EVALUATION OF RESILIENT MODULUS OF CEMENT AND CEMENT-FIBER TREATED RECLAIMED ASPHALT PAVEMENT (RAP) AGGREGATES USING REPEATED LOAD TRIAXIAL TEST

BY

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To my Mom, Dad, Advisor, Sister, Brother-in-law, and Satvik Varma

July 21, 2006

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ABSTRACT

EVALUATION OF RESILIENT MODULUS OF CEMENT AND CEMENT-FIBER TREATED RECLAIMED ASPHALT PAVEMENT (RAP) AGGREGATES USING REPEATED LOAD TRIAXIAL TEST

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Natural aggregates derived from a variety of source rocks have been used as a road base material. But the extraction of natural aggregates resources is increasingly being constrained by urbanization, increased costs and environmental concerns. Thus, increased amounts of reclaimed materials are being used to supplement natural aggregates in road construction. The 1993 EPA report mentioned that approximately 73 million tons of asphalt pavement material was recycled annually, which amounts to about 80% of the asphalt removed from pavements each year. The use of Reclaimed Asphalt Pavement (RAP) materials in road construction reduces both the amount of construction debris disposed of in landfills and the rate of natural resource depletion.

Although RAP aggregates could be used as a base material in pavement construction applications, product variability (source dependent) and strength characteristics usually limit their application in road bases. Hence, their use should be evaluated based on their cost and strength factors. Stabilization with lime or cement allows the use of low quality RAP materials meeting the targeted characteristics.

In this research, a comprehensive experimental program utilizing American Association of State Highway and Transportation Officials (AASHTO) recommended repeated load triaxial tests was designed to characterize the resilient behavior of RAP aggregates in both natural and stabilized forms. Amendments were done by using different dosage levels of Portland (Type I/II) cement and with fibrillated polypropylene fibers. Compacted aggregate specimens with no fibers (control specimens) were tested at 0, 2, and 4% dosage levels of Portland cement and those with fibers (fiber-reinforced) were tested at 2, 4, and 6% dosage levels of Portland cement.

Test methods provided repeatable and reliable results. The resilient moduli of untreated aggregates varied between 180 and 340 MPa and the same of cement and cement-fiber treated aggregates varied between 200 and 580 MPa. Test results indicate that cement and cement fiber treatment provided enhancements that are statistically significant. Both two and three parameter models were used to analyze the present experimental moduli results. The structural coefficients were determined using AASHTO recommended correlation and these values were used in the development of design charts and tables for the estimation of base material thickness for a variety of variables including subgrade, traffic and category of pavements.

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CHAPTER 1

INTRODUCTION

1.1 Aggregate Bases

A flexible pavement system basically consists of an asphalt surface layer, a base course, a subbase and the subgrade. The subbase layer is optionally employed. Whereas, the base course which is in between the surface layer and the subgrade plays a very prominent role in transferring the loads coming onto the surface layer to the natural soil subgrade. Thus, base courses in flexible pavements help distribute the traffic load. This ability to distribute load is primarily a function of depth of base course. The quality of the base course material also affects the rate of load distribution. While distributing the load, the base course itself must not be a cause of failure. Therefore, the base course must have enough strength to carry loads without shear failure.

Traditionally natural aggregates derived from a variety of source rocks have been used as a road base material. But the extraction of these natural aggregates resources is increasingly being constrained by urbanization, increased costs and environmental concerns. Thus, increased amounts of reclaimed materials are being used to supplement natural aggregates in road construction. The 1993 EPA report also mentioned that approximately 73 million tons of asphalt pavement material was recycled each year, which amounts to about 80% of the asphalt removed from pavements each year. The use of reclaimed pavement materials in road construction could serve the purpose of reducing the amount of construction debris disposed of in landfills (thereby reducing considerable amount of landfill costs), of reducing environmental disturbance and the rate of natural resource depletion. . In Brawley, California, the use of recycled pavement material in pavement construction reduced the cost of material per ton from $40 to $16 (Ayers, 1992). The use of reclaimed asphalt pavement (RAP) material as a base of a thoroughfare in El Cajon, California, resulted in considerable savings in the total cost of the project (Munzenmaier, 1994). This project was later awarded by the local American Public Works Association.

Although recycled aggregates could be used as a base material in pavement construction applications, product variability (source dependent) and strength characteristics usually limit their application in road bases (Goonam and Wilburn, 1998). Hence, their use should be evaluated based upon the relative cost and strength factors. The high volume usage of RAP in base applications is, therefore, better ensured by meeting the minimum standards set by AASHTO for material performance. Most reclaimed asphalt pavement materials, when used as a total substitute for natural aggregates in base applications, do not often meet the minimum requirements set by AASHTO. In such cases, stabilization with lime or cement allows the use of these low quality reclaimed asphalt pavement materials with the minimum required strength characteristics. Stabilized materials, in addition, help to prevent erosion of foundation soils.

