EFFECT OF FINE GRAINED SOIL IN THE STRENGTH OF CEMENT TREATED FLEX-BASE MATERIALS

by

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Abstract

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The recycled materials such as, Recycled Crushed Concrete Aggregates (RCCA) and Reclaimed Asphalt Pavement (RAP) treated with cement has been widely used as the alternative granular base in pavement construction in different states in USA due to the depletion of natural resources of virgin aggregates. While a number of factors drive the use of these recycled materials, the two primary factors are economic savings and environmental benefits.

In the flexible pavement systems, the base layer contributes to the structural capacity of the pavement systems, so, the quality performance of this layer is essential. However, presence of fine particles in the pavement system promotes the contamination of coarse granular material due to migration of fines from the subgrade which might adversely affect the strength and stiffness of flex-base. As such, the main purpose of this study was to examine the effect of fine contents in granular base materials in terms of strength and stiffness.

In this research, a comprehensive experimental program was designed to characterize resilient and compressive behavior of recycled materials in the presence of soil in both natural and stabilized forms. For this study, RAP and RCCA were mixed at different proportions from 0% to 100% with different amount of soil mixture varying between 0% and 24% with cement content ranging from 0% to 6% at 2% interval. Different laboratory tests were conducted to determine the Optimum Moisture Content (OMC), Maximum Dry Density (MDD), Unconfined Compressive Strength (UCS) and Resilient Modulus (M_R) of the mixes of RAP, RCCA, soil and Ordinary Portland Cement (Type I/II). Based on the preliminary data, it was found that with the intrusion of fines in cement treated as well as untreated recycled granular bases, both the strength and stiffness decrease as compared with the same specimens without fine particles. With the addition of 12% and 24% of soil in the combination of 30% RAP + 70% RCCA and 50% RAP + 50% RCCA, the value of resilient modulus decreased in the range of 30 -55% in the cement stabilized as well as natural forms. For example,the M_r value of (30/70) RAP/RCCA with 2% cement ranged between 10,000 psi and 45,000 psi, it was reduced to a range of 10,000-30,000 psi with 12% soil intrusion. Similarly, at 6% cement content the M_r value of (30/70) RAP/RCCA the highest value of resilient modulus of 75,000 psi was observed whereas with the 12% soil, the moduli value was reduced to 38,000 psi at the given maximum confining pressure of 20psi.

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Chapter 1

Introduction

1.1 Background

The depletion of conventional raw materials such as bitumen, crushed aggregates, and unbound aggregates mixtures began in the 80's that led to incorporate unconventional construction material in the road industry. The tremendous increment in number of vehicles and the evolution of road industry has been a rationale that has promoted exploiting all viable available resources. At present, some of the most dominant recycling materials that are in practice include recycled concrete aggregates and reclaimed asphalt pavement. In USA, for the construction of new infrastructure and pavements the annual consumption of aggregate materials is estimated about 1.5 billion tons (USGS 2005). Due to the rapid increase of construction of different types of infrastructures, it is estimated that more than 2.5 billion tons will be consumed by 2020. According to USDOT (2004), 123 million tons per year of recycled crushed concrete aggregate (RCCA) materials are expected to be obtained from the construction and demolition of concrete structures.

Reclaimed Asphalt Pavement (RAP) can be defined as a granular material containing a mixture of bitumen and aggregate that is removed or reprocessed as part of pavement reconstruction and resurfacing. According to the National Asphalt Pavement Association (NAPA), in 2013, approximately 350.7 million tons of plant mix asphalt were produced in the United States of America and the total reported RAP generation was around 76.1 million tons (Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2009-2013). Many studies from the past have found RAP as a viable, cost-effective option to use as a base material. Kolias (1996) investigated the compressive strength, tensile strength and modulus of elasticity of different RAP mixes with unbound granular materials and also recommended further research on cement treated RAP mixes. Taha et al., (2002); Guthrie et al., (2007); and Grilli et al., (2013) performed research on mechanical properties of different cement- treated RAP mixes. Currently, RAP is principally reused in hot mix asphalt production as an aggregate (Huang et al., Carter and Stroup-Gardiner, 2007). To incorporate RAP into pavement base or subbase applications, efforts have been made in recent years (e.g. Maher and Jr., 1997, Taha et al., 2002, Park, 2003, Taha, 2003, Blankenagel and Guthrie, 2006, Poon and Chan, 2006, Cho et al., 2011, Hoyos et al., Puppala et al., 2011, Piratheepan et al., 2013).

Although lots of studies were conducted for these recycled materials individually, there were very few studies regarding the use of combination of these materials as an alternative to natural aggregates. Lately, different combinations of recycled crushed concrete aggregates (RCCA) and reclaimed asphalt pavement (RAP) aggregates, under cement-treated or untreated conditions, were utilized to evaluate the applicability of these available materials to a flexible pavement base layer (Faysal 2017).

Even if these recycled materials can fulfill the strength and stiffness criteria required for the construction of the pavement, the chances of these materials in declining the performance of the pavement will be higher when the pavement is built on expansive soils. In the United States, several states have been affected by subgrade-related heaving and shrinkage problems for many years (Nelson and Miller, 1992). A majority of the expansive soils are montmorillonite-rich clays, over consolidated clays and shales (Nelson and Miller, 1992).

1.2 Problem Statement

There are numerous studies done regarding the use of recycled materials such as, Recycled Crushed Concrete Aggregates (RCCA) and Reclaimed Asphalt Pavement (RAP) as an alternative granular base in the pavement construction. Recycled materials are weaker than virgin aggregates (Taha, 2000). Several researches have been done on these type of materials by stabilizing using fly ash, foamed asphalt or cement to check whether these materials can fulfill the minimum strength requirement. Because of concerns related to lower shear strengths and excessive permanent deformations resulting from large strains as RAP content increases, there is a general trend of using upto 50% RAP content by weight in virgin or recycled aggregate base and subbase layer. RAP can be mixed with RCCA upto a ratio of 50/50, but it must be treated with 4% to 6% cement to fulfill the compressive strength requirement of 300 psi specified in the Texas Department of Transportation's guidelines (Faysal 2017).

As base layer contributes to the structural capacity of flexible pavement systems, the quality performance of this layer is essential. However, presence of fine particles in the pavement system promotes the contamination of coarse granular material which may adversely affect the strength and stiffness of flex-base. The possible chances of soil getting mixed with the recycled materials during demolition of old structures, storage of the recycled materials or during the mixing and construction process itself might lower the strength and stiffness of the pavement materials. Apart from these, migration of fines from the subgrade to the pavement system may perhaps be one of the vital cause in dropping the structural capacity and performance of the pavement system. Although the fine fraction within the recycled materials itself might have been considered in some of the studies, the effect of larger amount of expansive clay soils as fines intruding from the sub-grade towards the base layer of the recycled base materials has not been understood yet. To overcome this inadequacy in the available information, idea of performing experimental study of cement treated as well as untreated mix of RAP and RCCA with different proportion of soil was established to evaluate the effect of interference of soil particles on the strength and stiffness properties of the recycled materials.

Unconfined compressive strength (UCS) tests and resilient modulus (Mr) tests were performed to evaluate the strength and stiffness response of different cement-stabilized RAP and RCCA mixes under the funded project of the Texas Department of Transportation (TxDOT). An experimental program was designed and carried out to test and determine the optimum moisture content (OMC), maximum dry density (MDD), unconfined compressive strength (UCS) and resilient modulus (Mr) properties of the mixes of RAP and RCCA base materials by adding different proportion of soil as fines and with varying dosage of Portland cement.

1.3 Objective and Scope

The main objective of the present thesis was to understand and evaluate the effect of presence of fines on strength and stiffness properties of flex-base materials such as RCCA and RAP mix in untreated as well as cement-treated condition.

The following specific tasks were carried out during the course of the proposed project:

1. A comprehensive literature review on strength and durability of RAP and RCCA materials and the basic characteristics of expansive clay.
2. Carry out plastic limit and liquid limit test of the soil to find the plasticity of the soil.
3. Perform basic engineering tests such as particle-size distribution and optimum moisture content (OMC) tests for material characterization.

4. Determination of unconfined compressive strength (UCS) and resilient modulus (Mr) of untreated and cement treated recycled base materials for the different combination with soil.
5. Understand the stress- strain relationship of the combination of recycled materials with expansive clay soil.
6. Comparison of the Mr and UCS values of the different combinations of the materials with previous studies.
7. Comparison of resilient modulus values of the combination mix with respect to bulk stress.
8. Comparison of resilient modulus values of the combination mix with confining pressure.
9. Evaluation of the effect of presence of fines on the recycled base materials.

1.4 Thesis Organization

This thesis manuscript has been composed of five chapters:

- Chapter 1 provides the introduction, objective and thesis organization. The problem statement and objectives of research and the preliminary investigations are briefly mentioned here.
- Chapter 2 presents a literature review on previous studies conducted on recycled materials, expansive clay soils and available design guidelines. It also provides a summary of the different studies about the role of fine content on pavement base materials.
- Chapter 3 describes the experimental program; several test procedures such as, particle size distribution; atterberg limits; optimum moisture content (OMC); maximum dry density (MDD); unconfined compressive strength (UCS); and resilient modulus (Mr) tests.

- Chapter 4 presents test results, analysis and discussions of the results.
- Chapter 5 provides the summary and conclusion of the current study and also includes future recommendation.

Chapter 2

Literature Review

2.1 Introduction

In recent years, the use of recycled materials has increased considerably as they are widely used as the alternative granular base in pavement construction due to the depletion of natural resources of virgin aggregates. To improve their performance, durability and engineering properties these materials are treated with cement and fibers which makes it cost effective at the same time. This chapter gives overview about the recycled base materials, pavement design considerations, strength and stiffness parameters and the characteristics of expansive clays lying as a subgrade. The literature reviewed in this chapter was gathered from different journals, articles, design guidelines and other research projects. At first, a brief description about recycled pavement materials will be portrayed. Then by explaining the pavement design methods in short, subgrade material characteristics will be discussed. After that cement treated base materials characteristics and properties will be reviewed and various factors affecting the strength parameters of base materials will be further discussed in brief.

2.2 Recycled Crushed Concrete Aggregate (RCCA)

2.2.1 Use of RCCA in USA

With the increment in population and advancement of science and technology, the construction of highways, bridges and buildings has been increasing from the beginning of the past century. As these facilities need to be repaired or replaced with the passing of time either because of end of their service life or because of unfulfilling service demand, there have been tremendous amount of construction waste produced every year. In US alone, it was estimated that over 11 billion tons of construction and demolition waste are produced annually in which concrete waste accounts for a

4bout 50-70%. On the other hand, 2 billion tons of aggregate are produced each year and expected to increase more than 2.5 billion tons per year by the year 2020. These facts have raised two main concerns, one about the availability of natural virgin aggregates and other about the management of the construction and demolition waste. Although the common practice of handling construction and demolition waste was to dump in the landfill, disposing these wastes in landfills is becoming more restrictive in the present situation. Therefore, to address these concerns many state agencies has begun recycling concrete debris and use recycled crushed concrete as an alternative aggregate recognizing the engineering, economic and environmental benefit that can be accomplished by using RCCA. Apart from the several uses of RCA like as in rip rap, soil stabilization, pipe bedding, landscaping, etc. the principal application of RCA in the US has been as a base/subbase material. The following figures depict the extent of use of recycled concrete aggregate throughout the United States.

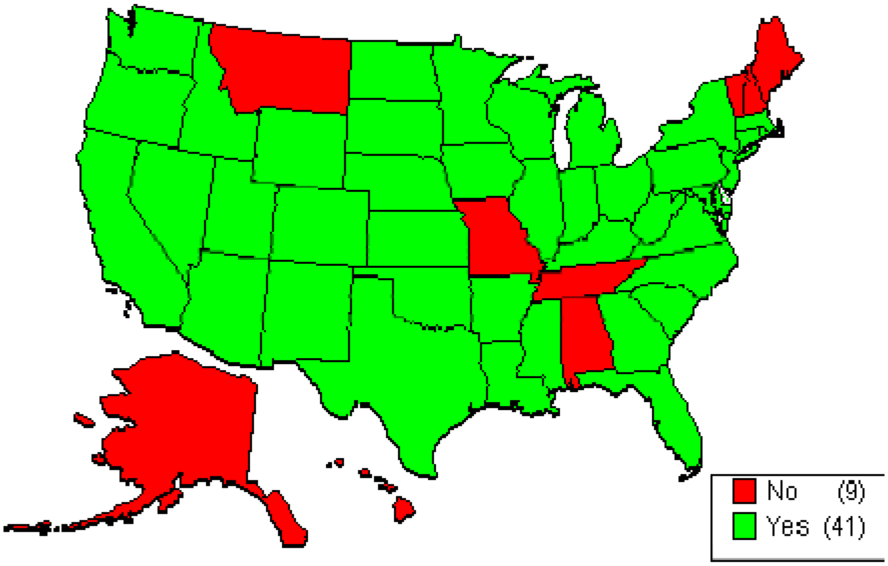


Figure 2-1 States using RCA as Aggregate (FHWA 2012)

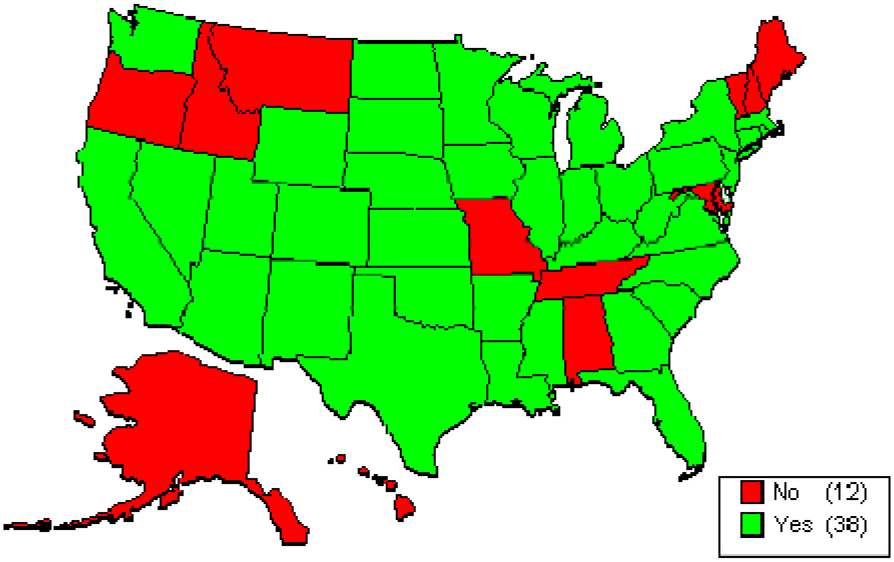


Figure 2-2 States using RCA as Aggregate Base (FHWA 2012)

2.2.2 Properties of RCCA

In comparison to natural aggregates, the main reason for the lower quality of RCCA is because a certain amount of mortar and cement paste from the original concrete remains attached to the stone particles when demolished concrete is crushed. In terms of shape and surface texture, the grains of recycled aggregates are irregular, mostly with angular shape, rough and with cracked surface and porous which significantly affects the workability of the concrete. It has been found that recycled concrete aggregate has significantly higher water absorption level compared to natural aggregates. Due to a higher porosity of mortar layer, the recycled aggregate has a lower value of bulk density in comparison to natural aggregates. About the mechanical properties, the resistance to crushing and abrasion of recycled aggregate is less than the respective resistance of natural aggregate which is a consequence of easier separation and crushing of the mortar layer around the recycled aggregate grains. However, characterizing this aggregate can be very difficult due to the variety of sources of RCA and diverse functions, environment, and wear of the concrete structures and pavements from which the RCA can be obtained. Therefore, for the adequate characterization of these variables, controlled studies must be performed on a regional basis.

2.3 Reclaimed Asphalt Pavement (RAP)

2.3.1 Use of RAP in USA

Reclaimed asphalt pavement RAP is the removed and/or reprocessed pavement materials containing asphalt and aggregates which are basically generated by crushing the recovered asphalt obtained from removed asphalt pavements during reconstruction, resurfacing or during preparation of access to buried utilities. According to the National Asphalt Pavement Association (NAPA), in 2013, approximately 350.7 million tons of plant mix asphalt were produced in the United States of America, and the total reported RAP generation was around 76.1 million tons (Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2009–2013). Also, from environmental Protection Agency (EPA), it was found that 80% of the total removed pavement materials are recycled each year. In USA, over 90 percent of U.S. highways and roads are constructed with hot mix asphalt (HMA). These highways and roads must be maintained and rehabilitated as the infrastructure ages. This has led to increase in demand of natural aggregates and binder supply causing depletion in the natural sources day by day. RAP being a useful alternative to virgin materials, HMA producers have begun using reclaimed asphalt pavement (RAP) as a valuable component in HMA. Additionally, using RAP reduces the amount of construction debris placed into landfills. Hence, the primary factors like economic savings and environmental benefits have influenced the use of RAP in asphalt pavement industry. From a survey conducted by North Carolina Department of

Transportation (NCDOT, 2007), data were collected to estimate RAP usage and potential for increasing the amount of RAP used across the United States. Figure 2-3 shows the number of State transportation departments that used and permitted a given amount of RAP in the intermediate layers in 2007.

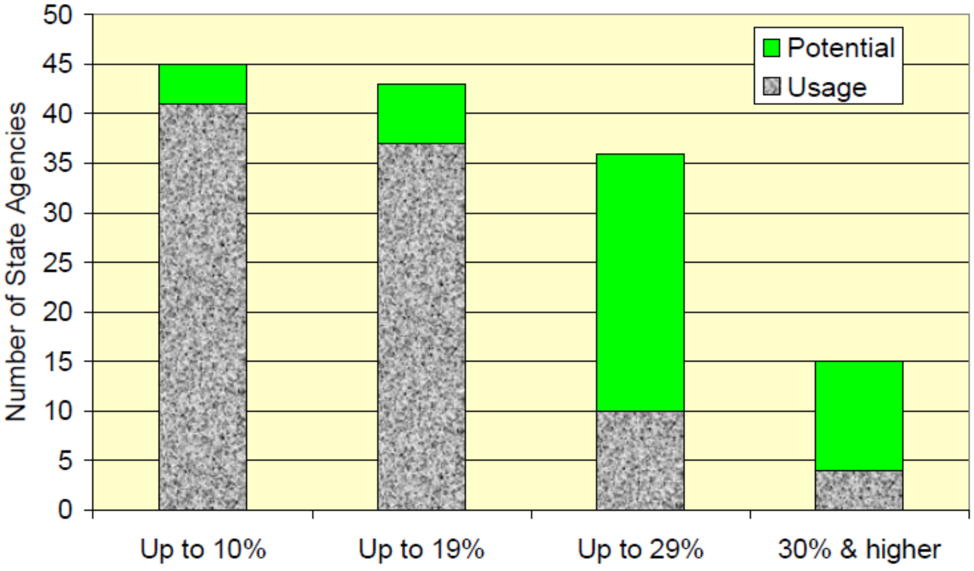


Figure 2-3 Usage and potential of various RAP percentages in the intermediate layer (NCDOT 2007)

2.3.2 Properties of RAP

The properties of RAP are largely dependent on the properties of the constituent materials and the type of asphalt concrete mix (wearing surface, binder course, etc.). The typical unit weight of RAP has been found to range from 120 to 140 lb/ft^3 which is slightly lower than that of natural aggregates and the moisture content varies from 5 to 8%. The asphalt cement content of RAP typically ranges between 3 and 7 percent by weight. With increasing unit weight, with maximum dry density values ranging from 100lb/ft^3 to 125 lb/ft^3 the compacted unit weight of RAP will decrease. Also, the California Bearing Ratio (CBR) values for RAP have been reported in the range of 20 to 25 percent. The following table provides a summary of the typical ranges of physical and mechanical properties of RAP.

Table 2-1 Properties of RAP Materials (Potturi, 2006)

Type of Property	**RAP Property**	**Typical Range of Values**
Physical Properties	Unit Weight	120 to 140 lb/ft^3
	Moisture Content	5 to 8%
	Asphalt Content	3 to 7%
	Asphalt Penetration	10 to 80 at 25°C
	Absolute Viscosity	4000 to 25000 poises at 60°C
Mechanical Properties	Compacted Unit weight	100 to 125 lb/ft^3
	California Bearing Ratio (CBR)	20 to 25% for 100% RAP

2.4 Use of RAP and RCCA Blend in Pavement Bases

The rehabilitation of pavements produces huge amounts of Reclaimed Asphalt Pavement (RAP) (Allan and Timothy, 1999, Daniel and Lachance, 2005). Likewise, huge amount of Recycled Concrete Aggregate (RCA) are generated from the construction sectors from the demolition of buildings and rehabilitation of concrete pavements (Oglesby et al., 1989, Apotheker, 1990, Wood, 1992, Gavilan and Bernold, 1994). The recycled materials that have been recently assessed to be viable materials for roads, pavements, footpaths and other civil engineering applications include reclaimed asphalt (Taha et al., 2002, Hoyos et al., 2011, Puppala et al., 2011) and recycled concrete (Poon and Chan, 2006, Azam and Cameron, 2012, Gabr and Cameron, 2012). As there is an increasing demand for the use of alternative materials in pavements due to excessive costs of landfills, associated energy costs and increasing costs of diminishing naturally occurring aggregates, RAP and RCA can be a very useful material.

Currently RAP is principally reused in hot mix asphalt production as an aggregate (Huang et al., Carter and Stroup-Gardiner, 2007). To incorporate RAP into pavement base or subbase applications, efforts have been made in recent years (e.g. Maher and Jr., 1997, Taha et al., 2002, Park, 2003, Taha, 2003, Blankenagel and Guthrie, 2006, Poon and Chan, 2006, Cho et al., 2011, Hoyos et al., Puppala et al., 2011, Piratheepan et al., 2013). In recent years, RCA is extensively being accepted for use in pavement base and subbase applications (Poon and Chan, 2006, Arulrajah et al., 2012b, Azam and Cameron, 2012, Gabr and Cameron, 2012). However, the application of blend of RAP and RCCA in pavement base or subbase as an aggregate has been limited due to the lack of reported laboratory testing and results from the field testing. Lately, different combinations of recycled crushed concrete aggregates (RCCA) and reclaimed asphalt pavement (RAP) aggregates, under cement-treated or untreated conditions, were utilized to evaluate the applicability of these available materials to a flexible pavement base layer (Faysal 2017). In his study it was reported that, RAP can be mixed with RCCA up to a ratio of 50/50, treating with 4% to 6% cement to fulfill the compressive strength requirement of 300 psi as specified in the guideline of Texas Department of Transportation. Also, it was indicated that the recycled base materials are an environmentally sound alternative to virgin aggregates and can be used in pavement bases or sub-bases layers. A multiple linear regression model proposed by Faysal (2017) to determine the resilient modulus value from the parameters obtained from the unconfined compressive strength tests can be very useful in determining the stiffness parameter of cement-treated base materials.

2.5 Fine Contents

2.5.1 High Plastic Clay

Introduction

High plastic clay or the expansive clay is a soil that is susceptible to large volume changes (i.e. swelling and shrinking) that are directly related to changes in moisture content. Globally, expansive soils create serious engineering problems and economic losses in at least 19 countries. Damage in the U.S. is generally concentrated in certain parts of Texas, Louisiana, Mississippi, Colorado, Nebraska, Wyoming, Montana, and North and South Dakota. In the United States, expansive soils cause $2.3 billion in damage to roads, houses, other buildings, pipelines, and other structures each year. This is more than twice the damage from floods, hurricanes, tornadoes, and earthquakes when combined. The distortion and cracking of highway pavements and buildings which are caused by the swelling or shrinkage of expansive clay foundation soils create major engineering problems in Texas, the great plains and western states, and many other areas of the world. In case of pavements, expansive clays create problems relating the service life and riding qualities of highway pavements in areas where unsaturated clay soils and non-uniform rainfall occur.

