CHARACTERIZATION OF CEMENTED AND FIBER-REINFORCED RAP AGGREGATE MATERIALS FOR BASE/ SUB-BASE APPLICATIONS

by

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ABSTRACT

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The engineering product known as RAP is a bonded base and sub-base material produced by the process of blending crushed recycled construction and demolition waste and debris to specified gradation requirements, and by bonding these with a fine silica Portland cement matrix at optimum moisture for compaction density. RAP has a great potential as an economically, environmentally, and structurally sound alternative to non-bonded materials conventionally used for base/sub-base applications in pavement engineering.

The present work is aimed at thoroughly testing the engineering properties of RAP product in order to assess its suitability as a structurally sound and environmentally safe material, as well as to maintain high standards in its production process and field applications. In order to accomplish this goal, a comprehensive series of *basic* and *engineering* tests were conducted on compacted RAP specimens at the UTA geotechnical and geo-environmental laboratories. RAP specimens with no fibers (control specimens) were tested at 0, 2, and 4% dosage levels of Portland cement. RAP specimens with fibers (fiber-reinforced) were tested at 2, 4, and 6% dosage levels of Portland cement.

Basic testing included gradation, specific gravity, Atterberg limits, and standard Proctor compaction tests. *Engineering testing* included permeability, leaching, unconfined compression, and small-strain shear modulus tests. The latter was accomplished via fixed-free resonant column testing for a purely qualitative analysis of RAP stiffness response. Leaching tests included pH, total and volatile dissolved solids, total and volatile suspended solids, and turbidity. Most tests were conducted as per current Texas Department of Transportation's (TxDOT) standard test methods.

Engineering test results on control and fiber-reinforced RAP materials were then compared to those reported in the literature for similar reclaimed asphalt pavement (RAP) materials. Results confirmed the potential of RAP material as an environmentally and structurally sound alternative to non-bonded materials for base/sub-base construction purposes.

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CHAPTER 1

INTRODUCTION

1.1 Background and Importance

The ever increasing generation of waste materials as a result of pavement and infrastructure rehabilitation projects, along with the concurrent gradual decline in landfill spacing, has made it imperative to find innovative ways for reusing recycled aggregates as an alternative base course material in the pavement industry. At the same time, pavement researchers are currently challenged by the need for developing high performance materials for constructing longer lasting pavement layers.

The use of recycled materials has increasingly become more popular in recent years given their potential for conserving resources, preserving the environment, as well as reducing the costs of pavement construction and maintenance. Potential savings in construction costs and time have made the use of recycled materials, such as RAP (reclaimed asphalt pavement) and crushed concrete, very attractive to highway material engineers.

Most recycled materials are used to replace coarse aggregates. Reclaimed or recycled asphalt pavement (RAP) and crushed concrete have been routinely used in construction of pavement granular bases. RAP consists of removed and processed asphalt pavement materials containing both aged asphalt and aggregates. The asphalt coated on the surface of the aggregates typically forms a film with a thickness between six to nine microns. 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). Recycled crush concrete comes from demolition of existing infrastructure, such as concrete pavements, bridge structures, and curb and gutter sections (Griffiths, 2002). Recycled concrete aggregates may also be generated from concrete over-runs or haul-backs associated with new constructions (Hansen, 1992).

In an attempt to improve the bearing capacity of the base and sub-base layers of the pavement structure made of Recycled materials, as well as to increase the stability of questionable soil conditions, various forms of chemical and mechanical stabilization techniques are currently performed in practice (Sobhan, 2003). Chemically stabilized foundation systems consist of such materials as soil-cement, aggregate-cement, lime-fly ash-aggregate, lean concrete, or roller compacted concrete. With measured dosages of cement and water, the treated materials gain in strength after compaction and curing, yielding more durable paving materials.

As a structural layer in pavements, stabilized materials behave as a slab when responding to loads, and its performance is influenced by the strength and modulus of the material; however, it is worthy to take into account the following statement: “It is not possible to assign values that will adequately characterize the range of strength and of stiffness likely to be encountered. Indeed, it must be accepted that the range is so wide that one cannot know ‘typical’ properties for raw materials, unless one confines the data to the end product of processing a particular and well defined raw material with a stated amount of cement" (Williams, 1986). This statement specially applies to recycled materials.

Moreover, pavement systems are subject to dynamic wheel loading from moving vehicles, and repeatable applications of such traffic loads can cause fatigue failure in the pavement. In the case of base courses containing recycled materials stabilized with cement, fatigue failure often occurs due to the growth and propagation of tensile cracks caused by repeated flexural stresses. Ideally, the inclusion of fibers will enhance the energy absorption capacity or toughness of the material and will serve to retard the crack propagation process (Balaguru and Shah, 1992).

Fibers reinforcement is considered to be a mechanical stabilization method, which mainly consists in the inclusion of discrete, randomly oriented fibers that act as micro reinforcements in the material, As the fracture process initiates and cracks start to develop within the base or sub-base material, the fibers serve the purpose of the bridging of cracks, providing additional resistance to crack propagation and crack opening, considerably retarding the complete pull-out or rupture of the structure.

The engineering product known as RAP is a bonded base/sub-base material produced by the process of blending crushed recycled construction and demolition waste and debris to specified gradation requirements, and by bonding these with a fine silica Portland cement matrix at optimum moisture for compaction density.

RAP has great potential as an economically, environmentally, and structurally sound alternative to non-bonded materials conventionally used for base/sub-base applications in pavement engineering. However, additional testing is still needed to fully assess the engineering properties of the product, to monitor its suitability as a structurally sound and environmentally safe material, and to maintain high standards in its production process and field applications. The present work was motivated by these research needs.

1.2 Objective and Scope

The present thesis work is aimed at thoroughly testing the engineering properties of RAP product in order to assess its suitability as a structurally sound and environmentally safe material, as well as to maintain high standards in its production process and field applications.

In order to accomplish this goal, a comprehensive series of *basic* and *engineering* tests were conducted on compacted RAP specimens at the UTA geotechnical and geo-environmental laboratories. RAP specimens with no fibers (control specimens) were tested at 0, 2, and 4% dosage levels of Portland cement. RAP specimens with fibers (fiber-reinforced) were tested at 2, 4, and 6% dosage levels of Portland cement.

Basic testing included gradation, specific gravity, Atterberg limits, and TxDOT moisture-density compaction tests. *Engineering testing* included permeability, leaching (COD, pH, TSS, TDS, Turbidity), unconfined compression, and small-strain shear modulus tests. The latter was accomplished via fixed-free resonant column testing for a purely qualitative analysis of RAP stiffness response. Leaching tests included pH, total and volatile dissolved solids, total and volatile suspended solids, and turbidity. Most tests were conducted as per current Texas Department of Transportation's (TxDOT) standard test methods.

Engineering test results on control and fiber-reinforced RAP materials were then compared to those reported in the literature for similar reclaimed asphalt pavement (RAP) materials. Results confirmed the potential of RAP material as an environmentally and structurally sound alternative to non-bonded materials for base/sub-base construction purposes.

1.3 Organization

A brief summary of the chapters included in this thesis document is presented in the following paragraphs.

Chapter 2 presents a brief literature review on base/sub-base pavement design concepts, types of recycled cemented materials previously investigated, and previously reported correlations between unconfined strength and modulus of elasticity.

Chapter 3 describes all the experimental variables and procedures, including the fundamentals of permeability, leaching, unconfined compression, and resonant column testing techniques, as well as the corresponding components, step-by-step assembling processes, and typical parameters obtained from these tests.

Chapter 4 presents all the experimental results obtained from the series of *basic* and *engineering* tests conducted on control and fiber-reinforced RAP materials, as well as a comprehensive analysis of all these test results. *Engineering* test results were also compared to those reported in the literature for similar reclaimed asphalt pavement (RAP) materials.

Chapter 5 summarizes the main conclusions from this thesis work and some key recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature reviewed in this chapter is a compilation obtained from journals, books, conference proceedings and electronic sources. This literature review was focused on pavement design and materials used for its construction. First, a brief description of the structural sections of a pavement will be presented and is going to be focused especially in the base and sub-base course structure materials. Design methods and failure criteria are going to be included in more detail. Next, a review about cement-treated materials characteristics and properties. This is going to be followed by a discussion of the use of recycled materials, as RAP and recycled concrete, in base sub-base of pavements. The literature survey presented in this chapter includes some UCS correlations and also typical recycled materials UCS values, K values, and estimations of Young's modulus (E).

The use of recycled materials nowadays play an important roll on projects of construction of pavement structures, by treating recycled materials with cement and reinforced them with fibers, its engineering properties are improved and the life of such materials is prolonged, improving this way cost effective effects of a project. But a comprehensive characterization of such materials is important because of its anisotropic composition. This literature review is to be used as the theoretical support to the experimental program explained in chapter three.

2.2 Pavement Structure

The pavement as a whole is a structure which main function is to limit stresses in the sub-grade to acceptable levels. Pavement structures undergo tensile and compressive stresses induced by heavy wheel loads, these stresses decrease with depth, allowing the use, particularly in flexible pavements, of relative strong and expensive materials for the surfacing and less strong and cheaper as we go deep. Previous statement is the base philosophy for the structural design of a pavement. Pavements can be rigid or flexible; flexible pavements generally consist of a prepared road base, sub-base and base courses and the surface course in which asphalt is usually used as a binder material whereas rigid pavements generally consists of a prepared road base underlying a layer of sub-base and a pavement slab. Pavement design is the process of find the most economical combination of pavement layers taking in to account both; thickness and type of materials to suit the soil foundation and the traffic to be carrying during the design life.

Pavement structure is generally conformed for three layers: sub-base base and surface course, next is a brief definition of them:

Roadbed course is defined as soil which is a layer of compacted roadbed soil to a specified density.

Sub-base course is defined as the portion of the pavement structure between the roadbed soil and the base course. It usually consists of a compacted layer of granular material, either treated or untreated or of a layer of soil treated with a suitable admixture. It is usually distinguished from the base portion for its lower requirements in strength properties, plasticity and gradation. For reasons of economy this portion of the structure is sometimes ignored when the roadbed soil has high engineering properties.

Base course is defined as the base is the pavement portion immediately below the surface course; this one is constructed on the sub-base course or if there is not sub-base, directly on the roadbed soil. Its major function on the pavement is structural support. It usually consists of materials as crushed stone, crushed slag, crush gravel and sand or combination of these materials. Specifications for base materials are more stringent than sub-base materials in strength, plasticity and gradation. But other treated materials can be used, and by treated, Portland cement, fly ash, lime and other materials can be used for. Consideration should be given to the use of such treated materials for base courses whenever they are economically feasible. Economic advantages may result not only form the use of low-cost aggregates but also from possible in the reduction of total thickness of the pavement structure that may result from the use of treatment given to the materials. Careful study is required to select the appropriate amount of cement to be added in order to get the optimum performance and economy.

Surface course it is usually constructed on a base course. In addition to its major function as a structural portion of the pavement, it must also be designed to resist abrasive forces of traffic, to reduce amount of surface water penetrating the pavement, to provide skid resistance surface, and to provide a smooth and uniform riding surface.

These three layer described above, interact distributing all tensile and compressive stresses, drainage is other important issue to take into account when designing pavement structures, water can generate stresses that can be reflected in the surface, gradation and drainage systems can take care of this aspect. Economic aspect influence a lot in the design of pavements, choose of materials and thick of layers goes on intimate relation with it, however when alternative materials or design method is very important to remark the follow of lab testing to ensure further performance of the pavement.

Figure 2.1 represents a typical cross section of a conventional pavement Structure.

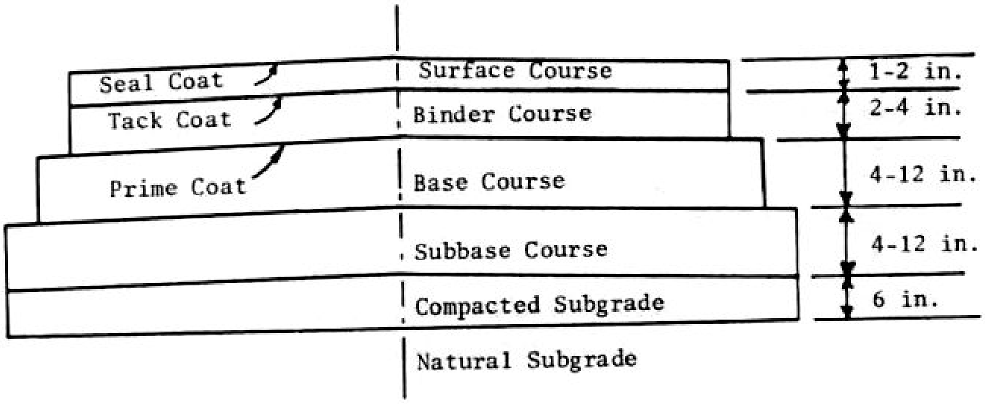


Figure 2.1 Typical pavement structure.

2.3 Design method classification

2.3.1 Empirical Methods

The use of empirical method without a strength test dates back to the development of public roads soil classification system (Hogentogler and Terzaghi, 1929), in which the sub-grade was classified as uniform from A-1 to A-7 and a group index was added to differentiate the soil within each group. The empirical method with a strength test was first used by the California highway department in 1929 (Porter, 1950). The thickness of layers was related to the California Bearing Ratio (CBR), defined as the penetration resistant of a sub-grade soil relative to a standard crushed rock.

The disadvantage of empirical method is that it can be applied only to a given set of environmental, material, and loading conditions. If these conditions are changed, the design is no longer valid and a new method must be developed through trial and error to be commensurate with the new conditions (Huang, 1993).

2.3.2 Limiting Shear Failure Methods

The limiting shear failure method is used to determine the thickness of pavements so that the shear failures will not occur. The major properties of pavements components and sub-grade soils to be considered are their cohesion and angle of internal friction. Barber (1946) applied Terzaghi's bearing capacity formula to determine the pavement thickness. McLeod (1953) advocated the use of logarithmic spirals to determine bearing capacity of pavements. These methods were reviewed by Yoder (1959) in his book *Principles of Pavement Design* but were not even mentioned in the second edition (Yoder and Witczak, 1975). This is not surprising because, with the ever increasing speed and volume of traffic, pavements should be designed for riding comfort rather than barely preventing shear failures (Huang, 1993).

2.3.3 Limiting Deflection Methods

The limiting shear failure method is used to determine the thickness of pavement so that vertical deflection will not exceed the allowable limit. The Kansas State Highway Commission (1947) modified Boussinesq's equation (Boussinesq, 1885) and limited the deflection of sub-grade to 0.1 in. The U.S. Navy (1953) applied Burmister's two-layer theory (Burmister, 1943) and limited the surface deflection to 0.25 in. The use of deflection as a design criterion has the apparent advantage that it can be easily measured in the field. Unfortunately, pavements failures are caused by excessive stresses and strains instead of deflections.

2.3.4 Regression Methods Based on Performance of Road Tests

A good example of the use of regression equations for pavement design is the AASHTO method based on the results of road tests. The disadvantage of the method is that the design equations can be applied only to the condition at the road test site. For conditions other than those under which the equations were developed, extensive modifications based on theory of experience are needed. Regression equations can also be developed from the performance of existing pavements such as those used in the pavement evaluation systems COPES (Darter et. al., 1985) and EXPEAR (Hall et al., 1989). Unlike road tests, the materials and construction of these pavements were not well controlled, so a wide scatter of data and a large standard error are expected. Although these equations can illustrate the effect of various factors on pavement performance, their usefulness in pavement design is limited because of the many uncertainties involved (Huang, 1993).

2.3.5 Mechanistic-Empirical Methods

The mechanistic-empirical method of design is based on the mechanistic of materials that relates an input, such as a wheel load, to an output or pavement response, such as stress or strain. The response values are used to predict distress based on laboratory test and field performance data. Dependence on observed performance is necessary because theory alone has not proven sufficient to design pavements realistically.

Kerkhoven and Dormon (1953) first suggested the use of vertical compressive strain on the surface of sub-grade as a failure criterion to reduce permanent deformation, while Saal and Pell (1960) recommended the use of horizontal tensile strain at the bottom of asphalt layer to minimize fatigue cracking, as shown in Fig 2.2 the use of the above concepts for pavement design was first presented in the United States by Dormon and Metcalf (1965).

The use of vertical compressive strain to control permanent deformation is based on the fact that plastic strains are proportional to elastic strains in paving materials. Thus, by limiting the elastic strains on the sub-grade, the elastic strains in the other components above the sub-grade will also be controlled; hence, the magnitude of permanent deformation on the pavement surface will be controlled as well. These two criteria have since been adopted by Shell Petroleum international (Claussen et al., 1977) and the Asphalt institute (Shook et al., 1982) in their mechanistic-empirical methods of design. The advantages of mechanistic-empirical methods are the improvement in the reliability of a design, the ability to predict the types of distress, and the feasibility to extrapolate from limited field and laboratory data (Huang, 1993).

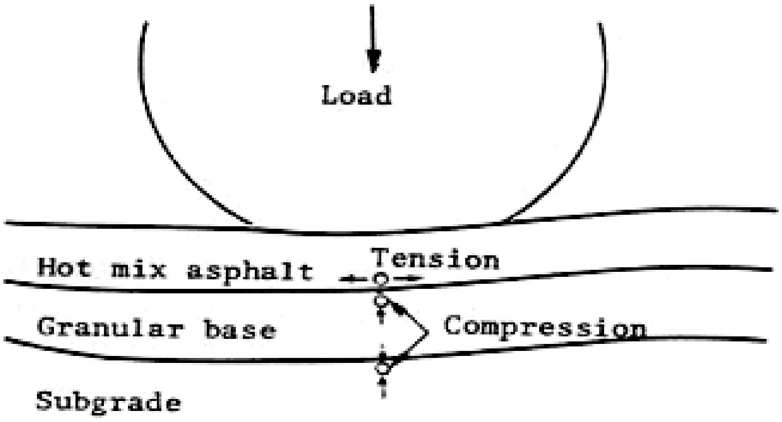


Figure 2.2 Tensile and Compressive strains in flexible pavements (Croney, 1997).

2.4 Failure Criteria in Flexible Pavements

It is generally agreed that fatigue cracking, rutting, and low temperature cracking are the three principal types of distress to be considered for flexible pavement design.

2.4.1 Fatigue Cracking

The fatigue cracking of flexible pavements is based on the horizontal tensile strain at the bottom of the structure element. The failure criterion relates the allowable number of loads repetitions to the tensile strain based on the laboratory fatigue test on small specimens. Due to the difference in geometric and loading conditions, the allowable number of repetitions for actual pavements is much greater than that obtained from laboratory tests. Therefore, the failure criterion must incorporate a shift factor to account for the difference.

2.4.2 Rutting

Rutting occurs only on flexible pavements, as indicate by the permanent deformation or rut depth along the wheel paths. Pavement may uplift along the sides of the rut. Rutting stems from permanent deformation in any of the pavement layers or the sub-grade, usually caused by the consolidation or lateral movement of the materials due to traffic loads.

2.4.3 Thermal Cracking

This type of distress includes both low-temperature cracking and thermal fatigue cracking. Low-temperature cracking is usually associated with flexible pavements in northern regions of the United States and much of Canada. Thermal fatigue cracking can occur in much milder regions if and excessively hard asphalt is used or the asphalt becomes hardened due to aging.

Thermal fatigue cracking is similar to fatigue cracking caused by repeated loads. It is caused by the tensile stress in the asphalt layer due to daily temperature cycle (Huang, 1993).

2.5 Failure Criteria in Rigid pavements

Fatigue cracking has long been considered the major or only criteria for rigid pavement design. Only recently has pumping or erosion been considered. Other criteria in consideration include faulting and join deterioration of JPCP and JRCP and edge punch-out of CRCP.

2.5.1 Fatigue Cracking

Fatigue cracking is most likely cause by the edge stresses at the mid slab. The allowable number of load repetitions to cause fatigue cracking depends on the stress ratio between flexural tensile stresses and the concrete modulus of rupture.

2.5.2 Pumping or Erosion

Although permanent deformations are not considered in rigid pavement design, the resilient deformation under repeated wheel loads will cause pumping of the slabs. Consequently, corner deflections have been used in the latest version of the PCA method (PCA, 1984) as an erosion criterion in addition to the fatigue criterion. Since pumping is caused by many other factors, such as types of sub-base and sub-grade, precipitation, and drainage, a more rational method for analyzing pumping is needed.

2.6 Cement-treated Sub-bases and Bases

Cement treated aggregate base (CTAB) is defined as a mixture of aggregate material and measured amount of Portland cement and water that hardens after compaction and cures to form a durable paving material (Sokie, 1979). It is widely used as a base course for either flexible or rigid pavements. Compared with other cement-treated or cement stabilized materials, CTAB generally involves higher contents of cement and, therefore, higher strength and stiffness. As a structural layer in pavement, CTAB behaves as a slab against loading, and its performance is influenced by the strength and modulus of the material. These properties are crucial for design purposes especially in those which stress strain relationship and fatigue characteristics are considered as parameters.

When the aggregates-cement process is used for improving the characteristics of a base or sub-base. The field operation must be preceded for a program of laboratory testing. This will be aimed at determining the cement and water contents to be used to obtain the required strength (Croney and Croney, 1997). This required strength can be evaluated with several tests but commonly, for its simplicity, unconfined compressive strength as mix design criteria for the construction of CTAB. Many previous studies have proposed empirical relationships between the compressive strength and flexural or tensile strength of cemented treated materials that are useful for the structural design of the layer, there are several correlations to get the shear modulus (G), resilient modulus (Mr), and in this study those empirical relations are going to be evaluated.

2.6.1 Design considerations

Most problems with cement-stabilized base layers in pavements stem from the fact that current design practices are based only on strength, without consideration of long-term durability or performance. For example, many state departments of transportation require sufficient cement to achieve high unconfined compressive strength values. While this level of cement results in a very stiff aggregate layer characterized by a high resilient modulus, it does not necessarily guarantee acceptable long-term pavement performance (Guthrie, 2002). In many roadways, especially in those stabilized with cement, shrinkage cracks, fatigue cracks and rutting within base layers reflect into the surface treatments and appear as transverse cracks with a spacing of between 3 ft and 60 ft. Although the cracks themselves may not present a structural problem, they often accelerate degradation of the pavement by allowing water to enter lower pavement layers. Is because of these types of failures in which no strength but durability characteristics plays the main role in the design considerations.

Several studies have been conducted in order to mitigate rutting and fatigue type of failure, one of them is by reinforcing the mixture with fibers, which is precisely what RAP material is reinforced with. This reinforcement can develop tensile properties that help to reduce crack propagation and sometimes can even mitigate this type of problems in the pavement.

2.6.2 Cement-treated RAP and RCA

Recycled asphalt pavement (RAP) is defined as a reprocessed pavement material containing asphalt and aggregate, and Recycled Concrete Aggregates (RCA) is the material produced by crushing demolished concrete elements. RCA differ from fresh aggregates due to the cement paste attached to the surface of the original natural aggregates after the process of recycling.

Since RAP and RCA were considered to be used as replacements for virgin aggregate products in pavement structures, researches have become very interested in the topic because of the potential savings in cost and time the use of such materials can implied. To use these types of material, minimum ASSHTO and state requirements has to be accomplish, that is why the inclusion of cement as an improving agent of the compressive strength properties of the materials. It has to be taking into account that stiff properties are not the only characteristics to improve in order to have a pavement structure with a good long-term performance, having high stiff material with high resilient modulus does not mean the pavement is going to behave properly to problems like cracking and rutting, being cracking the pavement a phenomenon caused by tensile stresses at the bottom of the asphalt layers, while rutting may be a result of accumulative pavement deformation throughout pavement system, to decrease Cracking effect RAP material has included glass fiber as a reinforcement of the base slab.

2.6.3 Unconfined Compressive Strength of Cement Treated Recycled Aggregates

When researching the performance of cement treated recycled materials it is known that addition of cement in the materials enhances the material's rigidity or stiffness properties. In order to evaluate such increases in the stiff properties of the material, UCS is one of the most used tests.

The increase in compressive strength with age of cemented materials with a wide range of compressive strengths has been studied over periods up to 10 years in the United Kingdom (Croney and Croney, 1997). From these data it can be deduced that 7 days is a time enough to reach around 70% of the 28 days strength Fig 2.3.

By virtue of the simplicity of the test method, the unconfined compressive strength is most commonly used as mix design criteria, however there are methods to determine the appropriate elastic modulus of cemented-treated recycled aggregates but they are complicated because of the difficulties associated with testing and interpreting the test results. A review of literature found that, in most cemented-treated aggregates, UCS values are used in empirical correlations to predict resilient modulus values and to find the structural number on the design of the pavement structure. That is why, for design purposes, a relationship between the strength and modulus of elasticity of the material was recommended. Many previous studies have proposed relationships between the unconfined compressive strength and modulus of elasticity of cemented materials, in the literature review, both the initial tangent of the unconfined compressive curve relationships are going to be evaluated.