The material used in this study is a fiber-reinforced reclaimed pavement material tested at a definite gradation and different dosage levels of Portland (Type I/II) cement.

The inclusion of fibers was to serve the purpose of enhancing the energy absorption capacity or toughness of the material and to retard the crack propagation process. Specimens with no fibers (control specimens) were tested at 0, 2, and 4% dosage levels of Portland cement and those with fibers (fiber-reinforced) were tested at 2, 4, and 6% dosage levels of Portland cement. A comprehensive series of resilient modulus tests were conducted on the compacted specimens (using the cyclic triaxial test setup) at the UTA geotechnical and geo-environmental laboratories. The main objective of the present research study and the organization of the whole research are as presented in the following sections.

1.2 Research Objectives

The main objective of this research is to evaluate the resilient moduli properties of reclaimed asphalt pavement materials using a repeated load triaxial test. The secondary objectives of the research are to determine the cement and cement-fiber treatments and their influence on resilient moduli properties. The following tasks are performed to complete the present research:

- To review the available literature on aggregate bases, resilient modulus testing, and pavement design concepts,
- To perform the resilient modulus testing using the repeated load triaxial test equipment on RAP material stabilized with cement and cement-fibers,
- To perform the data analysis using t-test in order to evaluate the improvements in terms of statistical significance,

- To model the resilient moduli test results of aggregate base materials utilizing two and three parameter models, and
- To develop the design charts and tables for determining the base layer thickness.

1.3 Thesis Organization

Chapter 1 introduces the aggregate materials, the need for present research. It also describes various chapters and their contents.

Chapter 2 presents an overview of literature review on aggregates, aggregate resilient moduli properties, test procedures to determine resilient moduli, pavement design concepts, and AASHTO flexible and rigid pavement design methodologies.

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

Chapter 4 presents the summary of test results. Repeatability and reliability assessments of test procedures are first evaluated. This is followed by a section that addresses the effects of confining pressure, deviatoric stress, cement content and cement-fiber dosages on the resilient moduli of aggregate base materials. Analyses of test results using t-tests are covered to evaluate the statistically significant improvements in the resilient moduli properties between untreated and cement treated aggregates as well as untreated and cement-fiber treated aggregates. Analysis of test results using two and three parameter models is comprehensively described. Potential use of these models to predict resilient properties of aggregate bases with different confining and deviatoric loads are explained.

Chapter 5 describes the structural coefficients of the present research aggregate materials. These coefficients are established based on the available statistical correlation that accounts for resilient moduli of the bases. Design charts and tables are developed by performing several software program runs that deal with flexible pavement designs. Three types of highways, three different traffic loads and three different resilient properties of subgrades are considered. These tables and charts provide design base layer thicknesses in terms of the above mentioned variables. One example is provided on how to use these tables and charts to design pavement base layer thicknesses.

Chapter 6 describes the summary and conclusions from the current study and also provides some important research direction to address the pavement design including the establishments of structural coefficients.

List of references and appendices are included towards the end of the report supporting the current research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The main objectives of this chapter were to present a brief review on the various recycled materials used in highway applications and, a review of the available pavement design procedures from the literature. Also, in designing the pavements, the structural numbers employed for the various recycled materials based on their resilient properties have been documented. The literature presented in this chapter was collected from libraries and other research projects.

2.2 Recycled Materials in Highway Applications

The beginning of the twentieth century has seen a tremendous growth in the Nation's infrastructure (Wilburn and Goonan, 1998). Much of the core infrastructure, including roads and bridges, constructed during the 1950's and 1960's has deteriorated and they need to be repaired or replaced (Wilburn and Goonan, 1998). With the increase in the need for repairs or renewals of these buildings and roads, the production of waste from these sources is continuing to grow. In the United States, approximately 4.5 billion tons of non-hazardous solid waste is produced each year (Padgett and Stanley, 1996). The primary method of disposing the waste is in landfills (Padgett and Stanley, 1996).

Depletion of the landfill space has in turn resulted in the increased cost of disposal. Also, the use of natural aggregate resources including crushed stone, gravel, and sand has been constrained by several factors such as increased costs and environmental concerns. Recycling of the waste for applications such as road and infrastructure construction thus seems to be a viable solution to address these problems. It not only reduces the amount of construction debris disposed of in landfills, but also might reduce the rate of depletion of natural resources, together with providing energy and cost savings.