Figure 2-4 Expansive Clay in North Texas

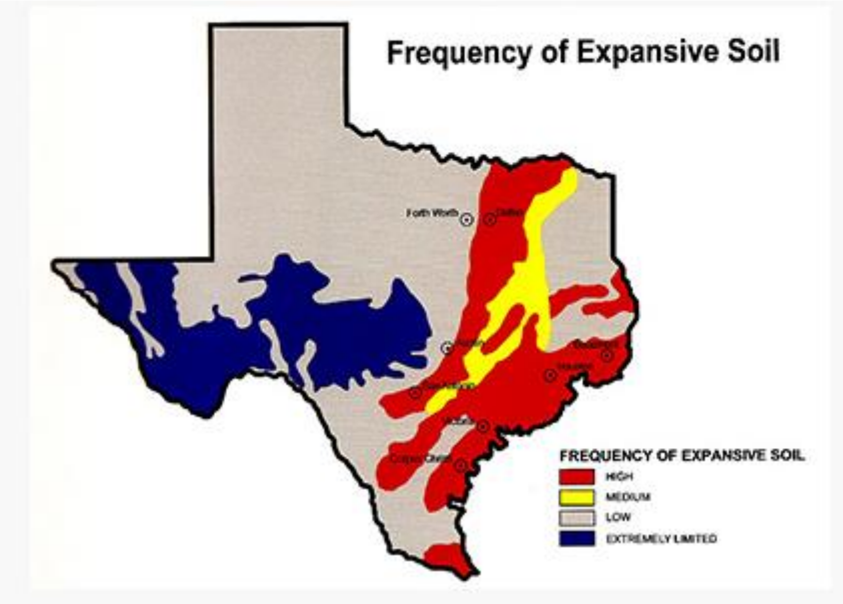


Figure 2-5 Frequency of Expansive Soil in Texas

Mineralogical aspect and shrink-swell behavior of expansive soil

Clay particles are very tiny, and their shape is determined by the arrangement of the thin crystal lattice layers that they form, with many other elements like hydrogen, sodium, calcium, magnesium and Sulphur which can be incorporated into the clay mineral structure. The existence and profusion of these dissolved ions can have huge influence on the behavior of clay minerals. The most commonly found clay minerals are kaolinite, halloysite, smectite, illite, etc. The soil that exhibits significant potential of shrinking and swelling contains smectite clay minerals including montmorillonite and bentonite. The formation of minerals of this type of soil is responsible for the moisture retaining capabilities. Upon the saturation of potentially expansive soils, more water molecules are absorbed between the clay sheets causing the bulk volume of the soil to increase or swell. Likewise, when the water is eliminated by the means of evaporation or gravitational forces, the water between the clay sheets is released causing the overall volume of the soil to decrease or shrink. However, swelling and shrinkage are not fully reversible processes (Holtz & Kovacs, 1981). The amount by which the ground can shrink and/or swell is determined by the water content in the near-surface zone. And unless this zone is extended by the presence of tree roots, significant activity usually occurs to about 3m depth (Driscoll, 1983; Biddle 1998). Another important characteristic of fine-grained clay-rich soils is that they can absorb large quantities of water after rainfall, becoming sticky and heavy. On the contrary, they can also become very hard when dry. This results in shrinking and cracking of the ground which leads to large differential settlement and decrease in ultimate bearing capacity. However, as long as the water content remains relatively constant in the soils with a high expansive potential, they are usually not problematic. This is generally control by (Houston et al., 2011):

- Soil properties, e.g. mineralogy
- Suction and water conditions
- Water content variations
- Geometry and stiffness of a structure

The changes in water content, or suction (increasing strength of the soil due to negative pore water pressures) in a partially saturated soil, boost the chances of occurring damages substantially.

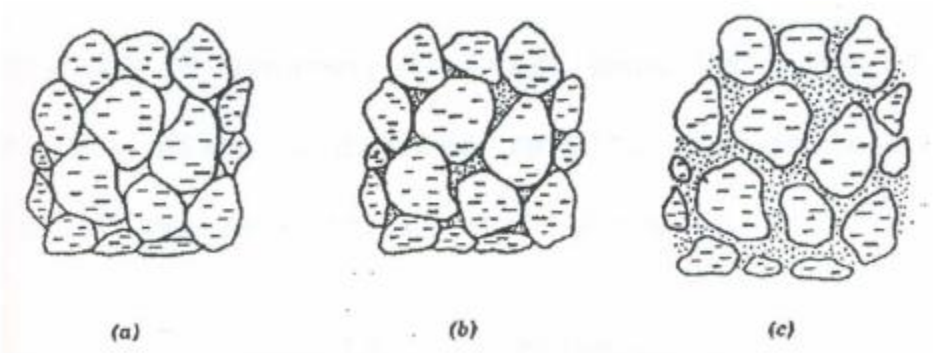
2.5.2 Intrusion of Fines on Base Materials

The base materials may get contaminated during the demolition of old structures, storage of the recycled materials or during the mixing and construction process itself, as there is a possibility of soil and other deleterious material getting mixed with these recycled base materials. However, the intrusion of fines on base materials is mainly due to migration of fines from the subgrade which may contaminate the base. The possibility of the migration of the fines is exaggerated by a) high water table during the rainy seasons, b) the lack of separating layer between the base and subgrade, c) the degrading subgrade or the use of a poor quality subgrade.

2.5.3 Effect of Fines on Base Materials

Thom (1988) and Kamal (1993) reported that the resilient modulus is negatively affected by fines. Resilient modulus generally decreases as the fine content increases. Hicks (1970) and Jorenby (1986) partially supports this finding as they reported that the resilient modulus increases at first with the addition of fines but drastically reduces after a certain limit. Hicks and Monismith found that the resilient modulus decreases as fines content increases for partially crushed aggregates, but the effect was opposite for fully crushed aggregates. They clarified that the initial increase of stiffness is due to the displacement among coarse particles as excess fines are added. This results in the loss of aggregate particle interlocks and load carrying ability rests only on the fines.

As the base course functions in prevention of pumping, prevention of volume change of sub-grade, increase in structural capacity and expedition of construction, to accomplish these functions high density and stability are required. An aggregate with little or no fines content (Figure 2-6 (a)) gains stability from grain to grain contact. Usually when an aggregate doesn’t contain any fines it has a relatively low density but is pervious and not frost susceptible. However, this material is difficult to handle during construction because of its non-cohesive nature. As shown in Figure 2-6 (b), if an aggregate contains sufficient amount of fines, it helps in filling all the voids between the aggregate grains and still gain its strength from grain to grain contact but has increased shear resistance. In this case, normally the density will be high but the permeability will be low. Although the material is moderately difficult to compact, it is ideal in the perspective of stability. The material that contains great amount of fines, simply float in the soil as shown in Figure 2-6 (c). Normally density of such material will be low and practically it is impervious is is frost susceptible. Also the stability of this type of material is prominently affected by adverse water conditions. Paradoxically, it is easier to handle materials during construction and it compacts quite readily (Yoder and Witczak, 1975). It may be concluded that with the increase in fine content, the dry density of optimum moisture content decreases. Also, aggregate gradation and amount of fines has an implicit consequence on the resilient behavior of unbound granular bases by affecting the impact of moisture and density of the system.



a. Aggregates with no fines b. Aggregate with sufficient fines c. Aggregate with great amount of fines

(Yoder and Witczak, 1975)

Figure 2-6 Aggregate and Fine Matrix

2.6 Pavement Structure

A typical pavement structure consists of superimposed layers of processed materials above the natural soil sub-grade, whose primary function is to distribute the applied traffic loads to the roadbed. The ultimate aim of the pavement structure is to ensure that the transmitted stresses due to wheel load are sufficiently reduced so that they will not exceed bearing capacity of the sub-grade. Based on the structural performance, pavements can be classified as flexible pavement, rigid pavement and composite pavement. Flexible pavement generally consists of a prepared or stabilized subgrade, base or sub-base course, and surface course. Flexible pavement has higher deflection at the edges and lower deflection at the center. Rigid pavement in general consists of Portland cement pavement slabs constructed on a granular base layer over the subgrade soil. The base layer serves to increase the effective stiffness of the slab foundation and also prevents pumping of the fine- grained soils at joints, cracks, and edges of the slab. Composite pavement is a combination of both rigid pavement and flexible pavement. A rigid section is overlain by flexible pavement and includes hot mix asphalt (HMA), open graded friction course or rubberized asphalt (Potturi, 2006). Typically, a concrete base layer provides structural capacity while an asphalt surface layer provides a wearing surface course.

2.6.1 Surface Course

Surface course is the top layer of a pavement structure that is directly in contact with the traffic wheel load. It is designed to accommodate the traffic load, drainage, resist skidding, traffic abrasion, and the disintegrating effects of climate.

2.6.2 Base Course

This layer is placed immediately beneath the surface course or on a subbase (if there is any) or subgrade to provide a uniform and stable support for binder and surface courses. The base layer typically provides a significant fraction of the structural capacity in a flexible pavement system. It contributes to additional load distribution and subsurface drainage. To withstand the high pressure imposed on it, this layer must possess high resistance to deformation. The key functions of a base course are prevention of pumping, drainage, prevention of volume change of sub-grade, increased structural capacity and expedition of construction. This layer usually consists of high quality aggregates, such as crushed virgin aggregate, crushed limestone, recycled crushed concrete aggregate and recycled asphalt pavement (RAP) treated with Portland cement, lime, or other binder materials. Selection of the base materials is done in accordance with the specification. Stabilization of the base layer reduces the total thickness of the pavement structure resulting in a more economical overall design.

2.6.3 Sub-Base Course

This layer is usually beneath the base layer to support the surface and base course. It consists of a compacted layer of granular material, with or without treatment of stabilizer. The primary functions of this layer are to provide structural support, improve drainage and reduce the intrusion of fines from the sub-grade in the pavement structure. If the strength of the base layer is high enough to sustain the wheel load, then the sub-base layer is not needed. As it requires less strength, the material quality of the sub-base is usually lower than the base layer.

2.6.4 Sub-Grade

The top soil or sub-grade is a layer of natural soil prepared to receive the stresses from the layers above. It is essential that at no time soil sub-grade is overstressed. It should be compacted to the desirable density near the optimum moisture content.

A typical cross section of a pavement structure is shown in Figure 2-7.

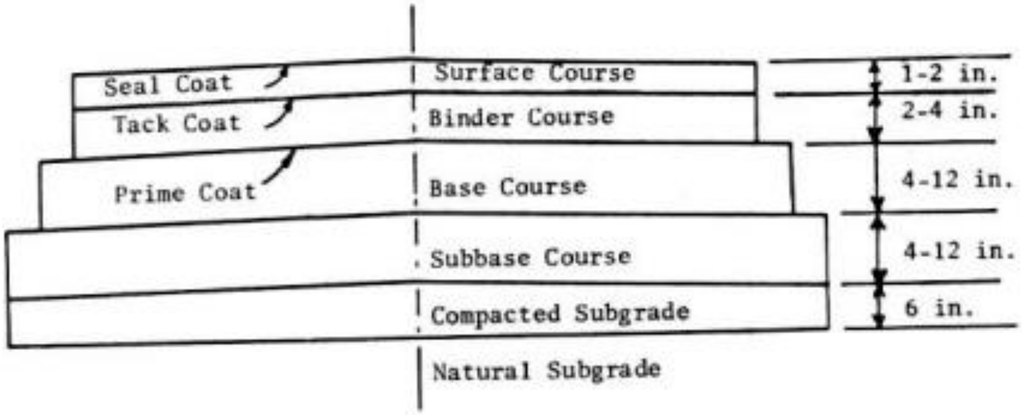


Figure 2-7 Typical pavement structure (Ordonez, 2006)

2.7 Pavement Design

Depending on the distribution of surface loads, pavement is classified to be “rigid” or “flexible” or “composite”. Rigid pavements are surfaced by Portland cement concrete slabs and they endure uniform settlements under loading. Flexible pavements are surfaced by asphalt concrete, stabilized or bound granular material or granular materials and their deflection profile show high deflection at the edges and low deflection at the center. Composite pavements typically consists of both rigid and flexible pavements usually constructing the flexible pavement above the rigid pavement. The upper flexible layer functions as a thermal and moisture blanket reducing temperature and moisture gradients within the rigid pavement section and also decreases deformation of rigid pavements. Additionally, flexible layer serves as a wearing course to reduce wearing effects of wheel loads.

In the design of a pavement, the main variable is its thickness. The main design criteria of the pavement thickness are:

a) The magnitude of the imposed loads

   To estimate the imposed load on the pavement, equivalent single axle load (ESAL) is used. The ESAL reference axle load is an 18 kip single axle with two tires and depending upon the truck type it varies. Trucks with different wheel configuration impart different ESAL number when they pass over the pavements. Over the period of design and analysis, traffic volume is predicted and converted into an equivalent number of 18 kip single-axle loads and totaled during the design period.

b) The strength and stiffness of the subgrade soil

   The strength and stiffness of the subgrade soil are the crucial parameters in the pavement design. In the past, there was a practice of using California Bearing Ratio (CBR), R-value, soil support value (SSV) and triaxial strength as the parameters of the pavement design which were mostly based on static type loading and the evaluation of loads depending on the failure of the soil specimen in the laboratory experiment. However later it was realized that these parameters do not represent traffic loads which are of repeated load types. Also, it was noted that the test conditions causing soil failure does not represent the actual dynamic traffic load condition of real life pavement since soil failure rarely occurs in the field. AASHTO (2003) recommended the use of resilient modulus as a soil parameter for the pavement design which represents dynamic elastic modulus and accounts for plastic deformation in subsoils.

   The input parameters required for the design of a pavement structure are: Design variables, Performance criteria, material properties, structural characteristics and

Reinforcement variables. Design variables such as performance period, traffic, reliability and environmental effects come into picture while designing for specific road sections. Performance criteria include serviceability criteria, allowable rutting, aggregate loss, etc. Material properties include effective roadbed resilient modulus, effective subgrade modulus, pavement layer material characteristics, PCC modulus of rupture and layer coefficients. Structural characteristics signifies the physical characteristics such as load transfer, and loss of support which may affect the pavement performance.And jointed and flexible pavements comes under reinforcement variables.

2.7.1 Design of Flexible Pavements

Basically, flexible pavement design requires the determination of the layer thicknesses and estimated traffic volume.The following paragraph describes the AASHTO (2003) procedure for design of flexible pavements in brief.

To begin with, based on the mean values of the required input parameters the structural number (SN) of the pavement is determined from the design chart. The input parameters like total predicted traffic passes of 18 kip ESAL load applications (W_{18}), reliability factor (R), design serviceability loss (ΔPSI), effective road bed soil resilient modulus (M_R), and the overall standard deviation (S_0) are required for the design chart. The design chart for the determination of the structural number is shown in the Figure2-8. When the structural number is determined, it is converted into the layer thickness, which is determined by the following equation:

$SN = a1 \times D1 + a2 \times D2 \times m2 + a3 \times D3 \times m3$

Where,

a_1, a_2, a_3 = layer coefficients for the surface, base, and sub-base

D_1, D_2, D_3 = thicknesses of the surface, base, and sub-base,

m_2, m_3 =drainage coefficients for the base and sub-base courses

The required SN value should be smaller than the value achieved from the equation mentioned above. The layer coefficients should be determined from the resilient or elastic moduli properties. AASHTO design guide has provided the correlations. Considering the cost effectiveness along with the construction and maintenance constraints is important in selecting the SN value.

2.7.2 Design of Rigid pavements

AASHTO developed design guidelines for rigid pavements too. The requirement of the design of rigid pavements is described in the following paragraph.

For the design of the rigid pavement, the value of the resilient modulus is usually converted to the modulus of the subgrade reaction (k). The Figure 2-9 and Figure 2-10 as shown below deliver process of estimating the modulus of subgrade reaction, k. The parameters such as roadbed soil resilient modulus (M_R psi), Subbase thickness (D_{SB}, inches), depth of subgrade to rigid foundation (D_G, ft.) and the subbase elastic modulus (E_{SB}, psi) are necessary to estimate the balue of k. The estimation of relative damage to rigid foundations is presented in a chart shown in Figure 2-11 below.

The effective modulus of subgrade reaction is reduced by a factor, LS to consider the loss of support by foundation erosion or differential vertical soil movements. The correction factor chart is shown in Figure 2-12. When the effective modulus of subgrade reaction is determined, the concrete slab thickness can be determined by using the charts shown in Figure 2-13 and Figure 2-14. Apart from the design variables used in designing flexible pavement the additional parameters required for the rigid pavement design are elastic modulus of concrete (E_c), the concrete modulus of rupture (S_c), the load transfer coefficient J and the drainage coefficient C_d.

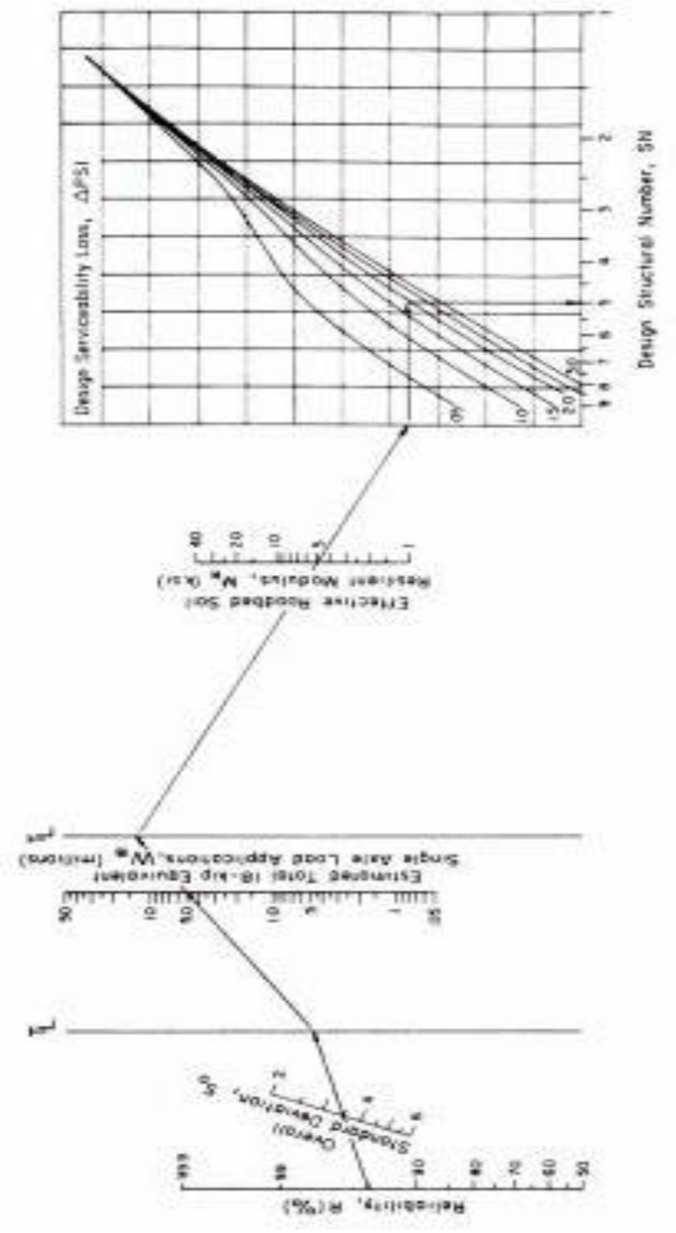


Figure 2-8 Flexible pavement design chart (AASHTO, 2003)

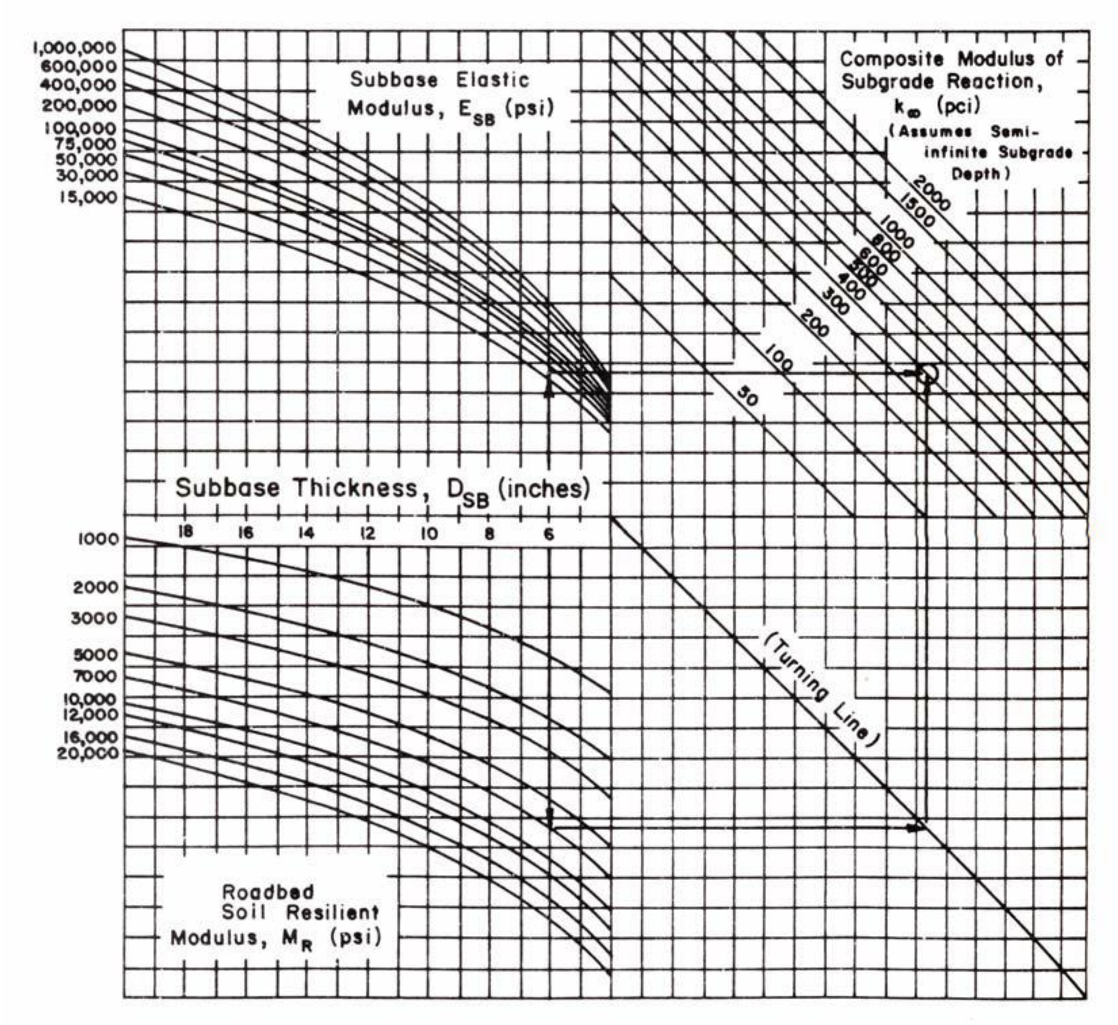


Figure 2-9 Chart for the determination of subgrade reaction (AASHTO, 2003)

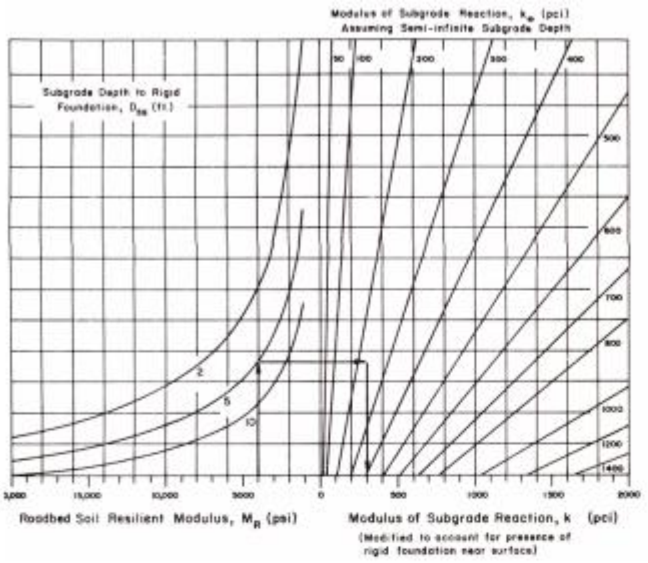


Figure 2-10 Chart for modifying modulus of subgrade reaction due to rigid foundation (AASHTO, 2003)

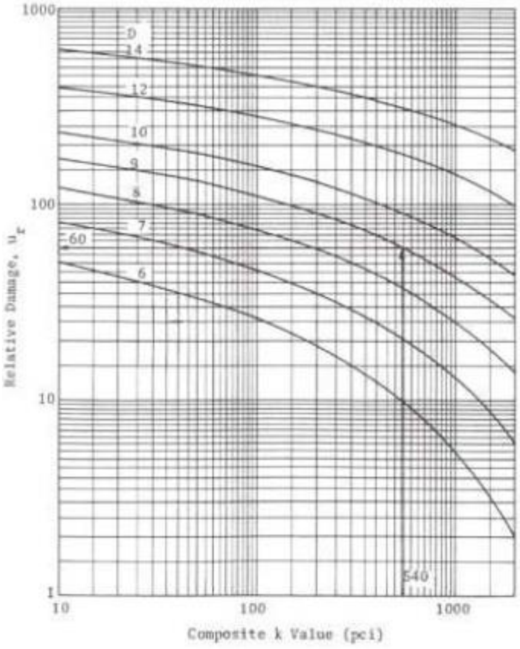


Figure 2-11 Chart for estimating the relative damage to rigid pavements (AASHTO, 2003)

