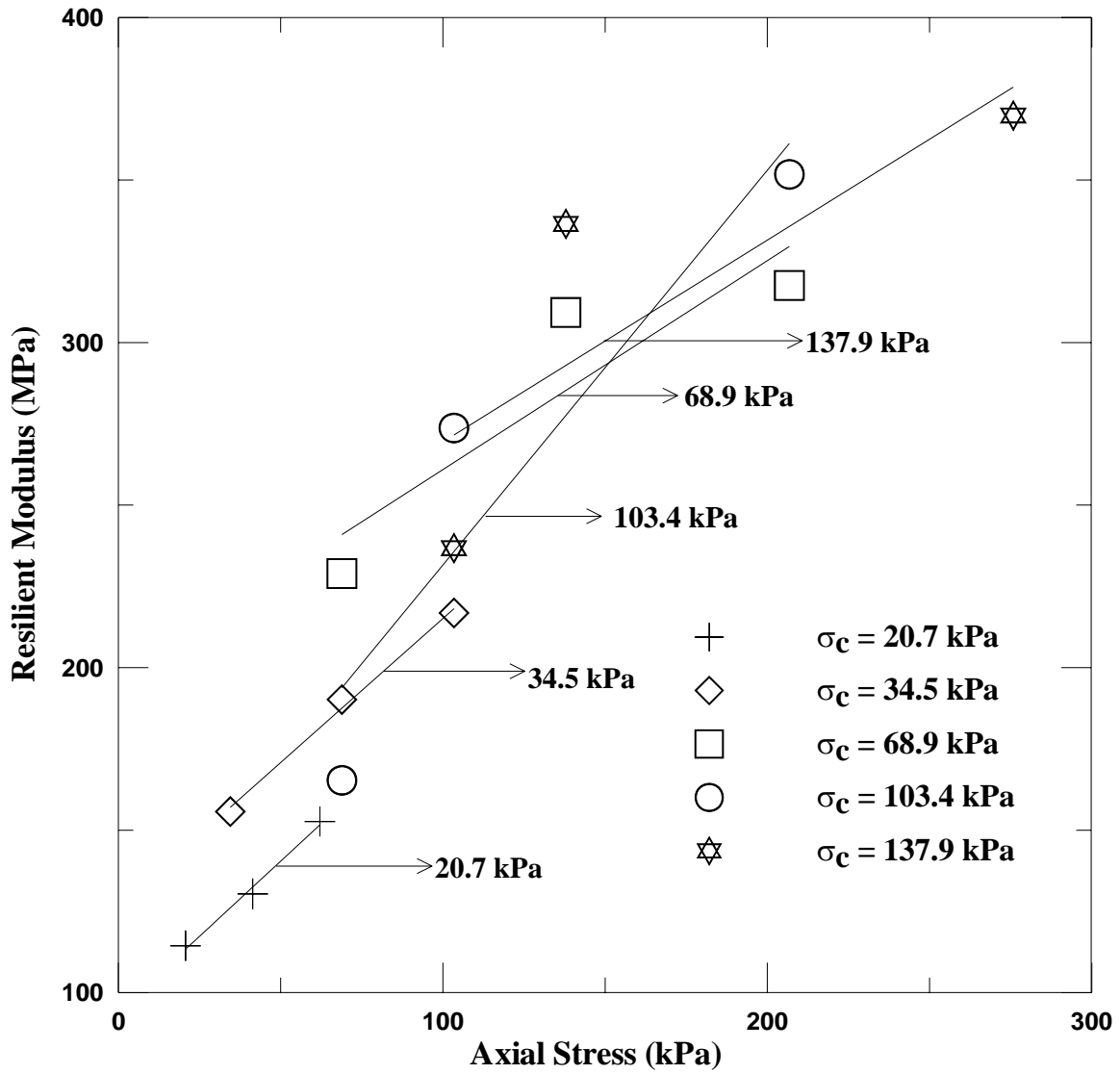


Figure 4.8 Variation of resilient modulus with axial stresses at different confining pressures for Cemented Quarry Fines

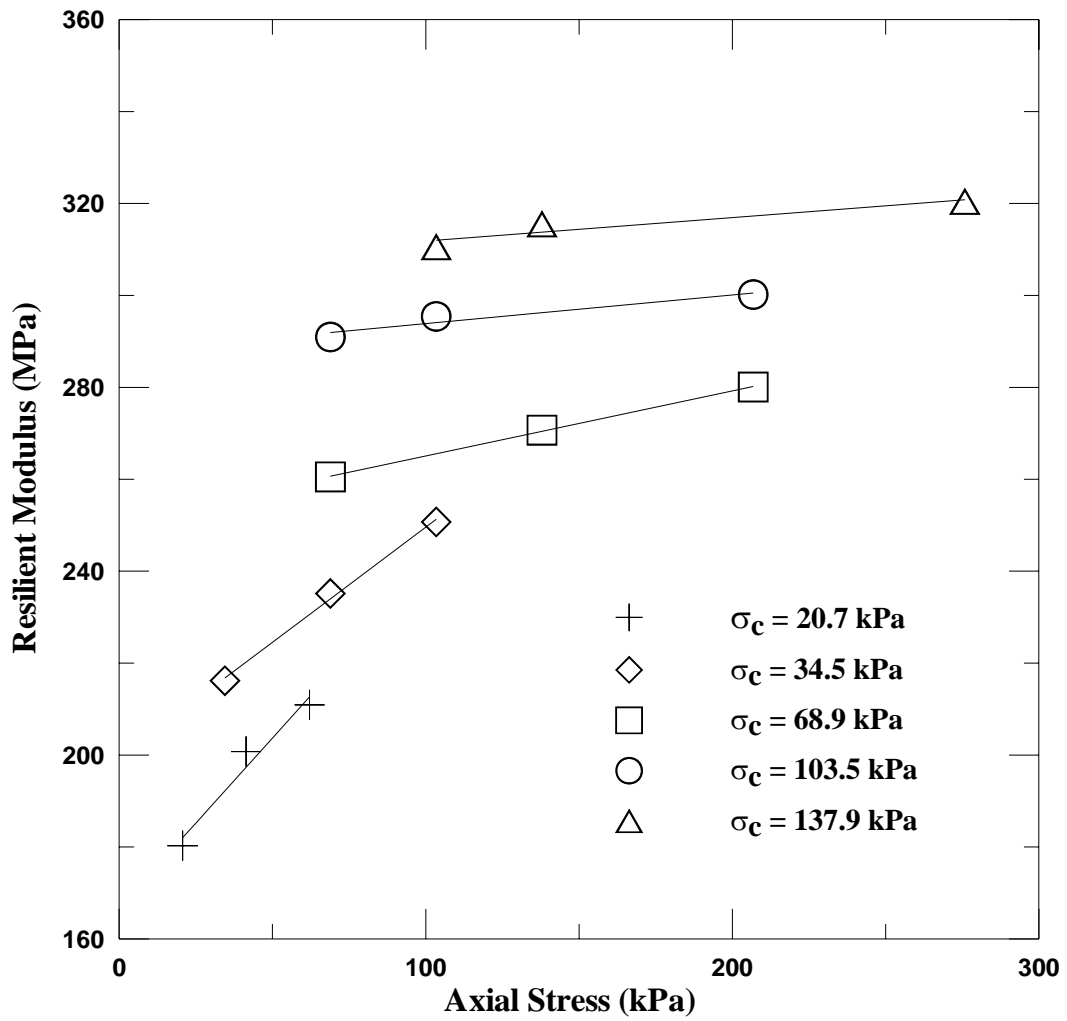


Figure 4.9 Variation of resilient modulus with axial stresses at different confining pressures for RAP material