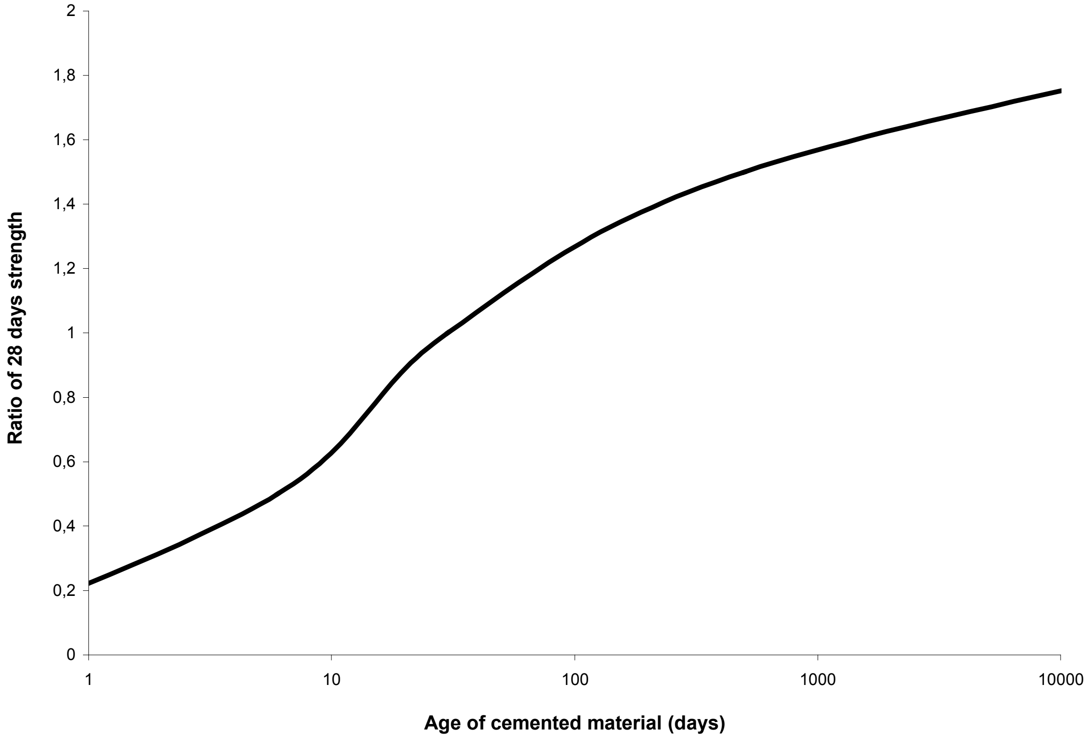


Figure 2.3 Variation of compressive strength with age
(Croney and Croney, 1997)

This investigation, which evaluated the correlation of modules to compressive strength, was conducted by Lim and Zollinger 2003 and from their study we can observe in table 2.1 measured compressive strengths of the test mixtures at different ages. The types of materials used in this research were two different aggregate bases. One is a conventional crushed limestone base material and the other is recycled concrete material. Both materials contain particles sized from 2 in. to – No 200 (75µm) in accordance with the grading requirements of the Texas Department of Transportation (TxDOT) Specification Item 276, Portland Cement-Treated base.

Table 2.1 Compressive strength of the CTAB Test Mixtures at Different Curing Times (Lim and Zollinger 2003)

Aggregate	**Mix ID**	**Compressive strength (psi)**			
		1 day	3 days	7 days	28 days
Recycled Concrete (RC)	1.0	257.8	243.8	397.4	603.7[e]
	2.0	195.0	282.2	455.0	646.6[e]
	3.0	257.7	286.3	454.5	550.8[e]
	4.0	208.2	400.2[b]	398.8	527.4[f]
	5.0	290.3	534.6	759.8[d]	1070.3
	6.0	345.1	647.3	886.6	1220.5
	7.0	289.1	--	797.0	963.0
	8.0	395.9	676.5[c]	819.6	908.6
Crushed Limestone (CL)	1.0	378.9	524.3	630.6	1012.1
	2.0	318.1	490.0	519.7	556.9
	3.0	472.2[a]	598.7	508.3	908.5[a]
	4.0	278.7	543.8[c]	461.4	734.2[h]
	5.0	630.7	1083.8	1221.1	1709.5
	6.0	606.8	988.0	1224.0	1319.3
	7.0	648.0	1224.3	1501.7[d]	1556.5
	8.0	550.5	921.7[c]	1190.4	1292.8

[a] tested at 2 days
[b] tested at 5 days
[c] tested at 4 days
[d] tested at 8 days
[e] tested at 34 days
[f] tested at 33 days
[g] tested at 29 days
[h] tested at 20 days

The test program of this research consisted of 64 different test conditions stiffness of CTAB mixture. Selected test variables were: content of coarse aggregates, content of fines and cement content. Two different application levels were selected for the respective mixture variables, as shown in Table 2.2 this two level, three variable factorial (2^3) design result in 16 different test mixtures in total; 8 for each aggregate type, that is recycled concrete and crushed limestone.

Table 2.3 shows the complete factorial of the test mixtures for each aggregate type. The symbols (-) and (+) in the table indicate the low and high application levels of cement the mixing variables, respectively (Lim, Zollinger, 2003).

Table 2.2 Test Variables and Application Levels for the CTAB test mix design (Lim, Zollinger 2003)

Test Variables	**Designation**	**Application Levels**	
		Low(-)	**High(+)**
Content of Coarse Aggregates	A	48%	58%
Content of Fines	F	5%	10%
Cement Content	C	4%	8%

Table 2.3 Complete Factorial of Test Mixtures for Each Aggregate Type (Lim and Zollinger, 2003)

	Test Variables and Application Levels		
Mix ID	**A**	**F**	**C**
1	--	--	--
2	+	--	--
3	--	+	--
4	+	+	--
5	--	--	+
6	+	--	+
7	--	+	+
8	+	+	+

It was observed that recycled material (crush concrete) developed about 30% less strength than crushed limestone material. This effect is though to be caused by the higher water demand of the recycled concrete material and subsequent higher water-cement ratio of the RC mixtures (Lim and Zollinger, 2003).

Most specifications require the minimum design strength of cemented treated aggregate base (CTAB) in the range of 350 to 500 psi at 7 days cure period (Lim and Zollinger, 2003).

Some weak correlations has been developed between dry density and unconfined compressive strength, Fig 2.4 shows an example of this, and presumably, because of the compounded effects of many factors on the strength development, it is very unlikely that any single factor becomes a decisive strength indicator. For the estimation of strength development of CTAB with time, the experimental ACI provide the model in the form of equation 1 with the coefficients a = 0.4 and b = 0.85 for normal concrete

$$f_c(t) = fc(28) \cdot \frac{t}{a + b \times t} \tag{2.1}$$

Where

$fc(t) =$ Compressive strength at time t

$fc(28) =$ Reference 28-day compressive strength

$a, b =$ Experimental coefficients.

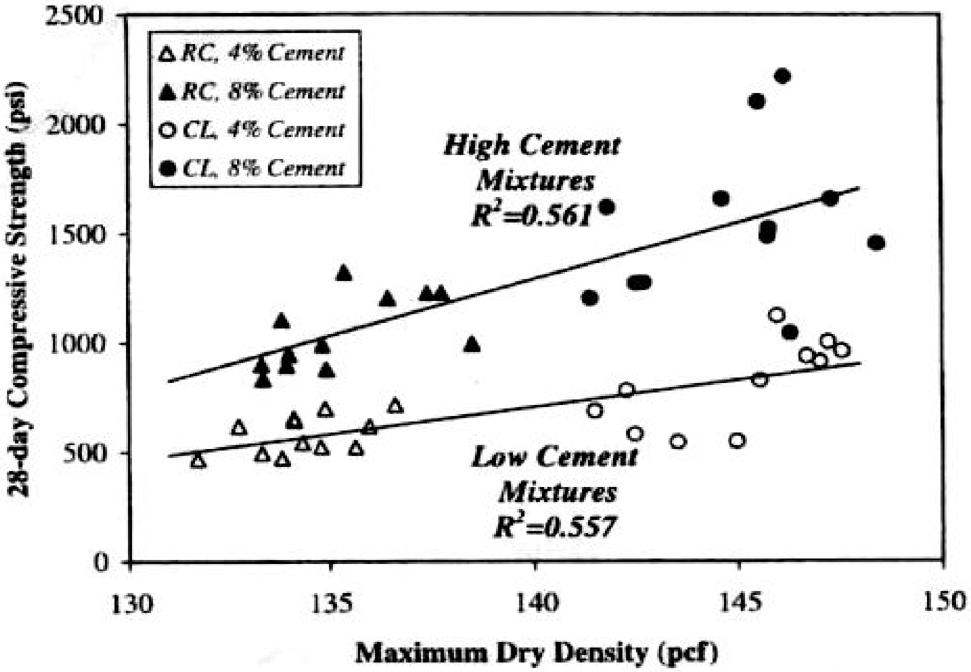


Figure 2.4 Scatter plot of the 28 day compressive strength and maximum dry density of the test mixtures (Croney and Croney, 1997)

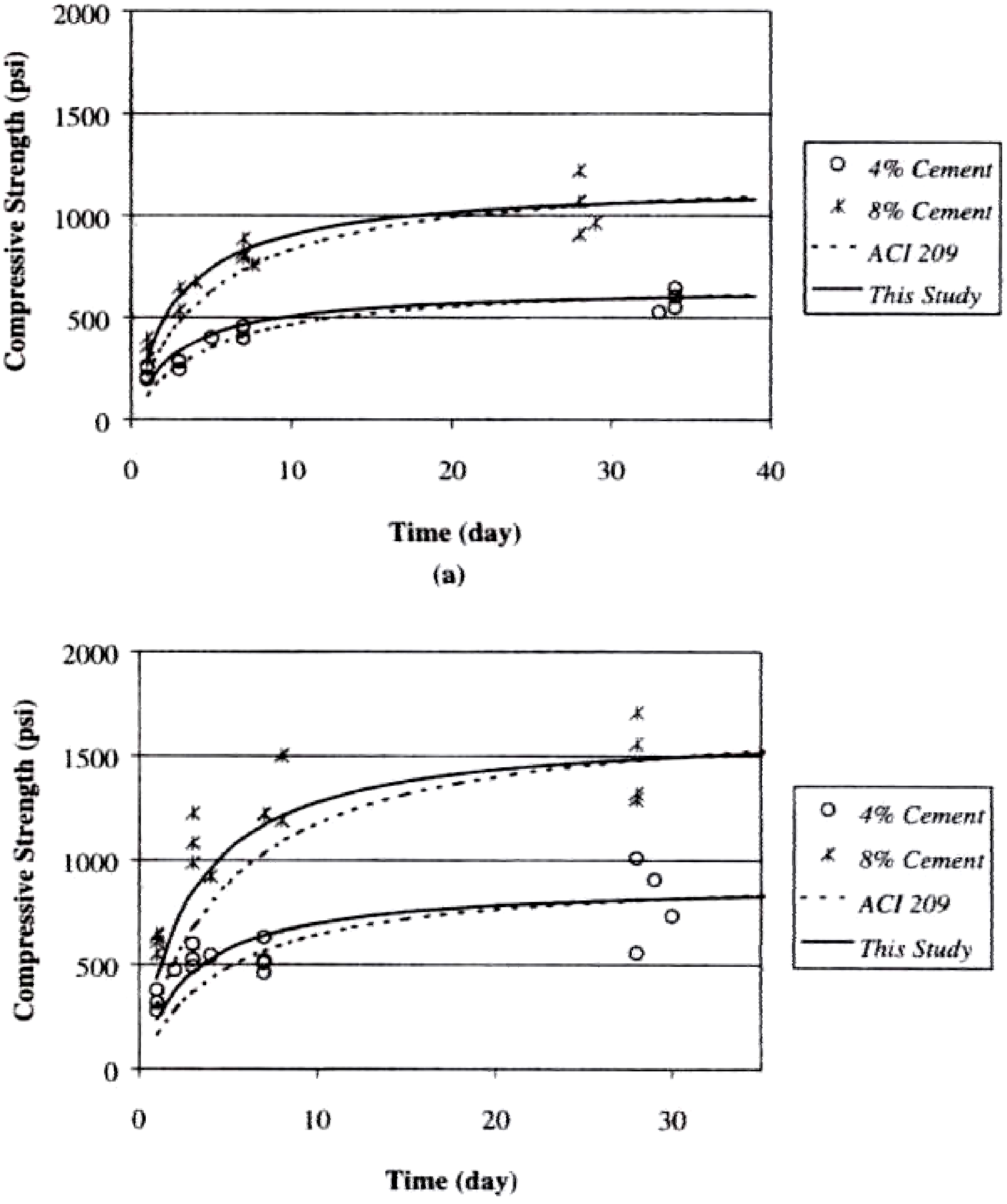


Figure 2.5 Prediction of the compressive strength development of CTAB mixtures: (a) recycled concrete (RC) mixtures and (b) crushed limestone mixtures (CL).
(Croney and Croney, 1997)

Calibration of the ACI model to the CTAB test data resulted in a new set of coefficients of a = 2.5 and b = 0.9. This new set of coefficients is expected to be applicable for any CTAB mixtures regardless of aggregate type and mixture proportioning (Lim and Zollinger, 2003); Figure 2.3 shows some predictions of the compressive strength development of CTAB of some specimens failed in Lim and Zollinger's work.

The development of elastic modulus of CTAB materials was investigated using the stress-strain relationships of the mixtures identified from the test. Young modulus is determined as the initial secant at 25% of the ultimate stress.

Table 2.4 shows the Elastic Modulus for the different mixtures at different ages. Like the results of the strength, the modulus of elasticity showed to be 20 to 30% less on recycled materials. It was also observed that the ratio of modulus of elasticity of high cement (8%) to that of low cement (4%) exceeds a value of 2 at the early ages, although it generally ranges from 1.3 to 1.7 for the mixtures aged more than 7 days.

Equation 2 represents ACI model, has been generally accepted for the estimation of modulus of elasticity of cemented treated base materials. However, ACI model was proposed for concrete materials, and it may not be relevant to CTAB materials.

$$E(t) = 33 \times w^{1.5} \times f_c(t)^{0.5} \tag{2.2}$$

$$E(t) = 4.38 \times w^{1.5} \times f_c(t)^{0.75} \tag{2.3}$$

Where E is in psi, and w is the density of the sample in pcf.

Table 2.4 Modulus of elasticity of CTAB mixtures (Lim, Zollinger 2003)

Aggregate	Mix ID	Modulus of elasticity (X10^6psi)			
		1 day	3 days	7 days	28 days
Recycled Concrete (RC)	1	0.464	0.377	0.628	0.847[a]
	2	0.289	0.391	0.807	0.858[a]
	3	0.38	0.515	0.864	0.996[a]
	4	0.322	0.727[b]	0.804	0.944[c]
	5	0.475	0.861	1.057[d]	1.426
	6	0.584	0.945	1.298	1.312
	7	0.551	--	1.111	1.243
	8	0.727	1.110[e]	1.2	1.276
Crushed Limestone (CL)	9	0.561	0.657	0.872	1.05
	10	0.76	0.823	0.842	0.878
	11	0.764[f]	0.837	0.843	1.198[g]
	12	0.516	0.905[e]	0.917	1.200[h]
	13	1.039	1.466	1.744	1.78
	14	1.038	1.454	1.614	1.545
	15	0.84	1.405	1.786[d]	1.91
	16	1.08	1.463[e]	1190.4	1.678

In this regard, the relationship between the measured compressive strength and modulus of elasticity of CTAB text mixtures was investigated. The empirical coefficients and exponents in equation 2 were adjusted again for the CTAB data obtained in this study. The result is shown in Equation 3. The time dependent strength, $f_c(t)$, can be estimated by Equation 1, and then the modulus of elasticity can be found with Equation 3 where E(t) is the modulus of elasticity (psi) and w is the mixture density (Lim, Zollinger 2003).

Figure 2.6 shows the relationships between compressive strength and the elastic modulus of cemented aggregates projected over the scatter plot of test data obtained in this study (Lim and Zollinger, 2003). It can be seen here that the proposed model for base materials treated with cement, matches properly with the data collected from the experimental program.

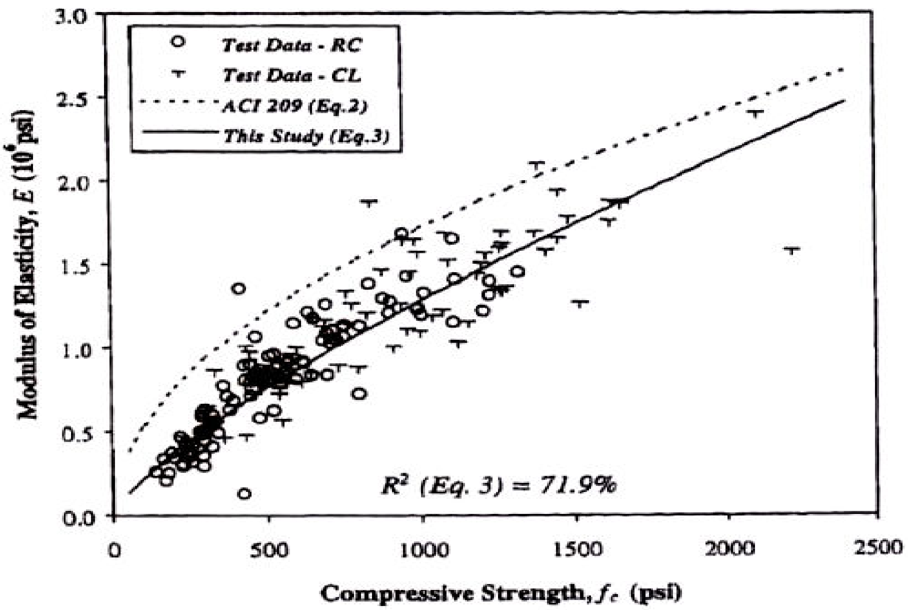


Figure 2.6 Relationship between the compressive strength and modulus of elasticity of cemented treated base materials (Lim and Zollinger, 2003)

Because of the comparison are reasonable, the proposed model, in Lim and Zollinger study, is expected to be applicable for estimation of modulus of elasticity regardless of aggregate type and mixture proportioning.

2.6.4 Fiber Reinforcement in cemented aggregates

From a mechanistic consideration, since a pavement layer undergoes repeated flexural stresses due to traffic loading, the tensile behavior of the material is critical to its performance. It is generally known that the inclusion of fibers in a cementitious composite such as concrete enhances its energy absorption capacity or toughness and serves to retard the growth and propagation of tensile cracks, thus increasing its resistance to fatigue failure (Balaguru and Shah, 1992). It is however, uncertain if such conclusions of fibers would be beneficial in a mix, which is not only lean in cement content, but composed mostly by recycled materials (Sobhan and Ahmad, 2003).

Only a few studies could be identified in the literature dealing with the laboratory and field performance of fiber reinforced, stabilized soils, and aggregate as applied to pavement. These studies involved various commercially available steel, polypropylene, and glass fibers, and in general reported improved performance of reinforced pavement layer in terms of bearing capacity, toughness, and resistance to permanent deformation (Sobhan et al, 1999).

When adding fiber to cement based composites is to increase its energy absorbing capacity, a more ductile post-peak behavior is expected. Although the area under the stress-train curve is a measure of the toughness of the material, the relevance of toughness in practice depends on the application. For earthquake or explosive load conditions, which may involve the total collapse of a structural element, it is appropriate to consider the total area under the stress-strain curve as the total energy absorption capacity. For highway pavements, however, it is more appropriate to consider a given level of serviceability, beyond which rehabilitation has to be undertaken. In such cases only a portion of the total area under the stress-strain curve is important.

Since a standard method for toughness calculations under splitting tensile loading conditions is not available, the following approach for quantifying the fiber toughening characteristics in the post peak region is presented (Sobhan, Ahmad, 2003). This approach uses the load deformation curves of Fig 2.7 And normalized them by their respective peak load along the Y axis, and by the specimen diameter along the X axis as shown in Fig 2.8 It has to be taking into account that the previous plots come from Splitting tensile tests Fig 2.9 Following with the toughness measurement, after normalized the curves a dimensionless splitting tensile toughness index, TI, is obtained. This TI is focused only on the post peak behavior of the test specimens, and is calculated as: $TI = \left(A_\varepsilon - A_\rho\right) / \left(\varepsilon - \varepsilon_\rho\right)$, where, A_ε is the area under the normalized curve up to any strain ε, A_p is the area under the normalized curve up to the peak, and εp is the strain corresponding to the peak load. For a reference elastic-perfectly-plastic material, the TI is equal to unity for any value of ε.

Is also important to note that one of the limitations of this TI is that a material with relatively low strength can still show a high value of TI (Sobhan, Ahmad, 2003). Studies revealed us statements like when stabilizing Recycled crushed concrete with cement, a 4% of dosage is enough to get a high quality base course material also that by getting the toughness index TI, as defined previously, the performance of fibers in stabilized materials can be evaluated. It was observed an increase of the order of 0 to 127% percent in the toughness behavior of the material when adding fibers.

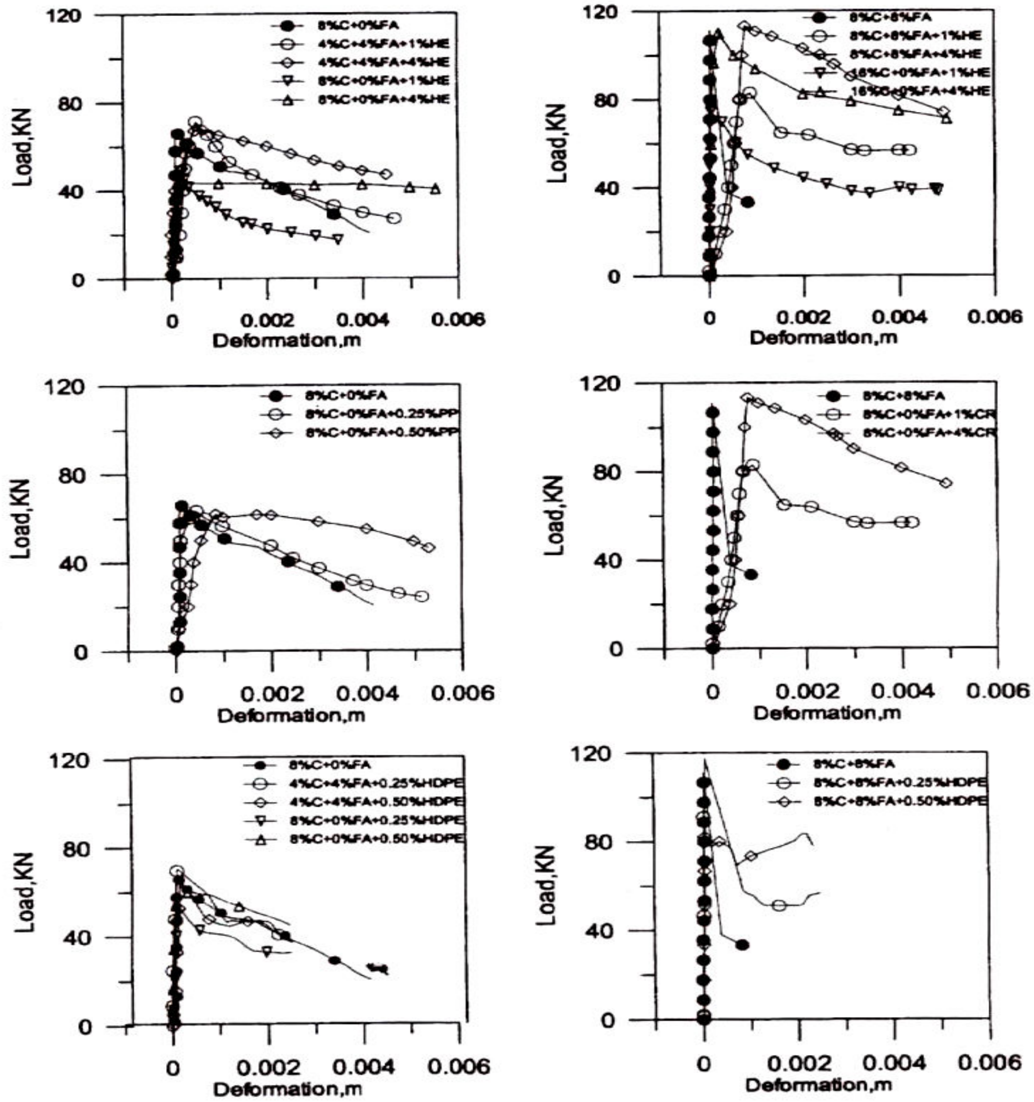


Figure 2.7 Load deformation curves for different mixes (Sobhan, Ahmad, 2003)

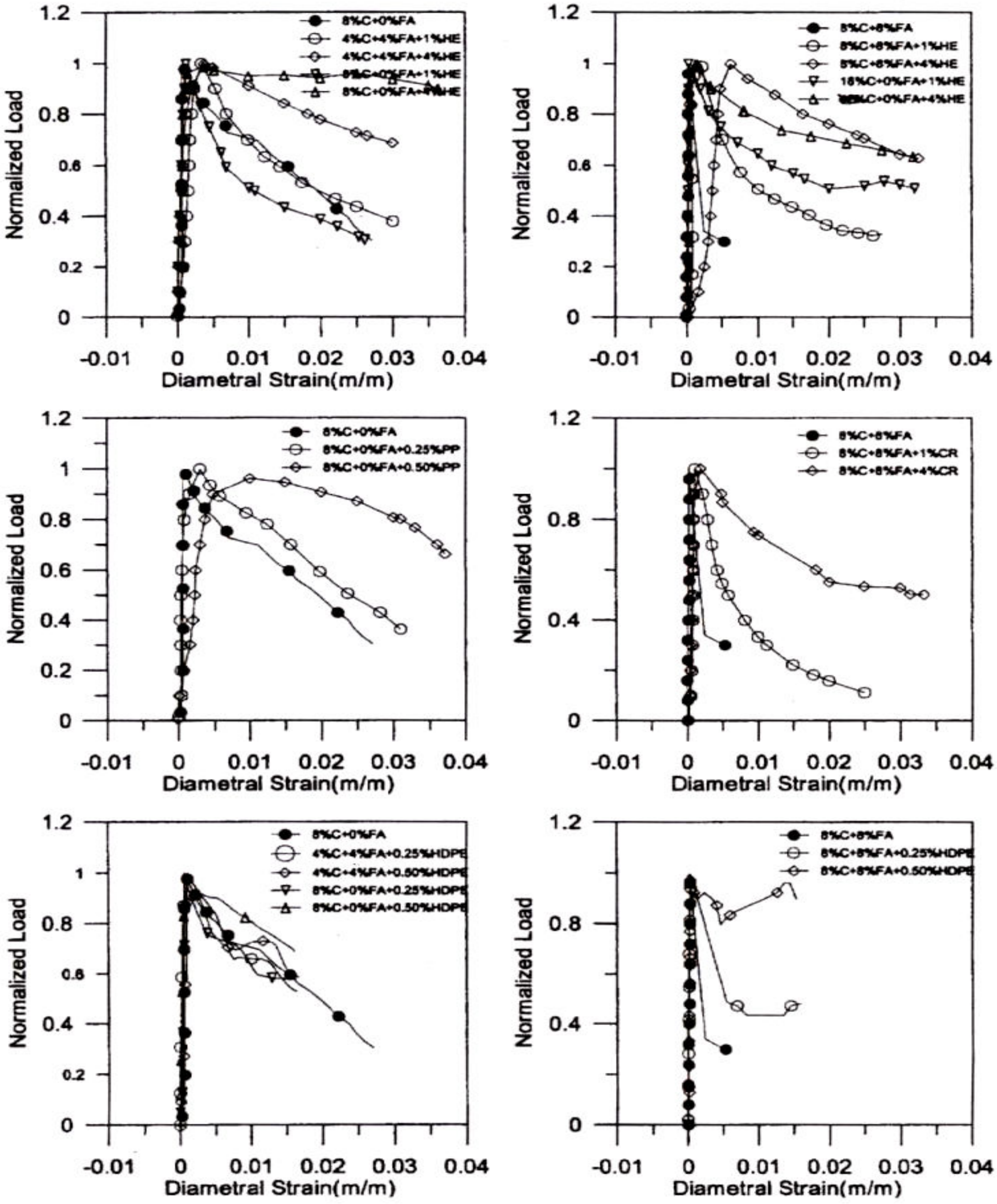


Figure 2.8 Normalized load-strain curves for different mixtures (Sobhan and Ahmad, 2003)