The United States Congress, for the first time, in 1965 passed the Solid Waste Disposal Act (SWDA) initiating research into the proper methods of recovery and disposal of solid waste (Rana, 2004). This act was then amended by the Resources Recovery Act (RCA) calling for the elimination of the requirement to use only virgin materials and thereby encouraging the procurement of products with recycled material content (Rana, 2004). Several federal laws have since then been introduced for the management of waste and by-product materials in the USA. Although these federal laws did not directly address the use of waste or recycled material in pavement construction applications, they provided a framework that was used by the different environmental agencies into adopting these recycled materials for pavement related applications.

In the early 1970’s, the Federal Highway Agency started several feasibility studies and demonstration projects on various waste materials for their suitability in highway applications. The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 established a high priority research area in recycling (Rana, 2004). As part of this, a guidance manual on the use of waste materials in pavement construction has been developed and published. In September 1998, a Recycled Materials Research Center

(RMRC) was created, as a partnership between the University of New Hampshire (UNH) and the Federal Highway Administration, to test the new recycled materials, and develop guidelines for their use in highway applications (Rana, 2004). Many research centers have since been introduced to encourage the continued usage of recycled secondary materials for pavement construction.

2.2.1 Recycled Materials

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

2.2.1.1 Bottom Ash

It is a coarse granular material ranging in particle size from fine sand to coarse gravel. It is collected from the bottom of furnaces that burn coal. When pulverized coal is burned in a boiler, about 80% of the unburned material (ash) is entrained in the flue gas and is captured as fly ash. The remaining 20% of the ash is bottom ash, which is a dark gray, granular, porous, 12.7 mm (1/2 in.) material (FHWA, 1998). In 1996, the utility industry generated about 16.1 million tons of bottom ash (American Coal Ash Association, 1997).

Bottom ash has a very porous surface texture with angular particles. It is predominantly composed of silica, alumina and iron with small percentages of calcium, magnesium, sodium and potassium (FHWA, 1998). The composition is mainly controlled by the source of coal rather than the type of furnace. The maximum dry density of bottom ash is usually 10 - 25% lower than that of naturally occurring granular materials. The typical range is in between 12.1kN/m^3 and 16.2 kN/m^3 (Lovell et al. 1991). Whereas, the optimum moisture content (OMC) for bottom ash is higher than that for naturally occurring granular materials. The typical OMC range for bottom ash is 12 to 24% (Lovell et al., 1991). The bottom ash has a friction angle of 38 to 42^o, which is typical of dense graded sand and has a CBR of 40 to 70% (Majizadeh et al., 1979).

Bottom ash could be used in a variety of highway applications as a fine aggregate substitute in asphalt wearing courses and base courses, as a granular base course and in stabilized base applications.

2.2.1.2 Waste Glass

Waste glass when crushed and screened could be used as a portion of fine aggregate in asphalt paving mixes. The resulting mixture has at times been called as glassphalt. It has been widely used since the 1960's to dispose the surplus waste glass. Waste glass constitutes about 7% of the municipal solid waste generated in the United States.

The high angularity of cullet, compared with the rounded sand, enhances the stability of asphalt mixes, when used properly. The stabilities reported were comparable and, in some case, even better than the conventional mixes (Molisch et al., 1975; Chesner and Petrarca, 1987; Petrarca, 1988). Some of the other benefits of using recycled glass include low absorption, low specific gravity and low thermal conductivity, which in turn offer enhanced heat retention in glass mixes (Petrarca, 1988). Also, the high frictional angle (approximately 50^o) of well crushed glass contributes to good lateral stability for pavement surfaces (Petrarca, 1988).

Early glassphalt projects used high percentages of glass with coarse gradations (1/2 in.). But current data suggested that most of the stripping and raveling problems reported during the early demonstrations in the 1970’s were due to use of high glass percentage and large particle sizes. Satisfactory performance has been obtained from asphalt pavements incorporating 10 to 15 % crushed glass in surface wearing courses.

2.2.1.3 Waste Tires

About 279 million waste tires are disposed off each year in the United States, representing over 4 million tones of scrap waste (Takallou and Takallou, 1991). In addition to this 2 to3 billion waste tires are stockpiled over the years in stockpiles all across the country (FHWA, 1998). This study stream of scrap tires, together with those in stockpiles has created a significant disposal problem. Innovative solutions to dispose off these tires have long been in development.