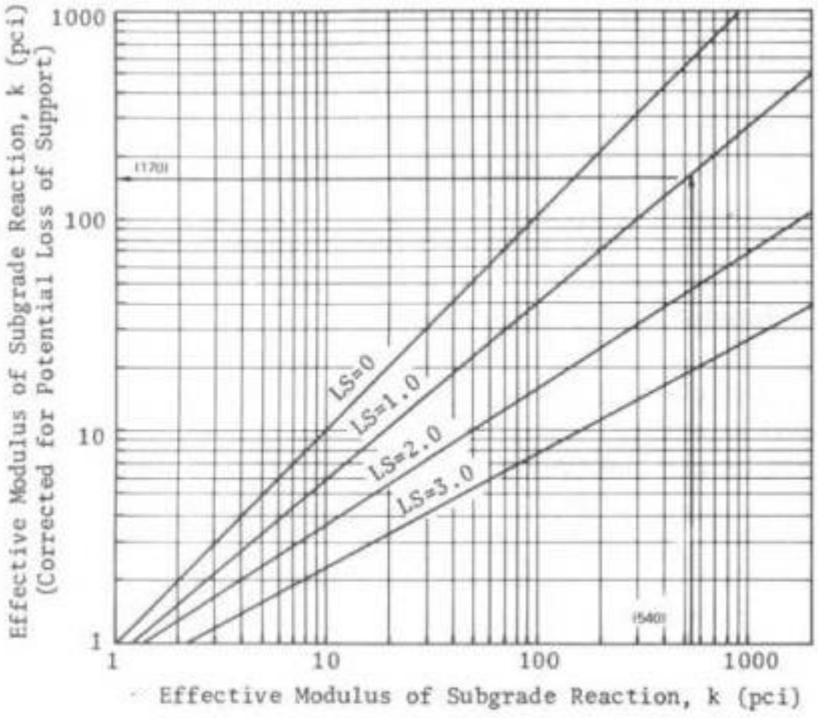


Figure 2-12 Correction of effective modulus of subgrade reaction (AASHTO, 2003)

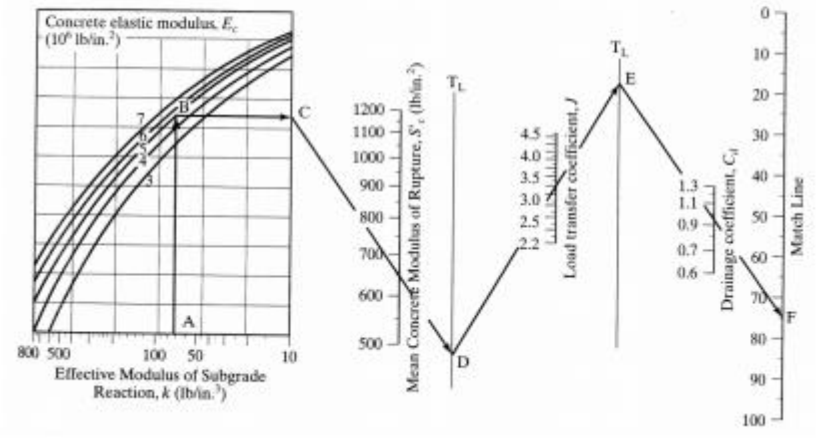


Figure 2-13 Design chart for rigid pavements (AASHTO, 2003)

From the design procedure of both flexible and rigid pavements, it is clear that resilient modulus M_R is one of the most important design parameter in pavement design. Therefore, it is essential to determine the resilient modulus value for any given type of base material mixture.

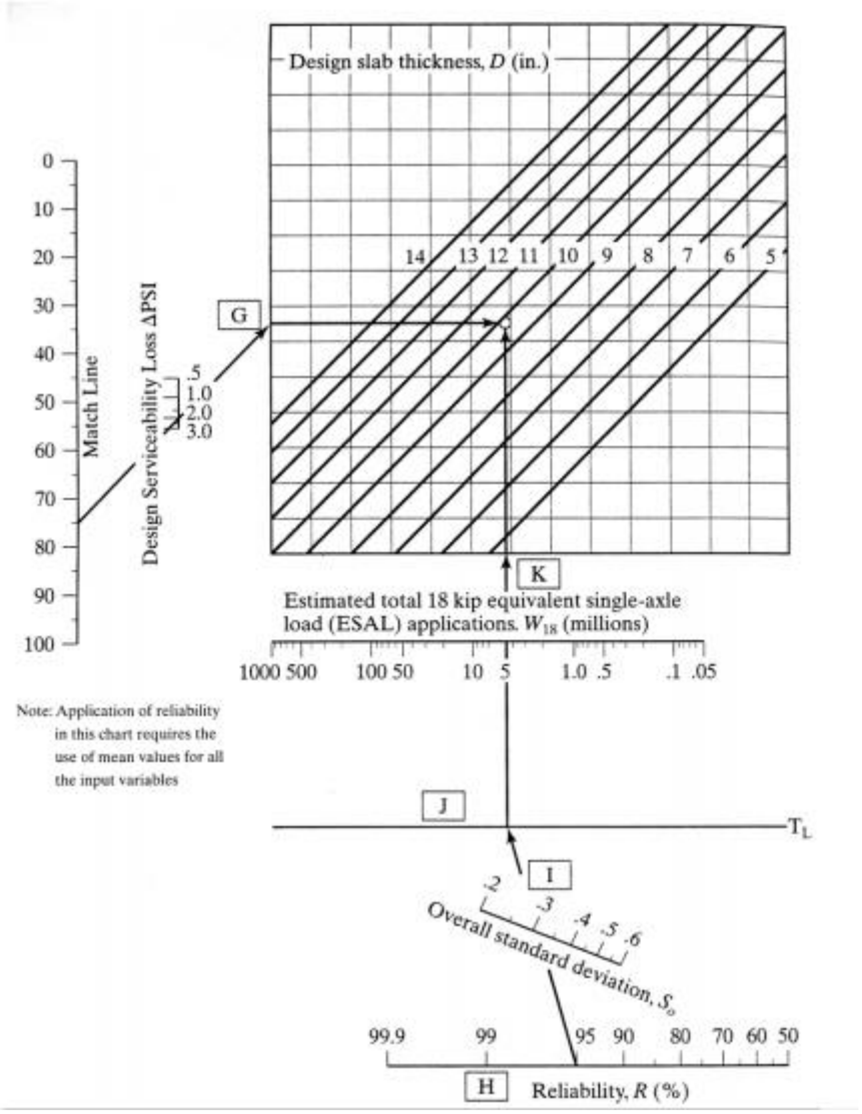


Figure 2-14 Design chart for the rigid pavements (AASHTO, 2003)

2.8 Cement-Treated Base (CTB)

Cement-treated base is a general term that applies to an intimate mixture of native soils/or manufactured aggregates with measured amounts of portland cement and water that hardens after compaction and curing to form a strong, durable, frost resistant paving material. CTB is widely used as a pavement base for highways, roads, streets, parking areas, airports, industrial facilities, and materials handling and storage areas. The structural properties and performance of CTB largely depends on the elastic modulus and strength of material, quantity of cement, curing conditions, and age. These properties are useful for developing design procedures based on the stress-strain relationship and fatigue characteristics parameters (George, 2004). The typical properties of CTB material are shown in the following table:

Table 2-2 Properties of CTB (Halsted, 2006)

Property	**7-Day Values**
Compressive Strength	300 – 800 psi (2.1 – 5.5 MPa)
Modulus of rupture	100 – 200 psi (0.7 – 1.4 MPa)
Modulus of elasticity	600,000 – 1,000,000 psi (4,100 – 6,900 MPa)
Poisson’s ratio	0.15

Designing the proper amount of water and cement for CTB is not only important to obtain a good final product, but also provides important information for quality control during construction. In general, a cement content that will provide a 7-day unconfined compressive strength between 300 and 400 psi is satisfactory for most mixed-in-place

CTB applications. The main reason for limiting strength is to minimize shrinkage cracking caused by higher cement and water content.

2.9 Design Considerations of RAP and RCCA Materials

Rather than the long term performance of the pavement, current design guideline are developed based only on the strength. As a result, transportation department of different states using higher cement content to achieve high strength values. Guthrie (2007) reported that this high strength of relatively stiff cement treated aggregate base layers may guarantee the strength and resilient modulus but not necessarily the long term pavement performance. Roadways which contain base layers treated with high cement content are subjected to rutting, shrinkage cracks, fatigue cracks, and transverse cracks, which may not cause structural deficiency, but allow water to penetrate the pavement layers and reduce the quality of the pavement. Tensile cracking takes place at the bottom of the pavement layers and as a result of the accumulation of the pavement deformation, rutting occurs. These problems such as, rutting, fatigue cracking, etc were addressed by using fiber reinforcement with the RAP material in the recent studies done by Potturi (2006). The use of fiber-reinforced cement-treated base materials have enhanced tensile strength, which diminishes the propagation of cracks and associated cracking in the pavement surface layer.

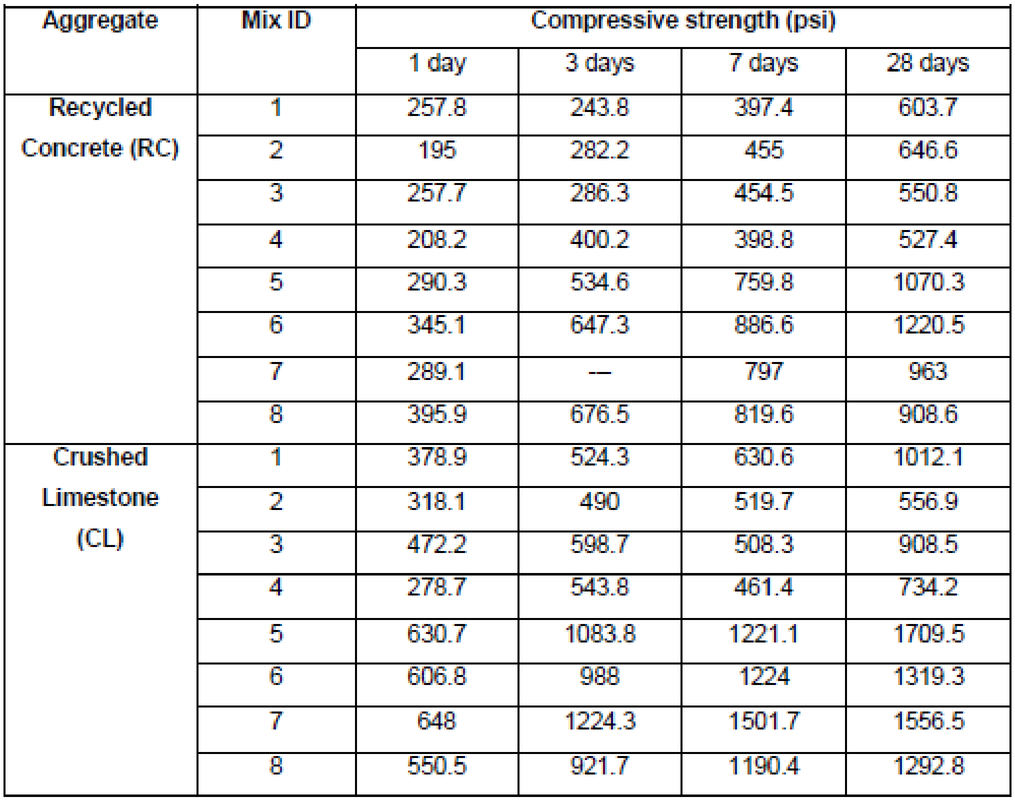
2.10 Cement-Treated RAP and RCCA

Recycled asphalt pavement (RAP) are generated by cold milling of the removed hot mix asphalt (HMA) pavement and consists of asphalt and aggregates. Usually, it is used as a replacement of the aggregate base course and processed to meet the requirements of the specific gradation. Recycled crushed concrete aggregates (RCCA) are produced by crushing the concrete to meet the specific particle size requirement. As cement is attached to the surface of the aggregates, its properties are different than the natural aggregates. RAP and RCCA materials must meet the minimum design criteria provided by the AASHTO guidelines and state transportation departments. The addition of cement improves the strength and stiffness of base materials but does not guarantee the proper performance and durability of the pavements against problems like rutting and cracking.

2.10.1 Unconfined Compressive Strength of Cement-Treated RAP or RCCA

The unconfined compressive strength of the cement-treated RAP or crushed concrete is determined by unconfined compression tests. A cement-treated base gains 70% of its strength in the first seven days, Croney and Croney (1997). The compressive strength of a cement-treated base aggregate increases with age (Lim and Zollinger, 2003) (Table 2-3). Lim and Zollinger used two types of aggregate base materials i. e., crushed limestone and recycled crushed concrete in their experiment.

Table 2-3 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	257.8	243.8	397.4	603.7
	2	195	282.2	455	646.6
	3	257.7	286.3	454.5	550.8
	4	208.2	400.2	398.8	527.4
	5	290.3	534.6	759.8	1070.3
	6	345.1	647.3	886.6	1220.5
	7	289.1	—	797	963
	8	395.9	676.5	819.6	908.6
Crushed Limestone (CL)	1	378.9	524.3	630.6	1012.1
	2	318.1	490	519.7	556.9
	3	472.2	598.7	508.3	908.5
	4	278.7	543.8	461.4	734.2
	5	630.7	1083.8	1221.1	1709.5
	6	606.8	988	1224	1319.3
	7	648	1224.3	1501.7	1556.5
	8	550.5	921.7	1190.4	1292.8

In this experiment, recycled crushed concrete materials obtained from road construction sites in Harris County, Texas were used. The base material particles sizes varied from 2 in. to No. # 200 sieve, and meets the specification requirements of the Texas Department of Transportation (TxDOT) Item 276. The test variables comprised of coarse aggregates, fines content and cement content. They are presented in the Table 2-4 below in which (-) and (+) signs indicate low and high application levels of cement (Lim and Zollinger, 2003). The total number of test mixtures of each aggregate is shown in the Table 2-5.

Table 2-4 Test Variables and Application Levels for the CTAB Test Mix Design (Lim and Zollinger, 2003)

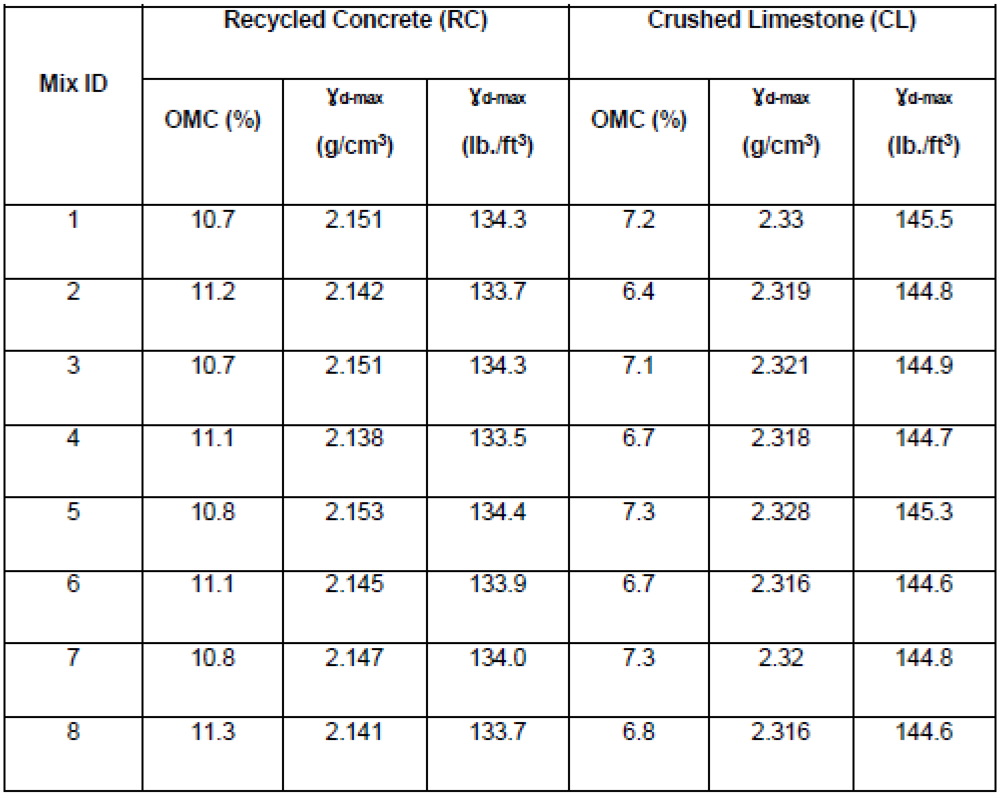
Test Variables	**Designation**	**Application Levels**	
		Low (-)	**High (+)**
Content of Coarse Aggregates	A	48%	58%
Content of Fines	F	5%	10%
Cement Content	C	4%	8%

Table 2-5 Complete Factorial of Test Mixtures for each Aggregate Type (Lim and Zollinger, 2003)

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

The optimum moisture content (OMC) test results are shown in Table 2-6. The recycled crushed concrete acquired 30% lower strength than the strength acquired by the crushed limestone material.The reason behind this might be due to the higher water demand of the coarse recycled concrete material and higher water-to-cement ratio of the corresponding mixtures (Lim and Zollinger, 2003). The minimum seven-day strength requirement of most specifications ranges between 350 to 500 psi (Lim and Zollinger, 2003).

Table 2-6 Optimum Moisture Content and Maximum Dry Density of Different Mixtures



Mix ID	Recycled Concrete (RC)			Crushed Limestone (CL)		
	OMC (%)	$\gamma_{d\text{-max}}$ (g/cm^3)	$\gamma_{d\text{-max}}$ (lb./ft^3)	OMC (%)	$\gamma_{d\text{-max}}$ (g/cm^3)	$\gamma_{d\text{-max}}$ (lb./ft^3)
1	10.7	2.151	134.3	7.2	2.33	145.5
2	11.2	2.142	133.7	6.4	2.319	144.8
3	10.7	2.151	134.3	7.1	2.321	144.9
4	11.1	2.138	133.5	6.7	2.318	144.7
5	10.8	2.153	134.4	7.3	2.328	145.3
6	11.1	2.145	133.9	6.7	2.316	144.6
7	10.8	2.147	134.0	7.3	2.32	144.8
8	11.3	2.141	133.7	6.8	2.316	144.6

Croney and Croney (1997) reported that, it takes about seven days to achieve 70% of the 28-day compressive strength as shown in the following figure.

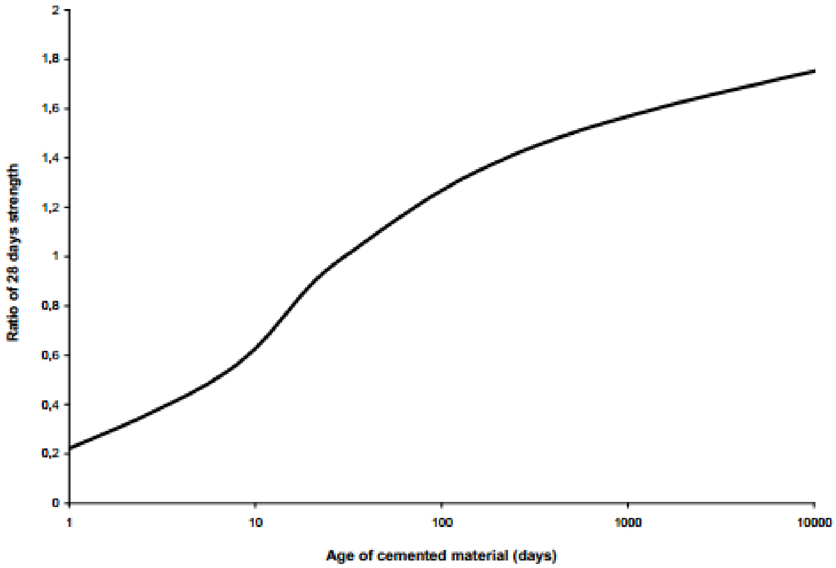


Figure 2-15 Increase in Compressive strength with time (Croney and Croney, 1997)

The effects of cement content on the strength of RAP base baterials was investigated by Ordonez (2006). Sample specimens were prepared at different cement contents such as, 0, 2, and 4% and tested after seven days of curing. The significant increment in unconfined compressive strength was noticed because of the use of cement. The strength increased to about five times more than that of untreated specimens when the cement content increased from 0 to 4%.

In the study conducted by Faysal (2017), the unconfined compressive strength (UCS) of cement treated material mix of RAP and RCCA decreased by about 12% with a 50% to 70% increase in RAP content. None of the combinations of the materials fulfilled the strength requirement of 300 psi (Texas Department of Transportation) at 0% and 2% cement content. The 100% RCCA materials met the requirement at 4% cement content whereas 100% RAP did not reach the requirement even at 6% cement content (Figure 2-

16). The combination of 30% RAP + 70% RCCA and 50% RAP + 50% RCCA materials meet the strength requirement of 300 psi at about 4.65% and at 5% to 5.5% cement content respectively as shown in Figure 2-17. Faysal (2017) concluded that the inclusion of RAP reduces the strength of the material mix.

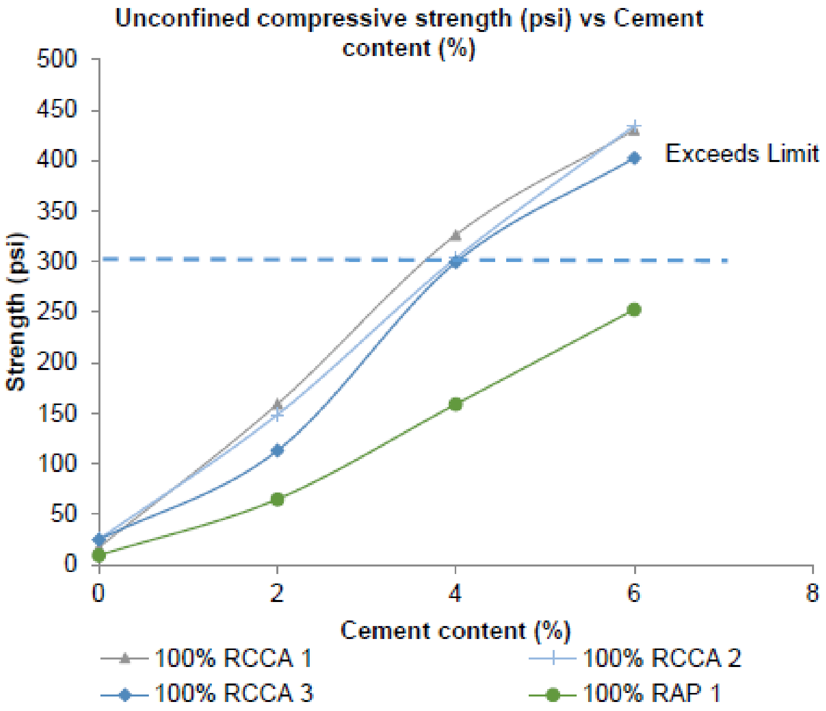


Figure 2-16 Unconfined compressive strength comparison (Faysal, 2017)

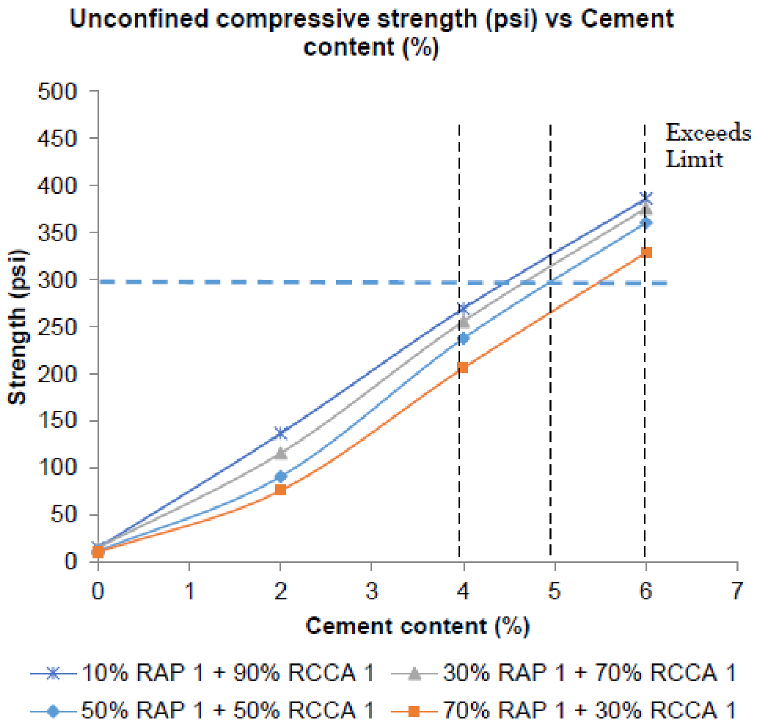


Figure 2-17 Unconfined compressive strength of RCCA and RAP mixes (Faysal, 2017)

Mohammadinia et., al.(2014) found RAP to be more strongrer than RCA based on the UCS results with the same cement content and under the same curing duration. The presence of bitumen in the RAP aggregates might be the reason of having higher UCS than other C&D materials. According to this study, 2% cement and 7 days of curing was sufficient to meet the local road-authority requirement of 4 MPa (i.e. 580 psi) whereas RCA required a minimum of 4% cement with 28 days of curing. In this experiment, the UCS tests were conducted on samples prepared with modified compaction with the split mold under static loads to ensure the homogenous compaction and prevent damage during removal from the mold (ASTM D5102 (ASTM 2009)). The materials were mixed with water and cured for 12 – 24 h in room temperature before compaction to ensure that there is enough free water for the hydration process and there would not be any loss of moisture due to water absorption. The cement was mixed with respective C&D material before compaction.