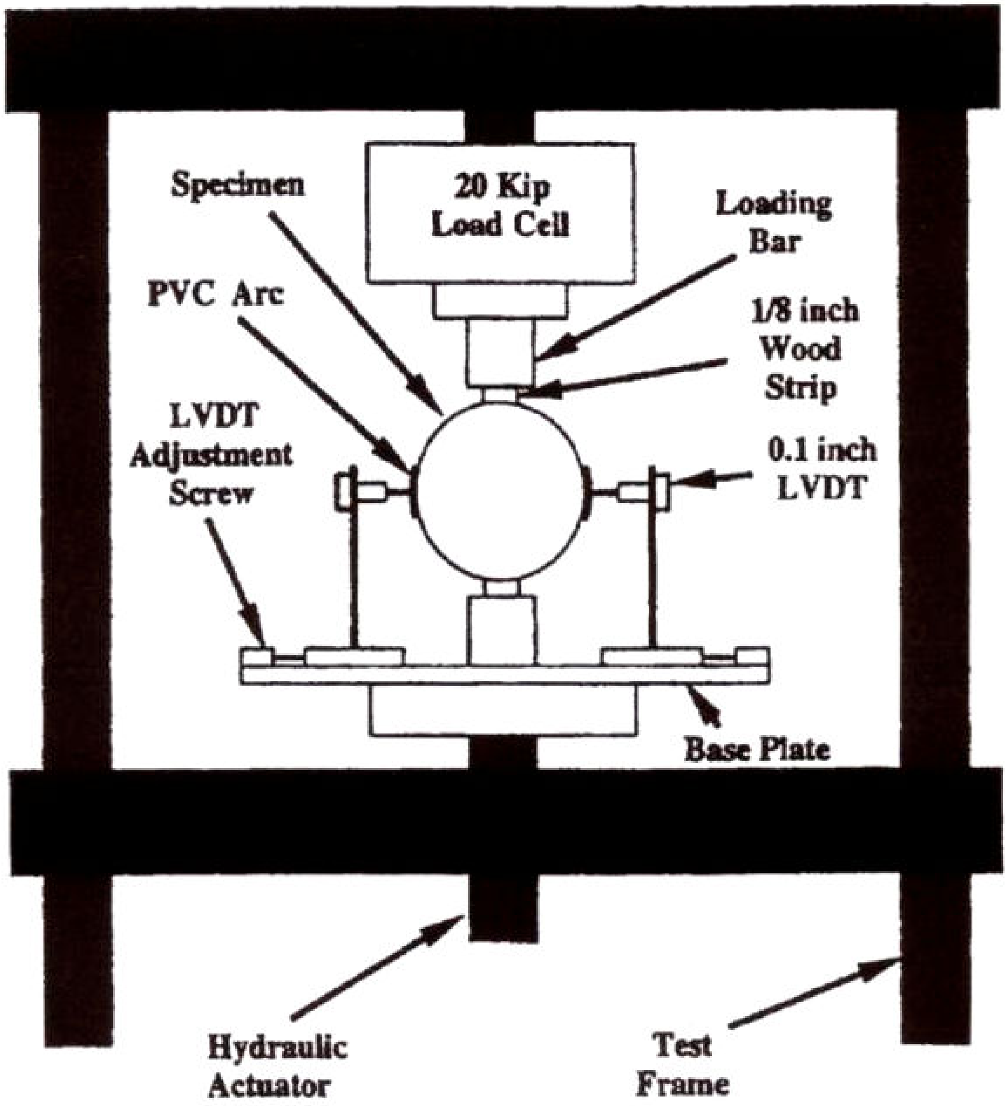


Figure 2.9 Schematic of splitting tensile test setup. (Sobhan and Ahmad, 2003)

Finally it can be concluded that the suitability of a stabilized pavement base course material depends largely on its performance under repeated loads. The studies reported herein evaluated the fatigue resistance of a stabilized recycled aggregate base course material, compared its behavior with other commonly used stabilized base course materials, and determine the beneficial effect of including 4% by weight of fibers in the cemented composite. The results showed that the proposed base course material manifests good resistance to fatigue failure and that fibers do improve the mechanical performance of a composite. Although the use of commercial steel fiber in pavement base course may not be economical in terms of initial material cost, the improved fatigue life due to fiber inclusions may ultimately bring about economic savings in life cycle costs resulting from the less frequent need for rehabilitation. In addition, these results open a motivation to investigate the use of alternate inexpensive fibers as they become available (Sobhan, 2003).

Next chapter summarizes all the experimental variables and procedures followed in this thesis work.

CHAPTER 3

EXPERIMENTAL VARIABLES AND PROCEDURES

3.1 Introduction

An experimental program was designed in order to asses the fundamental engineering properties of RAP material. The experimental program focused on strength properties, permeability analysis and leachate characteristics. The tests were carried out at The University of Texas at Arlington laboratories and basically consisted of two set of tests the first set comprised the basic characterization of the material where sieve analysis, specific gravity and optimum moisture content on samples at 0, 2, 4 and 6% of cement content were conducted. The second set consisted of engineering characterization, including permeability tests, unconfined compressive strength (UCS) and resonant column. Also leachate analysis test were conducted in order to analyze how the cement affects the holding of the aggregates in the presence of water.

The following sections describe the types of laboratory tests performed.

3.2 Primary Characterization of Material

The tests in this section are sieve analysis, specific gravity and optimum moisture content using TxDOT procedures.

3.2.1 Sieve Analysis

This method covers the quantitative determination of the distribution of particle sizes in soils. The distribution of particle sizes larger than 75 mm (N_o200) is determined by sieving, while the distribution of particle sizes smaller than 75 mm is determined by a sedimentation process, using a hydrometer to secure the necessary data.

If less than 1% by weight of the material is passing sieve N_o200, hydrometer analysis is not required. The sieve analysis tests conducted were in accordance with TEX 110 E Standard test method for particle size analysis of soils of TxDOT.

After collecting all weights retained on each sieve, the percentage of material passing through each sieve is calculated. This calculation basically consists of dividing each weight of the material retained on each sieve by the weight of the total sample, obtaining from this the percentage of material retained on each sieve. After having all percentages of material retained on each sieve by basic calculations the next step is to find the percentage of material passing through each sieve. When finishing the calculation phase, all the data is plotted on semi log paper. Table 3.1 resumes data obtained in the test and the grain size curve of RAP material is shown on Figure 3.1.

Table 3.1 Data from sieve analysis test of RAP material

Sieve No	**Material Pass, %**
3/4"	98.1
3/8"	65.4
No4	55.1
No40	19.2
No50	11.2
No100	1.8
No200	1.1

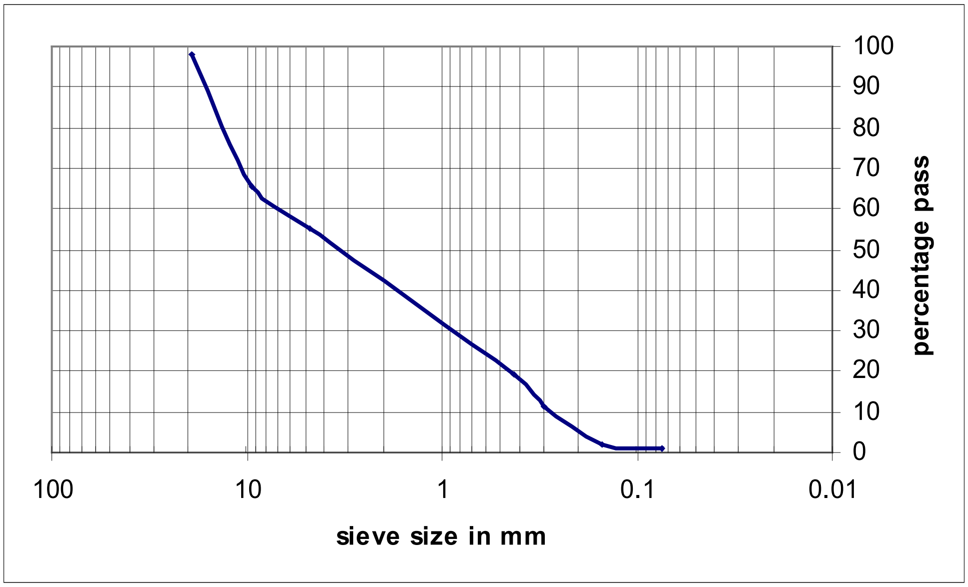


Figure 3.1 Grain size distribution of RAP material

3.2.2 Specific Gravity

Specific gravity is defined as the ratio of the mass of a given volume of solid or liquid to the mass of an equal volume of water at a specified temperature. Specific gravity test was performed in accordance to TxDOT procedure TEX 108 E, and it was performed on the material passing No 40 sieve.

First, the volumetric flask, used on the test, was calibrated. Specific gravity found in this test performed on RAP material gave us a result of 2.43.

3.2.3 Laboratory Compaction Characteristics and Moisture-Density Relationships

In order to determine the optimum moisture content for compaction of the specimens, TxDOT Tex-113-E Laboratory Compaction Characteristics and Moisture-Density Relationship test procedure was followed. This test procedure is similar than the followed for standard and modified proctor compaction tests, the difference is on the compaction effort applied to the specimens, which for TxDOT requirements is higher than for proctor standard but lower than for proctor modified. Table 3.2 shows the energy used in each compaction test procedure.

Table 3.2 Compaction energy on different laboratory compaction procedures

	Compaction Energy	**Reference**
Standard	7.18 ft-lb/in^3	ASTM D-698 A
Modified	32.41 ft-lb/in^3	ASTM D-1557
TxDOT	13.25 ft-lb/in^3	TEX-113-E

The compaction test was performed by using moulds with 4 inches diameter, in order to achieve the energy required by TxDOT a hammer of 10 pounds was used applying 17 blows falling from a height of 1.5 feet on three layers. The compaction test has to be done for at least 4 different moisture contents, calculating the density reached in each moisture content trial. After the calculation of the dry density, all the points are plotted in a moisture-dry density curve, then a trend curve is sketched and from this one the peak curve is analyzed estimating the optimum moisture content which is the moisture content that corresponds to the maximum dry density in the curve.

Figure 3.2 shows compaction curves for 0, 2, 4, 6 % cement dosage to RAP material.

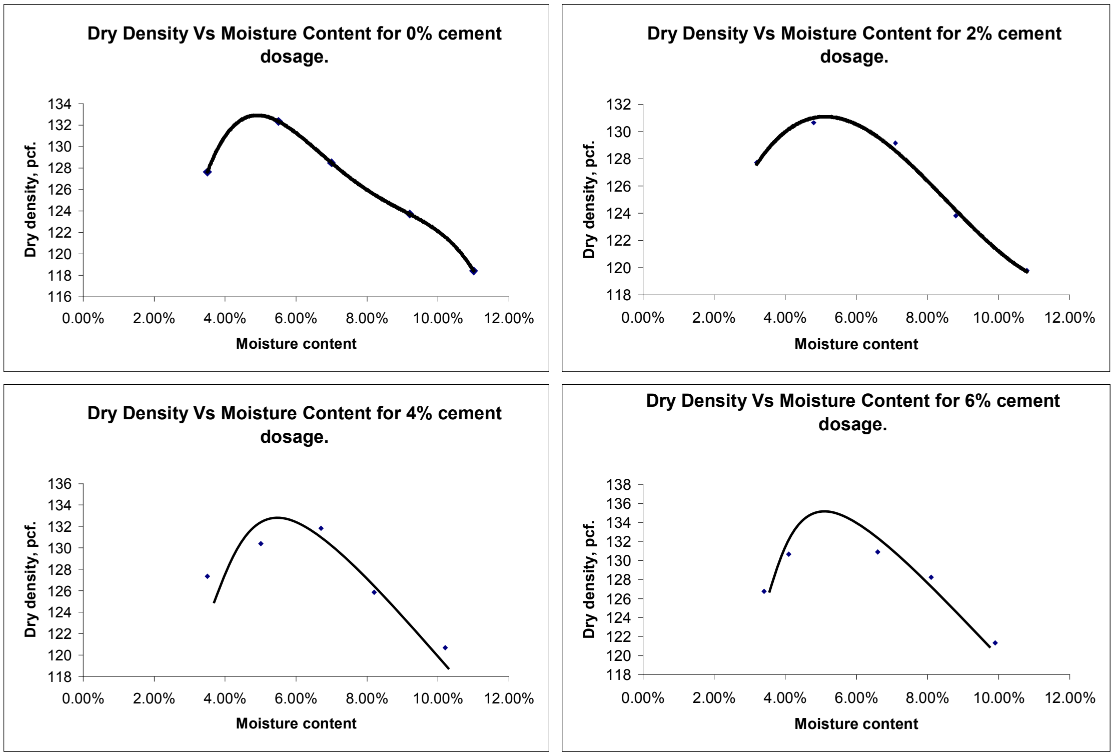


Figure 3.2 TxDOT compaction test curve results of RAP material

After having the compaction curves, from the peak of each curve the optimum moisture content for each cement dosage RAP material was obtained. Table 3.2 summarizes all the optimum moisture content and dry density for all cement dosages.

Table 3.3 Optimum moisture content and dry densities for 0, 2, 4 and 6 % cement content RAP material

Cement dosage %	**Optimun moisture content, %**	**Maximum dry density, pcf**
0	4.95	132.6
2	5.1	131.5
4	4.95	135.7
6	5.1	135.5

In reviewing all the compaction data, we have found an average +/- 0.5-pcf difference in density and +/- 0.75% difference in optimum moisture content between 4-in and 6-in specimens for all cement contents. This is more than acceptable to proceed with engineering testing (permeability, leaching, unconfined compression, and resilient modulus) on samples compacted with the 4-in mold.

Specimens were compacted at TXI company site using a mechanical compactor. Figure 3.3 shows the mechanical compactor used to compact the specimens.

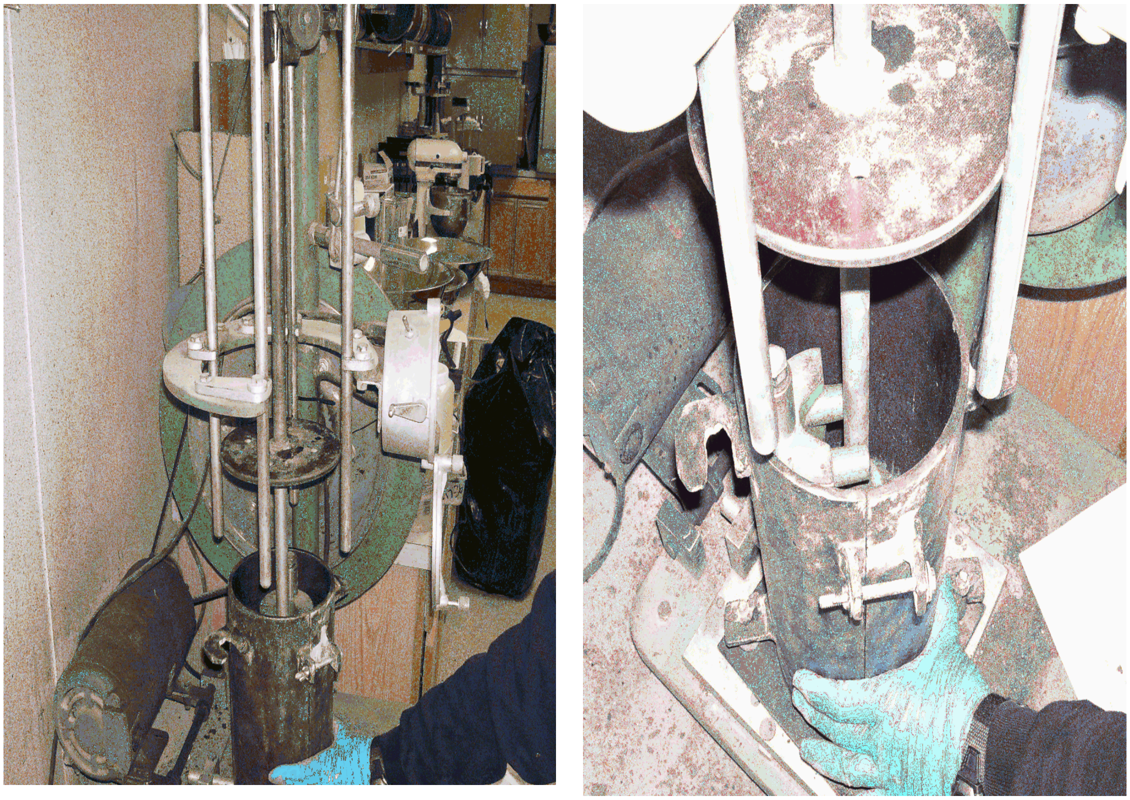


Figure 3.3 Mechanical compactor

3.3 Specimen Preparation

RAP specimens were prepared by mixing the material at 0, 2 and 4 % cement content without fibers and at 2, 4 and 6 % cement content with fibers. All specimens were mixed at optimum moisture content in order to obtain maximum dry unit weight levels, found on basic test of material. Figure 3.4 shows a typical RAP material mixture. After mixed, specimens were compacted. In the compaction process of the specimens, two different 10 and 5 pound hammers and three types of moulds of 2.8, 4 and 6 inches diameter were used. To achieve the energy required by TxDOT; for the specimens compacted on the 4 inch mould, 17 blows and three layers were applied; for the specimens compacted using the 6 inch mould, 50 blows and 4 layers were applied; and finally for the specimens on the 2.8 inch mould, 10 blows on three layers were applied. By using this variation of number of blows and number of layers, the required energy was obtained following Equation 4.1.

$$CE = \frac{Wr \times H \times Nb \times Nl}{V} \tag{3.1}$$

Where:

CE = Compactive effort

Wr = Weight of hammer

H = Height of drop

Nb = Number of blows

Nl = Number of layers

V = Volume of the specimen

The compacted samples were: 4 inch specimens for UCS and leacheate tests, 2.8 inches specimens for resonant column and 6 inches specimens for permeability test. The Samples were carefully extruded, wrapped and the placed on moisture room for 7 days period for curing.

Figure 3.4 Material mixture

From previous data it was observed that for the samples to be used in UCS and Leachate tests, the densities achieved were in the range of +/- 5% maximum dry density from laboratory compaction test. Samples compacted in the 6 inch mould for permeability test showed higher densities than the maximum dry density obtained from compaction laboratory tests, this can be explained by the change in grain size distribution of the material when some of the coarse aggregates got crushed because of the impact of the hammer, impact that is higher than in others because the thickness of layers is smaller and therefore the higher exposure. On the other hand, samples for resonant column showed values around 85% the value of maximum dry density obtained in the compaction test in the laboratory, this can be explained because of the size of the coarse particles in RAP material were too large for the 2.8 inch diameter mould therefore the low degree of accommodation of the particles inside the mould resulted in high void ratio.

Table 3.4 shows the actual unit weight and moisture content obtained on each sample and the values the samples were suppose to achieve.

Table 3.4 RAP specimens densities achieved on compaction process

		CEMENT CONTENT	**MOIST UNIT WEIGHT**	**MOISTURE CONTENT, %**	**DRY UNIT WEIGHT**
PERMEABILITY	**RAP WITHOUT FIBERS**	**0%**	142.0	5	135.2
		2%	144.9	5	138.0
		4%	146.8	5	139.8
	RAP WITH FIBERS	**2%**	140.7	5	134.0
		4%	143.7	5	136.9
		6%	143.0	5	136.2
LEACHATE	**RAP WITHOUT FIBERS**	**0%**	131.5	5	125.2
		2%	132.4	5	126.1
		4%	131.5	5	125.2
	RAP WITH FIBERS	**2%**	135.7	5	129.2
		4%	135.7	5	129.2
		6%	135.5	5	129.1
UNCONFINED COMPRESSIVE STRENGTH	**RAP WITHOUT FIBERS**	**0%**	135.3	5	128.8
		2%	135.5	5	129.1
		4%	136.3	5	129.9
	RAP WITH FIBERS	**2%**	138.7	5	132.1
		4%	139.6	5	133.0
		6%	140.1	5	133.4
RESONANT COLUMN	**RAP WITHOUT FIBERS**	**0%**	117.9	5	112.3
		2%	121.0	5	115.2
		4%	119.3	5	113.6
	RAP WITH FIBERS	**2%**	114.7	5	109.2
		4%	117.1	5	111.6
		6%	118.9	5	113.3

3.4 Engineering Tests

3.4.1 Permeability

The permeability tests were performed on accordance with Standard test method for permeability of granular soils constant head, ASTM D 24. It is known that hydraulic conductivity is a function of pore-size distribution, pore continuity and pore shape. These are affected by grain-size distribution, particle shape and relative density (Richardson, 1998).

Figure 3.5 represents a sketch of the constant head permeability set up used for test the hydraulic conductivity of RAP materials, this can be assembled with a acrylic cylinder with an inside diameter of 6 inches, two porous stones, a large funnel, a stand, clamps, and some plastic. The permeability setup as used for testing of RAP can be observed in figure 3.6.

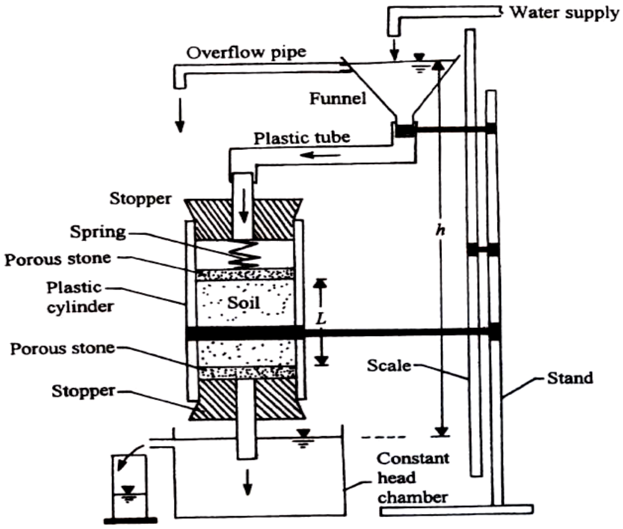


Figure 3.5 Constant head sketch

Figure 3.6 Permeability test setup

After the passing trough the specimen, water is collected and also the flow in unit time of water is measured. When having this data calculation process with following equations:

1. Calculate void ratio of compacted specimen.

$$e = \frac{G_s \rho_w}{\rho_d} - 1 \tag{3.2}$$

Where:

G_s = Specific gravity of soil solids.

ρ_w = Density of water.

ρ_d = Dry density of specimen.

2. Calculate coefficient of permeability (k) :

$$k = \frac{Q \cdot L}{A \cdot h \cdot t} \tag{3.3}$$

Where:

Q = Amount of collected.

t = Collection time.

h = Head pressure.

A = Area of specimen.

L = Length of specimen.

After having the hydraulic conductivity coefficient a correction factor has to be applied because of the change in viscosity of water due to temperature variations.

3.4.2 Leaching Tests

Leaching tests will be conducted on selected RAP specimens for each cement dosage level, for a total of 6 specimens to be tested for leaching (i.e., 3 tests on RAP without fibers, and 3 tests on RAP with fibers). Leaching tests included pH measurement, total and volatile dissolved solids, total and volatile suspended solids, turbidity, and a few other chemical identification tests.

1. *pH Test:* pH test was conducted according to ASTM D1287. pH is a measure of the water acidity. The scale goes from 0 to 14. A pH of 7.0 is neutral. Values less than 7.0 indicate acid conditions while readings over 7.0 indicate alkaline conditions. In order to measure pH a dual channel pH conductivity meter device was used. Figure 3.7 shows the mentioned device.

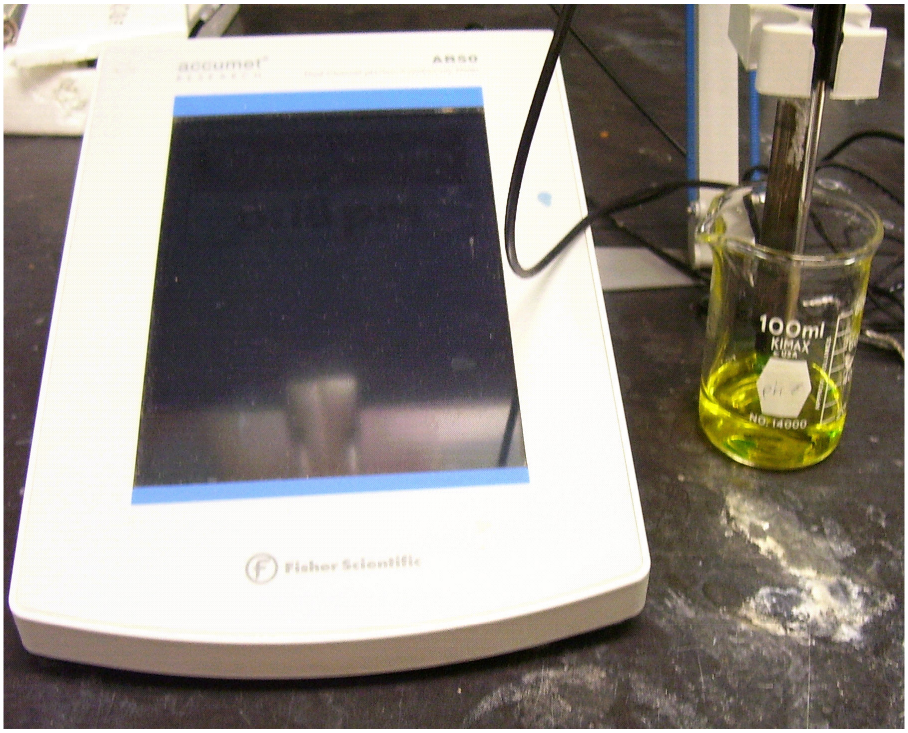


Figure 3.7 Dual channel pH/ion/conductivity meter

1. Chemical Oxygen Demand: This test method cover the determination of the quantity of oxygen that certain impurities in water will consume, based on the reduction of a dichromate solution under specified conditions ASTM D 1252. First a Transmittance vs concentration of COD was calibrated. After having the calibration curve samples were poured in COD vials and heated for two hours as digester period in the COD reactor (Figure3.8).