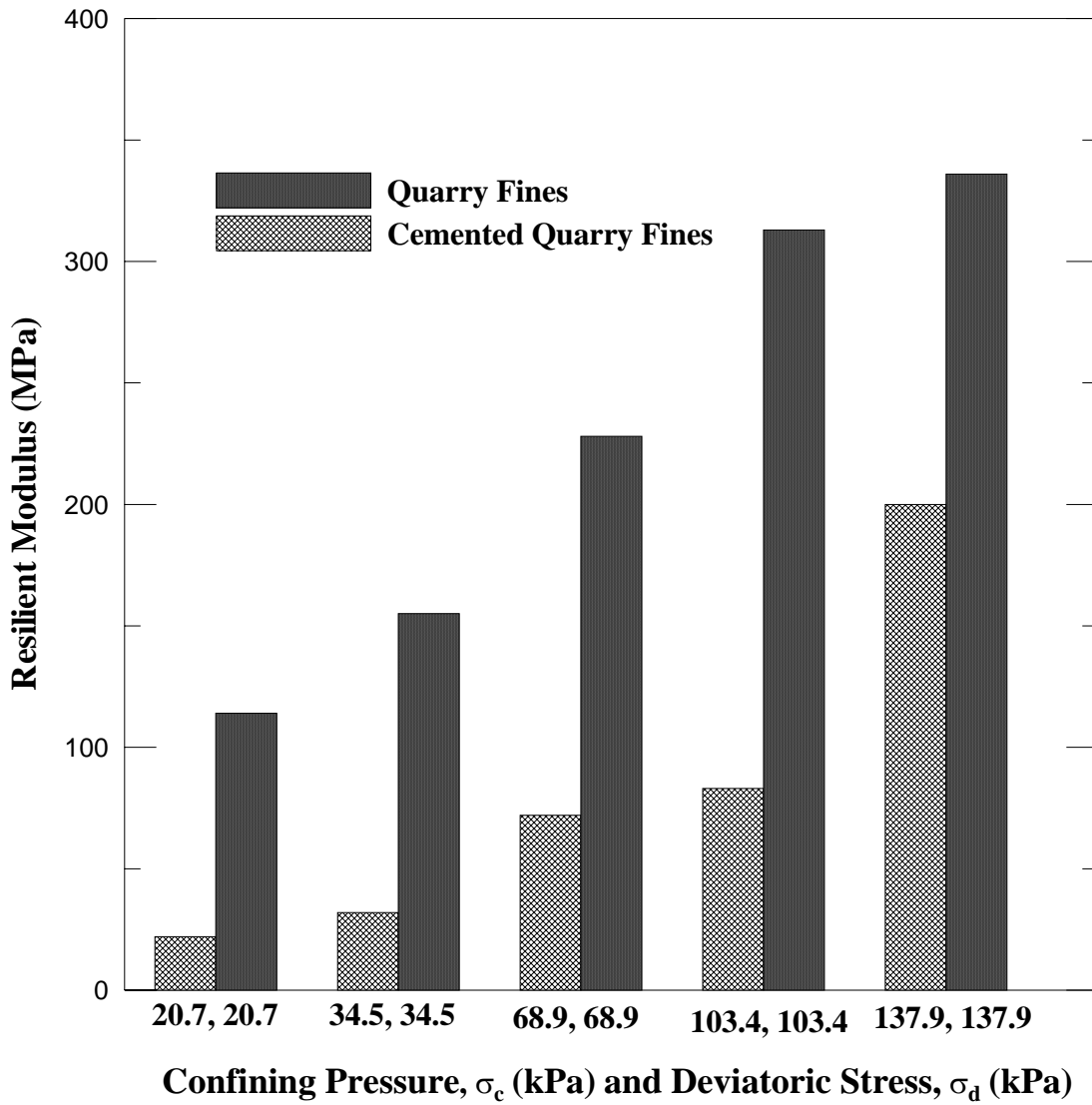


Figure 4.10 Comparison of Resilient Modulus for Quarry Fines and Cemented Quarry Fines

4.6 Leaching Tests

Leaching tests were conducted on all the recycled aggregate bases and the local subgrade materials. These tests include pH, turbidity, total suspended solids, total dissolved solids, volatile suspended solids, and volatile dissolved solids, and other chemical identification tests. These tests were evaluated by comparing the test values and the US EPA threshold values. All the values obtained were in permissible limits.

Leachate was collected from permeability setup. Sample was compacted in 6 × 9.6 in. (diameter × height) mould at optimum moisture content and then water was passed through the sample from the top and the leachate was collected at the bottom. About 1 liter of leachate was collected and used for above described tests. Table 4.2 gives the results for all the tests.

Table 4.2 Leachate test results

Type of Test	RAP	Quarry Fines	Local subgrade
pH	6.81	6.77	7.23
Turbidity (NTU)	2	2.5	3
Total Suspended Solids (mg/L)	65	65	70
Total Dissolved Solids (mg/L)	500	1500	1000
Volatile Suspended Solids (mg/L)	25	35	30
Volatile Dissolved Solids (mg/L)	250	500	500
BOD (mg/L)	17	13	27

Total Suspended Solids (TSS) test was conducted according to ASTM 2540 D. Figure 4.11 shows TSS test results. TSS results are not of significance in water quality or

potential pollution characteristics. High TSS values for all the samples may be attributed to the washing out of fines from the specimen due to their high porosity.

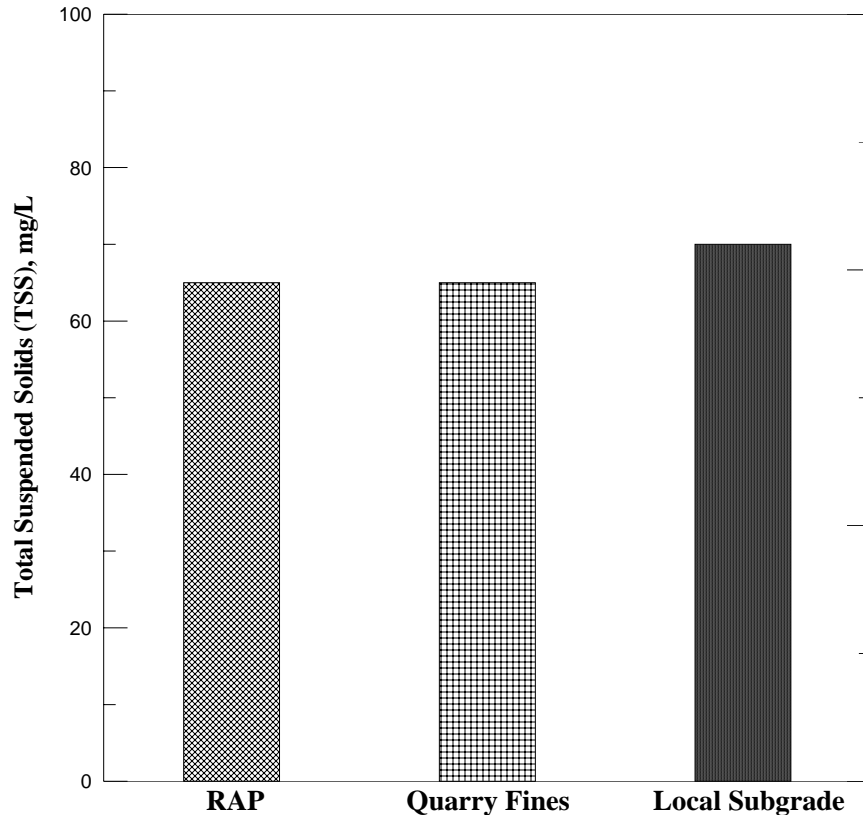


Figure 4.11 Total Suspended Solids (TSS) for different recycled materials tested

Total Dissolved Solids (TDS) test was done according to ASTM 2540 C. TDS values are important as it has chemical effect on the pure water. Materials in the soluble state may represent alkalinity, acidity, salinity etc. Figure 4.12 shows the total dissolve solids for different recycled materials. It can be seen that the QF have higher TDS values (≈ 1500 mg/L) than RAP and local subgrade materials. As per EPA threshold values (< 2000 mg/L) the values obtained from these recycled materials are in the permissible limits.