The Intermodal Surface Transportation Efficiency Act (ISTEA) has in 1991 mandated the use of recycled rubber in any federally assisted asphalt pavement project. It was required to use a minimum of 5% recycled rubber by weight of asphalt placed and the percent of rubber used was to increase gradually to 20% by the year 1997 (Khatib and Bayomy, 1999). Even when the mandate was revoked in 1996, recycled tire rubber could still be used in asphalt pavement construction (Khatib and Bayomy, 1999).

Waste tires could be used in several construction activities in various forms. Whole tires could be used to construct retaining walls by stacking them on top of each other, shredded tires have been used as a light weight fill material for embankments and crumb rubber is used in asphalt pavements, wherein the rubber is blended with asphalt binder (Rana, 2004).

2.2.1.4 Compost

Compost is a disinfected and stabilized decomposed organic material obtained from composting of different types of wastes. Composting has been recognized as one of the innovative ways of recycling organic waste materials, by converting materials rich with pathogens to materials that could be effectively used in various day to day applications, such as landscaping and erosion control (Puppala, 2005).

Compost has the ability to increase soil air space, drainage and moisture holding capacity. It also releases nutrients that help mitigate salt concentrations, buffer against heavy metals and extremes in soil pH, encourage earthworms and other beneficial microorganisms.

The major application of compost is along highways as mulch, blended topsoil replacement, commercial fertilizer supplement, and soil amendments (DeGroot et al., 1995). Compost used in highway applications is mostly derived from yard waste, either pre-source separated or commingled (Shelburne and DeGroot, 1998). Compost has several other potential applications and can be used by a variety of sectors (Puppala, 2005). These include landscaping, land reclamation, erosion control, top dressing (for golf courses, park land), agriculture, residential gardening and nurseries (Diaz et al., 1993). Many state Department of Transportation agencies are now utilizing compost in highway construction for different applications.

2.2.1.5 Construction and Demolition Wastes

These are materials such as concrete, masonry, and bituminous road materials, arising from the demolition of buildings, airfield runways and roads (Sherwood, 1995). These clearly fall into the category of recycled aggregates, as they contain natural aggregates that are being recycled. The recycling of construction materials has been recognized to have the potential to conserve natural resources and to reduce the energy used in production. The four main categories of construction and demolition wastes as distinguished by Mulheron and O'Mahony (1990) are:

a) Clean crushed concrete: crushed and graded concrete containing less than 5% of brick or other stone material.

b) Clean crushed brick: crushed and graded brick containing less than 5% of other material as concrete or natural stone.

c) Clean demolition debris: crushed and graded concrete and brick.

d) Crushed demolition debris: mixed crushed concrete and brick that has been screened and sorted to remove excessive contamination. It still contains a proportion of wood, glass or other impurities.

The crushed concrete arising from the demolition of disused airfield runways was widely available after World War II. According to the American Concrete Pavement Association (ACPA), about 322 kilometers of concrete pavement providing 2.6 million tons of reclaimed concrete is being recycled annually (FHWA, 1993).

The recycled crushed concrete aggregate has higher water absorption, lower specific gravity, higher thermal coefficient of expansion, and higher LA abrasion loss, when compared to the conventional aggregate (Won, 1999). One of the commonly used construction waste in highway industry is reclaimed asphalt pavement or RAP aggregate, which is focused in the present research. Detailed description of this material is presented in the following.

2.2.2 RAP Materials

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

2.2.2.1 Recycling Processes

Typically the asphalt pavement is either removed by milling of upper surfaces or full depth removal of the entire pavement section itself. A milling machine is used remove top 2 in. of the surface with a single pass whereas a rhino horn on a bulldozer is used for full depth removal of the entire pavement in several broken pieces. These pieces are subjected to crushing, screening, conveying and stacking in stockpiles. Typically, this processing is performed at a central processing plant.

Another form of RAP material can be produced by in situ recycling of the old pavements by pulverizing them first and then incorporating them into base courses with or without additives. These processes are referred in the literature as cold in-place and hot in-place recycling methods, with hot process requires the heating of the upper asphalt surface layers of typically 2 in. using a hot recycling machine shown in Figure 2.1. Cold in-place mixing can be carried out to different depths and a schematic showing this process of in-place mixing can be seen in Figure 2.2.

It should be noted that the RAP materials produced from both central processing facility and in situ recycling methods can be used in the following applications: asphalt concrete aggregate, asphalt cement binder, granular base aggregate, stabilized base aggregate and embankment or fill material. Utilizing in these applications result in several benefits, which are summarized in the following:

1. Lower costs
2. Lower utilization of virgin materials which are becoming scarce
3. Reduced land-filling
4. Reduced energy consumptions by eliminating fuel consumptions required for land-filling trips, and
5. Faster construction if in-place recycling methods are employed.