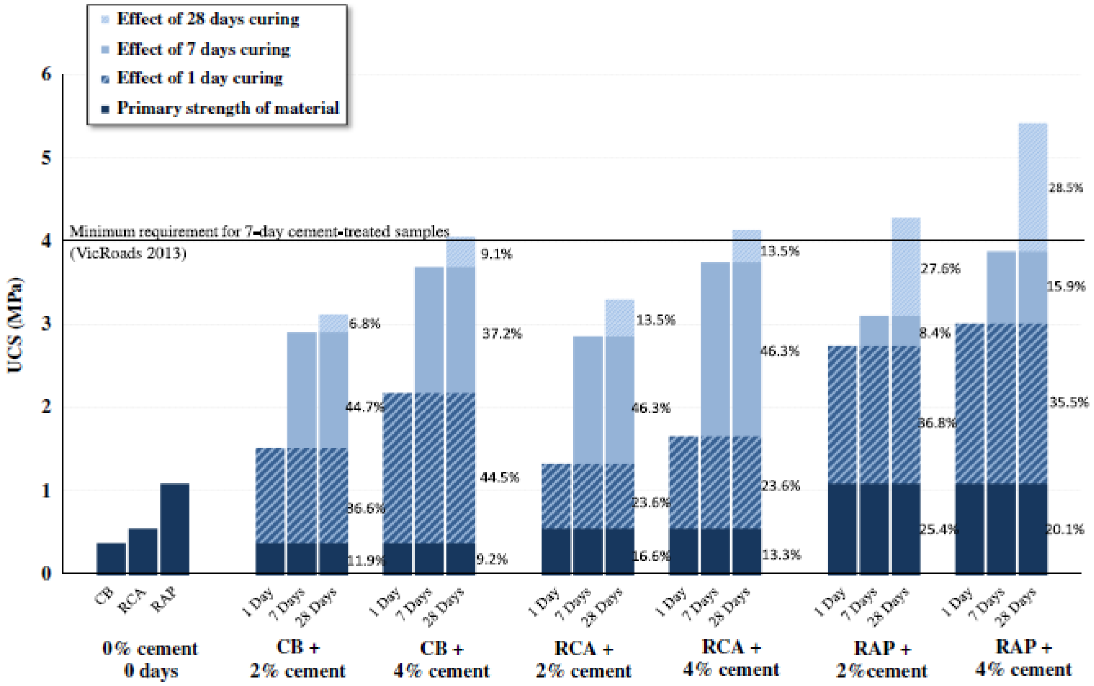


Figure 2-18 Development of unconfined compression strength in C&D materials with curing time (Mohammadinia et., al.2014)

2.11 Resilient Modulus and Permanent Deformation

Resilient modulus and pavement deformation or rutting are the two important parameters that determine the pavement performance. The common practice of determining these properties is by performing repeated load triaxial tests in a control of AASHTO T 307-99.

Resilient modulus is defined as the ratio of the repeated deviator axial stress to the resilient or recoverable strain and can be expressed as: $M_r = \sigma d / \varepsilon_r$

Here, M_r = resilient modulus

σ_d = repeated deviator stress

ε = recoverable or resilient axial strain in the direction of principal stress

According to Mahedi (2016), actual response of the pavement layers to traffic loading on pavement layers is determined using resilient modulus of pavement materials. The amount of deformation that may be recoverable by the exclusion of applied stress is resilient strain. The stress-strain response of loading and unloading cycles of a typical triaxial test is presented by Buchanan (2007). Permanent deformation is usually characterized by assuming that the permanent strain is proportional to the resilient strain (Huang, 2007). It is expressed as:

εp (N) = μ εr N-α

where, εp (N) = plastic or permanent strain due to single load application such as the Nth application,

εr = resilient or recoverable strain at the 200th repetition,

N = number of load applications

M and α = permanent deformation parameters.

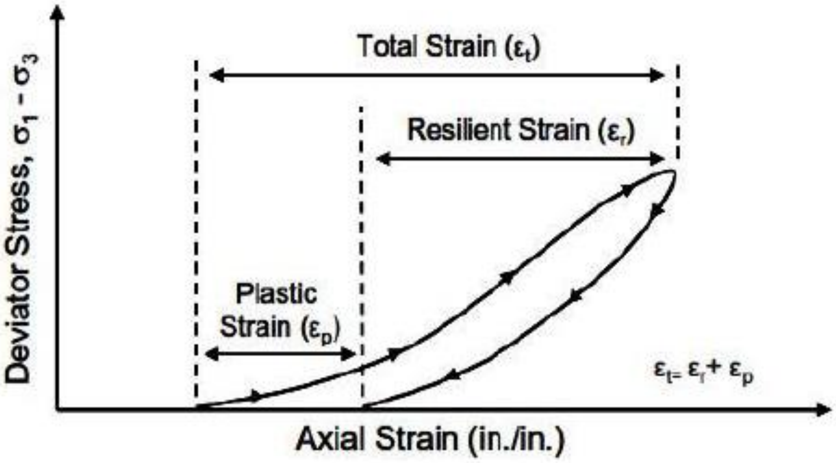
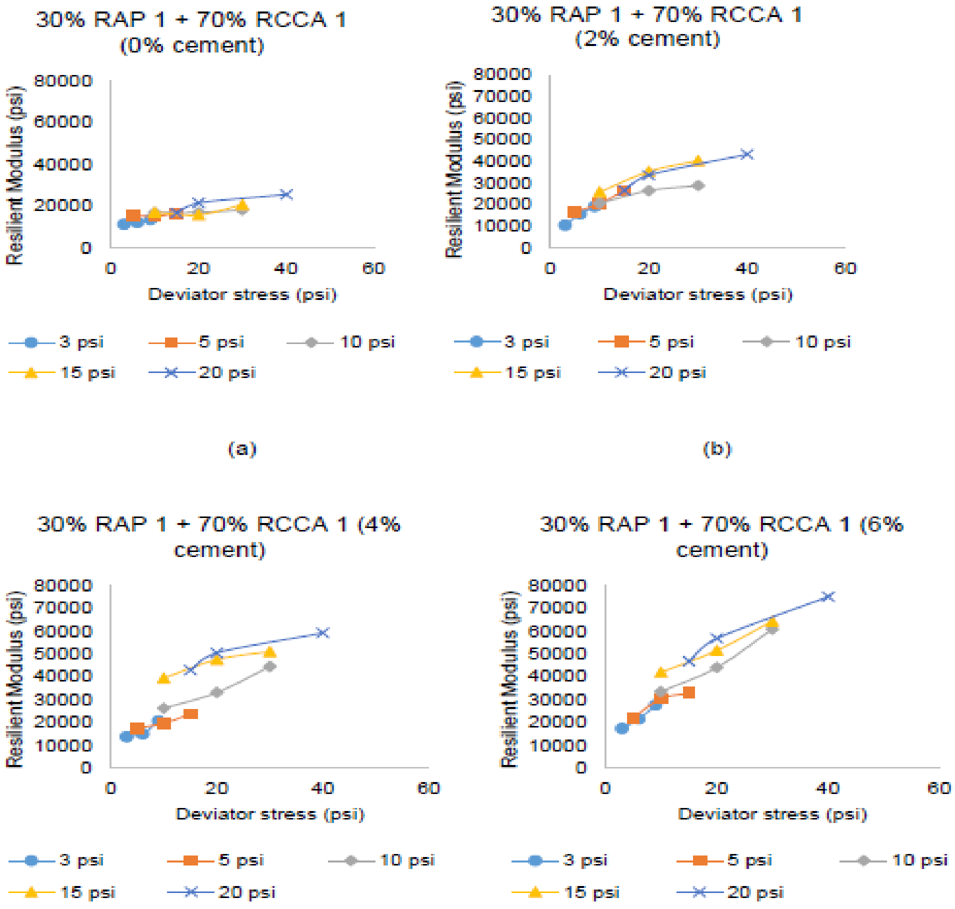


Figure 2-19 Response of specimen during cyclic axial loading (Buchanan, 2007)

According to AASHTO pavement design guidelines (1993), the value of resilient modulus Mr should be used for material characterization. It recommends the use of correlation between structural coefficients and resilient modulus. In few studies, it was found that the results obtained from different laboratory tests for modulus were different from the back calculated moduli. Lekarp et., 2000, reported that this might have occurred due to the cracks in the pavement structure.

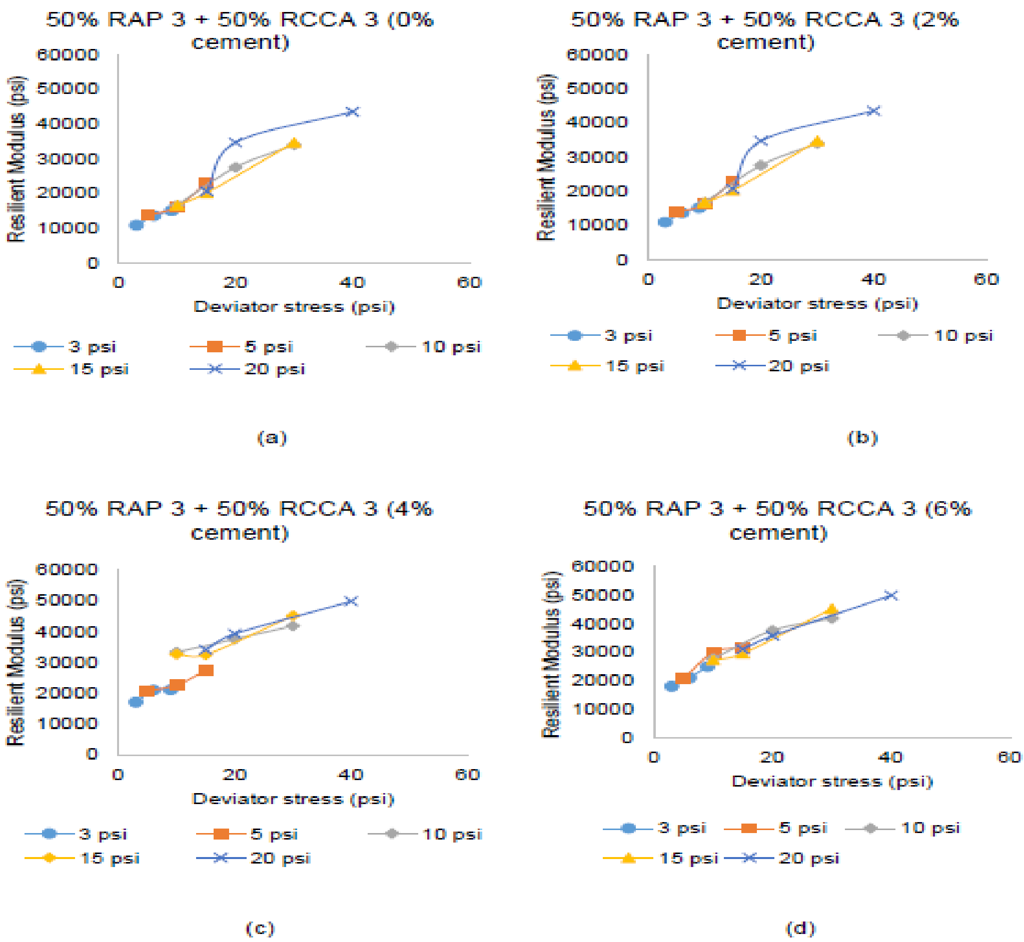
Faysal (2017) reported that RCCA materials are superior to RAP materials. The value of resilient modulus decreased by 50% with the inclusion of 50% RAP at any cement content.



(a)

(b)

Figure 2-20 Comparison of resilient modulus test results for 30%RAP 1 + 70%RCCA 1 combination (Faysal 2017)



(a) (b)

(c) (d)

Figure 2-21 Comparison of resilient modulus test results for 50% RAP 3 + 50% RCCA 3 combination (Faysal 2017)

2.12 Other Factors Affecting Strength and stiffness of Base Materials

The factors that affect the structural integrity of flexible sections are controlled by several parameters. The parameters are layer thickness, traffic volume, etc. Layer thicknesses are selected based on the criteria that the stresses at the contact point of HMA and the base, and the base and the sub-base or subgrade should be within limits to reduce the amount of cracking and rutting. The higher the thickness of the layers, lesser will be the stress on layers for a given traffic volume and the applied load (Gautam et al., 2009). The different factors such as material type, sample preparation method, stress state, the condition of the samples, and the strain sensitivity of the materials affects the resilient modulus of base materials (George and Uddin, 1994).

The strength of the base material can be improved by using an additive, such as cement, lime, etc, but an extremely strong mix is highly undesirable, as it creates potential cracking, and a weak mix will reduce the pavement performance. With the addition of the chemicals, the optimum moisture content (OMC) and maximum dry density (MDD) are affected too. Hence, it is necessary to consider the change in behavior of the material after adding these chemicals.

2.12.1 Size and Shape of Aggregate

Angularity, shape, and texture are the aggregate form characteristics of coarse aggregate that plays vital role in the performance of the material. These three aspects are affected by the mineralogical origins and the crushing processes used during production of the material (Prowell et al., 2005). The sharpness or roundness of the aggregate corners refers to the angularity of the particles. The surface roughness of the particles describe the texture. The studies have shown that as the angularity and surface texture of the particles increases, resilient modulus increases (Gautam et al., 2009). Another study (Barksdale and Itani, 1989) concluded that flaky particles are more susceptible to rutting than other types of coarse aggregates. The effect of shape on the performance of the aggregate is less well understood than angularity and surface texture. As the results were not clear from several studies, particle shape either does not have a major impact on the performance of unbound materials or has not been investigated thoroughly enough to understand the potential effects.

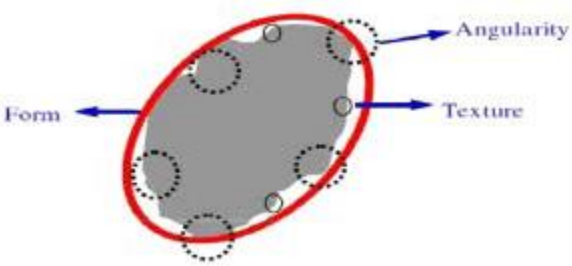


Figure 2-22 Compaction of aggregate shape: shape, angularity, and texture (Masad et al., 2003)

2.12.2 Compaction

Resilient modulus of base material can be affected by the factors such as, degree of compaction, degree of saturation, moisture content during compaction, and method of compaction (Nazarian et al., 1996). Base materials compacted on the wet-side of the optimum moisture content yield lower resilient modulus. Soils compacted to the maximum dry density for a certain degree of saturation results in a higher resilient modulus (Thompson and Barrenburg, 1989). There will be significant increase in the resilient modulus if the prepared sample is kept at a normal temperature before testing due to the thixotropic effect (gautam et al., 2009).

2.12.3 Dry Density

Generally, the higher the density, the stiffer the base/subbase course. According to Rada and Witczak (1981), the resilient modulus increase with an increase in density of the sample specimen, but the increment is comparatively smaller than the changes that occur due to the variations in moisture and stress level. Barksdale (1989) observes that increasing the density causes an increase in resilient modulus when the stress level is low. At high stress level, the effect of density is not as remarkable as the influence of gradation or material type (Thom, 1988).

In another study done by Allen (1977), it was reported that plastic strain reduced by 22% for gravel and 85% for crushed limestone when the method of compaction was changed from standard proctor to modified proctor. In the same compaction effort, the density of rounded aggregates was higher than that of the angular aggregates. The effect on change in density decreases, if the quantity of fine particles is higher in the aggregate.

2.12.4 Aggregate Gradation

A change in aggregate gradation produces a change in moisture content and dry density to form an appropriate aggregate assembly and the moisture content of unbound granular base significantly affects the resilient response. Thom and Brown (1988) observed that uniformly-graded aggregates showed higher resilient modulus than well-graded aggregates, which addects the permanent deformation. Resilient modulus increases with the increase in coarse particles. According to previous studies (Gray, 1962; Tian, 1998), the factors like coarse aggregate content and maximum particle size have a positive impact on resilient modulus. Rather than by compaction level, permanent deformation is more affected by the gradation of the particle.

2.12.5 Moisture Content

Generally, it is agreed that the moisture content or the degree of saturation significantly affects the resilient modulus of unbound aggregate base. The stability of unbound pavement materials generally decreases with increasing moisture content or the degree of saturation. From the study of the behavior of granular materials with high degree of saturation, Dawson et al. (2000) reported that the resilient modulus of granular materials decreases with approaching complete saturation level. Similarly, Lekarp et al. (2000) reported that the resilient modulus of the base material showed a drastic decrease as the saturation level reached to 100%. Also, Ekblad and Isacsson (2006) measured the resilient moduli of the coarse granular materials at various moisture contents up to saturation. The authors reported that the materials with high fines contents showed a significant reduction in their resilient moduli whereas the materials with less fines contents showed a minor reduction in their resilient moduli even when the moisture content increased up to saturation.

2.12.6 Stress Condition

Confining and deviatoric stress

It has been well known that the stress state is an important factor influencing resilient properties of unbound granular mterials. The effect of stress on resilient response of unbound aggregates is summarize in the study conducted by Lekarp (2000). The resilient modulus of materials increases with an increase in confining pressure. Smith and Nair (1973) suggested that the resilient modulus increases by 50% when the principal stresses are twice of the initial value.

Kolisoja (1997) concludes that the resilient deformation is most influenced by deviatoric stress level and the resilient modulus tends to decrease as the deviatoric stress level increases. Nazarian et al., 1996 observes that the deviator stress is much less influential on the resilient modulus than the confining stress. The accumulation of axial permanent strain is related to deviator stress and is inversely related to confining stress (Gautam, 2000).

Bulk Stress

Bulk stress is a function of confinement and applied stress. It can be calculated as,

$\theta = \sigma 1 + 2\sigma 3 = \sigma d + 3\sigma 3$

where,

θ = Bulk stress, psi

$\sigma1$ = Total applied stress, psi

$\sigma3$ = Confinement stress, psi

σd = Deviator (Axial) stress or ($\sigma1$ - $\sigma3$), psi

Within a pavement structure, bulk stress varies as a function of the applied traffic loading, in-situ pavement layer density, and material type. Buchanan (2007) reported that for any given loading, bulk stress decreases as the distance from the pavement surface increases.

2.12.7 Characteristics of Materials

To be taken into account, the base materials used in Texas must meet the specification requirements of the TxDOT Item 247. Soil gradation, liquid limit (LL), plasticity index (PI), and compressive strength are the main requirements to be considered. The required soil properties for Base materials are presented in the Table 2-7.

Table 2-7 Required Soil Properties for Base Materials (TxDOT Item 247)

Property	**Test method**	**Grade 1**	**Grade 2**	**Grade 3**	**Grade 4**
Master Gradation sieve size (% retained)	Tex-110-E				As shown on the plans
2.5 in.			0	0	
1.75 in.		0	0 to 10	0 to 10	
1 in.		10 to 35			
3/8 in.		35 to 50			
No. 4		45 to 65	45 to 75	45 to 75	
No.40		70 to 85	60 to 85	50 to 85	

Table 2-7 - *Continued*

Property	**Test method**	**Grade 1**	**Grade 2**	**Grade 3**	**Grade 4**
Liquid Limit (% max)	Tex-104-E	35	40	40	As shown on the plans
Plasticity index, max	Tex-106-E	10	12	12	As shown on the plans
Plasticity index, min.		As shown on the plans			
Wet ball mill, % max	Tex-116-E	40	45		As shown on the plans
Wet ball max. Increase passing the No. 40 Sieve		20	20		
Classification	Tex-117-E	1	1.1 - 2.3		As shown on the plans
Min. Compressive Strength, psi Lateral pressure 0 psi Lateral pressure 15 psi		45 175	35 175		As shown on the plans

Chapter 3

Methodology

3.1 Introduction

This experimental program was developed and carried out to determine the effect of fine particles on the strength and stiffness of recycled pavement base materials under cement treated or untreated scenarios. Unconfined compressive strength (UCS) and resilient modulus (M_r) were determined for different combinations of RCCA and RAP materials at different dosages of cement varying from 0% to 6% in the interval of 2% and with the addition of two proportions of fines - 12% and 24%. The results obtained from these tests were compared to achieve the strength and stiffness required by various guidelines. The following sections describe the testing materials used in this research, types of laboratory tests performed, test equipment used, and the test procedures followed.

3.2 Sample Collection

The recycled crushed concrete aggregates (RCCA) were collected from stockpiles of Big City Crushed Concrete (Figure 3-1) which is located on Goodnight Lane, Dallas, Texas and is one of the recycled aggregate stockpile facilities approve by TxDOT. Reclaimed asphalt pavement (RAP) was collected from the TxDOT-specified stockpiles (Figure 3-2) located at Dallas County and Ellis County. Soil samples were collected from S.H. 114, Dallas County (Figure 3-3).

Figure 3-1 RCCA sample collection, Big City Crushed Concrete, Dallas, TX

Figure 3-2 RAP sample collection from TxDOT stockpile at Dallas County

Figure 3-3 Soil sample collection, SH 114, Dallas County

3.3 Experimental Program

This research aims at evaluating the strength and stiffness parameters of combinations of untreated and cement treated recycled crushed concrete aggregate (RCCA) and reclaimed asphalt pavement (RAP) in the presence of fines. The experimental program undertaken in this research is the key of the entire assessment. The RCCA and RAP materials used for this research contained particle sizes ranging from 1 inch (25 mm) to No. 200 (75 μm). The tests such as the unconfined compression (UCS) and resilient modulus (M_r) are performed to evaluate strength and stiffness properties of the mix base. Different combinations of RAP and RCCA materials mixing with different proportion of soil particles as fines were tested under untreated or cement-treated conditions as shown in Table 3-1. These mixes were tested to determine optimum moisture conent (OMC) and maximum dry density (MDD). Then by using the corresponding OMC and MDD of a specific combination, the sample specimens were prepared. After curing these sample specimens for seven days, they were tested to determine unconfined compressive strength (UCS) and resilient modulus (M_r).

Table 3-1 Experimental Program

Combination of Materials	**Soil Intrusion (%)**	**Cement Content (%)**	**OMC & MDD**	**UCS Test**	**Resilient Modulus Test**
30% RAP+70%RCCA	12	0	✓	✓	✓
		2	✓	✓	✓
		4	✓	✓	✓
		6	✓	✓	✓
30% RAP+70%RCCA	24	0	✓	✓	✓
		2	✓	✓	✓
		4	✓	✓	✓
		6	✓	✓	✓
50%RAP+50%RCCA	12	0	✓	✓	✓
		2	✓	✓	✓
		4	✓	✓	✓
		6	✓	✓	✓
50%RAP+50%RCCA	24	0	✓	✓	✓
		2	✓	✓	✓
		4	✓	✓	✓
		6	✓	✓	✓

3.4 Aggregate Gradation

The sieve analysis was conducted as per the guideline of Tex 110E Standard Test Method for determining the particle size distribution of the materials greater than No. 200 (0.075 mm) seive. If the materials passing through the No. 200 sieve is less than 1% by weight, then a hydrometer analysis is required to determine the particle size. However, in this case, the amount of percent passing through the No. 200 sieve was less than 1%, and hence hydrometer analysis was not required. Through the sieve apparatus, a quantified amount of material was poured to transfer it from one sieve to other. The weight of materials retained on each sieve was measured before calculating the percentage of materials passing through the sieve. By dividing the weight of material retained on each sieve by the total weight of the sample, the percentage of the materials retained on each sieve was obtained. The amount of material that passed through each sieve was calculated by deducting the percentage retained on each sieve from 100%. The particle size distribution curve was obtained by plotting the percent of materials that passed through each sieve against the size of sieve on a semi-log graph.