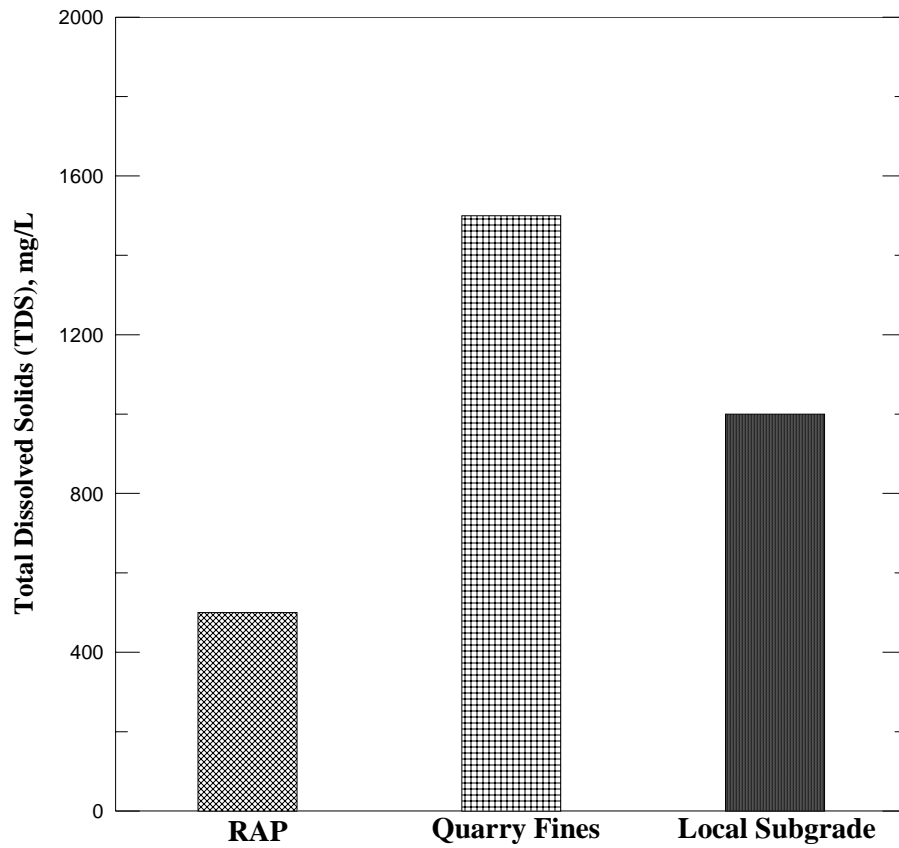


Figure 4.12 Total Dissolved Solids (TDS) for different recycled materials tested

Volatile Suspended Solids (VSS) test was done according to ASTM 2540 E.US EPA threshold values for the industrial activities was about 100 mg/L. The obtained VSS values for QF, RAP and local subgrade soils are in permissible limits.

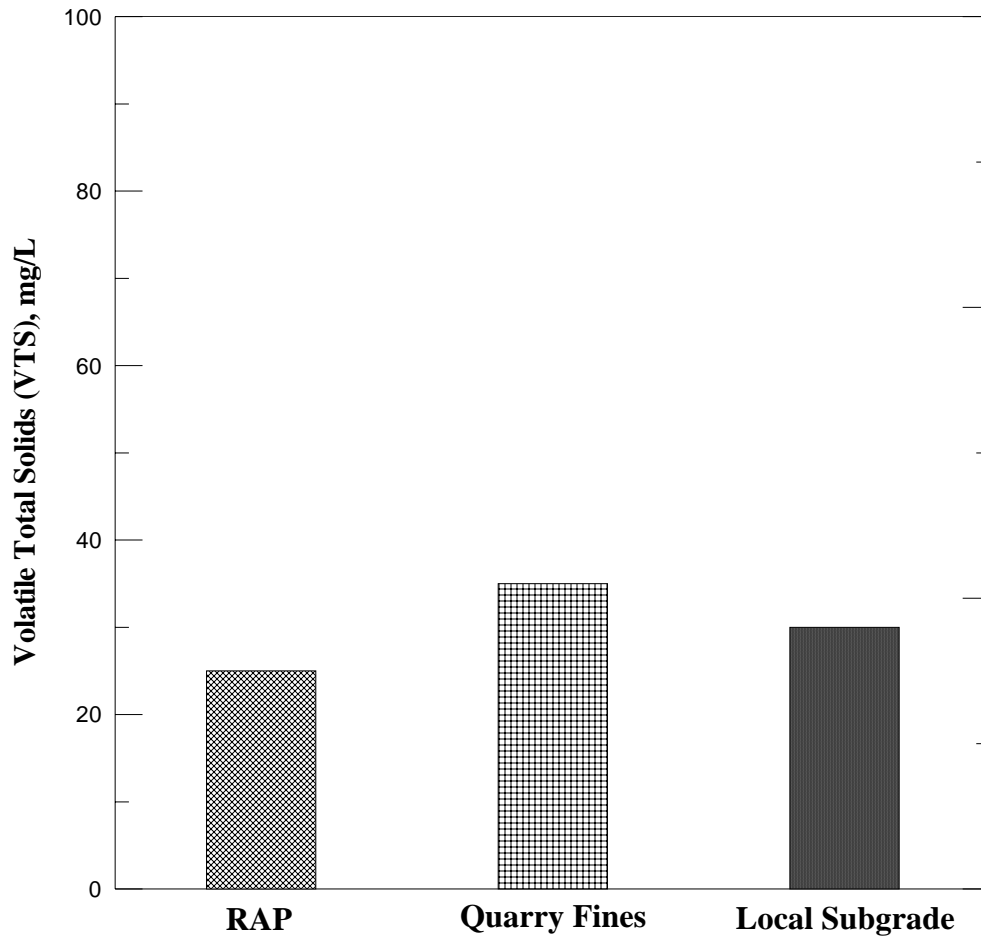


Figure 4.13 Volatile Suspended Solids for different recycled materials tested

Volatilic Dissolved Solids (VDS) test was done according to ASTM 2540 E. Figure 4.14 shows the results obtained from Volatilic Dissolved Solids test for QF, RAP and local subgrade materials. The values obtained are in permissible limits as per US EPA threshold values (<1000 mg/L).

Figure 4.15 shows the pH values for the recycled materials and the local subgrade material. As per US EPA, the range of pH values for the irrigation and drinking purposes should be between 6.5 and 8.4. The values obtained from these recycled materials are in the permissible limits.