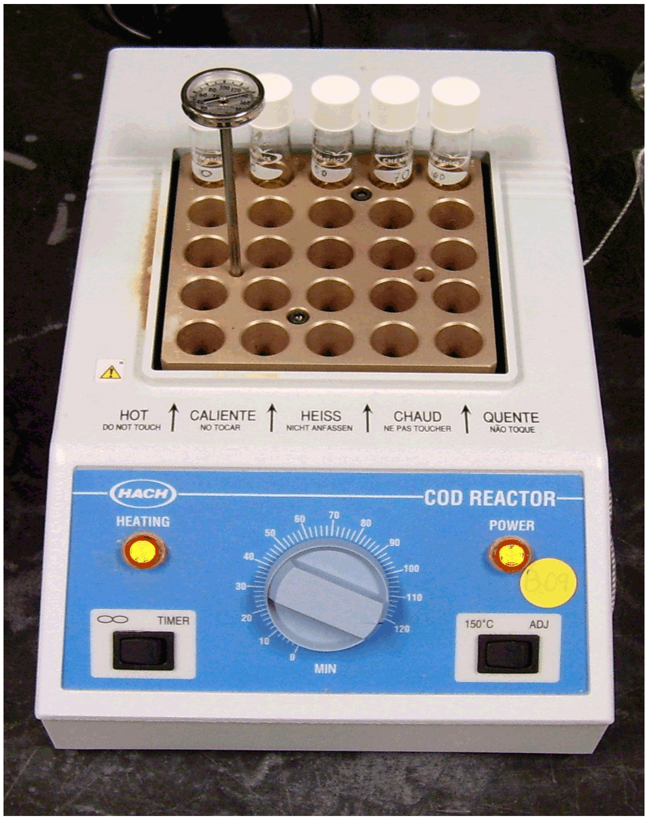


Figure 3.8 COD reactor and samples heated for digestion

2. *Total suspended and Total dissolved solids:* These tests were conducted according to Standard Test Method for Filterable and Non-filterable Matter in water, ASTM D 5907-03. Total suspended dissolved solids consider all suspended solids in the sample and by passing the water sample through a filter paper suspended solids are going to be retained on it. Total dissolved solids are the ones which enter in intimate contact with the sample changing its chemical properties like alkalinity, acidity, salinity, etc.

3. *Turbidity:* Turbidity is a way to measure particles in water by using the shine of a light passing through the sample. Turbidity was measured by introducing the samples in 2100P turbidimeter (Figure 3.9).

Figure 3.9 Turbidimeter

3.4.3 Unconfined compressive strength (UCS) Test

The UCS tests were conducted in accordance to ASTM D-2166 standards. Samples were prepared as explained in earlier section. After 7 days, cured samples were placed on the compressive test platform and loaded at a constant rate which was controlled by a loading device control. Axial load and deformation data were simultaneously collected by a computer attached to the test setup. The maximum axial compressive load at which the sample failed was used to determine the unconfined compressive strength of the samples. This strength usually depends on cohesion and particle interlocking of the soil particles. Figure 3.10 shows the machine used in the test.

Three samples at 0, 2 and 4% cement dosage of RAP material without fibers and three samples at 2, 4 and 6% cement dosage of RAP material with fiber reinforcement were tested in order to ensure repeatability of results.

Unconfined compressive strength is one of the most important tests for the present study in the way that, its results are going to be used as an attempt to find out the modulus of elasticity of RAP material, from which it will be determined how the stiffness properties of RAP materials change with the addition of cement. Even though UCS is not the best test to evaluate the performance of any material under tensile stresses, this study is going to try to observe in UCS test results if inclusion of fibers has any influence on the stiffness properties of the test.

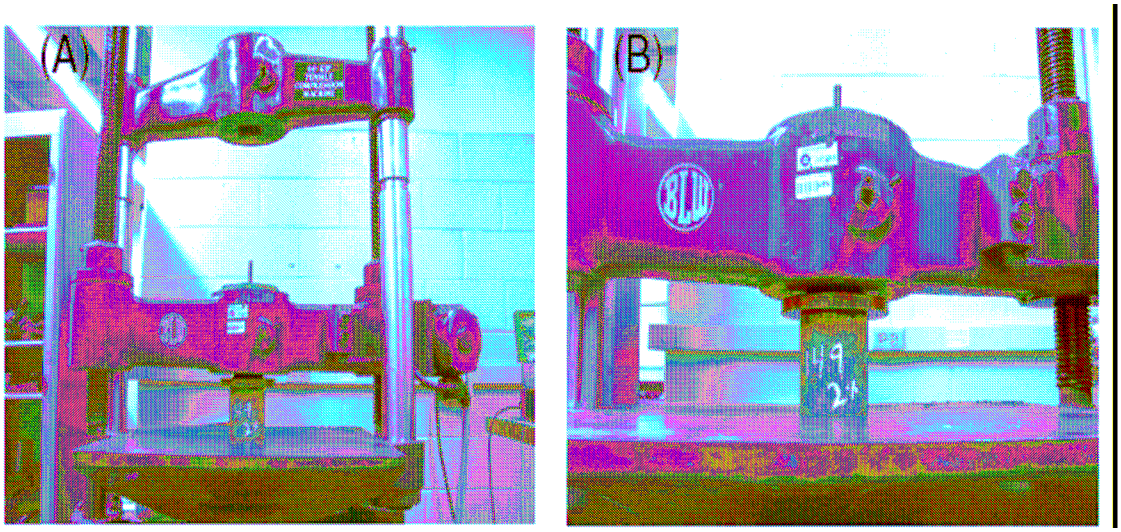


Figure 3.10 Compressive machine used for UCS test of RAP material

3.4.4 Resonant Column Test: A Qualitative Assessment of Stiffness Response

The resonant column (RC) testing technique was first used to study dynamic properties of rock materials in the early 1930s, and has been continuously evolving since then for the dynamic characterization of a wide variety of geologic materials (Huoo-Ni, 1987).

RC testing covers the determination of the shear modulus and shear damping of cylindrical specimens of soil by vibration. The vibration of the specimen is performed under a controlled ambient state of stress in the specimen. The vibration apparatus is enclosed in a chamber so confinement can be applied. The resonant column test is considered as non-destructive test.

The shear modulus of a given soil, as measured by the resonant column, depend upon the strain amplitude of vibration as well as the state of effective stress and void ratio of the specimen, given for the same material higher shear modulus when the void ratio is lower. The applicability of these results depend on how accurate is the duplication of field conditions when preparing samples in the lab.

The Stokoe torsional shear/resonant column (TS/RC) testing (ASTM D 4015-92) apparatus can be idealized as the fixed-free system shown in Figure 3.11 The sample stays fixed at bottom and is allowed to rotate on the top end where vibration is induced through a drive plate. The vibration consist on a cyclic torque of constant amplitude applied on top from which its frequency change is recorded by an accelerometer attached to the driven plate which sketch is on Figure 3.12 After having curve of frequency response, resonant frequency can be determined from the peak of the curve and shear modulus G can be calculated. Figure 3.13 represents a typical frequency response curve.

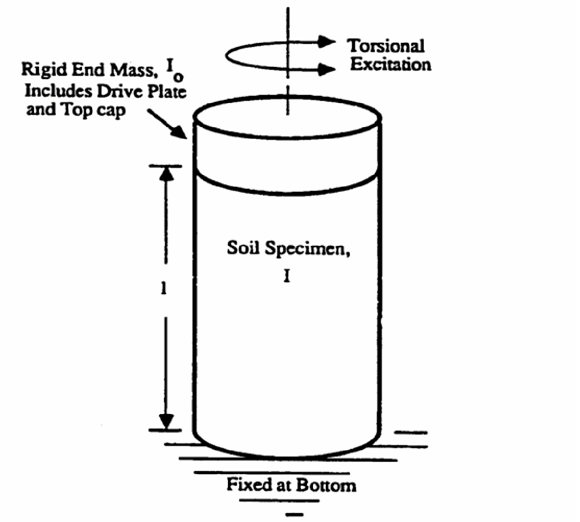


Figure 3.11 Idealization of fixed- free Rc device (Huoo-Ni, 1987)

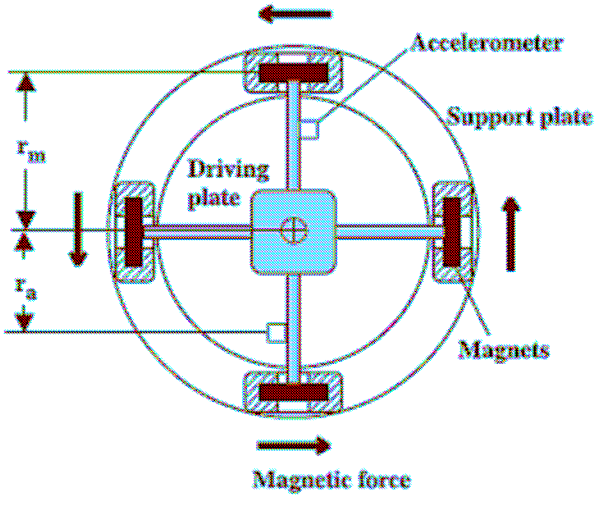


Figure 3.12 sketch of driven plate

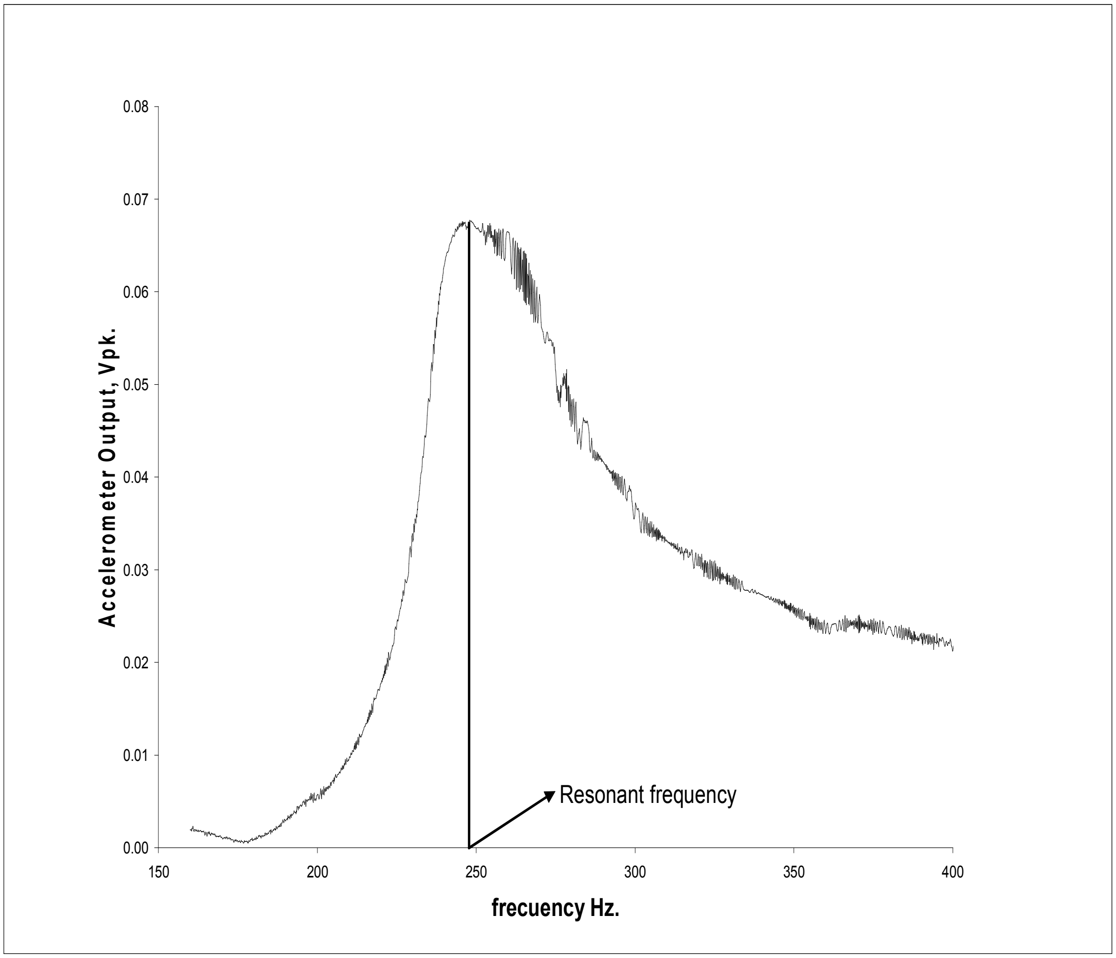


Figure 3.13 typical frequency response curve from a RC test on RAP material

3.4.4.1 Shear Modulus G

Shear modulus is defined as elastic modulus of an uniform, linearly viscoelastic specimen, necessary to produce a resonant column having the measured system resonant frequency. The stress-strain relation for a steady-state vibration in the resonant column is a hysteresis loop. The modulus will correspond to the slope of a line through the end points of hysteresis loop (Drnevich, 1978).

After having the resonant frequency Richart (1975) suggested a simplified method for calculating the shear modulus (G) using the resonant frequency (f_r), obtained from the frequency response curve (figure 3.10), and the geometric characteristics of the soil column and the top cap-driver system. The method can be summarized as follows:

$$G = \rho(2\pi L)^2 \left[\frac{f_r}{F_r}\right]^2 \tag{3.3}$$

Where:

$L =$ the length of the specimen

$F_r =$ is a dimensionless constant known as the frequency factor, and defined as,

$$F_r = \sqrt{\frac{I_s}{I_o}} \tag{3.4}$$

Where:

$I_s =$ Is the polar moment of inertia of soil.

$I_o =$ Is polar moment of inertia of the driver.

Equations (3.2) and (3.3) were used in the present study for calculating linear (low-amplitude) shear modulus (G).

3.4.2.2 Apparatus Assembly

In this section is a step by step description of the assembly process of RC testing device interacting with the frequency response measurement system, is presented in the following paragraphs:

1. Specimen placement: After cured period of 7 days the specimens are ready to test. The sample is carefully placed on bottom pedestal of RC device, then the top cap is placed and a latex membrane with 2 o rings at the extremes is rolled downward to protect the sample from contact with the water which is used to apply confinement isotropically. In figure 3.14 it can be observed the specimen placed as described.

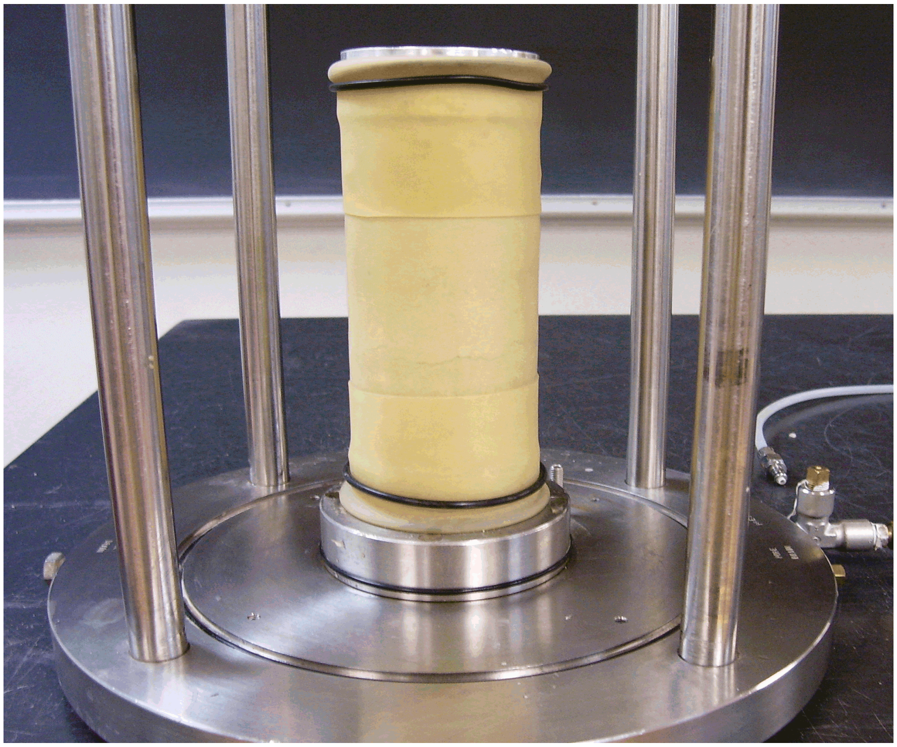


Figure 3.14 Specimen placed on pedestal of RC testing device

2. <u>Water bath application:</u> in order to minimize extrusion of the latex membrane and/or air migration through the specimen upon application of confining pressure, the specimen is submerged on water bath (Figure 3.15).

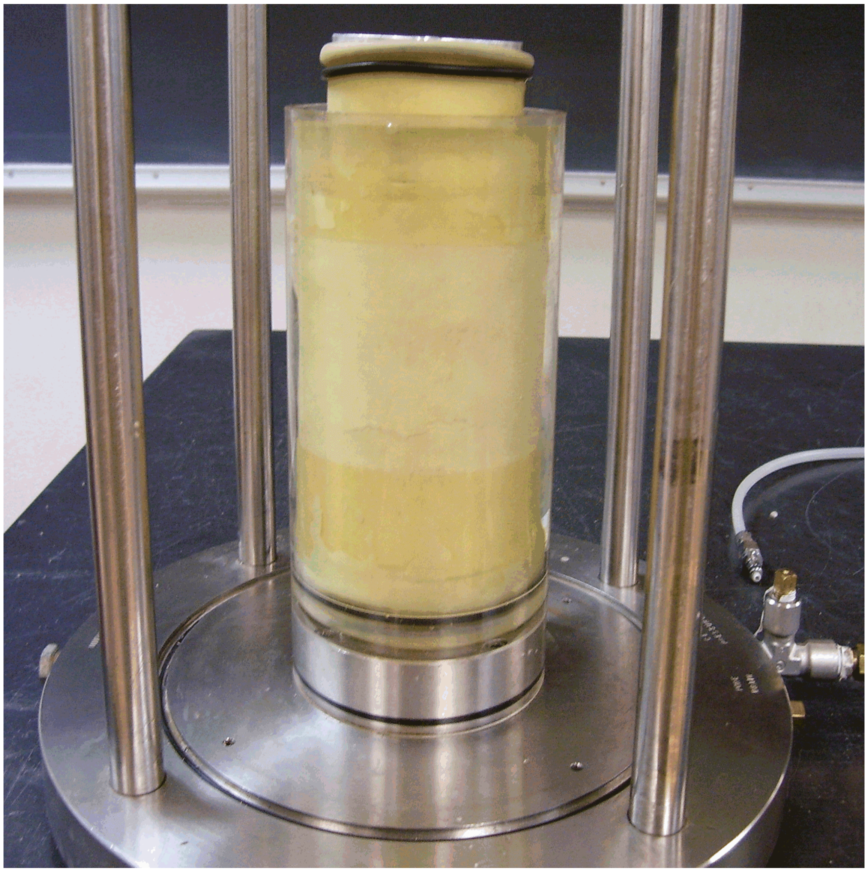


Figure 3.15 bath water applied in between the acrylic cylinder and soil specimen

3. <u>Torsional Driver Setup:</u> after the water bath was applied, a cylindrical cage is attached securely to the base plate and on top of it the torsional driver is placed and attached eventually. It is important when attaching the torsional driver that the coils and magnets don’t touch in between each other. Figure 3.11.

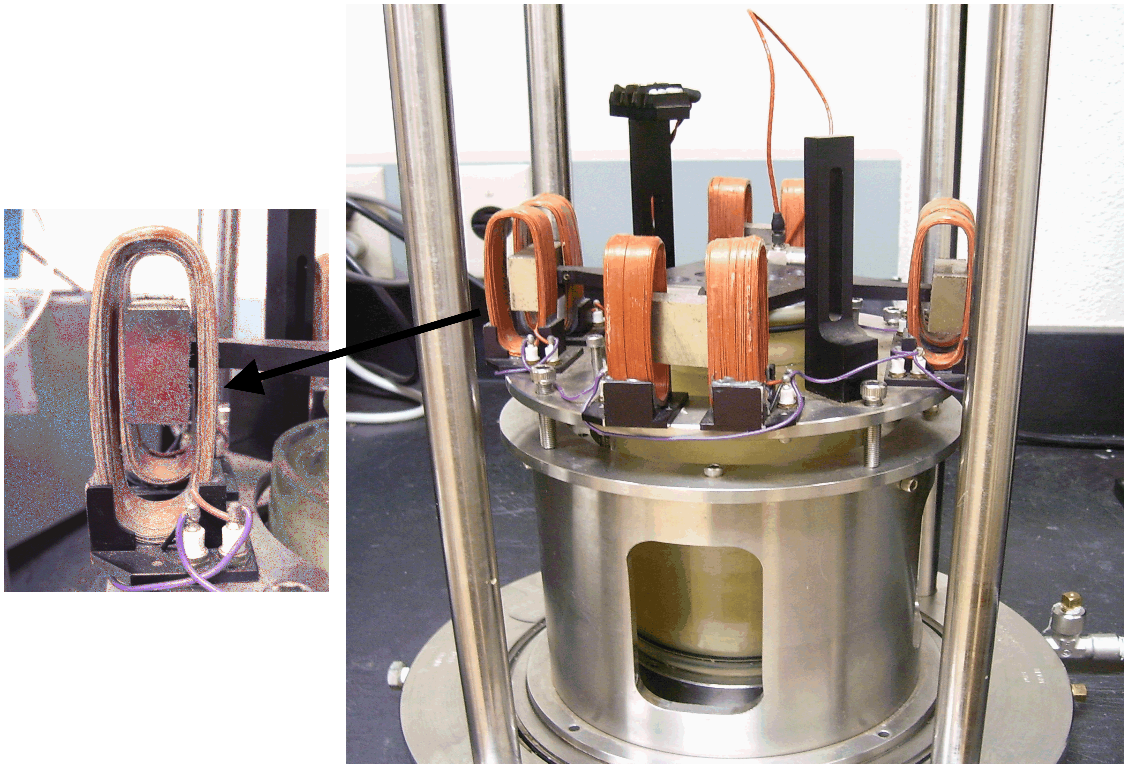


Figure 3.16 Torsional Driver of RC testing machine

4. Confining pressure application: after installation of torsional driver. The electrical wiring is then connected to the corresponding microdot connectors on the inner side of the thin-wall cylinder, that is, the input signal current wire and the accelerometer output wire. The cover plate is placed over the top of the vessel and bolted tightly with the four guide rods. Then, the soil specimen, along with the remaining components of the RC device, is pressurized with air at the desired isotropic confining pressure (σ'_o). Air pressure is supplied by a HM-4150-model pressure control panel (Humboldt Manufacturing Co.) via an inlet air-pressure port located at the base plate of the confining chamber (figure 3.17). This step concludes the assembly of the RC device prior to RC testing.

Figure 3.17 Application of confinement

5. Frequency response data capturing and storage: Once the swept-sine mode RC test has been completed, the frequency response curve and captured test data are transferred to the CPU of the PC-based computer terminal for future data processing using application software like Excel. A photograph of the dynamic analyzer interacting with the computer terminal is shown in figure 3.18.

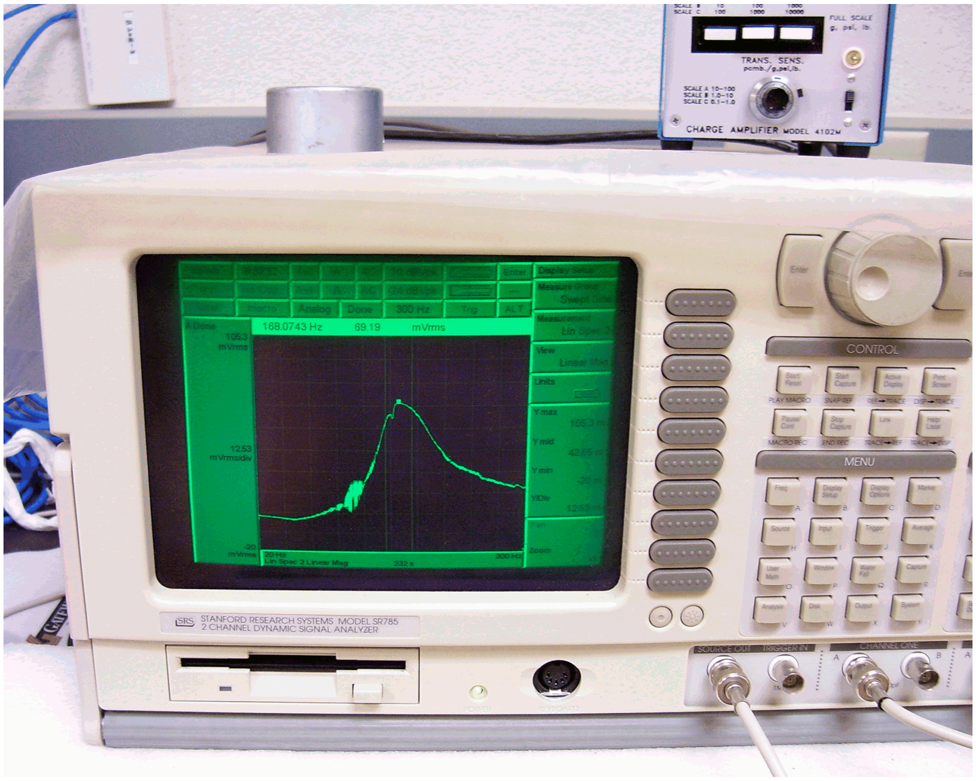


Figure 3.18 Frequency response analyzer of RC testing setup

Next chapter presents all the experimental results from the series of *basic* and *engineering* tests and the analyses of these results.