3.5 Plasticity of Soil

The ability of a soil to undergo deformation without cracking is the plasticity of a soil. Especially for fine grained soil like clayey soils, it is an important index property. The adsorbed water is the key element in clayey soils leading to the plasticity of soil. In the clay particles, presence of adsorbed water allows the particles to slip over one another. In this type of soil, the particles do not tend to return to its original position following the deformation of soil. The property of becoming plastic lies only on the soils having clay minerals.

The plasticity index (PI) is a measure of the plasticity of a soil, where the PI is the difference between the liquid limit (LL) and the plastic limit (PL). So, to determine the plasticity of a soil liquid limit test and plastic limit test were conducted and the procedure for these tests are described in the following paragraphs.

To determine liquid limit of the soil, 24 hr. oven dried soil was pulverized and by adding distilled water, sample was prepared. By placing a portion of the prepared sample in the cup of the liquid limit device (Casagrande apparatus) and spreading it to 10mm deep, the sample was divided into two halves from the middle by using grooving tool. Then the cup was lifted and dropped at a rate of 2 drops per second. When the two halves of the soil specimen met each other at the bottom of the groove, the number of drops was recorded. After repeating this process for few times, each time adding or removing water, soil sample was taken out and water content was determined. By plotting the no. of drops versus water content, the water content at 25 drops was determined. Hence the value obtained was the liquid limit of the soil used.

Plastic limit was determined by rolling the test specimen between the palm and fingers on a glass plate forming a thread. When the thread crumbles at approximately 3.2mm in diameter, it is considered to be at its plastic limit. Repeating this procedure for three times, the water content of the soil was determined and an average plastic limit for the sample was computed.

Figure 3-4 Liquid limit and Plastic limit test

3.6 Laboratory Compaction Characteristics and Moisture Density Relationships

As per TxDOT's specification of Tex0-113-E Laboratory Compaction Characteristics and Moisture-Density Relationship test procedure, the maximum dry density and optimum moisture content were determined. Comparing the compaction effort for TxDOT specification to standard proctor method and modified proctor compaction tests, the compaction effort for TxDOT is greater than for the standard proctor method and less than for the modified proctor compaction tests. Table 3-2 presents the differences in the compaction energy between the different methods of compaction in practice.

Table 3-2 Compaction Energy of Different Laboratory Compaction Procedures

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

The mold used in compaction test was 6 inches in diameter and 8 inches in height. A hammer of 10-lb was dropped from a height of 18 inches maintaining the compaction energy of 13.25 ft-lb/in^3. Four lifts were made in preparing each sample in the mold and 50 blows was applied to each of the four layers. The compaction tests were conducted at least on 5 different moisture contents and the dry density was determined for different moisture content range. Then the moisture content versus dry density curve was plotted to determine the corresponding optimum moisture content and maximum dry density from the peak of the curve.

3.7 Specimen Preparation

The specimens were prepared at optimum moisture content (OMC) and compacted at maximum dry density (MDD) with the values obtained from the respective tests.

Figure 3-5 Specimen Preparation

Figure 3-6 Typical M_r specimen

3.8 Unconfined Compression Test

The unconfined compression tests were conducted according to specification of TxDOT under the guidelines of Tex-120-E. The specimens of 6 inches in diameter and 8 inches in height were prepared at the optimum mousture content determined as described in the previous section. These specimens were cured for seven days in a moist room at 70°F. After curing, the samples were placed on the platform of a Universal Testing machine (UTM) and load was applied at a constant rate. To maintain a constant deformation rate on the specimen, the strain rate of 2.0 ± 0.3% was applied. The setup of the UTM is shown in fig 3-7.

Figure 3-7 Universal testing machine set up

The compressive strength typically depends on the interlocking and cohesion of the particles. It is determined from the maximum axial load at which the sample fails. To maintain the repeatability, three samples were tested for each combination of the materials. The following figure reflects the failure stage of the sample specimen.

Figure 3-8 Sample specimen at failure

3.9 Resilient Modulus (M_r) Tests

3.9.1 Specimen Preparation

Resilient Modulus (M_r) is a fundamental material property used to characterize unbound pavement materials. It is a measure of material stiffness and provides a mean to analyze stiffness of materials under different conditions, such as moisture, density and stress level. This test was conducted using the AASHTO T 307-99 guidelines (AASHTO 2003).

To perform the resilient modulus tests, the specimens of 6 inches in diameter and 12 inches in height were prepared. All of the specimens were subjected to compaction at optimum moisture content to achieve the maximum dry density from the moisture-density test results. Each sample specimens were compacted at 6 lifts having each lift of 2 inches in height and being subjected to 50 blows. The automatic compactor itself controlled the height of each lift. The maximum size of the particle was limited to 1.2 inch which was one- fifth of the maximum diameter of the mold. For the attainment of the satisfactory compaction, the density of the compacted specimens was within ±5% of the maximum dry density.

The test specimens were extracted from the mold by using the extruder. To avoid any disturbance in the specimens they were wrapped with plastic and stored in the moist room having controlled humidity of about 100% and a constant temperature of 70°F for curing period of seven days. Then the specimens were tested for their resilient modulus.

3.9.2 Resilient Modulus Testing Equipment

The testing equipment for resilient modulus of the compacted specimens is an automated system which meets the AASHTO T307-99 requirements.The system comprises of two major components: a fully automated unit and a computerized data acquisition system.The automatic unit consists of two LOADTRAC units, one cyclic-RM unit, a load frame, an actuator, a trixial cell, two linear variable displacement transducers (LVDT), and an electro-pneumatic air pressure controlling unit.

By using a cyclic-RM unit with Haversine pulse, the cyclic load was applied. The load pulse was applied for 0.1s, and the rest period was 0.9s. The load cell in an actuator has a capacity of 1000 lbf and applies upto 40 psi stress on the cylindrical specimens of 6 inches in diameter and 12 inches of height. From the electro-pneumatic air pressure regulator, confining pressure was applied. This regulator can increase air pressure automatically in the triaxial chamber. Two LVDTs were attached to the piston rod at equal distance and opposite to each other to measure the axial deformation of the sample.

During the test, initial inputs and data acquisition were taken care by RM6 software. As the sample became stiffer with time during the test, the load was maintained by the system controller and corrected to meet accurate values. Figure 3-3 shows the equipment setup used to conduct the resilient modulus test. Controlled air pressure was used to apply confining pressure. For subgrade soil and base materials, two types of loading sequences are specified in AASHTO T307-99. Comparatively, the higher amount of stress is applied for granular-base or sub-base material than for subgrade soil. Preconditioning is the first loading sequence and generally consists of 500 to 1000 cycles. In this study, 500 cycles were selected for preconditioning. The total load of 15 load sequences was applied after preconditioning and each load sequence consisted of 100 cycles which falls under the guidelines of AASHTO T307-99 code.

Figure 3-9 Resilient modulus testing machine

According to AASHTO T307-99, the test sequences for resilient modulus testing are listed in Table.

Table 3-3 Test Sequence for Resilient Modulus Testing

Sequence No.	**Confining Pressure (psi)**	**Max. Axial Stress (psi)**	**No.of Cycles**
Pre-conditioning	15	15	500-1000
1	3	3	100
2	3	6	100
3	3	9	100
4	5	5	100
5	5	10	100

Table 3-3 - *Continued*

Sequence No.	**Confining Pressure (psi)**	**Max. Axial Stress (psi)**	**No.of Cycles**
6	5	15	100
7	10	10	100
8	10	20	100
9	10	30	100
10	15	10	100
11	15	15	100
12	15	30	100
13	20	15	100
14	20	20	100
15	20	40	100

3.9.3 Resilient Modulus Values from the Tests

In accordance with the AASHTO T307-99 code, the resilient moduli of each load sequence under different confining and deviator stresses was calculated. The resilient modulus vs bulk stress graph and the test result chart was automatically generated by the RM6 software. Each value of M_r is the average of the last five cycles.

Chapter 4

Results and Analysis

4.1 Introduction

This chapter presents the test results of particle size distribution, optimum moisture content and maximum dry density, unconfined compressive strength, and resilient modulus tests. These results are analyzed and discussed with respect to the amount of cement content, fine particles (soil) intrusion, RAP and RCCA materials, etc.

4.2 Particle Size Distribution

According to Tex-110E specification, the distribution of particle size in the aggregates was determined by using the sieve analysis method. The sieve sizes used for the analysis were in accordance with the standard specifications. As the recycled materials passed through the No.200 sieve was less than 1%, hydrometer analysis was not required in this test.

Through the sieve apparatus, a quantified amount of materials was poured to transfer it from one sieve to other. The weight of materials retained on each sieve was measured before calculating the percentage of materials passing through the sieve. By dividing the weight of material retained on each sieve by the total weight of the sample, the percentage of the materials retained on each sieve was obtained. The amount of material that passed through each sieve was calculated by deducting the percentage retained on each sieve from 100%. The particle size distribution curve was obtained by plotting the percent of materials that passed through each sieve against the size of sieve on a semi-log graph. The grain size distribution curves of RCCA, RAP, 30% RAP + 70% RCCA and 50% RAP + 50% RCCA are illustrated in Figure 4-1.

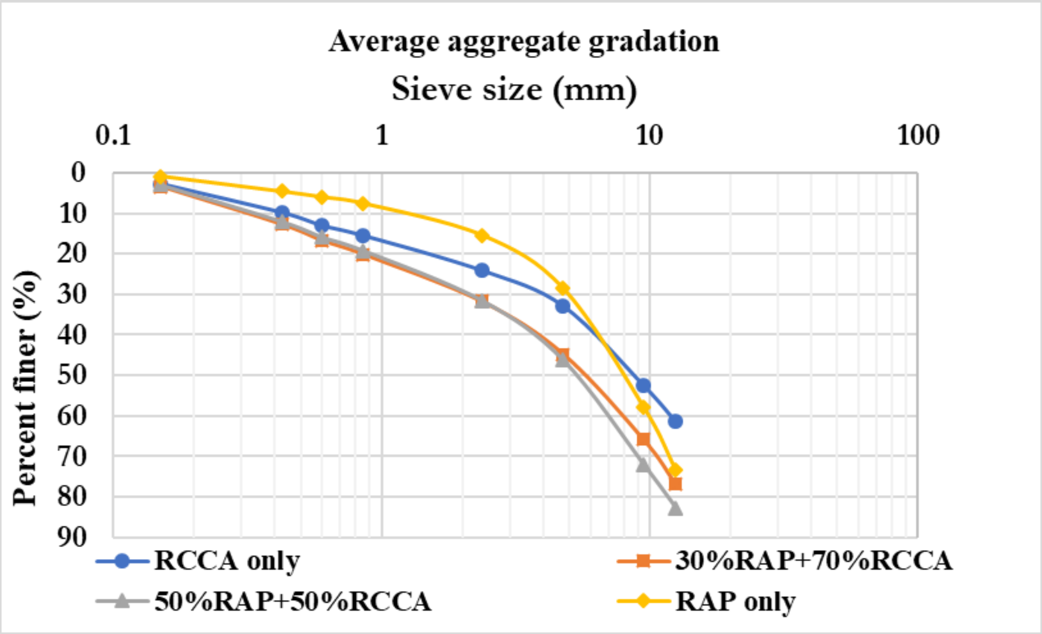


Figure 4-1 Sieve analysis result of RAP, RCCA & Mix Combination material (Tex-110E)

4.3 Liquid Limit and Plastic Limit Tests

Liquid limit (LL) of a soil is the water content in percent at the arbitrarily defined boundary between the semi-liquid and plastic states. Plastic limit (PL) is the water content at the boundary between the plastic and semi-solid states. As plasticity is an important parameter in characterizing the behavior of fine grained soil, plastic limit test and liquid limit tests are performed in this study to determine the plasticity index (PI) of the soil used as fines.

The 24 hr oven dried soil was pulverized and by adding distilled water sample was prepared. By placing a portion of the prepared sample in the cup of the liquid limit device (Casagrande apparatus) and spreading it to 10mm deep, the sample was divided into two halves from the middle by using grooving tool. Then the cup was lifted and dropped at a rate of 2 drops per second. When the two halves of the soil specimen met each other at the bottom of the groove, the number of drops was recorded. After repeating this process for few times, each time adding or removing water, soil sample was taken out and water content was determined. By plotting the no. of drops versus water content graph, the water content at 25 drops was determined which was its liquid limit and was found to be 64.

Plastic limit was determined by rolling the test specimen between the palm and fingers on the ground glass plate forming a thread. When the thread crumbles at approximately 3.2mm in diameter, it is considered to be at its plastic limit. Repeating this procedure for three times, the water content of the soil was determined and an average plastic limit for the sample was computed and found to be 25.

Finally, plasticity index of the soil was calculated by using the equation, PI = LL – PL. The value of plasticity index was calculated to be 39. With the value of plasticity index and liquid limit checked on plasticity chart, the soil used in this study was classified as high plastic clay (CH) as shown in fig4-2.

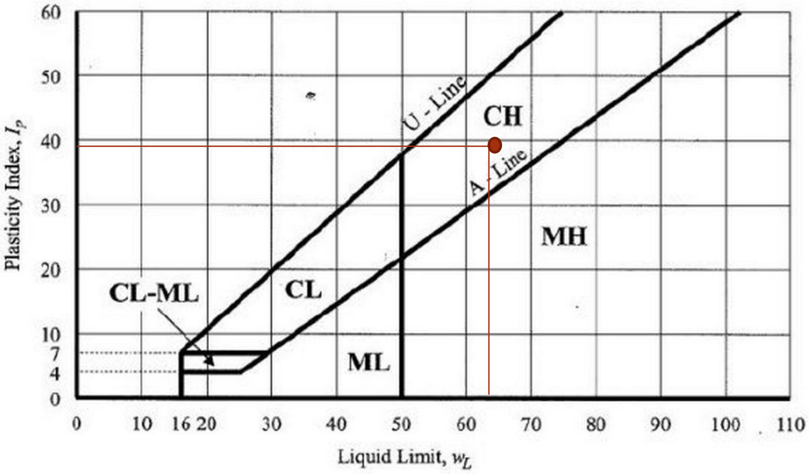


Figure 4-2 Plasticity Chart

4.4 Moisture-Density Tests

Optimum moisture content (OMC) for any material is the water content at which a maximum dry unit weight (MDD) can be achieved after a given compaction effort. In this study, Tex-113 E guidelines is followed to conduct OMC and MDD tests on each of the material combinations at different cement contents and different amount of soil intrusion, as shown in Table 3-1. The required compaction energy for compaction is 13.25 ft-lb/in^3. The materials were compacted on the mold of 8 inches in height and 6 inches in diameter. The compaction tests were carried out at least on 5 different moisture contents, and the dry density was determined for different moisture content range. The optimum moisture contents were determined from the peak of the trend curve plotted against the moisture content and maximum dry density. The values achieved for different combination of base materials is shown in Figure 4-3.

Table 4-1 OMC & MDD of the different mixtures of base materials with different cement content

Combination of Materials	**Soil Intrusion (%)**	**Cement Content (%)**	**Optimum Moisture Content (%)**	**Maximum Dry Density (pcf)**
30% RAP+70%RCCA	12	0	10.8	122.5
		2	8.80	121.2
		4	11.20	117.37
		6	10.60	124.5
30% RAP+70%RCCA	24	0	13.4	117
		2	13.4	118.5
		4	14.2	118
		6	11.5	120.56
50%RAP+50%RCCA	12	0	11.7	122.5
		2	14	117.5
		4	13.3	118
		6	11.6	122
50%RAP+50%RCCA	24	0	11.4	115.5
		2	10.8	116.8
		4	10.3	115.8
		6	10.7	117

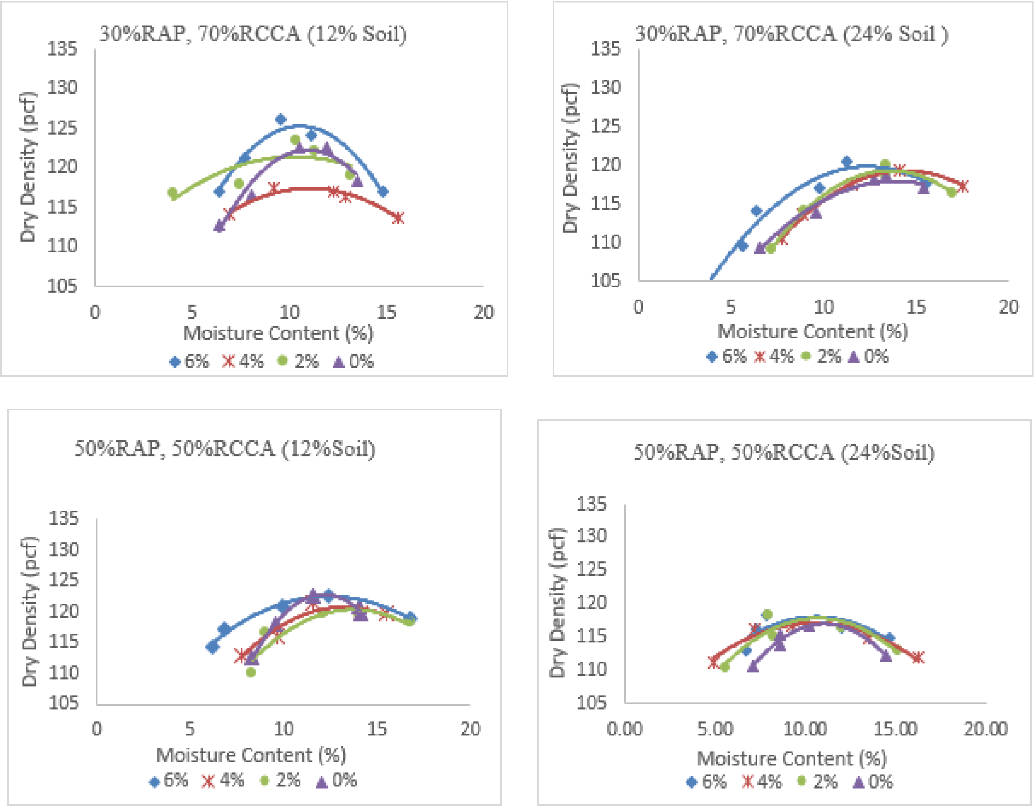


Figure 4-3 Determination of Optimum moisture content and maximum dry density

With the maximum dry density values ranging from 114-126 pcf, the value of optimum moisture content varied about 10%. The addition of soil in the mixture of cement treated base materials (i.e. RAP and RCCA) resulted in a slight decrease in the maximum dry density values. The percent cement treatment did not result in any major variation in compaction dry unit weight and moisture content conditions except for the combination of 30% RAP, 70% RCCA and 12% soil on which the maximum dry density values ranges between 116 pcf to 125 pcf. Faysal (2017) observed that there is no significant effect of increment or decrement of RAP and RCCA materials on the optimum moisture content or maximum dry density of the material mixes without considering soil intrusion. Similarly, previous study of Faysal et. Al., 2016, showed that similar gradation of RAP and RCCA materials yielded similar values of OMC and MDD. Guerrero (2004) reported that OMC and MDD of soil are highly affected by particle size of the soil, especially the fines fraction. The materials containing great amount of fines will simply float in the soil and have lower density, Yoder and Witczak (1975). Mohammadinia et. al. (2014) found higher OMC for RCA in comparison to RAP and was believed that due to the lower water absorption of RAP resulting from bitumen coating of the RAP aggregates, OMC of combination with higher RAP content might be lower than OMC of combination with RCCA. The RCCA and RAP materials used by Mohammadinia, et., al. (2014) in their study had identical grain size distribution and low fines fraction. However, the quantity of soil used in these tests contributes to the larger fraction of fines. The results of these tests were used in the preparation of the specimens at the optimum moisture content and maximum dry unit weight conditions. The Table 4-1 contains the values of optimum moisture content (OMC) and maximum dry density (MDD) obtained from the tests

4.5 Specimen Preparation

The specimens were prepared according to the TxDOT guideline (Tex-113E). For the preparation of UCS samples the mold of 6 inches (152.4mm) in diameter and 8 inches (203.2mm) in height was used. Similarly, for the resilient modulus test, samples were prepared in the mold of 12 inches (254 mm) in height and 6 inches in diameter by compacting at 6 lifts and each layer subjected to 50 blows to achieve the required compaction at OMC level. The compaction was done using an automated mechanical compactor which met the TxDOT specifications. In accordance with the soil-cement testing procedure (Tex-120 E), the prepared specimens were cured for seven days keeping in a moist room before testing. The steps followed for the specimen preparation are shown in Figure 3-5.

4.6 Unconfined Compressive Strength Test Results

After curing the prepared 6 inches × 8 inches sample specimens, they were tested in the compression testing machine in the UTA structures lab. For each of the combination of material mixes, three identical specimens were tested. The average value of the three specimens was plotted to show the variation with change in cement content and fines intrusion.

As per TxDOT design guidelines Item 276, “Cement Treatment (Plant Mixed)”, for construction of pavement bases, the minimum unconfined compressive strength requirement is 300 psi. Faysal (2017) observed that 100% RCCA materials meet the requirement at 4% cement content whereas 100% RAP did not reach 300 psi of compressive strength even at 6% of cement content. Also, as shown in Figure 4-4 the combination of 30% RAP + 70% RCCA and 50% RAP + 50% RCCA materials meet the strength requirement of 300 psi at about 4.65% and at 5% to 5.5% cement content respectively. Faysal (2017) concluded that the inclusion of RAP reduces the strength of the material mix.

In this experiment, as illustrated in Figure 4-5, none of the combinations of the RAP and RCCA materials fulfilled the strength requirement of 300psi at any percent of cement content and fines. As depicted in Figure 4-5, untreated specimens for all the combinations of RAP, RCCA and soil were found to have almost same strength values. As the cement content increased in the mix, unconfined compressive strength values increased. Except in the case of 30% RAP+ 70% RCCA and 24% soil, all other combinations somehow showed a tentative linear trend after 2% or 4% cement inclusion.

The combination of mix with the proportion of 50% RAP and 50% RCCA has slightly higher strength values in comparison to mix of 30% RAP and 70% RCCA at constant cement and fines condition. However, the main objective of this research is to examine if the recycled base materials can withstand the local design requirement when the sufficient quantity of fines is included in the mix base; consequently, none of these combinations could meet the minimum requirement of 300 psi as specified. In comparison to the UCS values of recycled base mix without the inclusion of fines obtained by Faysal (2017), the values are observed to be decreased by more than 50% when 12% to 24% fines were added to the mix.