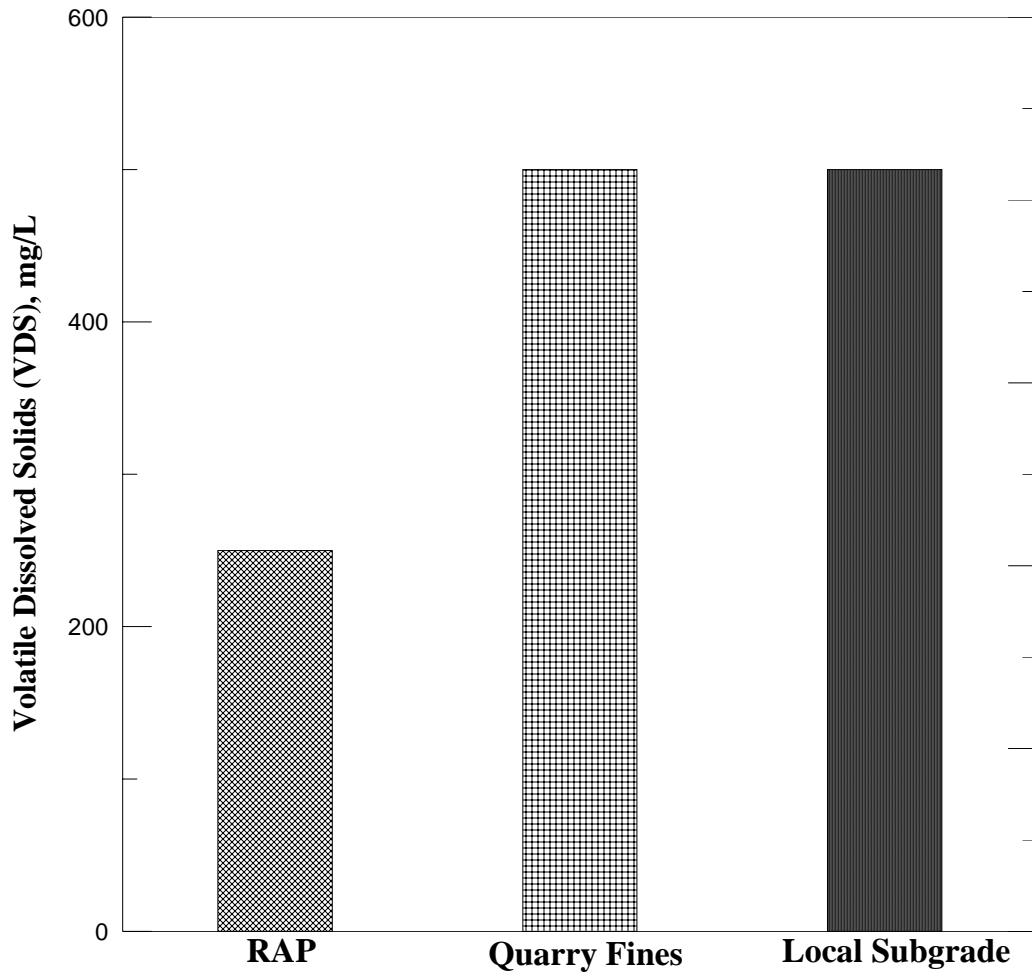


Figure 4.14 Volatile Dissolved Solids in mg/L for different recycled materials tested

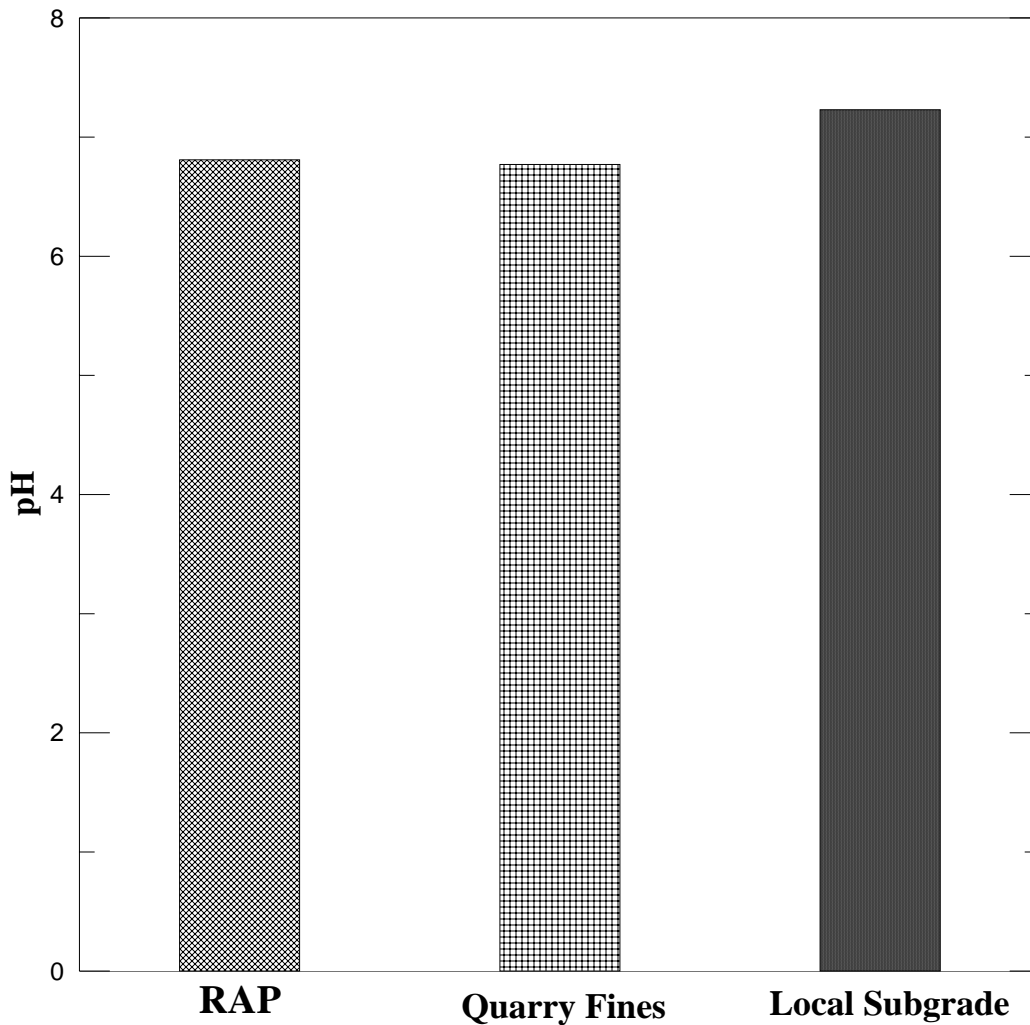


Figure 4.15 pH values for recycled materials and the local subgrade

Turbidity test was carried out according to ASTM 2130 B. Turbidity is measured accurately with a Nephelometric turbidimeter in units called Nephelometric Turbidity Units (NTU). Figure 4.16 shows the turbidity values for recycled materials and local subgrade material. The values obtained from the turbidimeter are in permissible limits as per US EPA values (<3 NTU).