CHAPTER 4

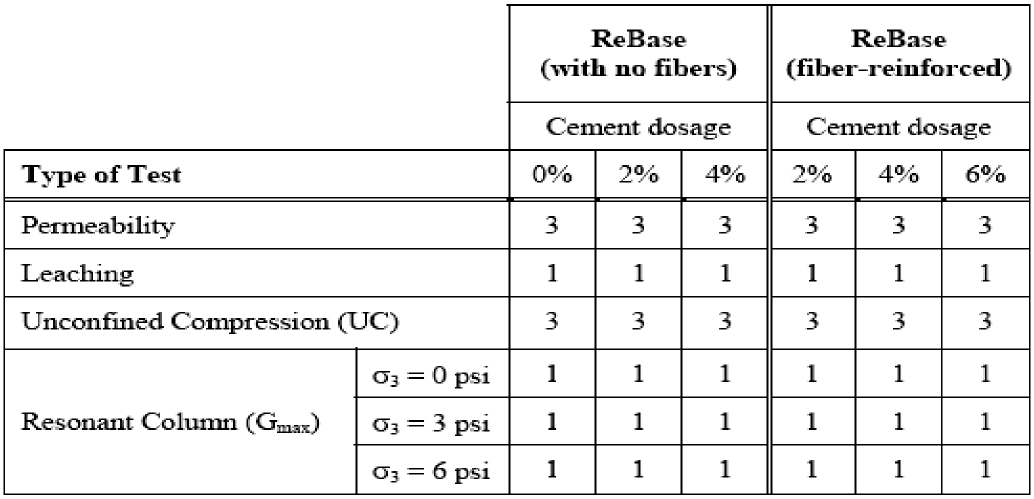
ANALYSIS OF TEST RESULTS

4.1. Introduction

Results from permeability, leaching, unconfined compression, and resilient modulus tests, all together, will provide valuable insight on potential improvements of the structural support of flexible pavements resting on RAP base/sub-base layers, as per recent AASHTO design method.

Table 4.1 summarizes the entire engineering test program accomplished during this research work along with, the number of specimens tested for each proposed test for repeatability purposes. All tests were performed at UTA geotechnical laboratories, which are fully equipped with unconfined compression, permeability setup, and resonant column test devices.

Table 4.1 Engineering Test Program and Number of Specimens



		ReBase (with no fibers)			**ReBase (fiber-reinforced)**		
		Cement dosage			Cement dosage		
Type of Test		0%	2%	4%	2%	4%	6%
Permeability		3	3	3	3	3	3
Leaching		1	1	1	1	1	1
Unconfined Compression (UC)		3	3	3	3	3	3
Resonant Column (G_{max})	σ_3 = 0 psi	1	1	1	1	1	1
	σ_3 = 3 psi	1	1	1	1	1	1
	σ_3 = 6 psi	1	1	1	1	1	1

4.2 RAP Aggregate Basic Properties

RAP aggregates have a uniform grain-size distribution, as obtained at TXI location, and by sieve analysis test performed at UTA, described in previous chapter. Atterberg limits were not necessary because the material did not have enough percentage if fines (less than 1%). The optimum moisture content was 5% +/- 0.05% for RAP aggregates at all cement dosages.

In most of the specimens the required density was achieved. The specimens prepared using the 2.8 inch mould (resonant column samples) had approximately 80-88% density compared to the maximum dry density from moisture-dry density curves obtained in the lab.

RAP specimen densities achieved in the compaction process can affect the results obtained in the different tests performed (UCS, Permeability, Resonant Column). The influence on each on the tests is analyzed in each section of this chapter.

4.3 Permeability

Permeability test was performed at UTA geotechnical laboratories on RAP samples after 7 days of cure period. Samples used for this test had a diameter of 6 inches and densities close to the maximum dry density obtained from Laboratory Compaction Characteristics and Moisture-Density Relationship of RAP Materials.

Table 4.2 summarizes all data collected from permeability tests of RAP aggregates and other RAP hydraulic conductivity values reported in other papers, a decrease in the hydraulic conductivity when the cement dosage is increased was observed. The values shown in this report are slightly higher than those values reported in other papers. Samples from other reports are recycled asphalt pavement (RAP), and were collected from three stockpiles in southern Wisconsin referred to herein as PDF, PDV, and WSP (Trzebiatowski, 2005).

Table 4.2 Saturated hydraulic conductivity of RAP and RAP aggregates at different cement dosages results from permeability test

Material	Compactive Effort	Dry Unit Weight (pcf)	Hydraulic Conductivity (m/s)
RAP without fibers 0% cement dosage.	TxDOT	135.24	2.10E-06
RAP without fibers 2% cement dosage.	TxDOT	138.01	1.45E-06
RAP without fibers 4% cement dosage.	TxDOT	139.79	1.31E-06
RAP without fibers 2% cement dosage.	TxDOT	133.97	1.38E-06
RAP without fibers 4% cement dosage.	TxDOT	136.89	1.29E-06
RAP without fibers 6% cement dosage.	TxDOT	136.19	1.19E-06
PDV RAP	Standard	120.05	3.80E-05
PDV RAP	Modified	129.48	1.70E-06
PDF RAP	Standard	120.05	9.00E-05
PDF RAP	Modified	130.11	4.90E-07
WSP RAP	Standard	125.71	2.40E-05
WSP RAP	Modified	137.02	4.50E-08

The higher values can be explained due to the differences in densities of the samples because of the compaction effort, also the grain size distribution take a roll here, because while RAP material has less than 1% of fines, RAP materials form other reports have fines in between a range of 2.1 and 8.4% of fines and it is known that the fines help to fill the voids, giving this way, less communication in between voids resulting with a smaller value of hydraulic conductivity.

Figure 4.1 represents the variation of hydraulic conductivity with addition of cement for RAP material without and with fibers and compacted RAP materials (Trzebiatowski and Benson, 2005). The author believed that there is not any influence of the fiber inclusion on the hydraulic conductivity behavior of the material.

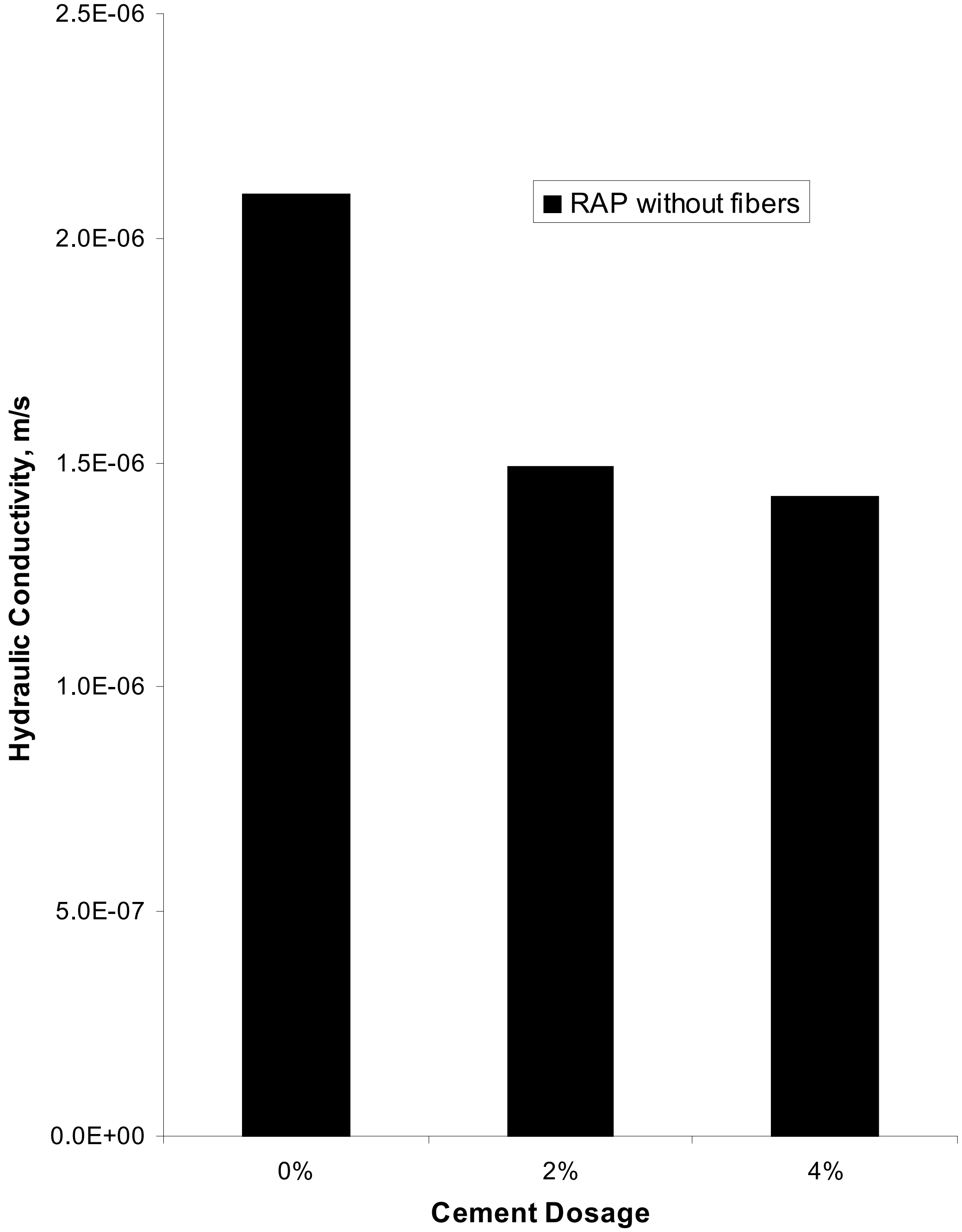


Figure 4.1 Variation of the hydraulic conductivity with the addition of cement on RAP materials without fibers

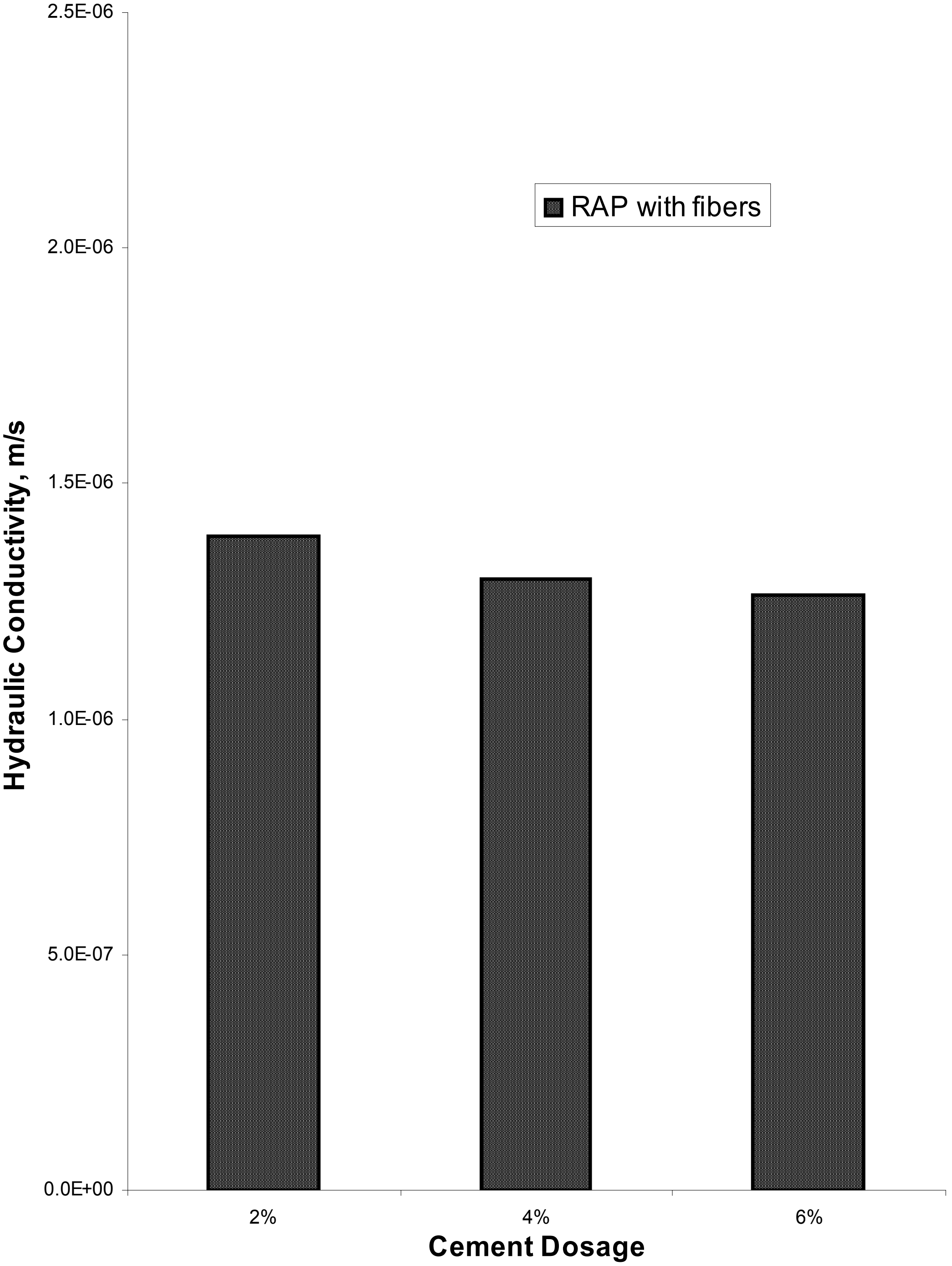


Figure 4.2 Variation of the hydraulic conductivity with the addition of cement on RAP materials with fibers

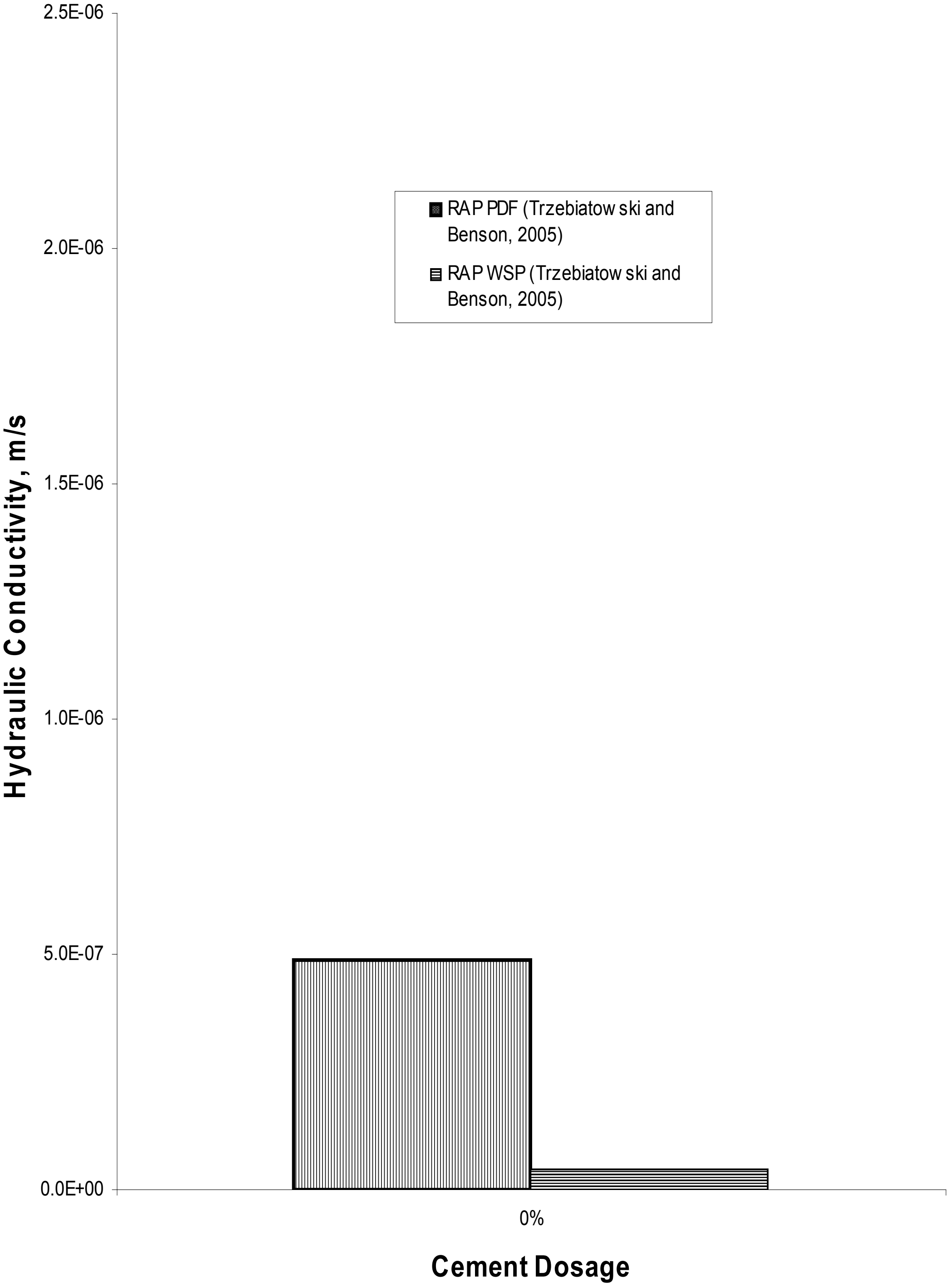


Figure 4.3 hydraulic conductivity on RAP materials (Trzebiatowski and Benson, 2005)

4.4 Leaching Tests

Leaching tests were conducted on selected RAP specimens for each cement dosage level, for a total of 6 specimens tested for leaching (i.e., 3 tests on RAP without fibers, and 3 tests on RAP with fibers). Leaching tests included pH, total and volatile dissolved solids, total and volatile suspended solids, turbidity, and a few other chemical identification tests.

Leaching tests were conducted on water samples in which RAP specimens were soaked for 24 hours (figure 4.4).

Figure 4.4 RAP specimens soaked for 24 hours

4.4.1 pH Test

This test was performed according to ASTM D1287 test procedure. Results showed an increase in pH when the cement dosage was increased. Table 4.3 shows all of the results from the 6 specimens tested for leaching and figure 4.3 and 4.4 presents the variation of pH at different levels of cement content on RAP aggregate without fibers and with fibers.

Table 4.3 pH test results for RAP aggregates

	CEMENT DOSAGE	PH READING
RAP WITHOUT FIBERS	0%	6.58
	2%	10.88
	4%	11.2
RAP WITH FIBERS	2%	11.18
	4%	11.34
	6%	11.44

According to US EPA benchmarks for stormwater sampling pH should be in the range of 6-9. As it can be observed, cement-treated RAP leachate samples have a pH higher than the maximum specified.

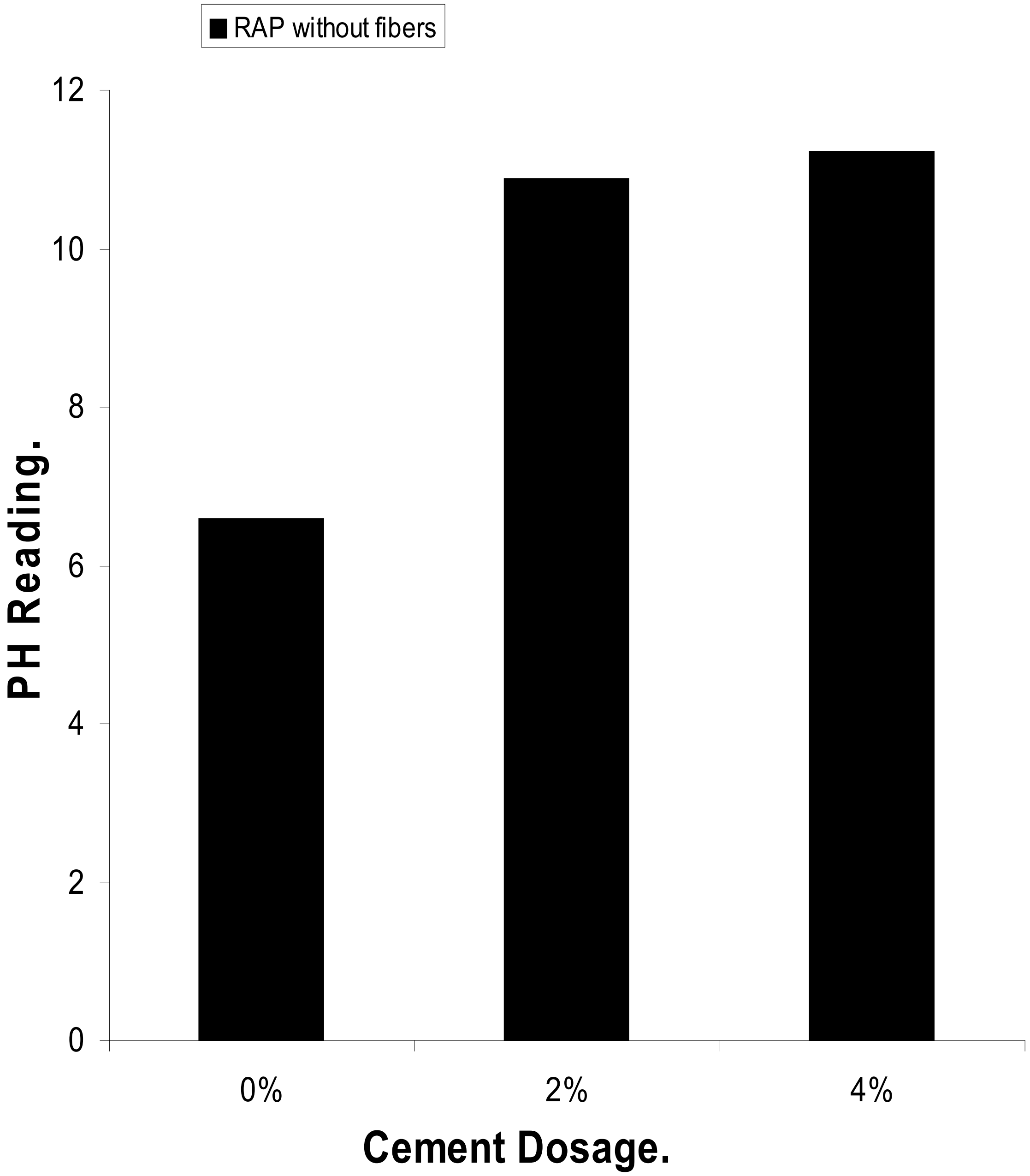


Figure 4.5 Variation of the pH with the addition of cement on RAP materials without fibers

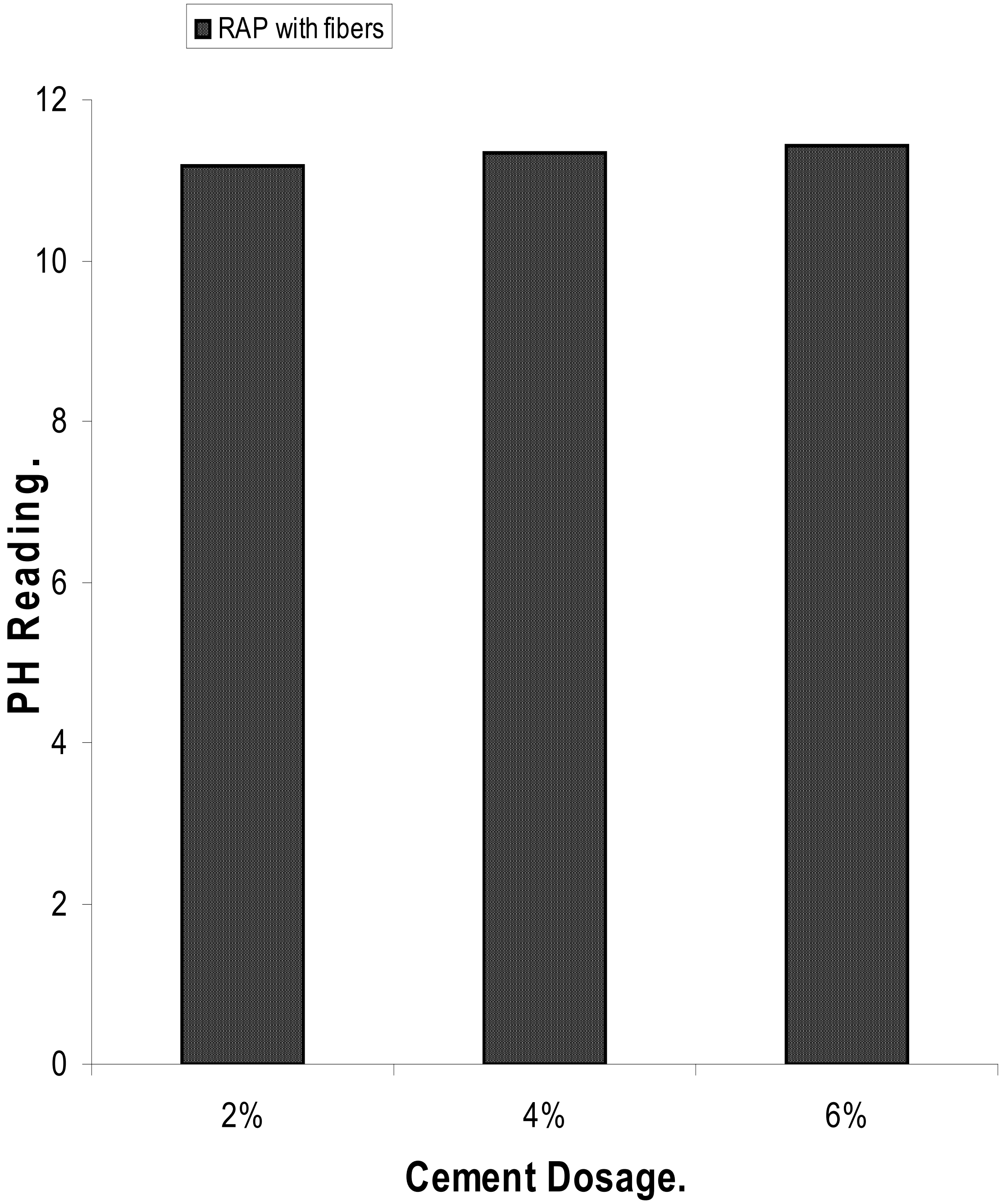


Figure 4.6 Variation of the pH with the addition of cement on RAP materials with fibers

pH test showed an increment in samples as the cement dosage was increasing, it can be concluded that some components of cement were diluting on the presence of water. It is also observed that the increase in pH, once cement was added to RAP specimen, did not vary significantly.