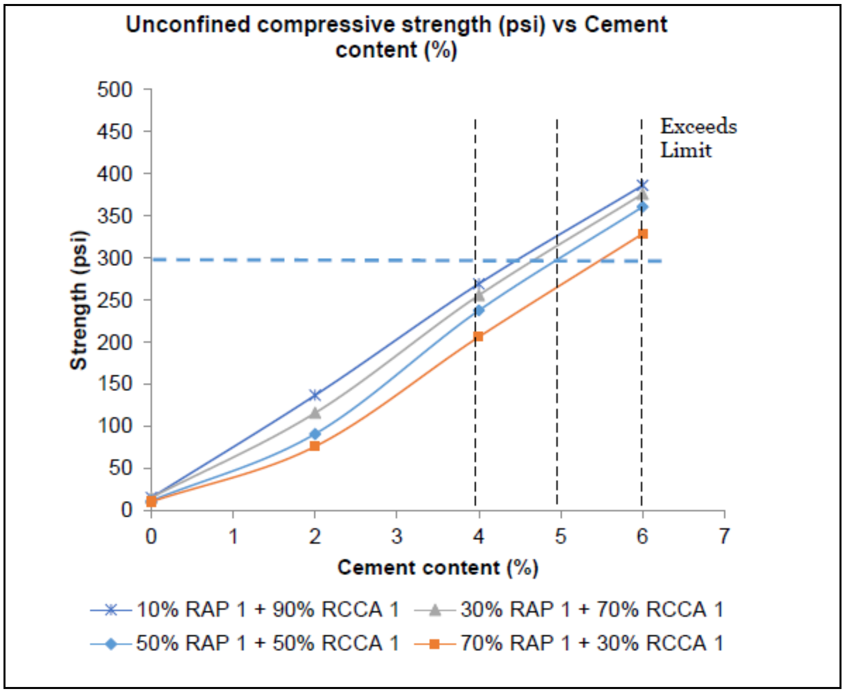


Figure 4-4 Unconfined compressive strength of RCCA and RAP mixes (Faysal, 2017)

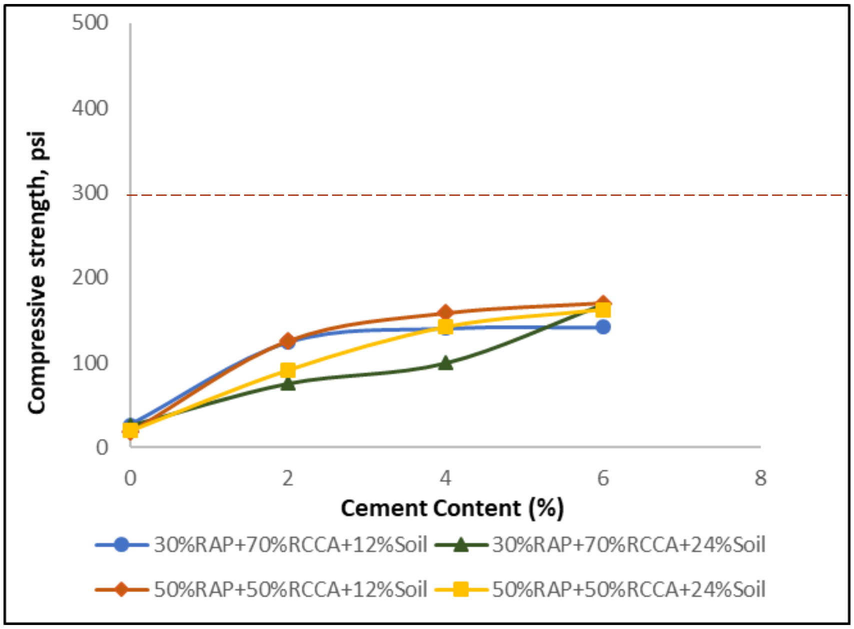


Figure 4-5 Comparison of UCS of different combination of material mixes

4.7 Effect of Strain

The stress-strain relationship developed from the unconfined compressive strength test was employed in investigating the modulus of elasticity of cement-stabilized RAP-RCCA and soil blends. A typical stress-strain curve plotted from the unconfined compressive strength test as presented in the Figure 4-6 indicates the non-brittle response of RAP-RCCA and soil blends.

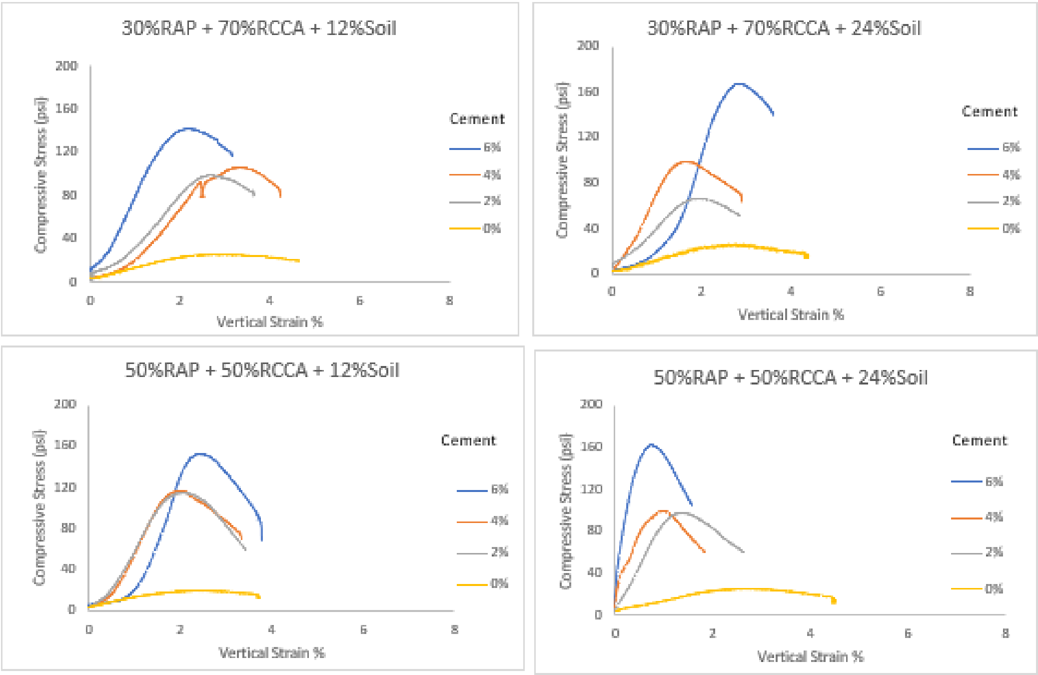


Figure 4-6 A typical stress-strain curve

4.8 Resilient Modulus Test Results

Obtaining resilient modulus (M_R) of the materials under different confining pressures and deviatoric stress is an important aspect of pavement design. The resilient modulus for untreated and cement treated specimens with different quantity of fines is illustrated in Figure 4-7, and Figures 4-9 to 4-11. Both the confining and deviator stresses were found to have remarkable effects on resilient modulus response. At higher confining stresses the resilient modulus values increased. It is believed that with the increment of confinement (i.e., increment in stiffness) materials tend to get denser, and therefore, yield lower recoverable deformations that in turn results in higher resilient modulus. The resilient modulus increases with an increase in deviator stress. The rate of increase in resilient modulus due to an increase in deviator stress is higher for low confining pressures as this stress condition is closer to the failure criteria. The influence of deviatoric stress turns out to be more moderate on the resilient moduli as confinement increases and the material gets denser and stiffer.

Also, moduli values increased noticeably at every confinement with the increment of cement content. With the addition of fines increasing from 12% to 24%, the moduli values are found to be decreasing. Slightly lower values of resilient modulus are found for the combination of 30% RAP + 70% RCCA materials in comparison to the combination of 50% RAP + 50% RCCA materials for untreated as well as cement treated scenarios for both cases with the addition of soil as fines. While comparing these results with the similar combinations of 50%RAP + 50% RCCA and 30% RAP + 70% RCCA at similar content of cement as Faysal (2017) observed, the values of resilient modulus are found to be extensively decreasing after the addition of fines as shown in Figure 4-12.

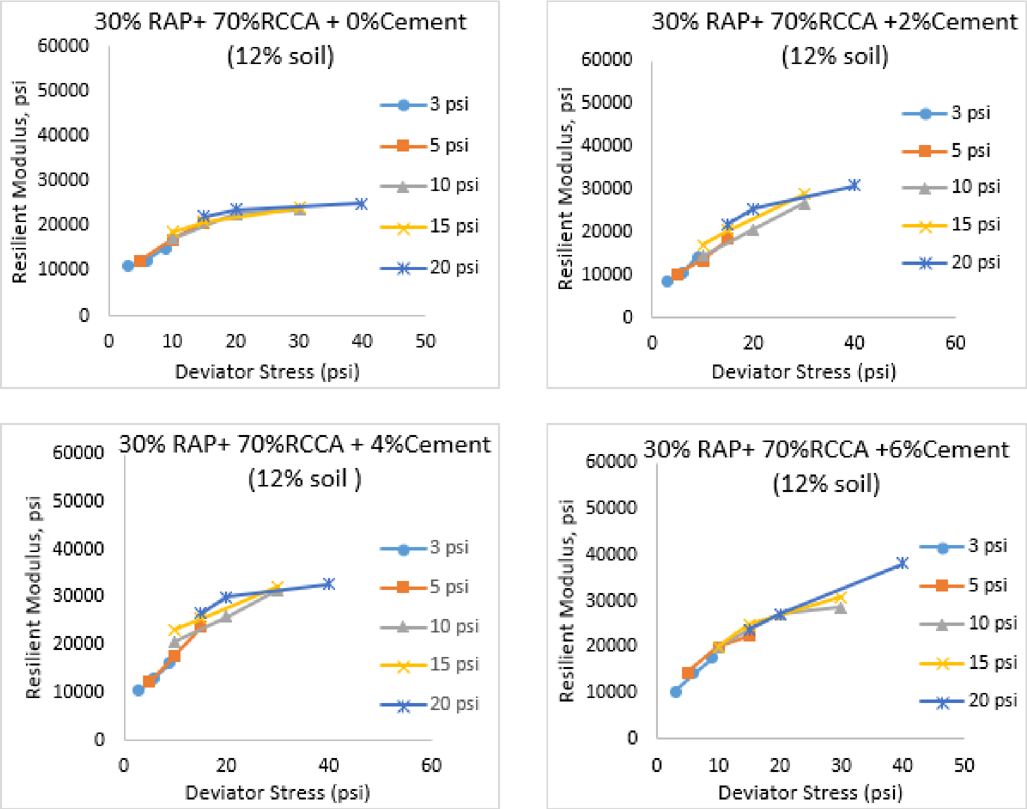


Figure 4-7 Comparison of resilient modulus test results for 30%RAP + 70% RCCA combination with 12% soil

Table 4-2 Resilient modulus test results for combination of 30% RAP+ 70%RCCA+ 12% Soil at different cement content

30% RAP+ 70%RCCA+ 12% Soil					
Confining pressure (psi)	**Deviator stress (psi)**	**Resilient Modulus(psi)**			
		0% cement	**2% cement**	**4% cement**	**6% cement**
3	3	11109	8415	10309	10340
	6	12373	10379	13012	14186
	9	15079	14238	16236	17660
5	5	12324	10226	12146	14410
	10	16959	13492	17771	19990
	15	20711	18408	23758	22467
10	10	17088	14328	20601	19957
	20	22792	20671	25884	27164
	30	23754	26688	31553	28692
15	10	18689	17046	23224	19978
	15	20893	20401	25578	24822
	30	24087	28898	32237	30922
20	15	22114	21827	26667	23787
	20	23593	25530	30050	27148
	40	24987	30839	32843	38126

4.8.1 *Repeatability of Tests*

In an attempt to evaluate the repeatability and reliability of the resilient modulus test results, each test had been carried out with identical conditions. In this assessment, a total of three identical specimens were tested. The scope of repeatability of test was to confirm the uniformity in the test results. To perform the repeatability assessment, randomly the test results from the mix of 30% RAP, 70% RCCA, 6% Cement with 12% of soil is taken into consideration. The standard deviation and coefficient of variation were found to be within the acceptable limits, which signify that the results are fairly similar between the specimens. As seen in Figure 4-8, it shows coefficient of variation within 0.9% - 2.7% which is very reasonable. The final results were averaged out to be used in the detailed analysis. Single operator uses, and suitable mixing could be attributed for the low variant results.

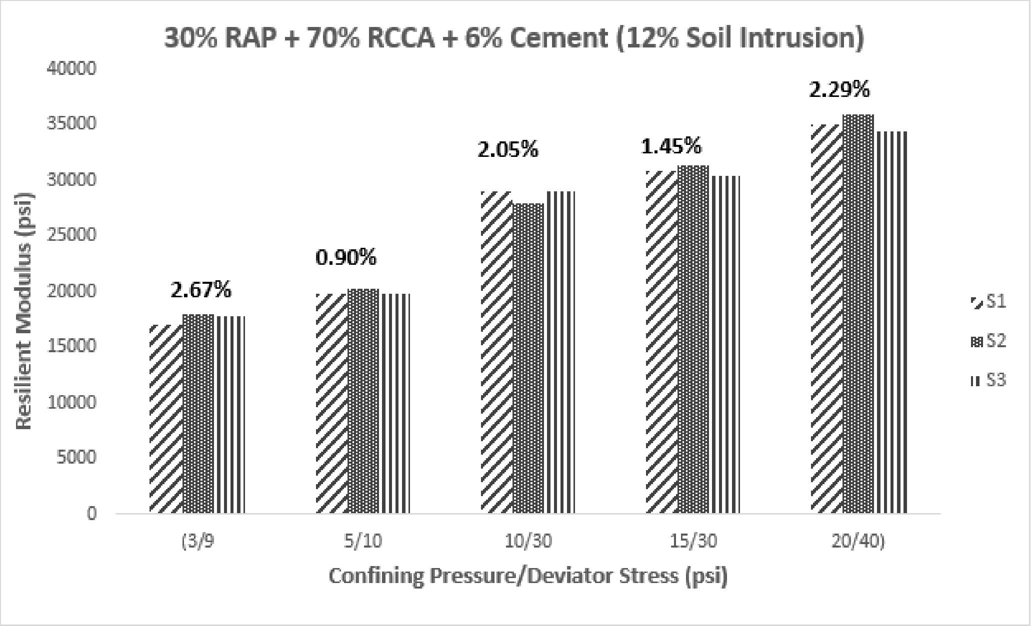


Figure 4-8 Repeatability of Test with three identical specimens with coefficient of variation

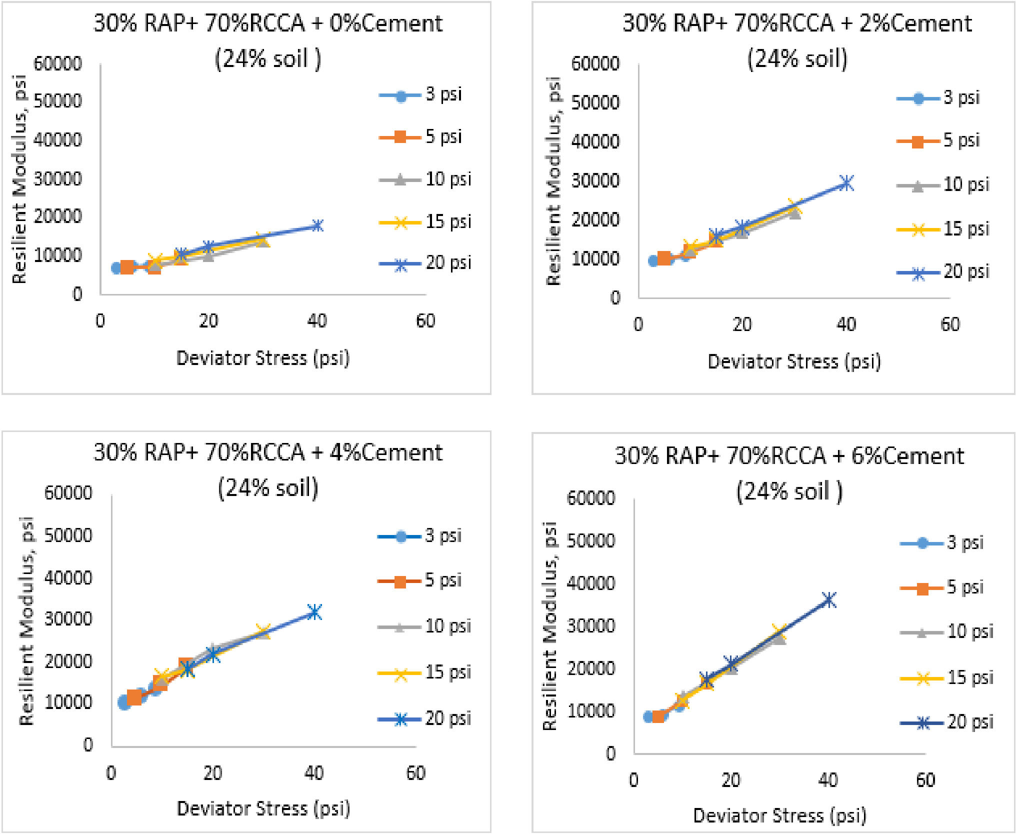


Figure 4-9 Comparison of resilient modulus test results for 30%RAP + 70% RCCA combination with 24% soil

Table 4-3 Resilient modulus test results for combination of 30% RAP+ 70%RCCA+ 24% Soil at different cement content

30% RAP+ 70%RCCA+ 24% Soil					
Confining pressure (psi)	**Deviator stress (psi)**	**Resilient Modulus(psi)**			
		0% cement	**2% cement**	**4% cement**	**6% cement**
	6	7217	10213	11716	9680
	9	7486	10871	13401	11779
5	5	6983	9983	11337	8862
	10	7118	11784	14550	12615
	15	9061	14566	18825	16870
10	10	7778	12381	16041	13502
	20	10099	16735	23507	20305
	30	13680	22048	27118	27214
15	10	9024	13167	16574	12702
	15	9941	14947	18123	16591
	30	14364	23490	27501	28887
20	15	10658	16102	18355	17804
	20	12600	18349	21878	21171
	40	17907	29516	31974	36237

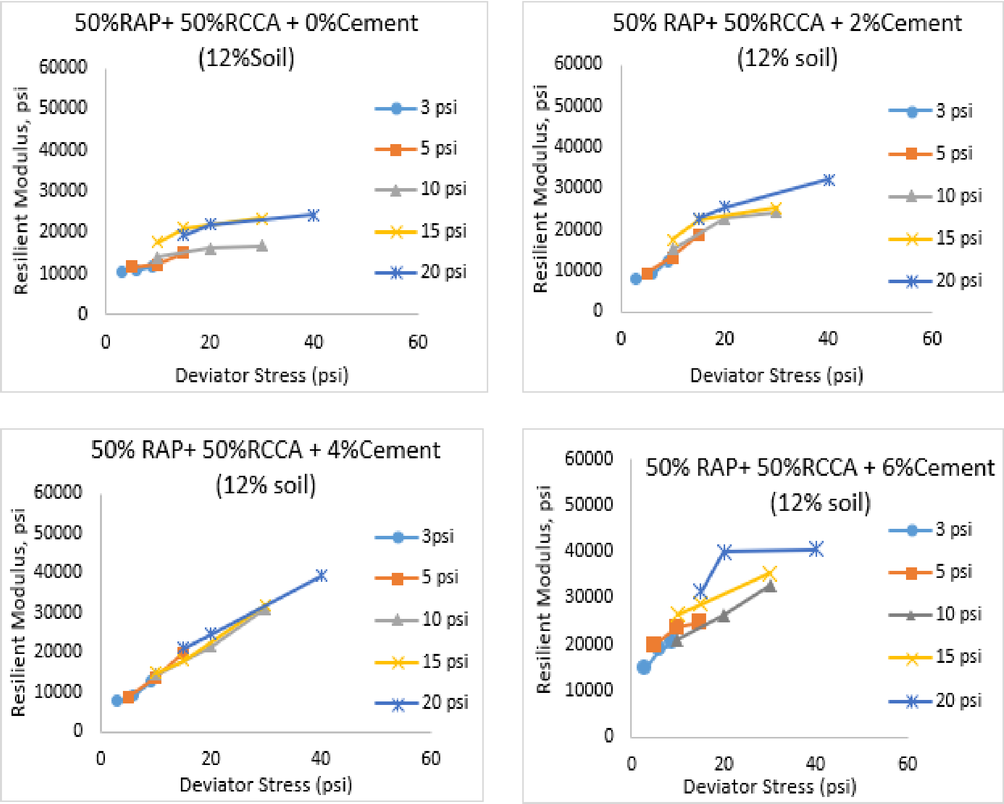


Figure 4-10 Comparison of resilient modulus test results for 50%RAP + 50% RCCA combination with 12% soil

Table 4-4 Resilient modulus test results for combination of 50% RAP+ 50%RCCA+ 12% Soil at different cement content

50% RAP+ 50%RCCA+ 12% Soil					
Confining pressure (psi)	**Deviator stress (psi)**	**Resilient Modulus(psi)**			
		0% cement	**2% cement**	**4% cement**	**6% cement**
3	3	10576	7993.2	7759	14873
	6	10808	9341.8	9230	18730
	9	11805	12444	12752	20257
5	5	11726	9544	8887	19743
	10	12326	13438	13804	23519
	15	15048	18799	19937	24710
10	10	14074	15227	14464	21077
	20	16265	22865	21515	26392
	30	16838	24210	31140	32834
15	10	17630	17516	15052	26392
	15	21046	22623	17982	28618
	30	23512	25249	32093	35370
20	15	19513	22673	21232	31448
	20	22019	25597	24715	39921
	40	24427	32099	39391	40588

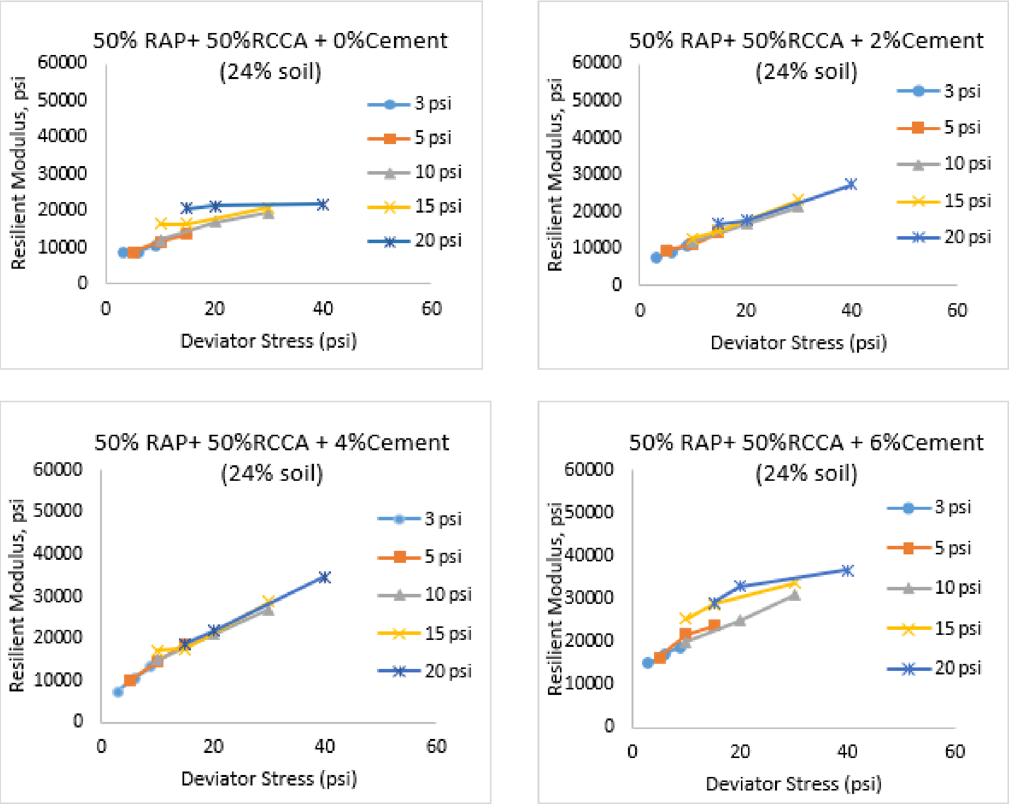
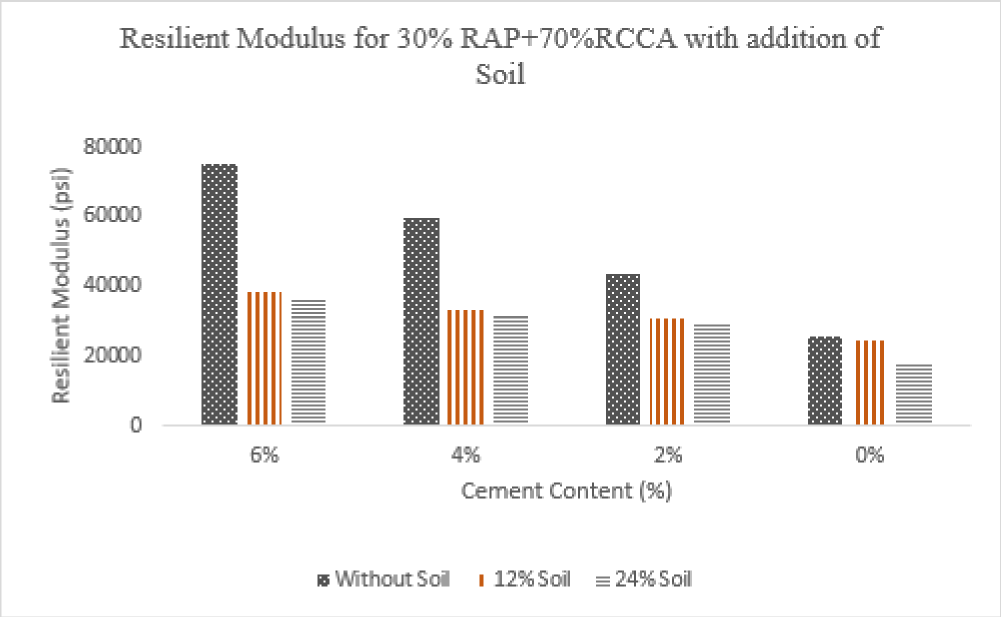