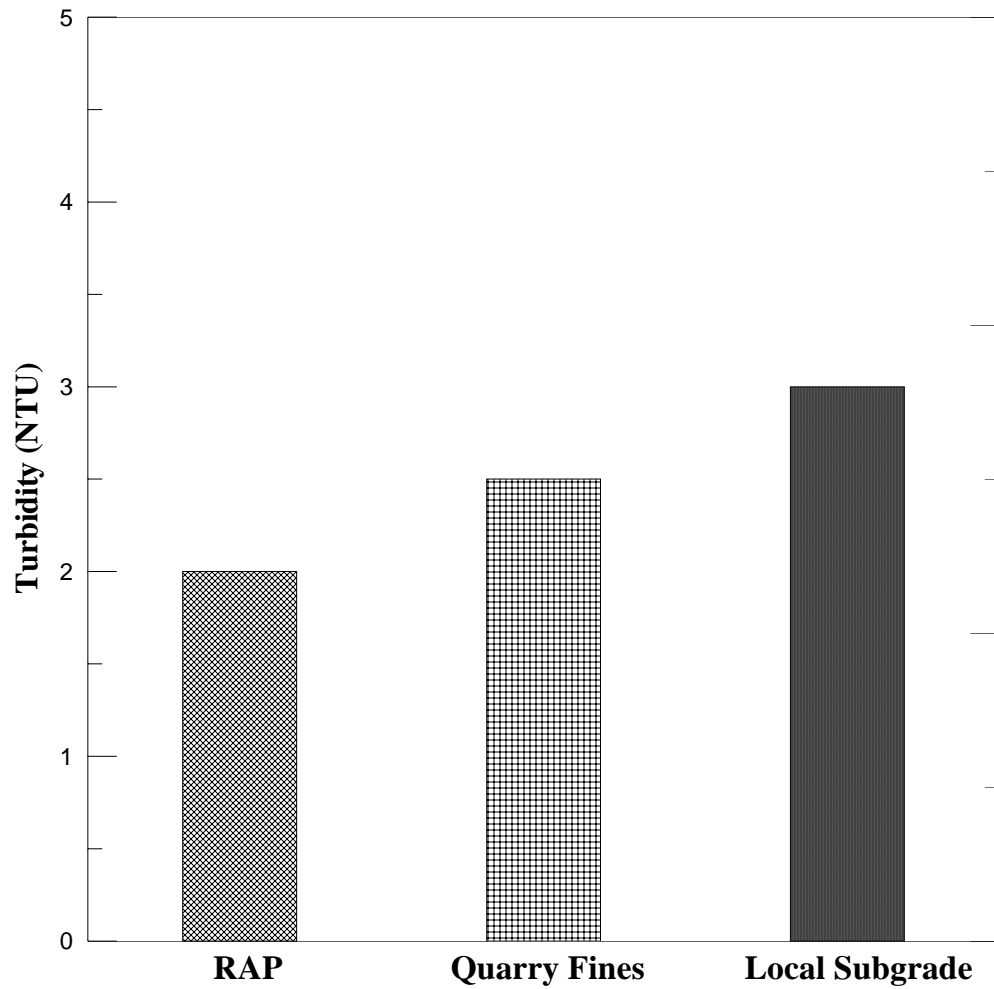


Figure 4.16 Turbidimeter values for the recycled materials and the local subgrade

Figure 4.17 shows the results obtained from Biological oxygen Demand (BOD) tests on recycled materials and local subgrade materials. This test was performed according to ASTM 5210 B. The values obtained from the test are in permissible limits for the recycled materials but for the local soil it was moderately higher as per US EPA values (< 20 mg/L).

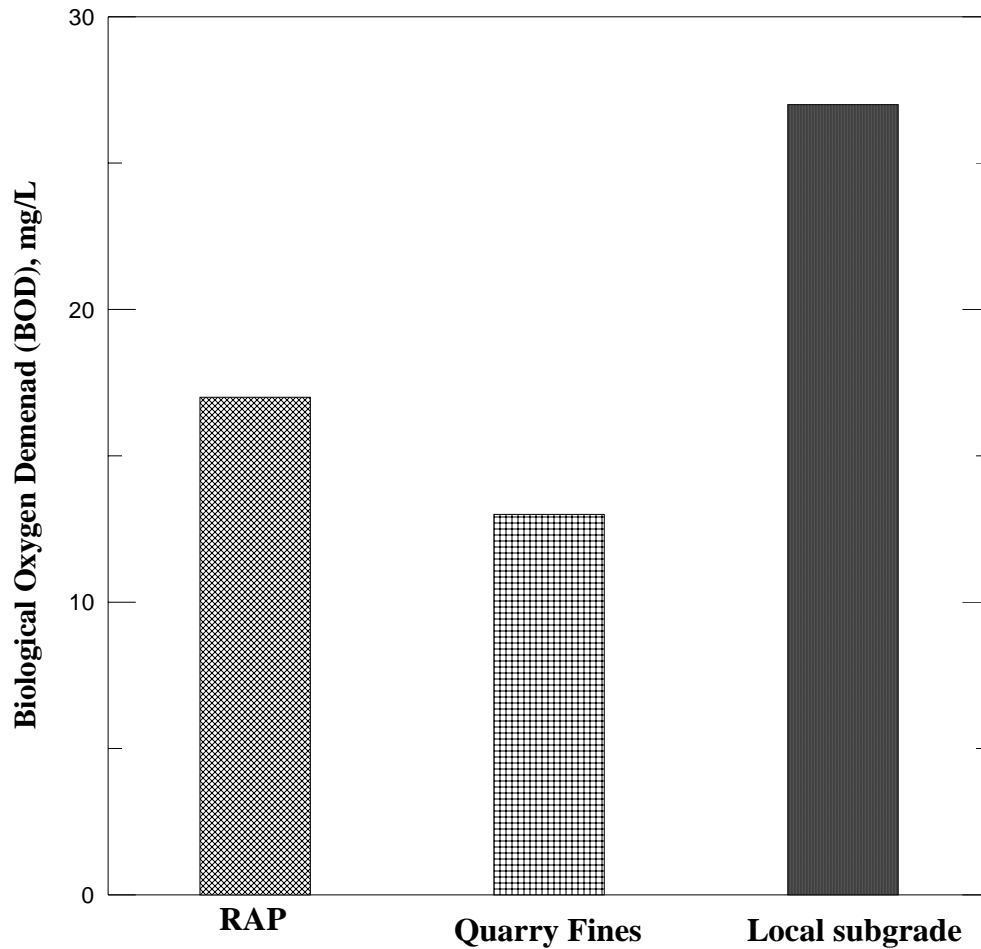


Figure 4.17 Biological oxygen Demand (BOD) for recycled and local subgrade materials
4.7 Summary

This chapter mainly discusses the engineering tests, which include unconfined compressive strength, swell strain, consolidation, and resilient modulus. It also discusses environmental assessment tests. It was observed that values from all the engineering tests carried out for the treated quarry fines were higher than the untreated samples. RAP material showed the general trend values for all the engineering tests. The values obtained from the environmental assessment tests were all in the permissible limits as per US EPA threshold values.

CHAPTER 5

FIELD MONITORING RESULTS

5.1 Introduction

In this project, two types of recycled materials namely, reclaimed asphalt pavement (RAP) and quarry fines were utilized as roadway base materials. The present research study in which these materials are utilized is situated on SH360 at Green Oaks Blvd in South Arlington in Tarrant County. Figure 5.1 shows the location of the site.