4.4.2 Chemical Oxygen Demand COD test

This test was performed according to Chemical Oxygen Demand of water (COD) ASTM D1252-00 test procedure at geo-environmental laboratories of UTA. This test method covers the determination of the quantity of oxygen that certain impurities in water will consume, based on the reduction of a dichromate solution under specified conditions. It was observed a decrease in COD when the cement dosage was increasing. Table 4.4 resumes all results from the 6 specimens tested for leaching. Figure 4.5 and 4.6 represent the variation of pH at different levels of cement content on RAP aggregate without and with fiber inclusion.

Table 4.4 Chemical Oxygen Demand Results of RAP Leaching Tests

	Cement Dosage,%	**Chemical Oxygen Demand (mg/l)**
RAP Without Fibers	0	59.3
	2	42.3
	4	40
RAP With Fibers	2	58.3
	4	49.6
	6	37

According to US EPA benchmarks for stormwater sampling COD should be in less than 120 mg/l. As it can be observed, cement-treated RAP leachate samples have a COD concentration lower than the maximum specified.

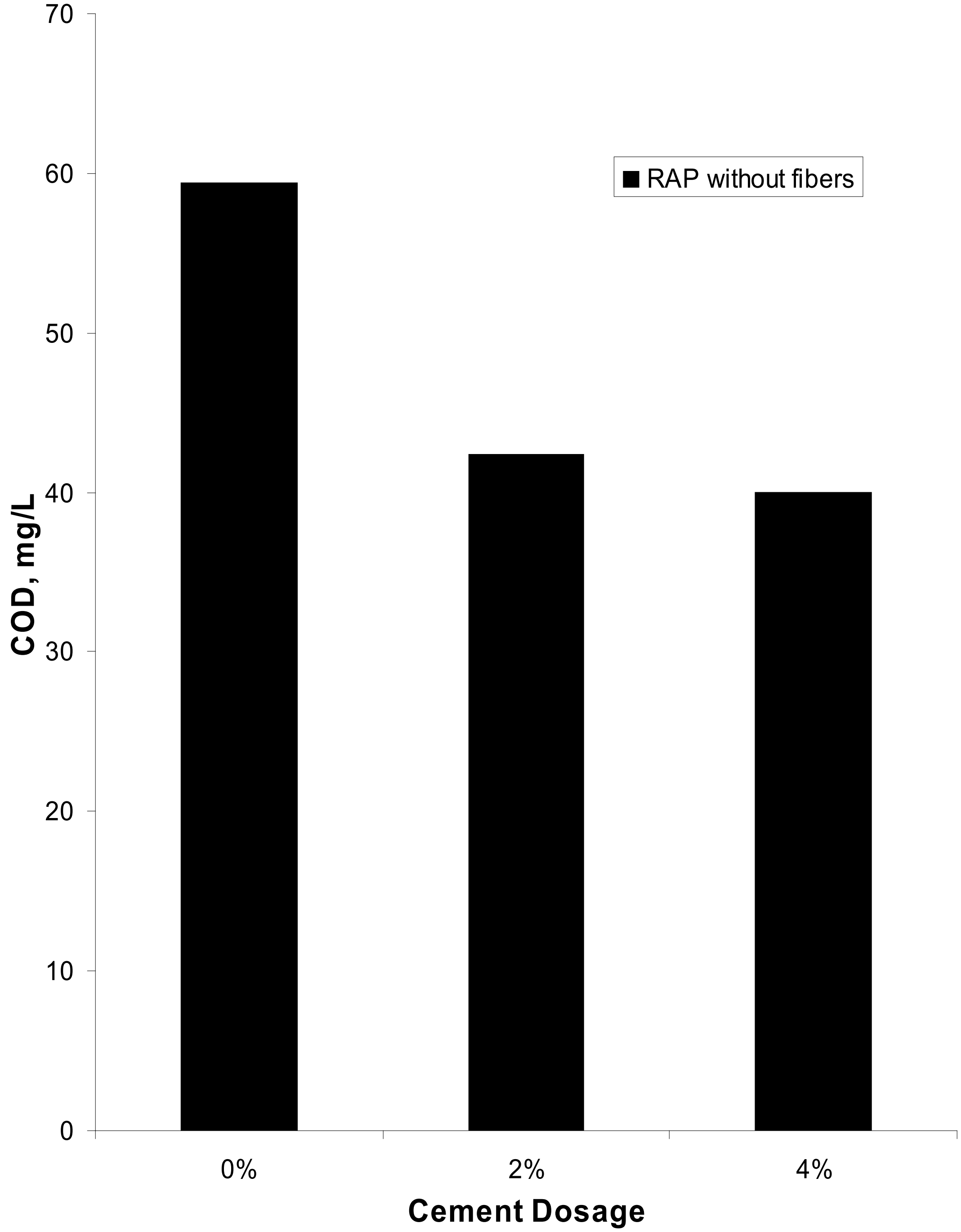


Figure 4.7 Variation of the COD with the addition of cement on RAP materials without fibers

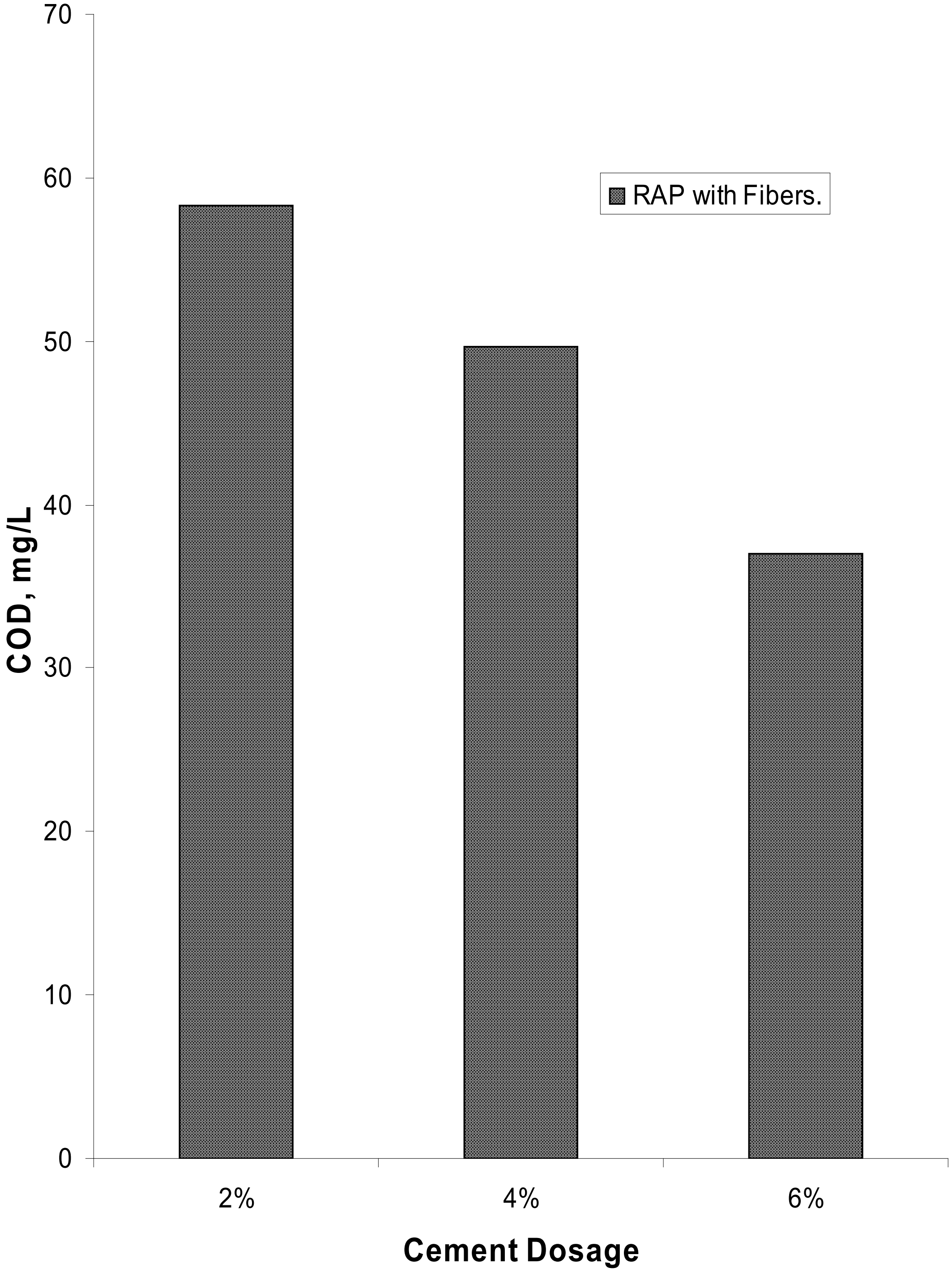


Figure 4.8 Variation of the COD with the addition of cement on RAP materials with fibers

4.4.3 Total Dissolved Solids

Total dissolved solids results are not of significance in water quality or potential pollutional characteristics; however, the associated adverse effect of high dissolved constituents has result in the establishment of upper limits for various beneficial uses. Dissolved materials are of potential importance as a result of their chemical makeup and effect. Materials in the soluble state may represent alkalinity, acidity, salinity etc.

Table 4.5 shows all of the collected data from leaching test and their variation is showed in figure 4.7 and 4.8.

Table 4.5 Results of Total dissolved solids on RAP Leaching specimens

	Cement Dosage %	**Total Dissolved Solids (mg/l)**
RAP Aggregates Without Fibers	0	410.2
	2	479.3
	4	505.3
RAP Aggregates With Fibers	2	465.3
	4	495.3
	6	508.4

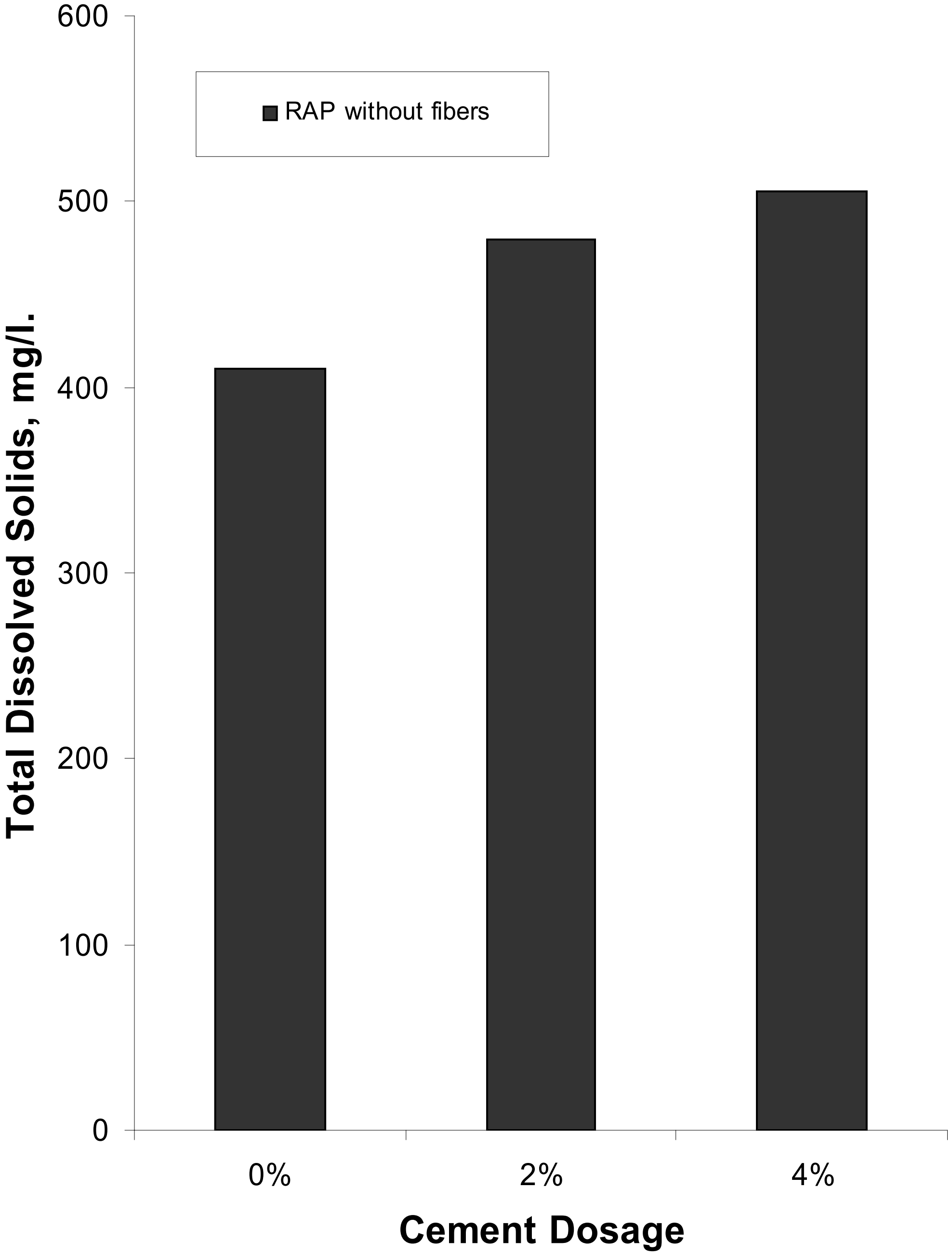


Figure 4.9 Variation of the TDS with the addition of cement on RAP materials without fibers

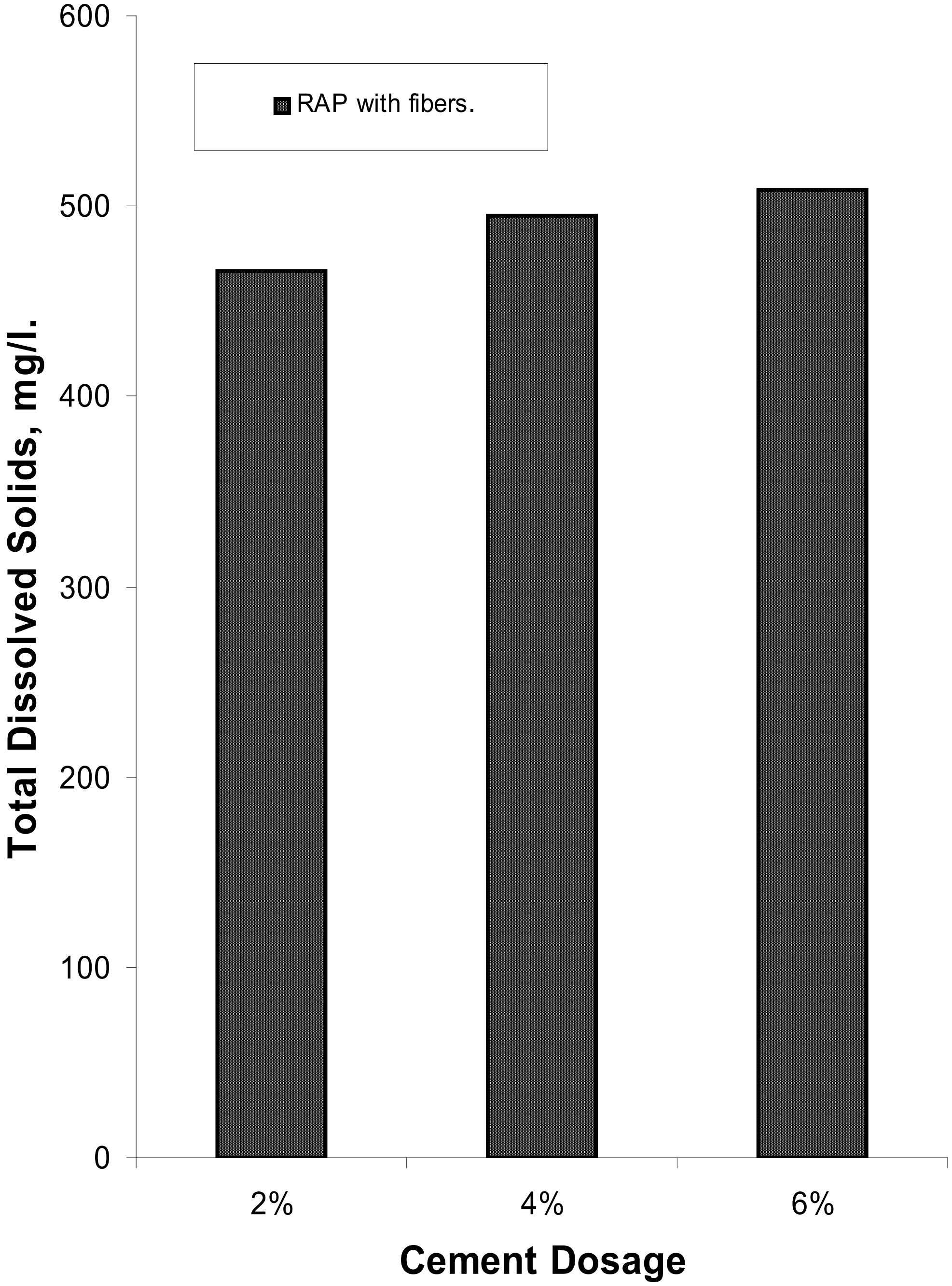


Figure 4.10 Variation of the TDS with the addition of cement on RAP materials with fibers

4.4.4 Total Suspended Solid

The suspended soil determination is valuable in the analysis of pollute waters. All suspended solids are considered to be settable solids as by bacterial decomposition and chemical flocculation deposition of these solids eventually does take place.

Table 4.6 resumes all collected data from leaching test and their variation at different levels of cement dosage is showed in figure 4.9 and 4.10.

Table 4.6 Results of Total Suspended solids on RAP Leaching specimens

	Cement Dosage %	**Total Suspended Solids (mg/l)**
RAP Without Fibers	0	1357.3
	2	505.3
	4	477.3
RAP With Fibers	2	616
	4	458.6
	6	466

According to US EPA benchmarks values for stormwater sampling TSS should be less than 100 mg/l. As it can be observed, cement-treated RAP leachate samples have higher concentration than the maximum specified. Because of TSS concentration was inversely proportional to cement dosage addition of cement could be considered as a potential solution to this issue.

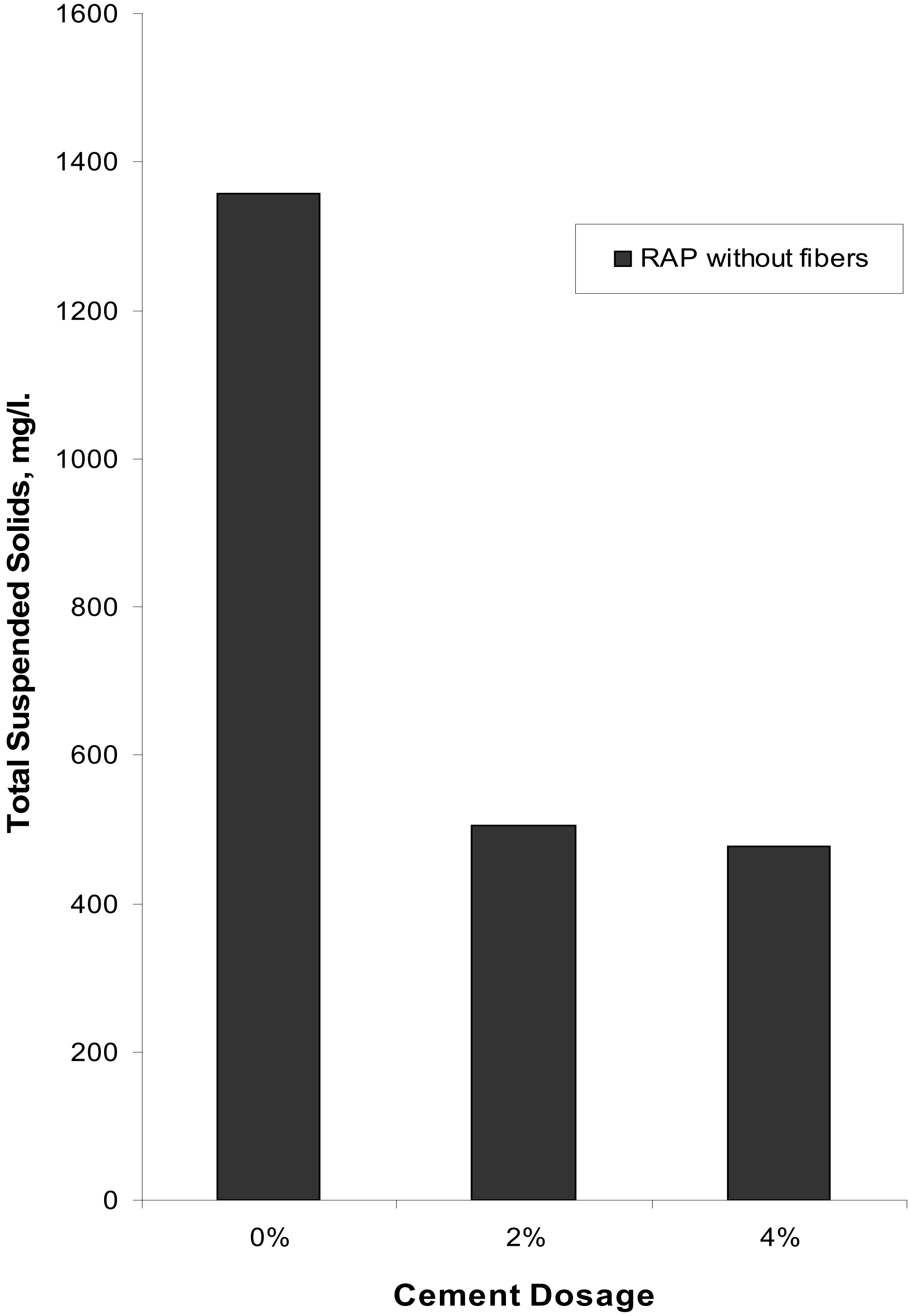


Figure 4.11 Variation of the TSS with the addition of cement on RAP materials without fibers

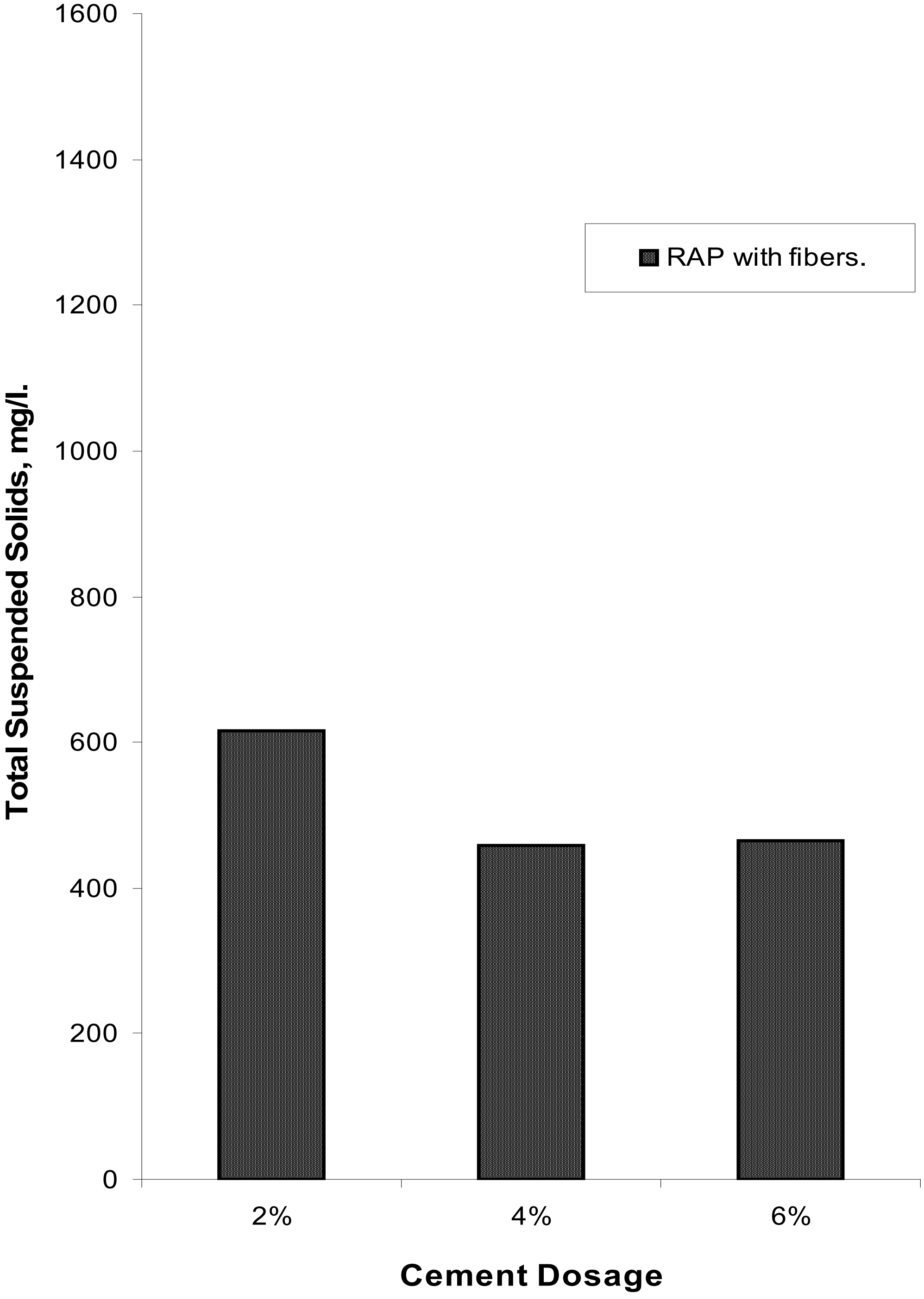


Figure 4.12 Variation of the TSS with the addition of cement on RAP materials with fibers

4.4.5 Turbidity

Turbidity a measure of the amount of solid particles suspended in water that causes light rays shining through the water to scatter. Turbidity is measured accurately with a nephelometer (turbidimeter) in units called nephelometric turbidity units, or NTUs.

Table 4.7 shows all collected data from leaching test and their variation at different levels of cement dosage is showed in figure 4.11 and 4.12.