Figure 4-11 Comparison of resilient modulus test results for 50%RAP + 50% RCCA combination with 24% soil

Table 4-5 Resilient modulus test results for combination of 50% RAP+ 50%RCCA+ 24% Soil at different cement content

50% RAP+ 50%RCCA+ 24% Soil					
Confining pressure (psi)	**Deviator stress (psi)**	**Resilient Modulus(psi)**			
		0% cement	**2% cement**	**4% cement**	**6% cement**
	6	8801	8971.3	10418	17297
	9	10483	10763	13232	18883
5	5	8812	9437.9	9962	16549
	10	11297	11003	14275	21559
	15	13482	14153	18542	23500
10	10	12003	11820	14747	19898
	20	16560	16522	20917	24680
	30	19517	21228	26851	30890
15	10	16182	12639	16906	25315
	15	16298	14536	17559	28561
	30	20685	23040	28666	33565
20	15	20558	16365	18606	29112
	20	21196	17320	21576	32681
	40	21810	27150	34463	36810



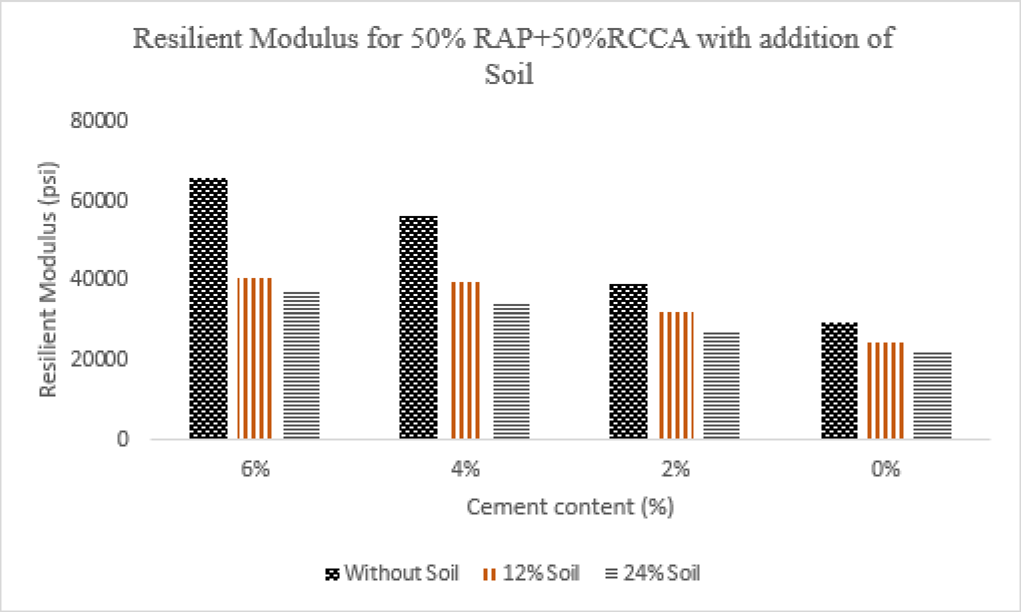


Figure 4-12 Influence of cement content and fines on resilient modulus

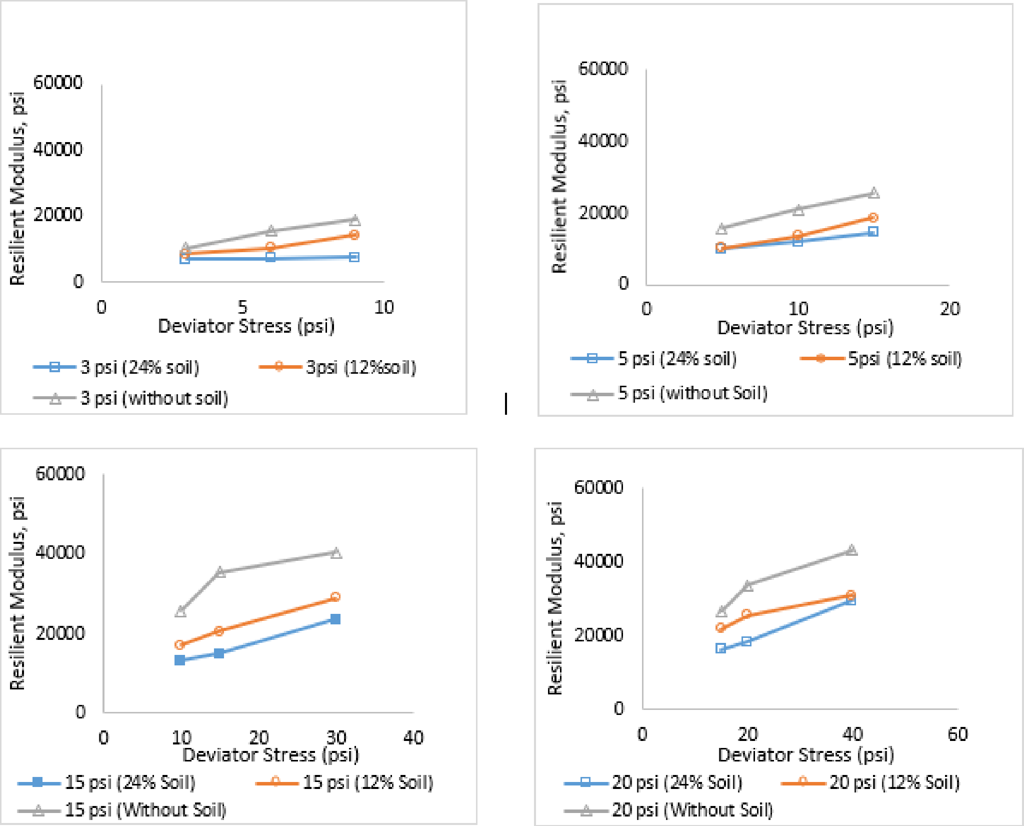


Figure 4-13 Comparison of Resilient Modulus of 30% RAP + 70% RCCA + 2% cement with 12% Soil, 24% Soil and without Soil with respect to Deviator Stress at different confining pressures (3psi, 5psi, 15psi and 20psi)

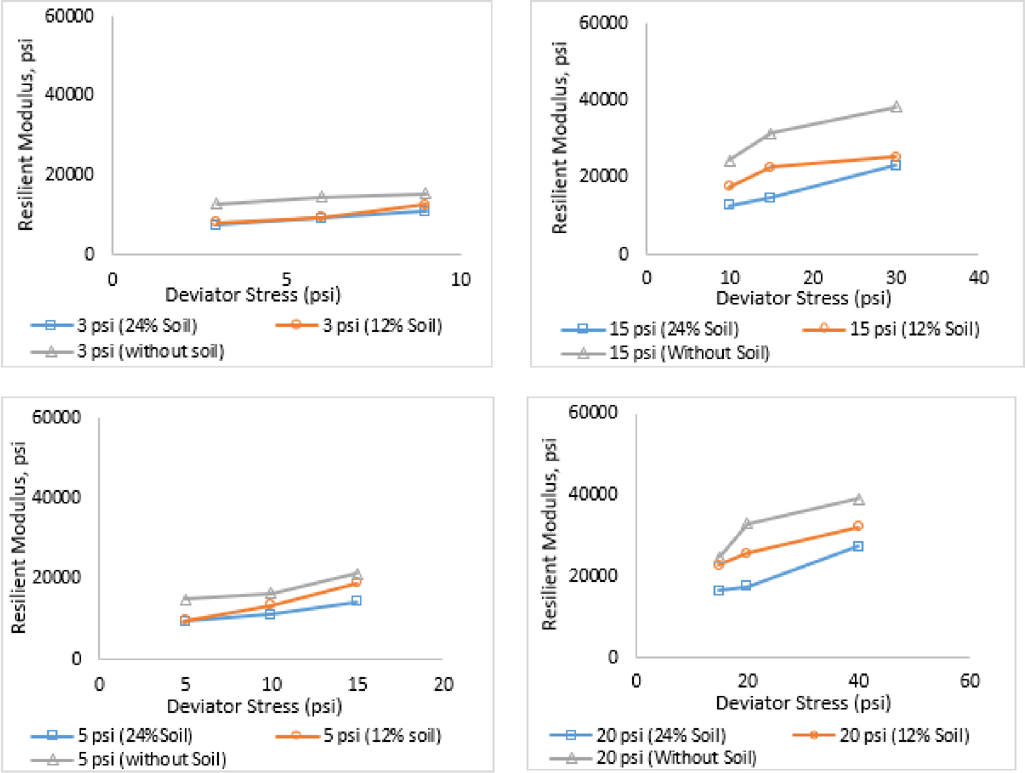


Figure 4-14 Comparison of Resilient Modulus of 50% RAP + 50% RCCA + 2% cement with 12% Soil, 24% Soil and without Soil with respect to Deviator Stress at different confining pressures (3psi, 5psi, 15psi and 20psi)

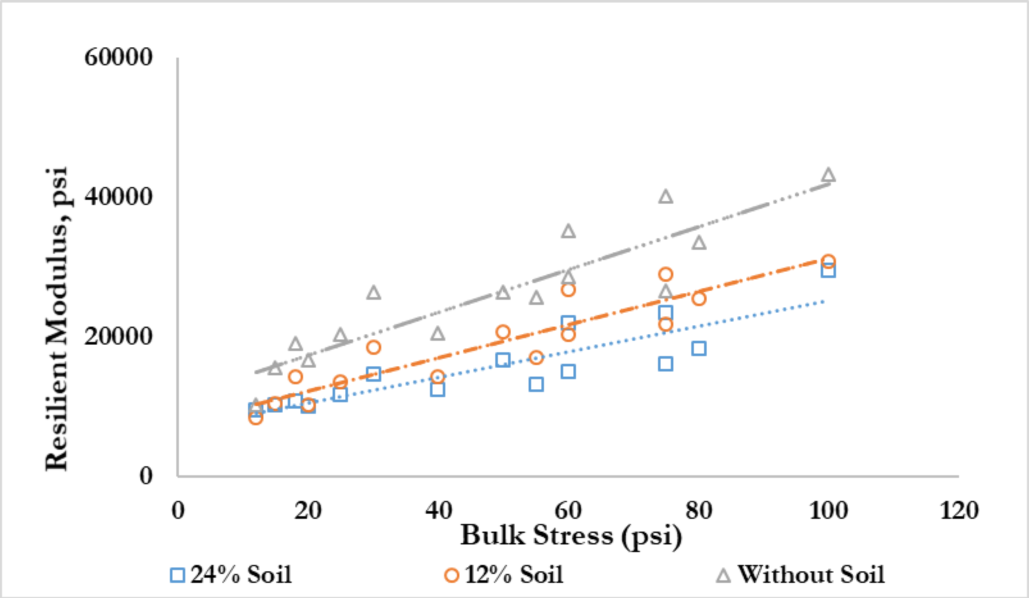


Figure 4-15 Comparison of Resilient Modulus of 30% RAP + 70% RCCA + 2% cement with 12% Soil, 24% Soil and without Soil with respect to Bulk Stress

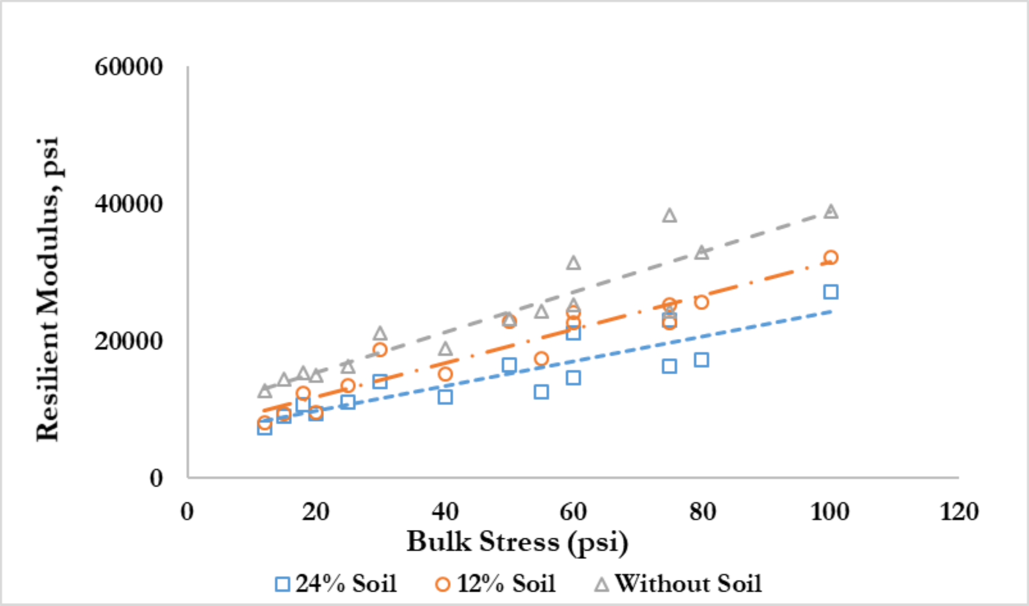


Figure 4-16 Comparison of Resilient Modulus of 50% RAP + 50% RCCA + 2% cement with 12% Soil, 24% Soil and without Soil with respect to Bulk Stress

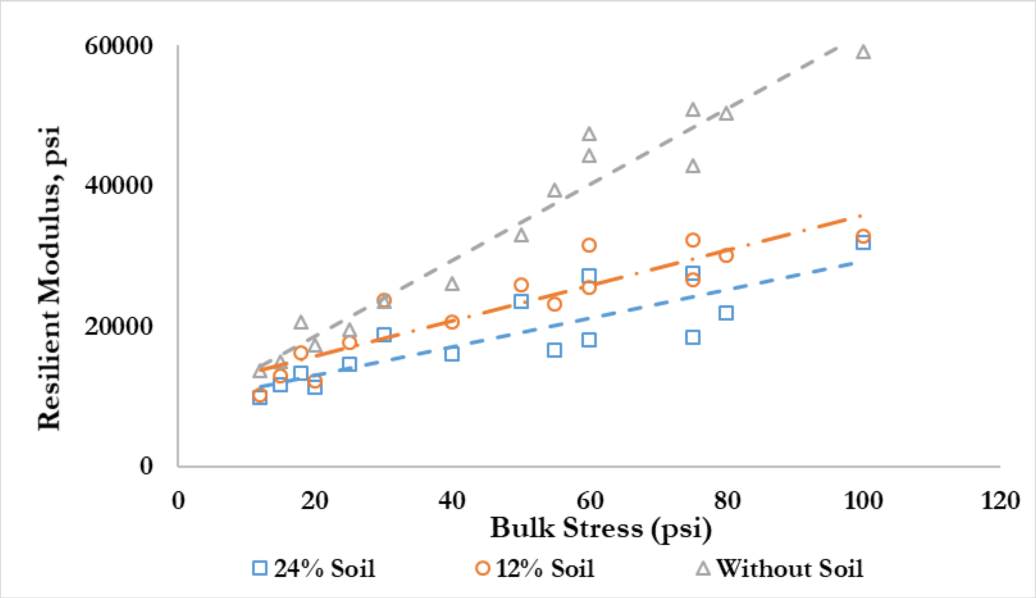


Figure 4-17 Comparison of Resilient Modulus of 30% RAP + 70% RCCA + 4% cement with 12% Soil, 24% Soil and without Soil with respect to Bulk Stress

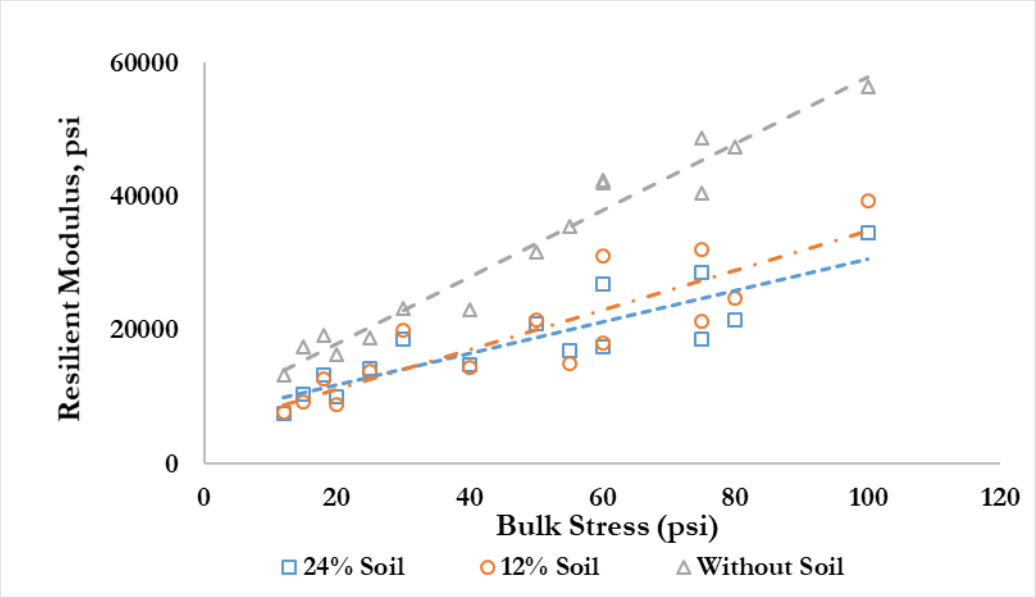


Figure 4-18 Comparison of Resilient Modulus of 50% RAP + 50% RCCA + 4% cement with 12% Soil, 24% Soil and without Soil with respect to Bulk Stress

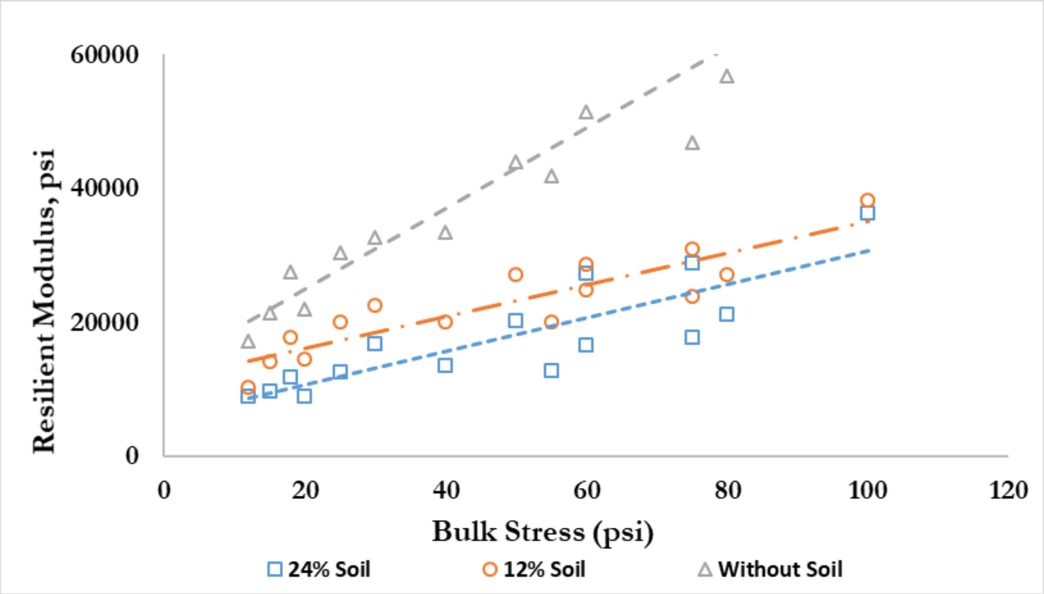


Figure 4-19 Comparison of Resilient Modulus of 30% RAP + 70% RCCA + 6% cement with 12% Soil, 24% Soil and without Soil with respect to Bulk Stress

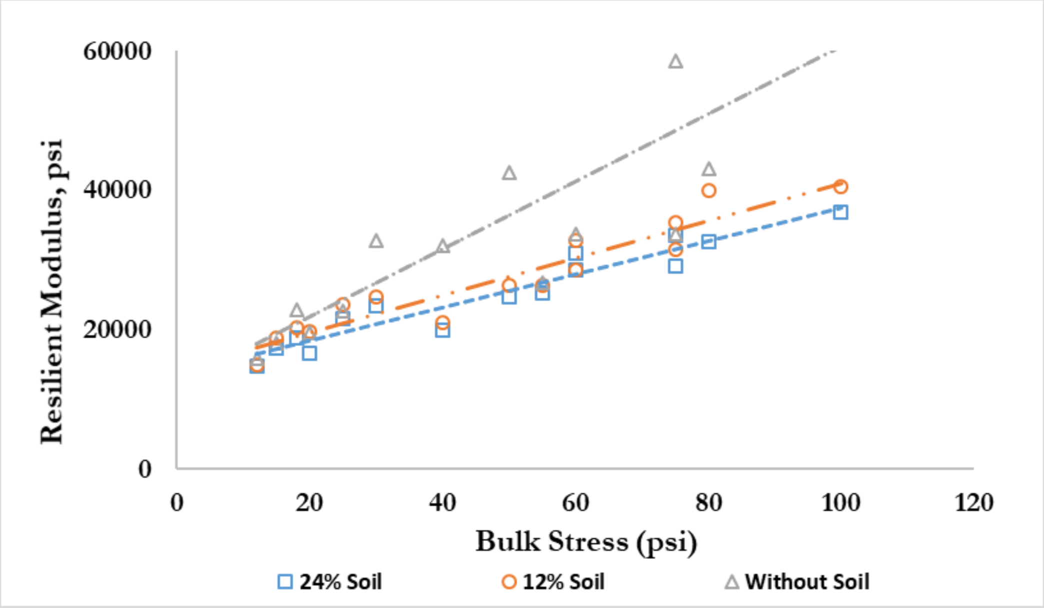


Figure 4-20 Comparison of Resilient Modulus of 50% RAP + 50% RCCA + 6% cement with 12% Soil, 24% Soil and without Soil with respect to Bulk Stress

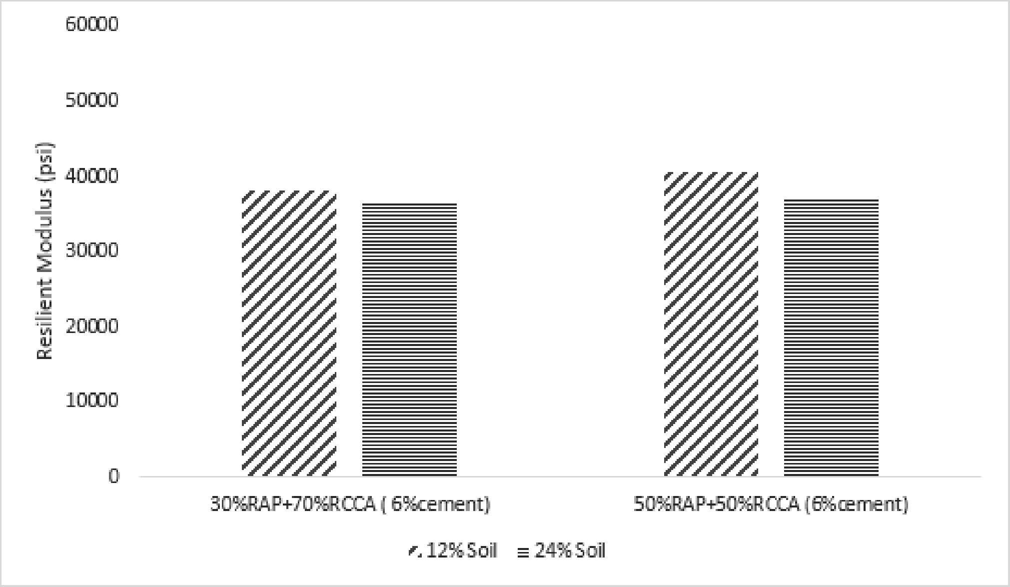


Figure 4-21 Comparison of Resilient Modulus between 30% RAP + 70% RCCA and 50%RAP + 50%RCCA with both 12% Soil and 24% Soil and at 6% Cement content

4.9 Effect of Cement Content on M_r

In this study, resilient modulus of all material combinations used showed a positive correlation with cement content. Figure 4-12 suggests that resilient modulus consistently increase with increasing cement content. In the same figure, data for the similar combinations of materials without fines used from Faysal (2017) also shows the similar trend of moduli values increasing with the increment of cement content. It can be inferred that effect of cement stabilization on resilient modulus values is more pronounced in the combinations with higher RAP content. The difference in resilient modulus values is higher in the combinations of 50% RAP + 50% RCCA as cement content increases whereas, in the combinations of 30% RAP + 70% RCCA the variation due to cement content in moduli values is minimum.