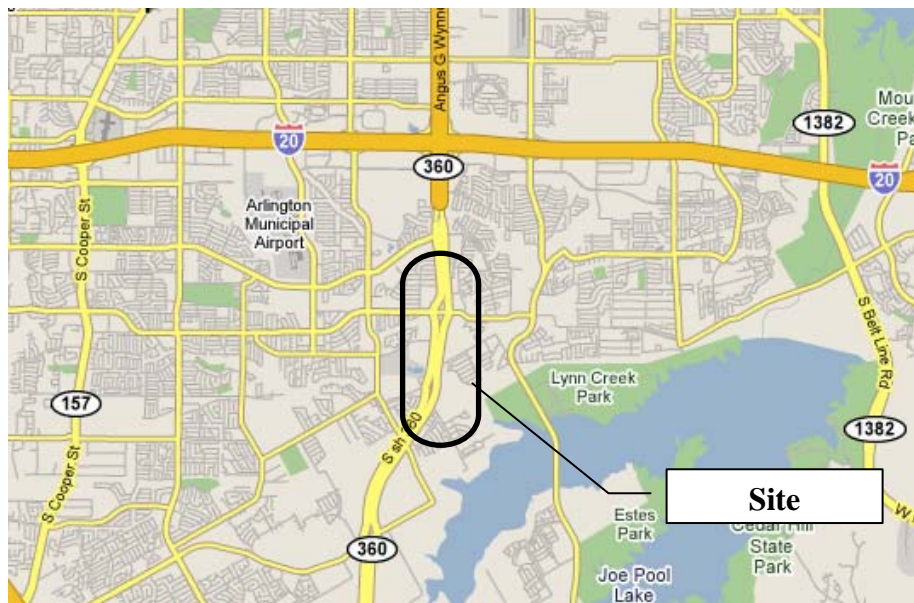


Figure 5.1 Site Location of SH360

5.2 Construction and Stabilization Process

The south bound (SB) direction of the SH360 main lanes used the RAP as the base course and the north bound (NB) direction of the SH360 main lanes used the quarry fines as the base course. On the SB direction, the upper 36 in. of soil subgrade was treated and stabilized with lime. The lime treated soil supports 15 in. of RAP base material which was compacted in two layers with smooth wheeled rollers. This base layer supports 4 in. of hot-mix asphalt concrete (HMAC) and 11 in. of reinforced concrete pavement. On the NB direction, the upper 18 in. of soil subgrade was treated and stabilized with lime, followed by 33 in. of limestone quarry fines in which the top 8 in. was stabilized with cement. The base layer supports 4 in. of HMAC and 11 in. of reinforced concrete pavement.

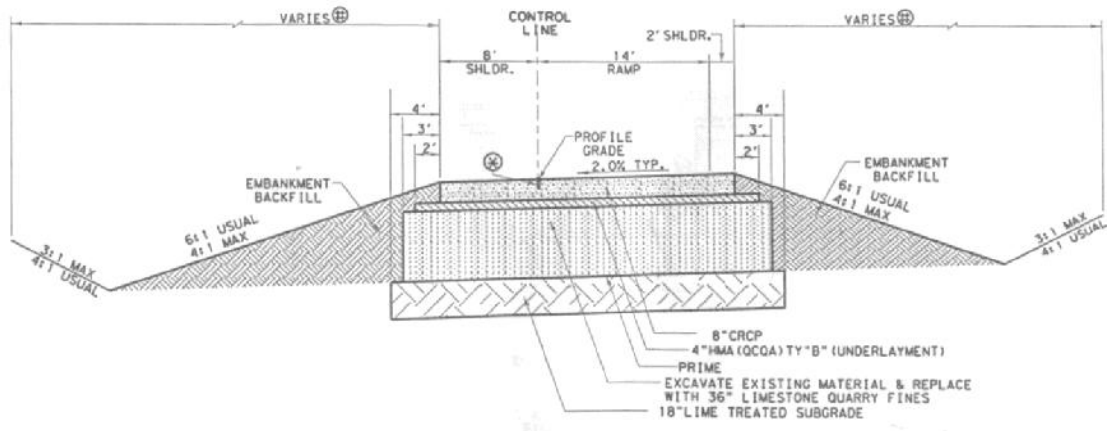


Figure 5.2 Typical Section for Cement Treated Quarry Fines

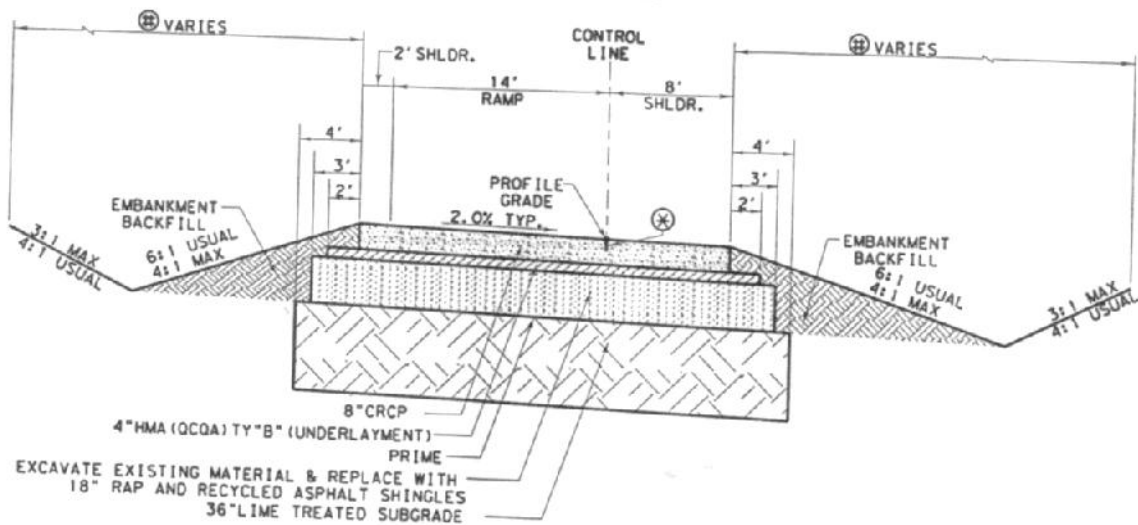


Figure 5.3 Typical Section for RAP material

5.3 Instrumentation and Field Monitoring Data

5.3.1 Pavement Site

Four horizontal inclinometers were installed in the two recycled base materials to monitor the vertical deformations underneath the pavements as shown in Figures 5.2 and 5.3. The inclinometer casings were installed to measure vertical movements before they grew large enough to be observed on the pavement surface with normal pavement data collection equipment. Large movements will necessitate engineering decisions on how to suppress future pavement distress. These casings were placed 8 in. below the 'base - HMAC' interface. The majority of the soil movements are expected to occur from the subgrade, treated subgrade and base layers. The inclinometer readings will provide direct measurements of these soil movements.

Inclinometers were of the closed end type with the pulley system and they are placed along the transverse direction of the roadways covering all travel lanes and

shoulders both inside and outside. All the inclinometers were inclined about 5° down slope to prevent water from entering. After the ditch was made, a thin sand layer was placed on the bottom as bedding material for full support of the casing and the inclinometer casing placed on top. Additional sand was added around and above the inclinometer to the top of the ditch to provide a cushion against crushing from future construction equipment (Fig. 5.2).

The readings from the four horizontal inclinometers (H2 and H3 for Cemented Quarry Fines and H1 for RAP Materials) are presented in Figure 5.6, 5.7 and 5.8. Readings were taken once in month from Aug 2006-07. The results indicated that there were very small movements and these movements may be due to the erosion of soil underneath the casing. Further monitoring is required to observe these movements. Tests were not conducted at the H4 inclinometer location due to difficulties in pushing the probe into the casing. Pavement construction might have induced some damage to the inclinometer casing, which made it difficult to operate the pulley-inclinometer system. An investigation is being conducted to determine the reason for not being able to collect the data at this location.