Table 4.7 Results of Turbidity on RAP Leaching specimens

	Cement Dosage, %	**Turbidity NTU**
RAP Without Fibers	0%	1.4
	2%	1.05
	4%	0.72
RAP With Fibers	2%	0.95
	4%	0.68
	6%	0.74

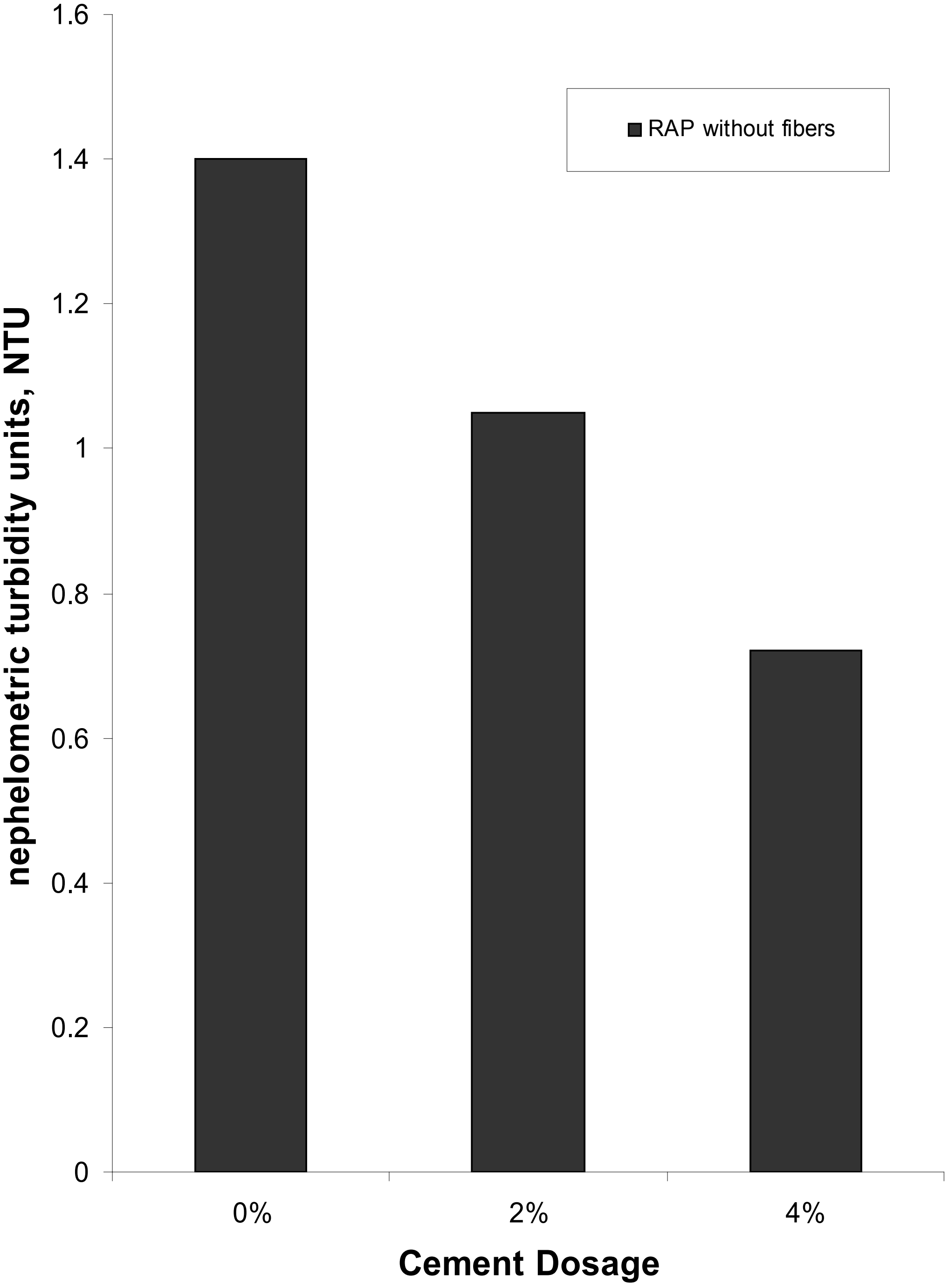


Figure 4.13 Variation of the Turbidity with the addition of cement on RAP materials without fibers

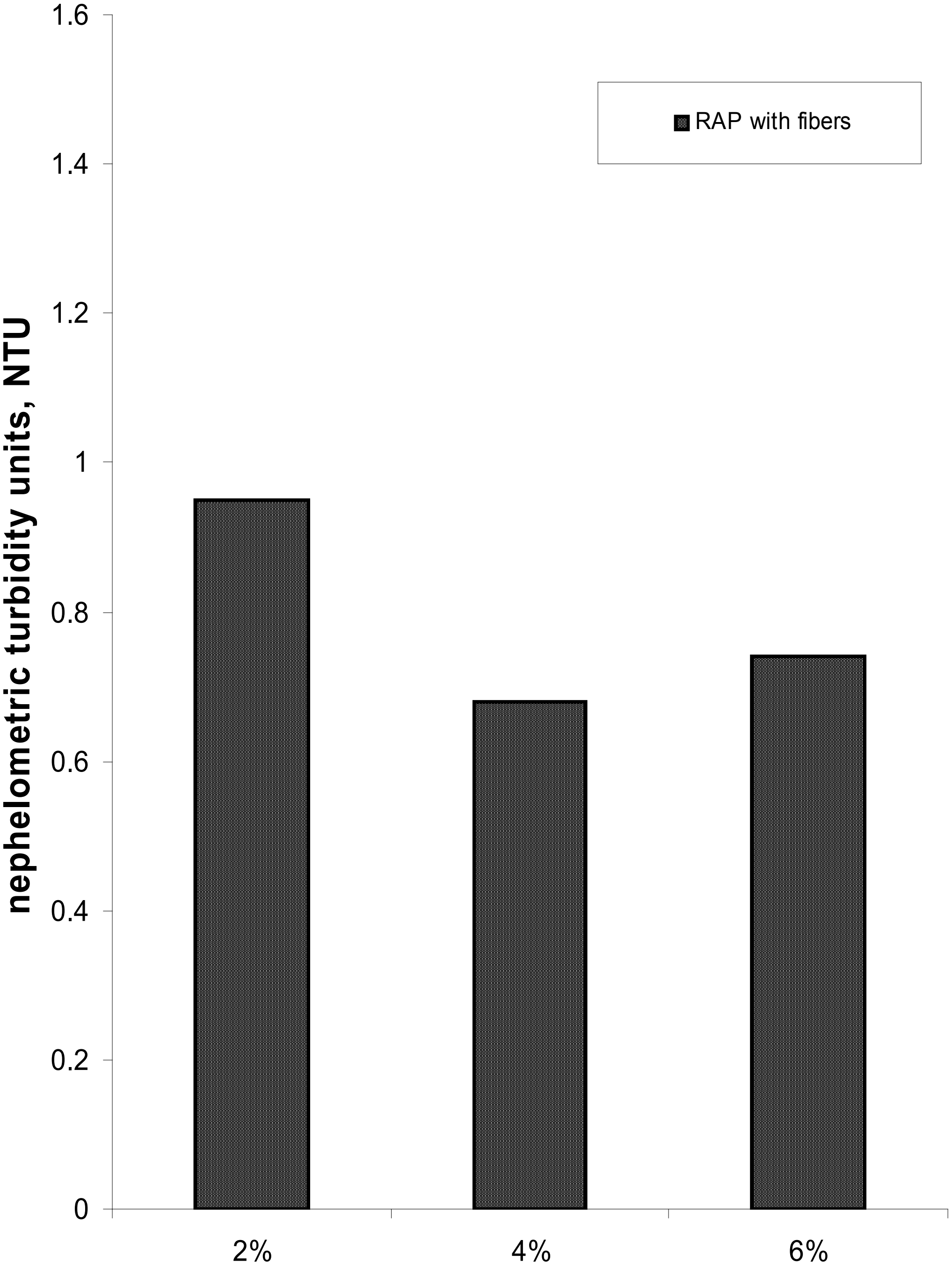


Figure 4.14 Variation of the Turbidity with the addition of cement on RAP materials with fibers

4.5 Unconfined Compressive Strength Test

After seven days of curing, specimens were tested in the compressive machine located at UTA structures lab. The results are shown in table 4.8 and the variation of UCS with RAP material at different cement contents are shown in Figure 4.13, 4.14 and 4.15 in which are included other values of UCS of RAP material reported in other studies and mentioned in chapter 2.

Table 4.8 UCS at 7 days cured period of RAP aggregates

	CEMENT DOSAGE, %	**UCS (psi)**
RAP WITHOUT FIBERS	0	50.7
	2	229.6
	4	363.9
RAP WITH FIBERS	2	241.1
	4	350.1
	6	531.6

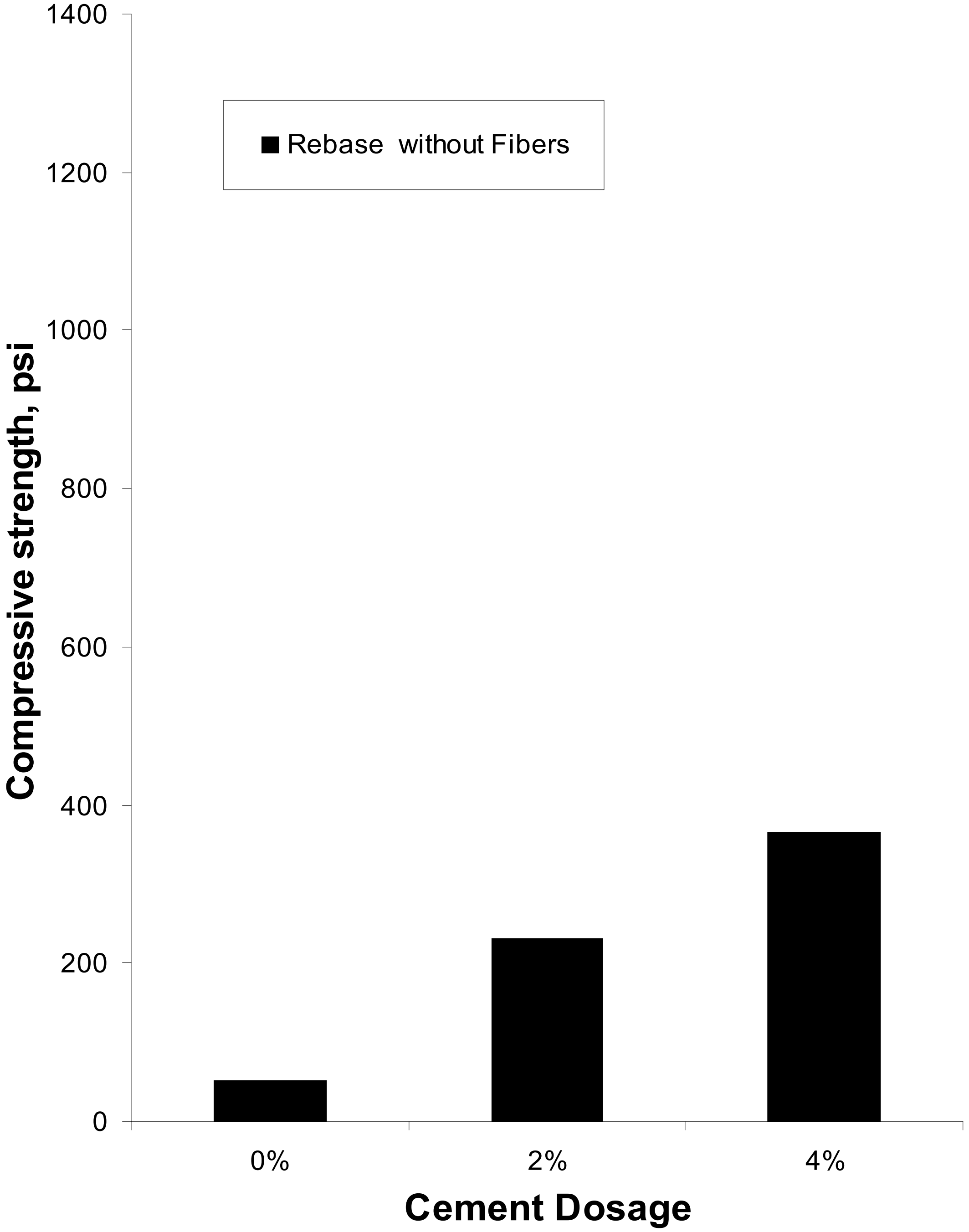


Figure 4.15 Variation of UCS with the addition of cement on RAP materials without fibers

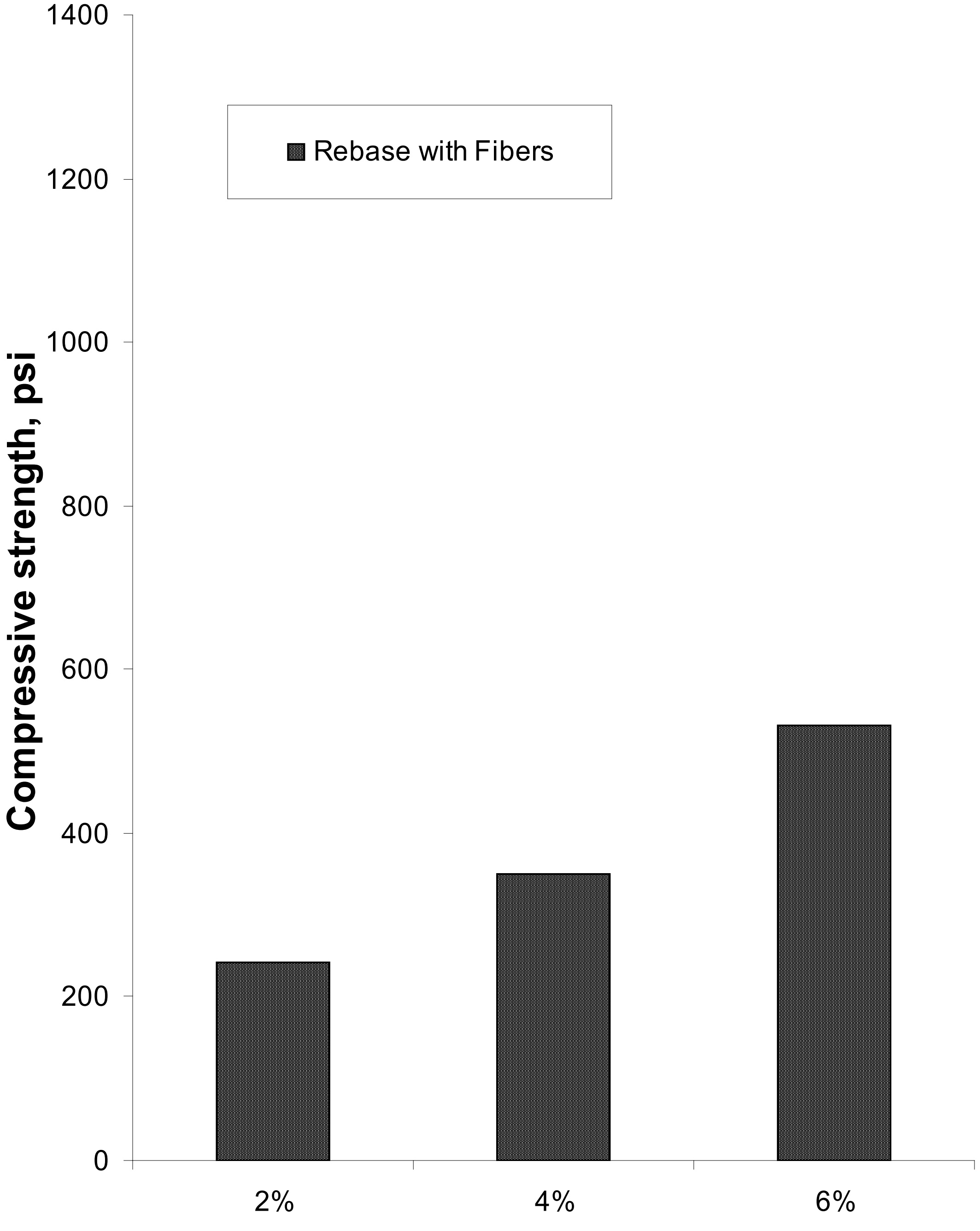


Figure 4.16 Variation of UCS with the addition of cement on RAP materials with fibers

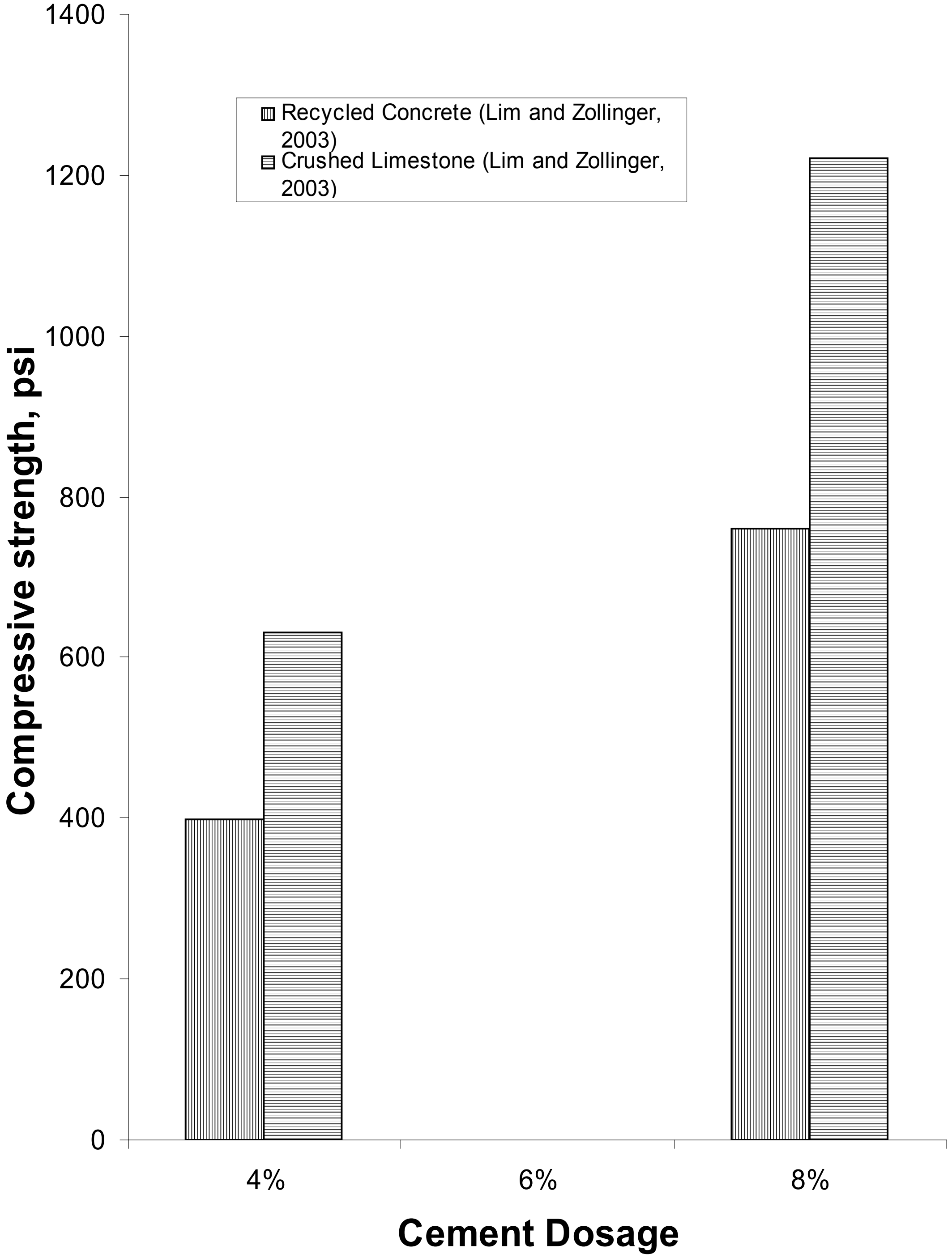


Figure 4.17 UCS at different cement dosages of other materials
(lim and Zollinger, 2003)

The development of Elastic modulus of RAP materials with and without fibers was estimated using the stress strain relationships of the material at different levels of cement dosage. Modulus of elasticity was determined as initial secant modulus at 25% of the ultimate stress. Figure 4.9 shows a typical stress-strain relationships obtained in this study and the modulus of elasticity is basically the slope of that secant.

Table 4.9 shows the modulus of elasticity found for RAP specimens with and without fibers at different cement dosages.

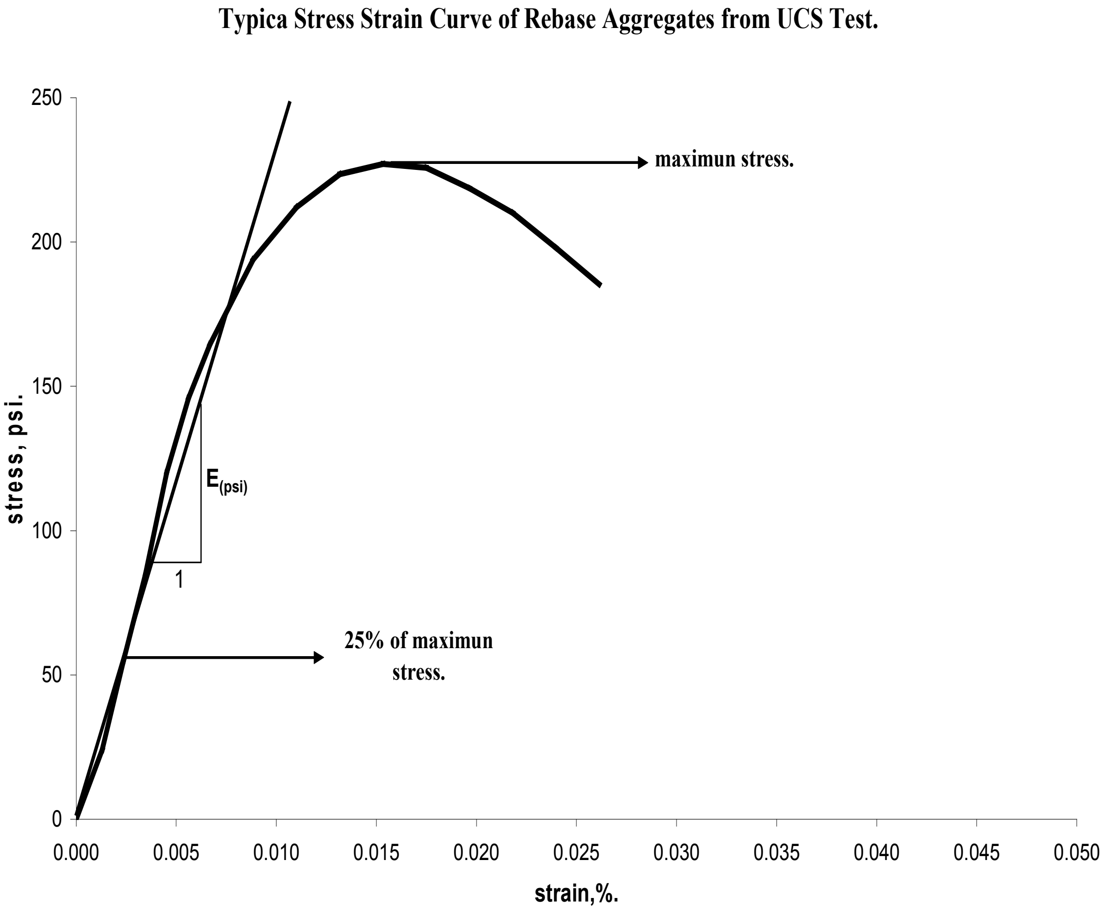


Figure 4.18 Typical Stress Strain Curve from UCS test of RAP aggregates

Table 4.9 Result of Modulus of Elasticity of RAP Materials

	CEMENT DOSAGE, %	UCS (psi)	DENSITY (pcf)	E(7days) (ksi)
RAP WITHOUT FIBERS	0%	59.7	128.8	4.9
	2%	229.6	129.0	21.9
	4%	363.9	129.8	19.9
RAP WITH FIBERS	2%	241.1	132.1	20.7
	4%	350.1	132.9	23.7
	6%	531.6	133.3	37.9

Equation 4.1 was adjusted empirically and is a good estimate of modulus of elasticity having the UCS for RAP materials. Figure 4.16 and 4.17 show the relationships between the compressive strength and elastic modulus of RAP aggregates. As it can be observed, the proposed model (Equation 4.1) provides a good agreement with the test data.

$$E_{(7days)} = 0.0617 \cdot UCS_{(7days)} + 3.2701 \qquad (4.1)$$

Where the modulus of elasticity is in ksi and the UCS in psi. It is important to take into account that this relationship should be reviewed with more sampling.