4.10 Effects of Stress Conditions on M_r

4.10.1 Confining and deviatoric stress

In accordance with AASHTO 2003 design guide, the sample specimens were subjected to different confining stresses and each confining stress was subjected to three different deviator stresses. From figure 4-14, it can be observed that both confining and deviatoric stresses have a significant effect on the resilient modulus of the recycled aggregates base materials. The modulus of the materials increased due to the stress hardening of the specimen with an increase in the deviatoric stress and this effect is more noticeable at lower confinements. It can be attributed that at higher confinements the specimen is much stronger and hence does not respond as much as it does at lower confinements to increased axial stresses. Also, it is noticeable that the modulus of the cement aggregate material increased with increasing confinements.

4.10.2 Bulk Stress

Bulk stress, being a function of the position of the material in the pavement structure and applied traffic loading, resilient modulus of granular materials greatly depends with the bulk stress (Buchanan, 2007). In these experiments, the resilient modulus values are found to be increasing with the increase in bulk stress. The Figures from 4-15 to 4-20 shows the comparison of resilient modulus values of the cement treated recycled mix base without soil (from Faysal, 2017) and with the addition of 12% and 24% of soil in the similar mix. With respect to bulk stress, the higher resilient modulus values were observed in the combinations of mix base without soil which gradually decreased with the addition of soil (fines).

4.11 Effect of Fine Content on M_r

Faysal (2017) reported that the value of resilient modulus decreases with an increase in RAP. Thom (1988) and Kamal (1993) reported that the resilient modulus is negatively affected by fines. After, the addition of fines in the different combinations of RAP and RCCA untreated as well as treated with cement, the moduli values are found to be decreasing in comparison to the combinations without soil. In these experiments, substantial proportion of fines were used in the mix bases and stiffness values are found to be considerably decreasing in both the combinations of 30% RAP + 70% RCCA and 50% RAP + 50% RCCA treated/untreated with cement, as fines content is increased from 12% to 24%. In all the cases as illustrated in Figure 4-12, it is observed that the combinations without the fines has higher values of resilient modulus followed by the combination with 12% soil and 24% soil in a decreasing order. Comparatively, slightly higher values of resilient modulus are observed in the combinations of 50% RAP + 50% RCCA than in the combination of 30% RAP + 70% RCCA materials, however the difference is not significant. As observed in Figure 4-12, the combination of 50% RAP + 50% RCCA with 12% of soil at 6% and 4% cement content were able to meet the moduli values at 2% cement content when fines were not included in the mixture as obtained by Faysal (2017). Whereas, combination of cement treated materials of 30% RAP + 70% RCCA with fines were not able to meet the moduli values at any proportion of cement when compared to the values obtained by Faysal (2017) when fines were not included in the mix base Figure 4-12. These results indicate that the presence of fines significantly reduces the stiffness values of the recycled materials. It is believed that the loss of aggregate particle interlocks results in load carrying ability of the materials to rest only on the fines which might be the reason to lower the stiffness values of materials. Therefore, fine content plays a vital role in the stiffness parameter of pavement design, so extensive research with relatively lower fraction of fines in the recycled materials mix is suggested to conclude the behavior of fines.

4.12 Implication of fines intrusion on base layer

According to experience of the TxDOT, several times during coring in the pavements of Texas in various locations, the base materials were found to be very dirty mixed with fines which is suspected to be migrated from the sub-grade towards top. Also, for some situations, traffic pounding might be the reason to cause the migration of fines from sub-grade to base. Generally, this interference of fines with pavement materials was encountered on the base layer from 1 inch to 3 inches of height from the bottom of this layer. In this study, it has been observed that because of the addition of soil in the mix of RAP and RCCA materials the strength and stiffness values of the combination drops down significantly. With the addition of 12% of soil, the combination of 30% RAP + 70% and 50% RAP + 50% RCCA treated/untreated with cement could not reach the minimum unconfined compressive strength of 300 psi specified by TxDOT. Similarly, resilient modulus values also reduced by 40-50% in the combinations of mix base with soil. As the height of base layer of flexible pavement varies between 4 inches to about 12 inches depending upon the service nature of the pavement, interference of fines from 1 inch to 3 inches of base layer accounts for huge loss in strength and stiffness of pavement base materials and this may lead to major problems in the pavement performance.

Chapter 5

Conclusion and Future Recommendations

5.1 Introduction

From the number of studies and researches on recycled flex base materials, it has been found that the combination of recycled materials such as recycled crushed concrete aggregate (RCCA) and reclaimed asphalt pavement (RAP) can be used as an alternative to natural aggregates in stabilized forms. And mostly, these materials are recommended for the base layer of the flexible pavement system. However, practically, several times TxDOT has found the contamination of coarse granular materials in the pavement system due to the presence of fine particles which is suspected to be migrated from the subgrade and this might probably reduce the strength and stiffness of the flex-base. Although the fine fraction within the recycled materials itself might have been considered in some of the studies, the effect of larger amount of expansive clay soils as fines intruding from the sub-grade towards the base layer of the recycled materials has not been considered yet. Therefore, it was necessary to conduct a study on the recycled flex-base materials mixing it with expansive clay soil available in North Texas, in order to evaluate the effect of fines in the strength and stiffness properties of recycled base materials. The overall objective of this study was to understand and evaluate the effect of presence of fines on strength and stiffness properties of flex-base materials such as RCCA and RAP mix both in untreated as well as cement-treated condition. For this, a comprehensive experimental program was designed to characterize resilient and compressive behavior of recycled materials in the presence of soil in both natural and stabilized forms.

5.2 Summary and Conclusions

A summary of the conducted research test results is as follows:

1. To ensure that the quality of recycled materials were similar to that used for construction, RCCA and RAP materials were collected from TxDOT-specified sources.
2. The physical properties of RAP and RCCA materials, such as particle size gradation and dry density were determined.
3. Atterberg's limit tests were done for the soil to determine the plasticity of the soil.
4. The value of unconfined compressive strength and resilient modulus increases with an increase in cement content.
5. With the intrusion of soil, the cement treated as well as untreated specimens of combination of RAP and RCCA could not reach the TxDOT 's requirement of minimum compressive strength of 300 psi.
6. The value of unconfined compressive strength was found to be 15% more in the combination of 50% RAP + 50% RCCA in comparison to 30% RAP + 70% RCCA with 12% soil and 6% of cement content in both cases. However, the strength values were found to be almost similar at 2% cement content in the same case.
7. The value of Resilient Modulus decreases with the addition of soil. With the addition of 12% of soil in the combination of 30% RAP + 70% RCCA at 6% cement, the value of resilient modulus decreased by 50%. Similarly the moduli value decreased by about 40% in the combination of of 50% RAP + 50% RCCA with 12% soil at 6% cement content.
8. The value of Resilient Modulus increases with the increment of cement content in the combination. For example, in the combination of 30% RAP + 70% RCCA +

12% Soil, the value of resilient modulus increased by about 52% when the cement content was increased from 0% to 6%.

9. When the quantity of soil was increased from 12% to 24% in the combination, the value of resilient modulus decreased by 5% and 10% in the combination of 30% RAP + 70% RCCA and 50% RAP + 70% RCCA respectively at 6% cement content.
10. The Resilient Modulus values increases with the increment in confining pressure.
11. With respect to bulk stress, the resilient modulus values increases as the stress increases.

5.3 Recommendations for Future Study

1. Cement was used as the stabilizing agent in the current study. Other stabilizers like fly ash or lime can be used as an alternative for future studies.
2. Larger fraction of expansive clay soil were used to represent the fines that may intrude in the base layer. However, there is no account of exact amount of possible fines to intrude, so, the effect due to lower fine fractions can be studied in future.
3. The source of recycled materials could be varied to cover other regions as well so that more comprehensive results can be achieved.
4. Geosynthetic materials can be used in order to see if it can control the intrusion of fine grained soils

Appendix A Sample Resilient Modulus Test Data

RESILIENT MODULUS TEST DATA

Project: QA/QC Location: tx Project No.: 123
Boring No.: Tested By: sita Checked By:
Sample No.: S-1 Test Date: 11/27/2017 Depth:
Test No.: T-1 Sample Type: remolded Elevation:

Soil Description:
Remarks:

Sequence: 1 of 16
Confining Pressure: 15 psi
Nom. Max. Deviator Stress: 15 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %
496	415.19	372.43	42.757	14.684	13.172	1.5122	0.0081597	0.069444	18968	0.13074
497	414.56	371.64	42.916	14.662	13.144	1.5178	0.0081267	0.069163	19005	0.13045
498	414.84	371.76	43.079	14.672	13.148	1.5236	0.0081597	0.069444	18933	0.13045

499	414.79	372.08	42.715	14.67	13.16	1.5107	0.0081597	0.069444	18950	0.13074
500	415.78	372.79	42.995	14.705	13.185	1.5206	0.0083579	0.071131	18536	0.13102
AVG	415.03	372.14	42.892	14.679	13.162	1.517	0.0081928	0.069726	18878	0.13068
SD	0.42649	0.42527	0.13813	0.015084	0.015041	0.0048854	8.3573e-005	0.00071126	172.9	0.00021039

Sequence: 2 of 16

Confining Pressure: 3 psi

Nom. Max. Deviator Stress: 3 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %
96	84.701	75.432	9.269	2.9957	2.6679	0.32782	0.0038321	0.032614	8180.2	0.06832
97	84.829	75.598	9.2317	3.0002	2.6737	0.32651	0.0038321	0.032614	8198.2	0.068882
98	84.631	75.278	9.3529	2.9932	2.6624	0.33079	0.0038321	0.032614	8163.6	0.068882
99	84.471	75.199	9.2713	2.9875	2.6596	0.32791	0.0038321	0.032614	8155	0.068882
100	83.646	74.375	9.2713	2.9584	2.6305	0.32791	0.0038321	0.032614	8065.6	0.068601
AVG	84.456	75.176	9.2792	2.987	2.6588	0.32819	0.0038321	0.032614	8152.5	0.068713
SD	0.42104	0.42341	0.03978	0.014891	0.014975	0.0014069	6.8341e-017	5.8163e-016	45.917	0.00022492

Sequence: 3 of 16

Confining Pressure: 3 psi
Nom. Max. Deviator Stress: 6 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %
96	168.02	150.4	17.618	5.9424	5.3193	0.62311	0.0067062	0.057074	9320	0.082096
97	169.13	151.51	17.618	5.9818	5.3586	0.62311	0.0066731	0.056793	9435.5	0.082377
98	168.81	151.14	17.669	5.9704	5.3455	0.6249	0.0067062	0.057074	9365.9	0.081815
99	168.37	150.84	17.536	5.955	5.3348	0.6202	0.0067062	0.057074	9347.1	0.082096
100	167.54	149.85	17.689	5.9255	5.2999	0.62564	0.0067392	0.057355	9240.5	0.082377
AVG	168.37	150.75	17.626	5.955	5.3316	0.62339	0.0067062	0.057074	9341.8	0.082152
SD	0.56249	0.57808	0.053151	0.019894	0.020445	0.0018798	2.0893e-005	0.00017782	63.418	0.00021039

Sequence: 4 of 16
Confining Pressure: 3 psi
Nom. Max. Deviator Stress: 9 psi

Cycle	Applied Maximum Deviator Load	Applied Cyclic Deviator Load	Applied Contact Deviator Load	Applied Maximum Deviator Stress	Applied Cyclic Deviator Stress	Applied Contact Deviator Stress	Recov. Def. LVDT	Resilient Strain	Resilient Modulus	Permanent Strain

	lb	lb	lb	psi	psi	psi	in	%	psi	%
96	251.64	225.47	26.164	8.8999	7.9745	0.92537	0.0075651	0.064384	12386	0.097841
97	251.41	225.64	25.761	8.8917	7.9805	0.91112	0.007532	0.064103	12450	0.098122
98	251.09	225	26.083	8.8804	7.9579	0.92249	0.007499	0.063821	12469	0.098122
99	251.87	225.99	25.88	8.9082	7.9929	0.91532	0.007532	0.064103	12469	0.098122
100	251.6	225.57	26.036	8.8986	7.9777	0.92084	0.007532	0.064103	12445	0.098403
AVG	251.52	225.54	25.985	8.8957	7.9767	0.91903	0.007532	0.064103	12444	0.098122
SD	0.26336	0.31914	0.14519	0.0093145	0.011287	0.0051352	2.0893e-005	0.00017782	30.497	0.00017782

Sequence: 5 of 16
Confining Pressure: 5 psi
Nom. Max. Deviator Stress: 5 psi

Cycle	Applied Maximum Deviator Load	Applied Cyclic Deviator Load	Applied Contact Deviator Load	Applied Maximum Deviator Stress	Applied Cyclic Deviator Stress	Applied Contact Deviator Stress	Recov. Def. LVDT	Resilient Strain	Resilient Modulus	Permanent Strain
	lb	lb	lb	psi	psi	psi	in	%	psi	%
96	139.75	125.05	14.693	4.9425	4.4228	0.51967	0.0054178	0.046109	9592.2	0.082659
97	139.97	125.06	14.914	4.9506	4.4231	0.52749	0.0054508	0.04639	9534.6	0.082377
98	139.28	124.47	14.803	4.9259	4.4023	0.52354	0.0054839	0.046671	9432.6	0.082377
99	140.54	125.72	14.817	4.9705	4.4465	0.52404	0.0054178	0.046109	9643.4	0.082377
100	139.79	124.86	14.931	4.9441	4.416	0.52807	0.0054508	0.04639	9519.3	0.082096

AVG	139.86	125.03	14.832	4.9467	4.4221	0.52456	0.0054442	0.046334	9544.4	0.082377
SD	0.40793	0.40461	0.085899	0.014428	0.01431	0.003038	2.4721e-005	0.00021039	71.139	0.00017782

Sequence: 6 of 16

Confining Pressure: 5 psi

Nom. Max. Deviator Stress: 10 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %
96	279.69	250.54	29.149	9.8919	8.861	1.031	0.0077303	0.065789	13469	0.10403
97	279.31	250.24	29.073	9.8785	8.8503	1.0282	0.0077303	0.065789	13452	0.10403
98	279.32	250.28	29.04	9.8788	8.8517	1.0271	0.0077963	0.066352	13341	0.10346
99	279.35	250.58	28.777	9.8801	8.8623	1.0178	0.0077633	0.066071	13413	0.10374
100	281.42	252.45	28.973	9.9532	8.9285	1.0247	0.0077633	0.066071	13514	0.10374
AVG	279.82	250.81	29.002	9.8965	8.8707	1.0258	0.0077567	0.066014	13438	0.1038
SD	0.81348	0.82722	0.1262	0.028771	0.029257	0.0044633	2.4721e-005	0.00021039	58.237	0.00021039

Sequence: 7 of 16

Confining Pressure: 5 psi

Nom. Max. Deviator Stress: 15 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %
96	412.61	369.5	43.107	14.593	13.069	1.5246	0.0081597	0.069444	18819	0.12652
97	414.74	371.36	43.382	14.669	13.134	1.5343	0.0082258	0.070007	18761	0.12624
98	413.96	370.77	43.191	14.641	13.113	1.5276	0.0081597	0.069444	18883	0.12652
99	412.81	369.82	42.984	14.6	13.08	1.5202	0.0081597	0.069444	18835	0.12652
100	413.45	370.11	43.343	14.623	13.09	1.5329	0.0082258	0.070007	18698	0.12624
AVG	413.51	370.31	43.201	14.625	13.097	1.5279	0.0081861	0.069669	18799	0.12641
SD	0.77815	0.66971	0.14758	0.027521	0.023686	0.0052196	3.2368e-005	0.00027547	63.865	0.00013774

Sequence: 8 of 16

Confining Pressure: 10 psi

Nom. Max. Deviator Stress: 10 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %

96	276.94	247.81	29.128	9.7948	8.7646	1.0302	0.0068383	0.058198	15060	0.11921
97	276.24	247.46	28.772	9.7698	8.7522	1.0176	0.0067062	0.057074	15335	0.11949
98	276.28	247.1	29.184	9.7716	8.7394	1.0322	0.0068053	0.057917	15089	0.11949
99	276.73	247.74	28.996	9.7874	8.7619	1.0255	0.0067392	0.057355	15277	0.11865
100	276.73	248.13	28.607	9.7874	8.7756	1.0118	0.0067062	0.057074	15376	0.11949
AVG	276.59	247.65	28.937	9.7822	8.7587	1.0234	0.006759	0.057524	15227	0.11926
SD	0.27658	0.34544	0.21793	0.0097821	0.012217	0.0077075	5.3676e-005	0.00045682	128.96	0.00032788

Sequence: 9 of 16

Confining Pressure: 10 psi

Nom. Max. Deviator Stress: 20 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %
96	548.31	491.31	57.001	19.392	17.376	2.016	0.0088865	0.07563	22976	0.1746
97	547.19	489.4	57.789	19.353	17.309	2.0439	0.0088865	0.07563	22887	0.17403
98	547.55	490.52	57.031	19.366	17.349	2.0171	0.0089526	0.076192	22770	0.17403
99	548.15	491	57.153	19.387	17.365	2.0214	0.0089195	0.075911	22876	0.1746
100	548.38	491.55	56.831	19.395	17.385	2.01	0.0089526	0.076192	22817	0.1746

AVG	547.92	490.76	57.161	19.379	17.357	2.0217	0.0089195	0.075911	22865	0.17437
SD	0.46482	0.75852	0.33016	0.01644	0.026827	0.011677	2.9548e-005	0.00025147	69.55	0.00027547

Sequence: 10 of 16
Confining Pressure: 10 psi
Nom. Max. Deviator Stress: 30 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %
96	802.4	718.02	84.386	28.379	25.395	2.9845	0.0090186	0.076754	33086	0.28509
97	800.91	715.64	85.266	28.326	25.311	3.0157	0.0089856	0.076473	33097	0.28509
98	801.75	716.67	85.075	28.356	25.347	3.0089	0.0089856	0.076473	33145	0.28565
99	801.11	716.23	84.88	28.334	25.332	3.002	0.0089195	0.075911	33370	0.28677
100	801	715.88	85.115	28.33	25.319	3.0103	0.0089195	0.075911	33354	0.28677
AVG	801.43	716.49	84.945	28.345	25.341	3.0043	0.0089658	0.076304	33210	0.28587
SD	0.56679	0.83897	0.30537	0.020046	0.029672	0.0108	3.9642e-005	0.00033738	125.46	0.00076274

Sequence: 11 of 16
Confining Pressure: 15 psi
Nom. Max. Deviator Stress: 10 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %
96	275.24	246.39	28.853	9.7347	8.7143	1.0205	0.0058142	0.049483	17611	0.24938
97	274.97	246.04	28.934	9.7251	8.7017	1.0233	0.0058472	0.049764	17486	0.24882
98	275.73	247.06	28.669	9.7519	8.738	1.0139	0.0058472	0.049764	17559	0.2491
99	273.76	245.04	28.715	9.6822	8.6666	1.0156	0.0058472	0.049764	17415	0.24882
100	274.95	246.35	28.608	9.7245	8.7127	1.0118	0.0058472	0.049764	17508	0.2491
AVG	274.93	246.17	28.756	9.7237	8.7066	1.017	0.0058406	0.049708	17516	0.24904
SD	0.65057	0.65799	0.12016	0.023009	0.023272	0.0042499	1.3214e-005	0.00011246	66.179	0.00021039

Sequence: 12 of 16

Confining Pressure: 15 psi

Nom. Max. Deviator Stress: 15 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %

96	409.48	366.97	42.508	14.482	12.979	1.5034	0.0070365	0.059885	21673	0.26007
97	408.96	366.66	42.307	14.464	12.968	1.4963	0.0070365	0.059885	21654	0.25978
98	408.96	365.9	43.062	14.464	12.941	1.523	0.0070365	0.059885	21610	0.25978
99	407.3	364.51	42.79	14.405	12.892	1.5134	0.0070035	0.059604	21629	0.25978
100	408.45	364.83	43.612	14.446	12.903	1.5425	0.0070365	0.059885	21547	0.2595
AVG	408.63	365.78	42.856	14.452	12.937	1.5157	0.0070299	0.059829	21623	0.25978
SD	0.74187	0.97118	0.45616	0.026238	0.034349	0.016133	1.3214e-005	0.00011246	43.65	0.00017782

Sequence: 13 of 16
Confining Pressure: 15 psi
Nom. Max. Deviator Stress: 30 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %
96	791.69	707.44	84.243	28	25.021	2.9795	0.0081597	0.069444	36030	0.30617
97	790.66	706.38	84.283	27.964	24.983	2.9809	0.0081267	0.069163	36122	0.30617
98	794.07	634.98	159.09	28.084	22.458	5.6266	0.0049223	0.041892	53609	0.33485
99	791.13	706.37	84.76	27.981	24.983	2.9978	0.0081267	0.069163	36121	0.30702
100	790.9	705.38	85.515	27.972	24.948	3.0245	0.0082588	0.070288	35494	0.30702
AVG	791.69	692.11	99.578	28	24.478	3.5218	0.0075188	0.06399	39475	0.31225

SD	1.2361	28.574	29.759	0.04372	1.0106	1.0525	0.0012992	0.011057	7070.9	0.011309

Sequence: 14 of 16
Confining Pressure: 20 psi
Nom. Max. Deviator Stress: 15 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %
96	409.27	365.15	44.119	14.475	12.915	1.5604	0.0066731	0.056793	22740	0.28537
97	409.03	366.02	43.015	14.466	12.945	1.5214	0.0067062	0.057074	22681	0.28537
98	407.85	365.19	42.664	14.425	12.916	1.5089	0.0067062	0.057074	22630	0.28509
99	409.28	366.53	42.743	14.475	12.964	1.5117	0.0067722	0.057636	22492	0.28481
100	409.2	366.49	42.706	14.472	12.962	1.5104	0.0066731	0.056793	22823	0.28537
AVG	408.93	365.88	43.049	14.463	12.94	1.5226	0.0067062	0.057074	22673	0.2852
SD	0.54515	0.60585	0.549	0.019281	0.021428	0.019417	3.6188e-005	0.00030799	111.16	0.00022492

Sequence: 15 of 16
Confining Pressure: 20 psi
Nom. Max. Deviator Stress: 20 psi

Applied Applied Applied Applied Applied Applied

Cycle	Maximum Deviator Load lb	Cyclic Deviator Load lb	Contact Deviator Load lb	Maximum Deviator Stress psi	Cyclic Deviator Stress psi	Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %
96	545.4	487.04	58.361	19.289	17.225	2.0641	0.0078954	0.067195	25635	0.29437
97	544.94	488.18	56.754	19.273	17.266	2.0073	0.0078954	0.067195	25695	0.29465
98	546.06	488.74	57.322	19.313	17.286	2.0274	0.0079615	0.067757	25511	0.29437
99	545.7	488.65	57.05	19.3	17.283	2.0177	0.0079285	0.067476	25613	0.29493
100	546.11	489.09	57.019	19.315	17.298	2.0166	0.0079615	0.067757	25529	0.29465
AVG	545.64	488.34	57.301	19.298	17.271	2.0266	0.0079285	0.067476	25597	0.29459
SD	0.43611	0.71311	0.55963	0.015424	0.025221	0.019793	2.9548e-005	0.00025147	68.319	0.00021039

Sequence: 16 of 16

Confining Pressure: 20 psi

Nom. Max. Deviator Stress: 40 psi

Cycle	Applied Maximum Deviator Load lb	Applied Cyclic Deviator Load lb	Applied Contact Deviator Load lb	Applied Maximum Deviator Stress psi	Applied Cyclic Deviator Stress psi	Applied Contact Deviator Stress psi	Recov. Def. LVDT in	Resilient Strain %	Resilient Modulus psi	Permanent Strain %
96	1025.2	912.92	112.24	36.258	32.288	3.9695	0.0082919	0.070569	45754	0.37281
97	1024.6	910.47	114.14	36.238	32.201	4.0368	0.0082258	0.070007	45997	0.37337

98	1024.6	911.54	113.08	36.238	32.239	3.9992	0.0082588	0.070288	45867	0.37365
99	1024.4	912.29	112.1	36.23	32.266	3.9648	0.0082258	0.070007	46089	0.37365
100	1024.9	912.73	112.19	36.249	32.281	3.968	0.0082588	0.070288	45927	0.37365
AVG	1024.7	911.99	112.75	36.243	32.255	3.9877	0.0082522	0.070232	45927	0.37343
SD	0.26891	0.8967	0.77844	0.0095107	0.031714	0.027532	2.4721e-005	0.00021039	113.89	0.00032788

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