Figure 5.4 Horizontal Inclinometer Installation

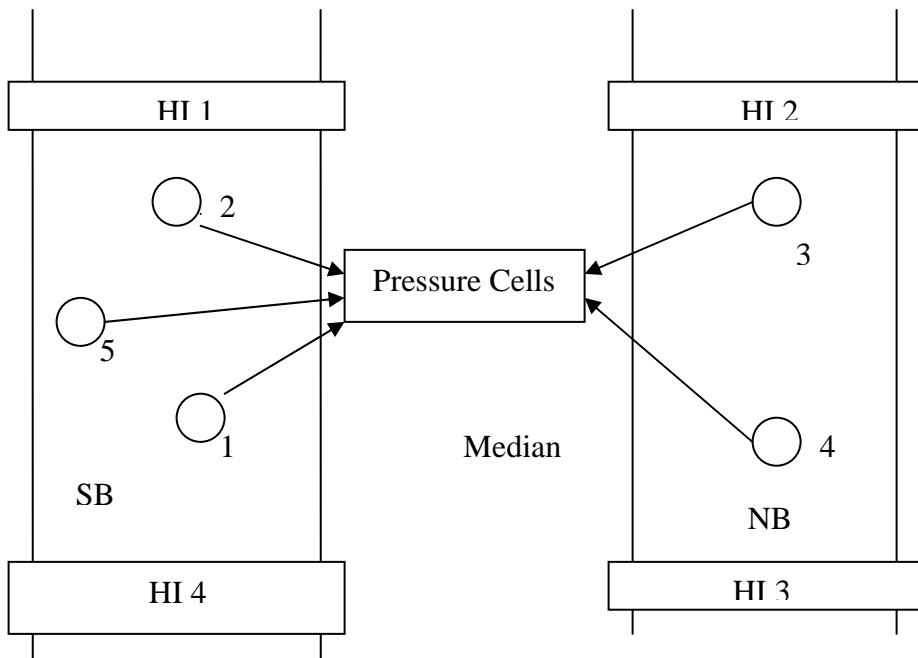
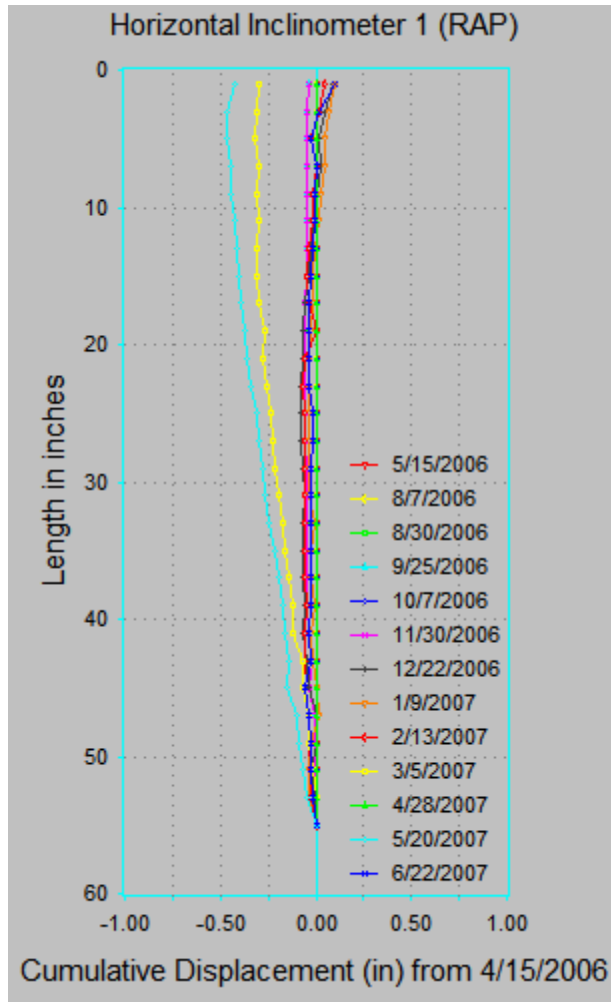
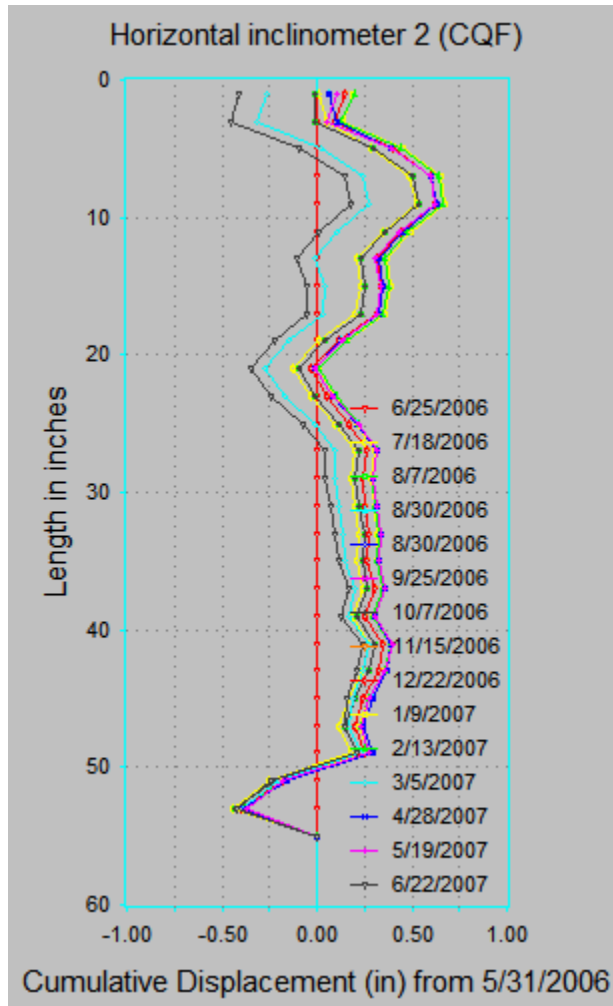


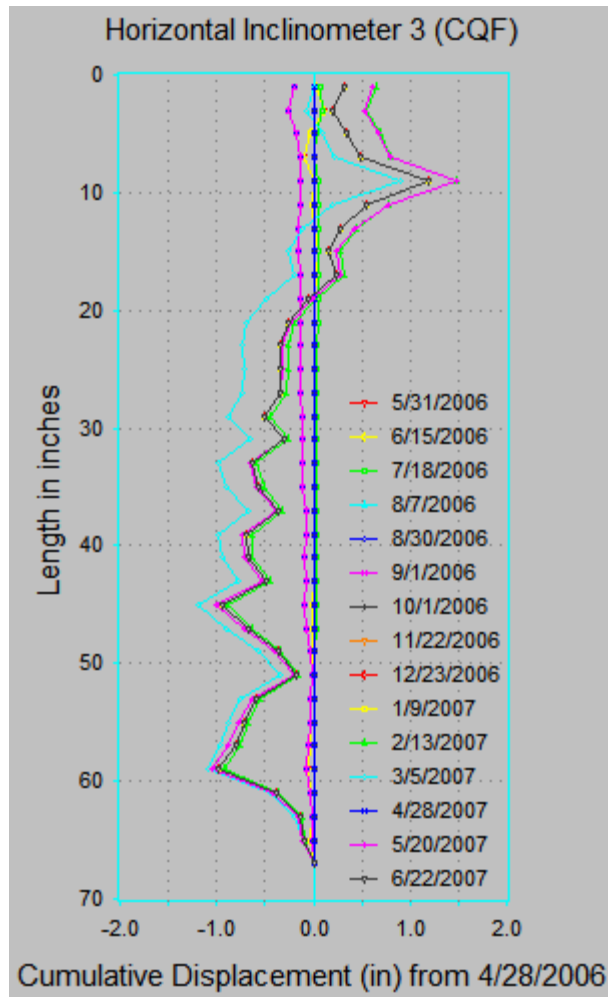
Figure 5.5 Location of Horizontal Inclinometers and Pressure Cells (Plan View)



5.6 Horizontal Inclinerometer 1



5.7 Horizontal Inclinometer 2



5.8 Horizontal Inclinerometer 3

5.4 Pressure Cells

Five Pressure cells (P1, P2, P3, P4 and P5) were installed in the pavement site as shown in Figures 5.9. They measure combined pressure of effective and pore water pressure. These are generally used to verify design assumptions and to warn of soil pressures in excess of those that a structure is designed to withstand.