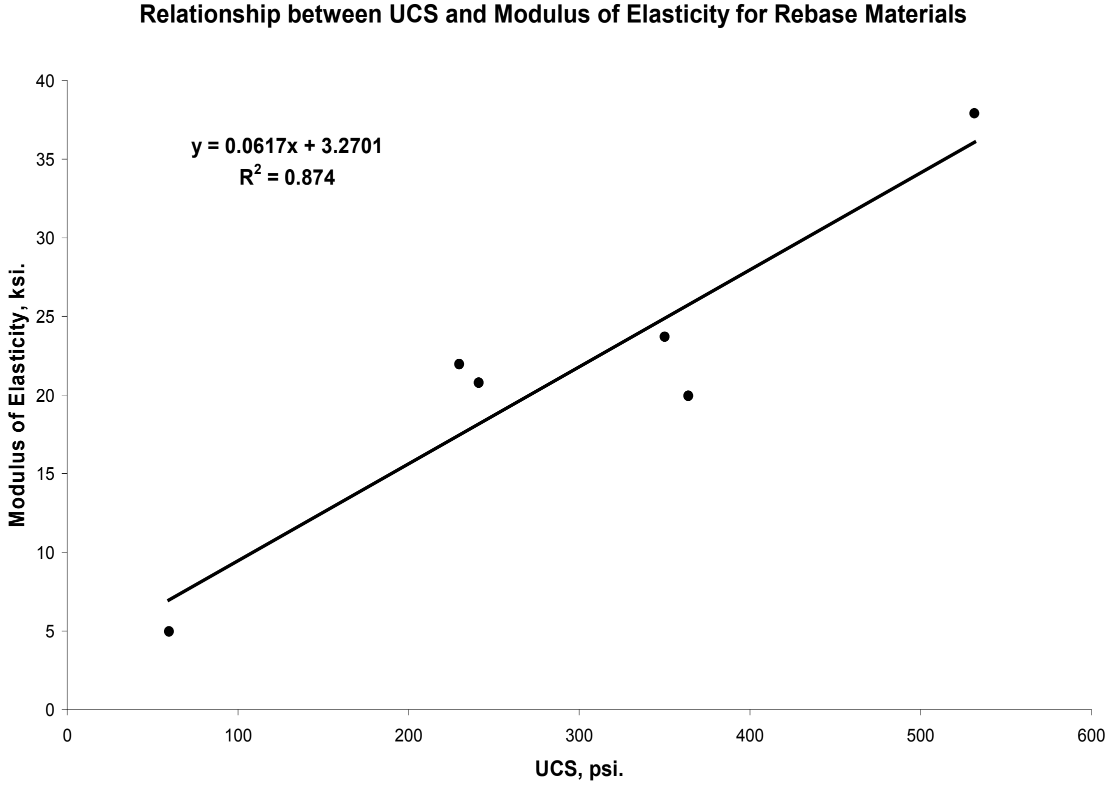


Figure 4.16 Relationship between the UCS and modulus of elasticity of RAP materials

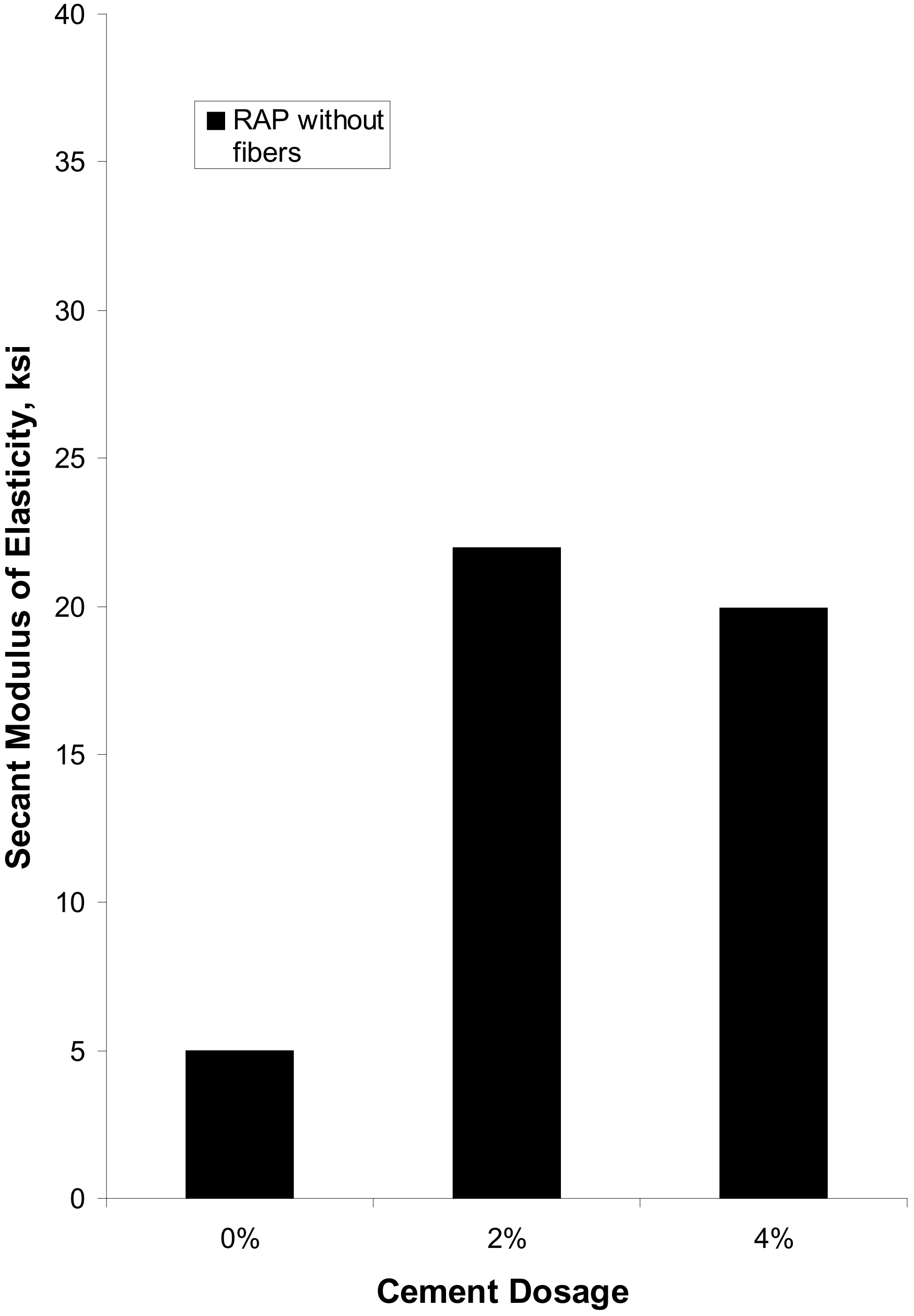


Figure 4.20 Variation of secant modulus of elasticity with the addition of cement on RAP materials without fibers

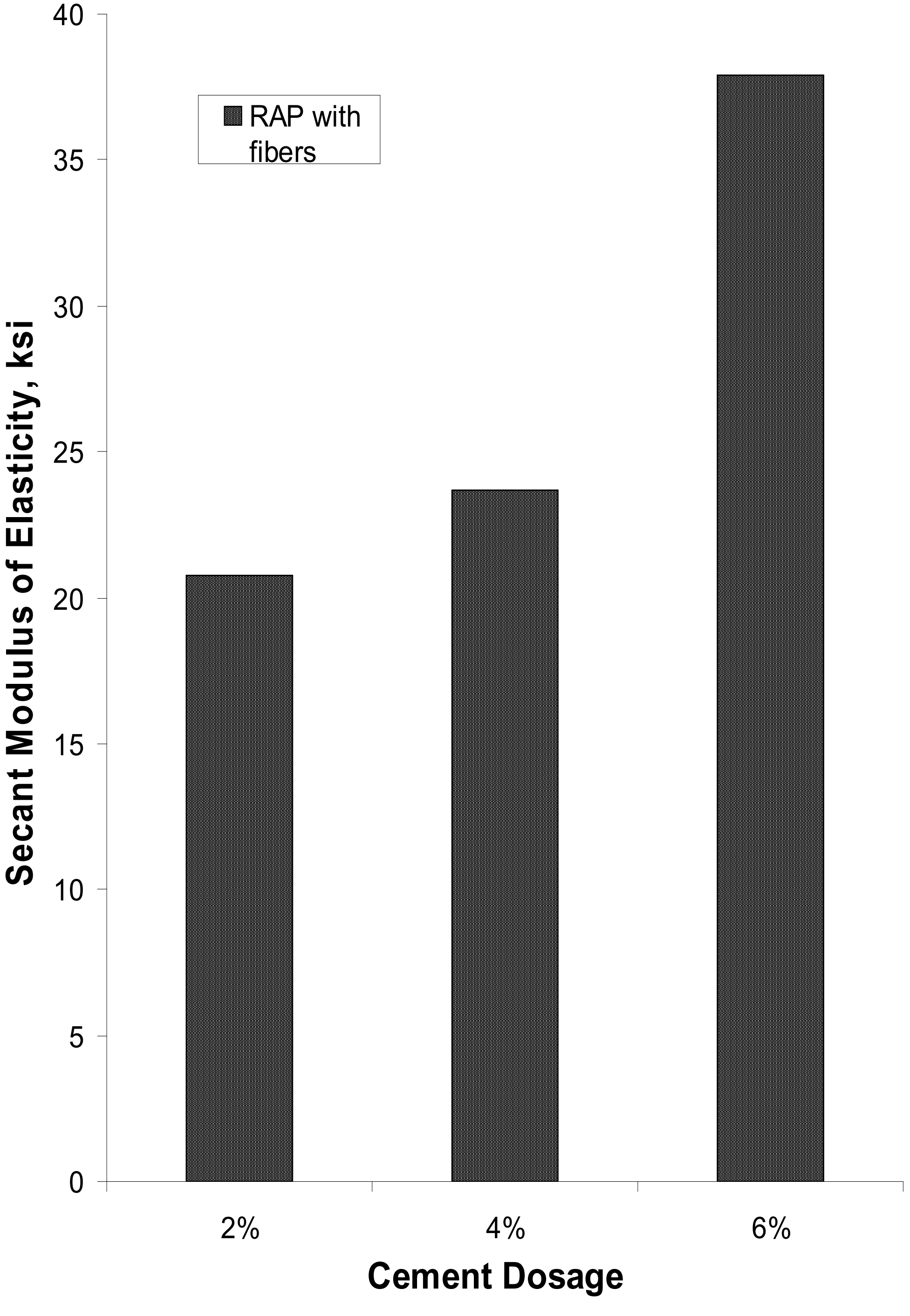


Figure 4.21 Variation of secant modulus of elasticity with the addition of cement on RAP materials with fibers

4.6 Resonant Column Test Results: A Purely Qualitative Assessment

After the 7 days cured period, RC test were performed on the samples. RC tests was used as a purely qualitative assessment. Differing from the samples used in other tests of the experimental program, RC samples din not achieve the densities obtained from Laboratory Compaction Characteristics and Moisture-Density Relationship of RAP Materials. The densities achieved for these samples, prepared using 2.8 inch mould, were around 85% of the maximum achieved in the lab test. This can explain the influence of confinement in the shear modulus of the material observed in RAP aggregates. Because of that and because of Resonant Column test is a test not suitable for materials as RAP aggregates, the results of this are going to be analyzed in a qualitative rather than a quantitative way.

In addition to the specimens mentioned in the experimental program, two more couple of “core" samples, 2.8-in diameter, directly from the already existing test plots at TXI were tested. These core samples were tested for the sake of analysis of the consistence of the results obtained from samples prepared at lab.

Table 4.10 resumes shear modulus results of all samples tested including the core samples toke at TXI Company.

Table 4.10 Results from RC test on RAP Aggregates

		RAP WITH NO FIBERS			**RAP WITH FIBERS**			**CORE SAMPLES**
		Cement dosage, %			Cement dosage, %			Cement dosage,%
		0	2	4	2	4	6	6
SHEAR MODULUS (Gmax), ksi.	Σ_3=0psi	6.39	25.1	55.7	18.3	38.0	68.0	116.1
	Σ_3=3psi	10.64	35.5	68.0	28.1	85.6	97.2	124.2
	Σ_3=6psi	18.33	53.6	82.3	37.4	105.7	115.0	126.0

Figures 4.13, 4.14 and 4.15 represent the variation at different cement dosages of shear modulus obtained from RC test for RAP material without fibers, with fibers and core samples.

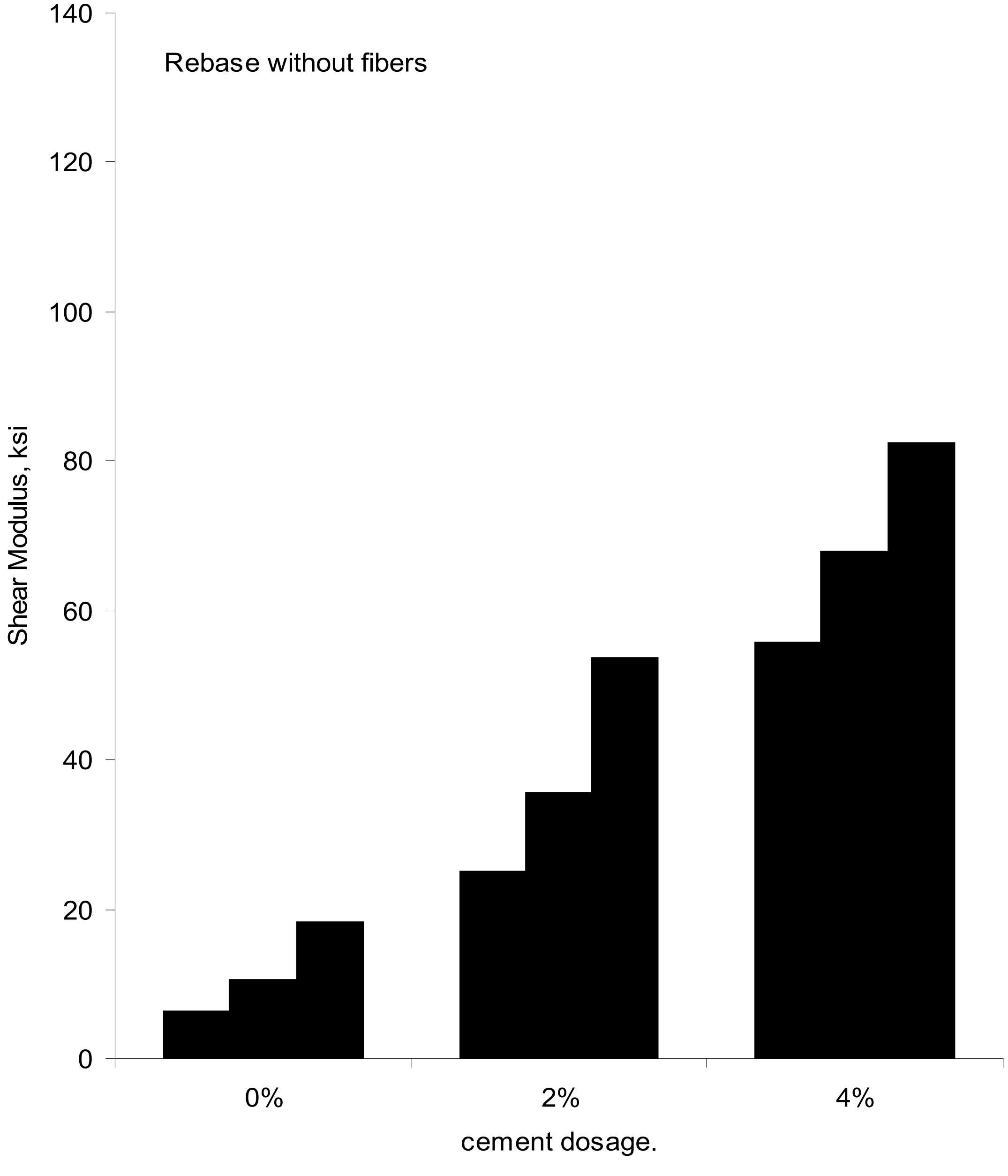


Figure 4.22 Variation of Shear Modulus with the addition of cement on RAP materials without fibers

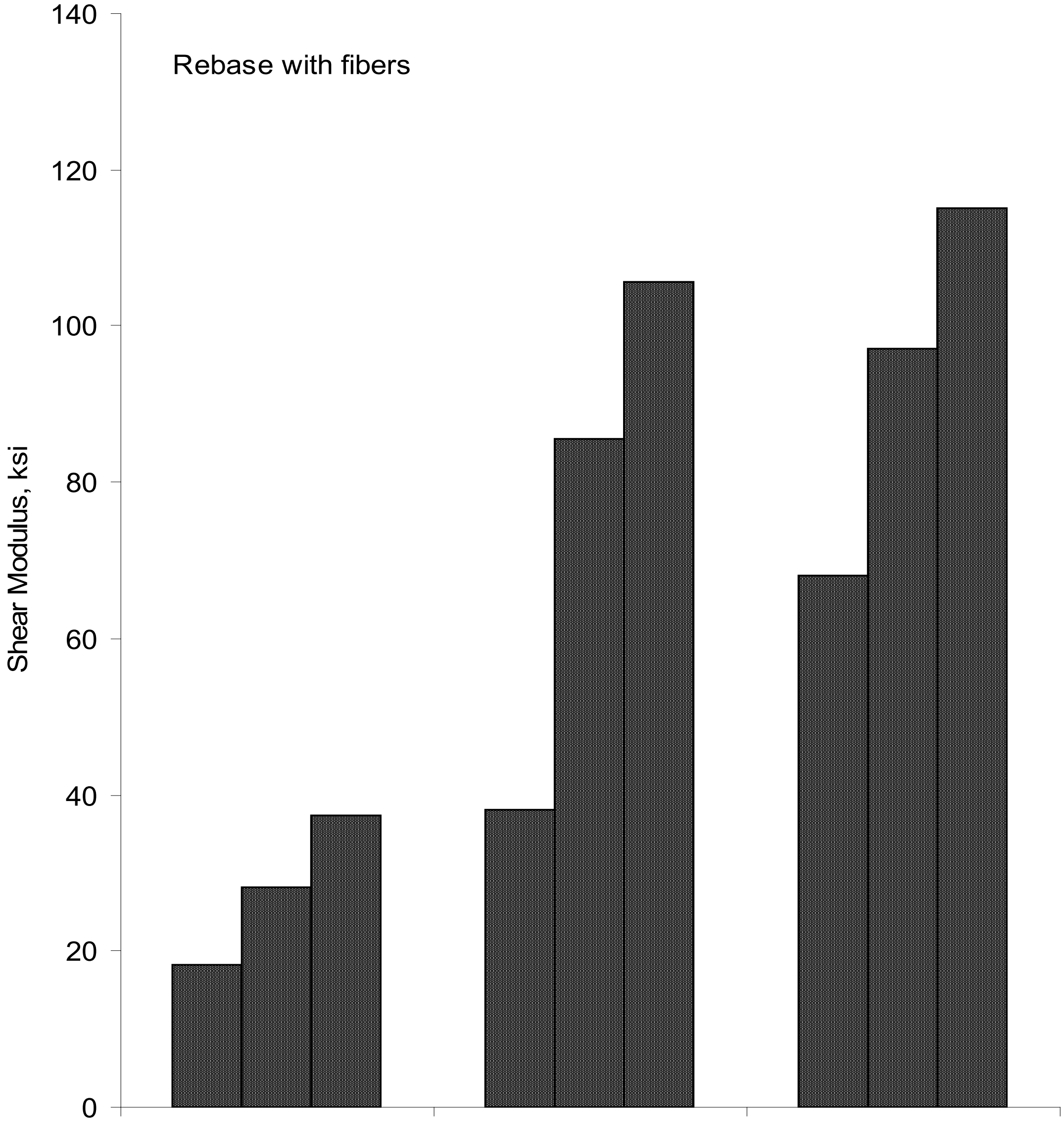


Figure 4.23 Variation of Shear Modulus with the addition of cement on RAP materials with fibers

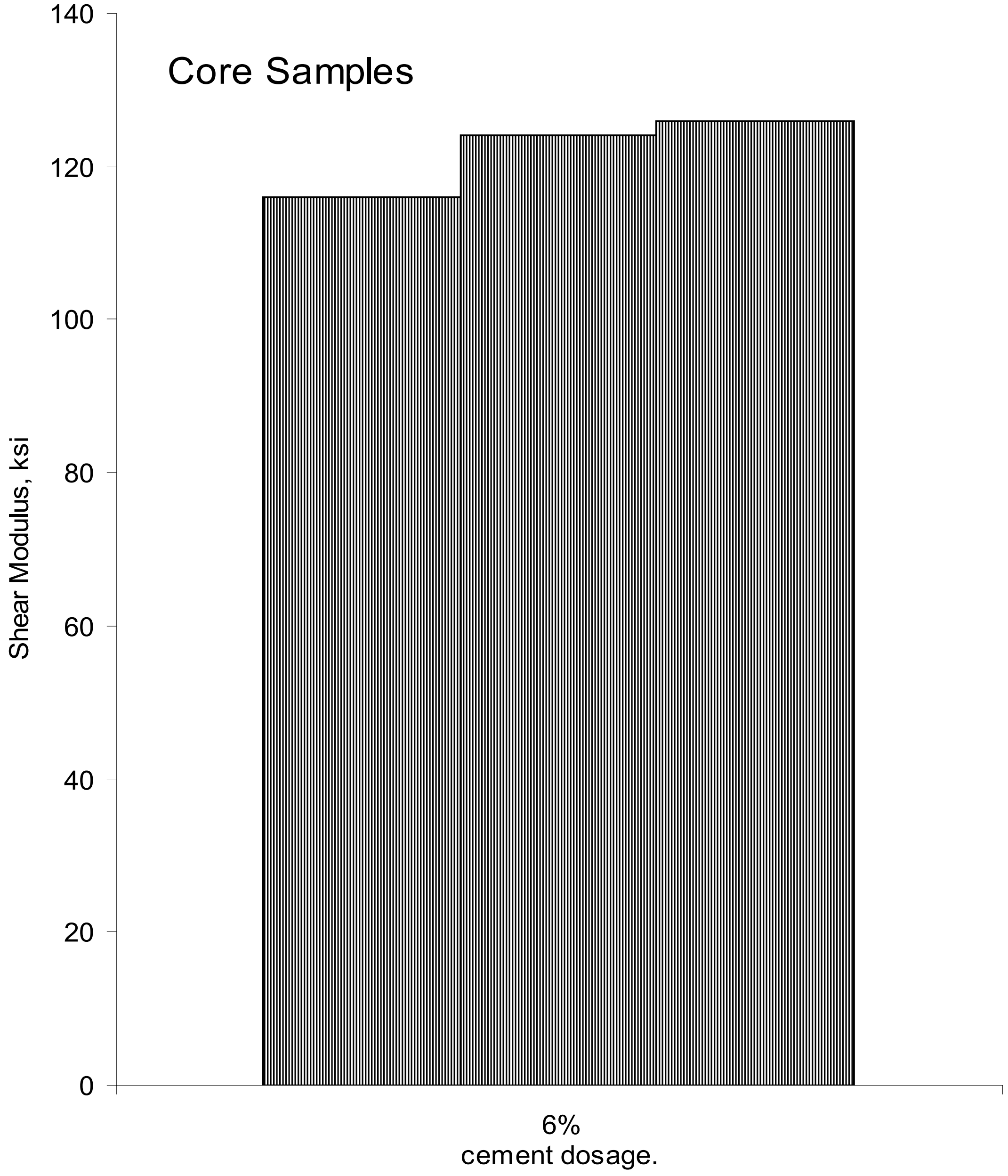


Figure 4.24 Shear Modulus of core samples.

As it can be observed, the influence of the confinement on the specimens prepared at lab is much higher than the one on the core samples. This can be explained due to the difference in cured period and compaction process. As it can be read in chapter 2, strength developed in first 7 days is just about 25% of the total strength developed for the material, thus the rigidity of core samples is much higher than samples in lab and that can be the influence of confinement in the results. Other explanation could be that the size of the particles is too large to be compacted with the 2.8 inch mould used, therefore a relatively high percentage of voids can be created even though the density is similar to the density of the core samples.

The next chapter summarizes the main conclusions and some recommendations for future work.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMENDATIONS

5.1 Summary and Conclusions

The present work is aimed at thoroughly testing the engineering properties of RAP product in order to assess its suitability as a structurally sound and environmentally safe material, as well as to maintain high standards in its production process and field applications. In order to accomplish this goal, a comprehensive series of basic and engineering tests were conducted on compacted RAP specimens at the UTA geotechnical and geo-environmental laboratories. RAP specimens with no fibers (control specimens) were tested at 0, 2, and 4% dosage levels of Portland cement. RAP specimens with fibers (fiber-reinforced) were tested at 2, 4, and 6% dosage levels of Portland cement. The following summarizes the main concluding remarks from this thesis work.

Basic Testing:

1. Saturated hydraulic conductivity decreased as cement dosage in RAP aggregate material increased. This can be directly attributed to the inclusion of cement (bonding material), which, upon reacting with water, decreases the void ratio of the treated specimens.
2. Results from pH tests performed on RAP aggregate materials show an increase in the amount of cementitious components diluted in water. However, it

is worth noting that all samples were tested after 7-day curing, in which period the samples may have not achieved full strength and chemical stabilization; therefore, increases in pH values might considerably decrease for RAP material treated with cement for longer curing periods.

3. Chemical Oxygen Demand (COD) shows a decrease in COD units as the cement dosage increases. On the contrary, Total Dissolved Solids (TDS) tests show an increase in TDS units as the cement dosage increases. Both tests corroborated the pH test results. TDS units represent the amount of flushed-out cementious components that have reacted chemically with free water.

4. Consequently, Total Suspended Solids (TSS) tests also show a decrease in TSS units as the cement dosage increases. TSS units represent the amount of filterable fine materials that came off the core RAP specimen.

5. Turbidity tests further substantiated the TDS and TSS test results. As the total amount of soils is calculated as the amount of TDS solids plus the amount of TSS solids, it is hence inferred that an increase in cement dosage yielded a lower value of turbidity.

6. According to US EPA, pH and total suspended solids were out of the specified values opposite to chemical oxygen demand concentration which is within the benchmarks values.

7. The inclusion of fibers apparently did not have any significant effect on the pH, COD, TDS, and TSS response of tested materials.

Engineering Testing:

8. In general, results from the series of engineering tests performed on control and fiber-reinforced specimens show a considerable increase in unconfined compressive strength (UCS), modulus of elasticity (E), and small-strain stiffness (G_{max}) as the cement dosage is increased.

9. A reasonable, empirical correlation between unconfined compressive strength (UCS) and modulus of elasticity (E) was devised based on control and fiber-reinforced data. However, further testing is required corroborate the empirical trends and the analytical correlation derived herein.

10. The resonant column testing program undertaken in this work was primarily aimed at completing a <u>purely qualitative assessment</u> of small-strain stiffness response of control and fiber-reinforced materials, given the well known limitations of this technique for extremely rigid

11. materials. Results show a considerable increase in material stiffness with an increase in cement dosage.

12. Engineering test results on control and fiber-reinforced RAP materials were compared to those reported in the literature for similar reclaimed asphalt pavement (RAP) materials. Results confirmed the potential of the tested material as an environmentally and structurally sound alternative to non-bonded materials for base/sub-base construction purposes.

5.2 Recommendations for Future Work

From the results obtained in the course of this research, the following recommendations should be considered for future works:

More number of samples should be tested to address the corroboration of the equation given in this study.

In order to analyze the influence of fiber inclusion on RAP aggregate material a special experimental program varying percentage of fibers, performing tensile tests and in-situ test should be developed. One of the potential tests of this experimental program could be Flexural tests.

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Carlos Augusto Ordonez graduated Civil Engineering department, Universidad del Cauca, Colombia in 2003 with a Bachelor's degree in Civil Engineering. He started his graduate studies at The University of Texas at Arlington in January 2005. He has been a research assistant from January 2005 to August 2005 then a teaching assistant from August 2005 to August 2006. His Masters' degree study was concentrated in the geotechnical area.