P1 (SB), P4 (NB), P5 (SB) were placed at 6 in. and P2 (SB), P3 (NB) were placed 1 ft below the asphalt base. All these were placed in the travel lanes were actual

dynamic response can be measured. The calibration factor for the pressure cells was $1\text{mA} = 43.75\text{ kPa}$. The initial reading was taken before laying the asphalt pavement. The current reading was taken after laying the concrete pavement. Difference of these two readings gives the actual pressure exerted by the traffic. Figure 5.10 shows the typical readings.



Figure 5.9 Installation of Pressure Cells

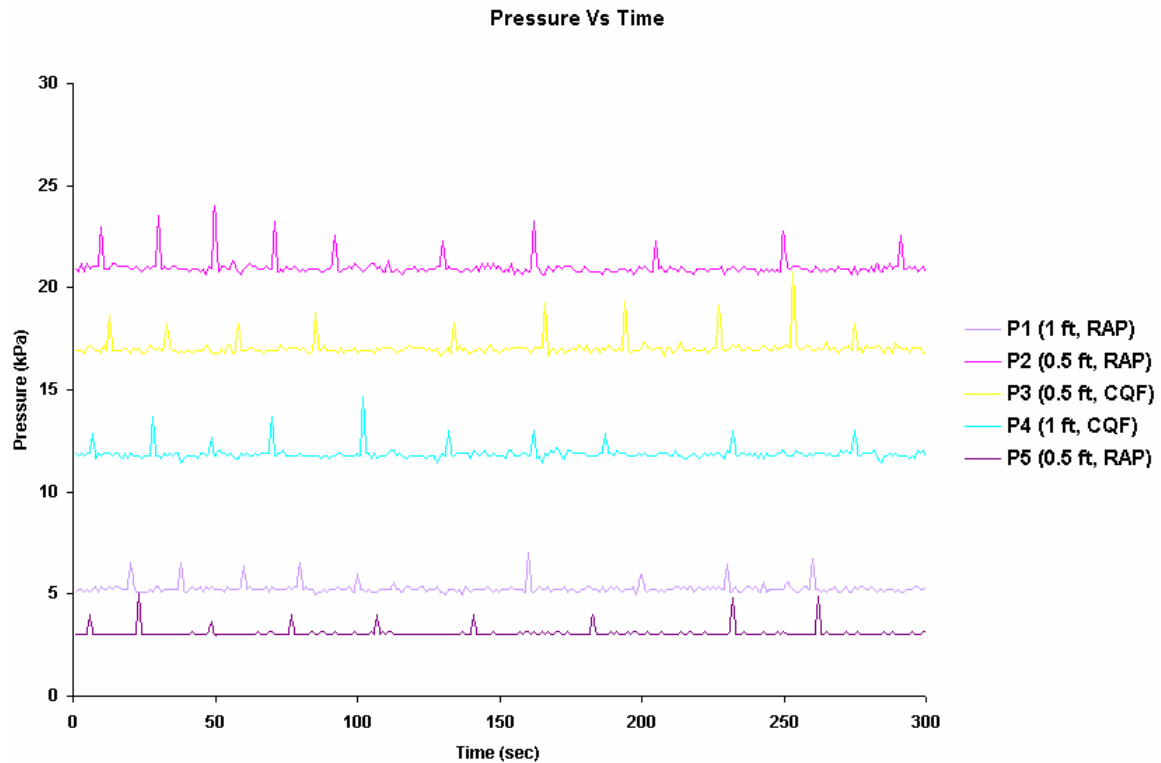


Figure 5.10 Pressure cells readings

5.5 Summary

The data observed from these instruments plays a vital role in verification of the design assumptions. These instruments were located at places where all the critical movements in the pavements occur. Readings were taken from horizontal inclinometers and pressure cells once a month since May 2006-07. Monitoring results from these instruments indicate that the vertical deformations were in permissible limits. Pressure results from the recent surveys shows that the readings were almost consistent throughout the monitoring period. From these observations it can be observed that the recycled materials performance are upto the expectations and can be used in the future for any pavement applications.

CHAPTER 6
SUMMARY, CONCLUSIONS AND FUTURE RESEARCH
RECOMMENDATIONS

6.1 Introduction

The main objective of the present research was to discuss about the performance of recycled materials as a pavement base material and to recommend these materials for the future research projects. These objectives were accomplished and the test results of this research are presented in Chapter 4 and Chapter 5. Some of the salient research findings of this research are summarized in the following section.

6.2 Summary and Conclusions

In this research project mainly two types of recycled materials were used as a pavement base materials, which include recycled asphalt pavement material and limestone quarry fines which was stabilized with cement as these quarry fines were weak in engineering properties which are discussed in the test results section. A series of laboratory tests were performed which include basic tests like compaction, sieve analysis and free vertical swell. Finding the compaction characteristics for these materials further tests were conducted at the optimum moisture content. To find long-term compatibility of these recycled materials as a pavement base material strength tests were performed which include unconfined compressive strength, consolidation tests and resilient modulus. To be in consistent in the test results each sample for the strength tests was performed three times. To find the leachate behavior of these recycled

materials a series of leachate tests were performed, this includes total suspended solids, total dissolved solids, volatile suspended solids, volatile dissolved solids and chemical tests like biological oxygen demand. Based on the experimental test data and analyses following conclusions were drawn:

1. Standard Procter tests were conducted on the recycled materials. Cemented quarry fines showed an increase in the moisture content and decrease in dry density, this may be due to the excessive hydration caused by the pozzalonic reactions with the addition of cement.
2. Quarry fines show a tremendous increase in unconfined compressive strength when treated with cement. A 12 fold increase in strength was observed over untreated sample. This strength was attributed to the pozzalonic reactions during the curing period. RAP material showed a fair strength which was expected by these materials. For comparison of these test results a local subgrade material which is used as a base material for other sections of the same site was selected. Local subgrade material has a lower unconfined compressive strength compared to RAP and CQF materials.
3. Swelling characteristics of these recycled base materials revealed that the untreated quarry fines have moderately swelling behavior. Cement treated quarry fines show practically no swell behavior. RAP material also showed a moderate swell behavior and was about 0.7%.

4. Compressibility tests were conducted on these materials and the slope was almost zero for the cemented quarry fines and the slope for quarry fines was and for RAP was 0.04 and 0.03 respectively.
5. Resilient Modulus testing showed a good improvement in the resilient properties for the cemented quarry fines which was due to the cementations in the soil structure. RAP material also showed good stiffness properties. This data showed that resilient modulus increase with an increase in axial and confining stresses for more number of cycles.
6. Leachate tests showed that the quarry fines may yield a lot of leachate due to their higher porosity. It is also observed that the evolved leachate from materials may not be harmful to the ground water since their characteristics are well with in the US EPA norms. RAP and cemented quarry fines showed very negligible amount of leachate.
7. Extensive instrumentation including horizontal inclinometers and pressure cells were installed in the site to monitor for their long term stability and performance. Filed monitored data imparted that these recycled base materials perform very well during the monitored period. It is advisable to continue the monitoring of these sections for a longer period would give a better understanding of these recycled base materials.

6.3 Future Research Recommendations

The following recommendations will further advance the state-of-understanding of these recycled materials as a base for the pavement:

1. RAP materials derived from different sources should be used as base materials for the pavements.
2. RAP materials with different dosages and with different stabilizing agents should be investigated.
3. Effect of increase in dosage of cement in the cemented quarry fines should be investigated.
4. Quarry fines can utilize different pozzalonic compounds which can increase the strength parameters should be investigated.

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BIOGRAPHICAL INFORMATION

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