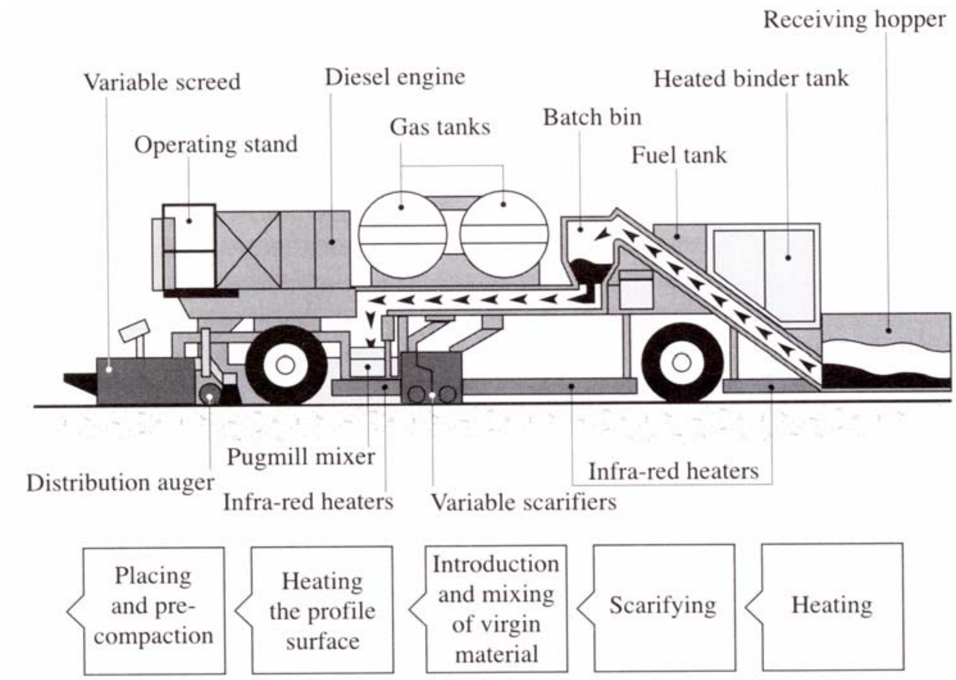


Figure 2.1 Schematic of Hot-In Place Recycling Machine (from Sherwood, 1995)

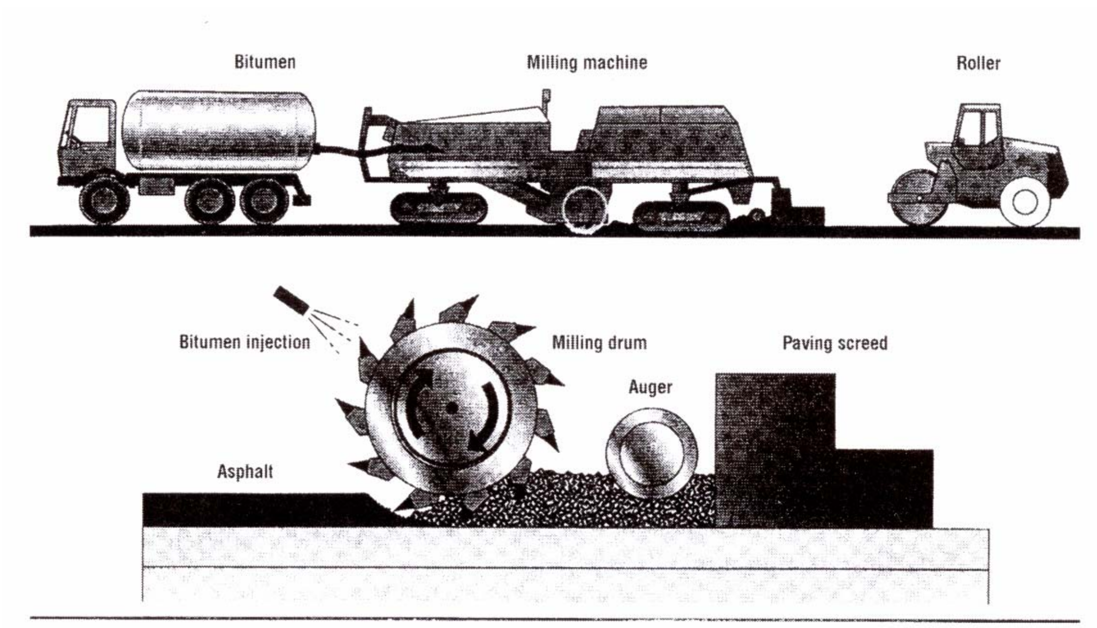


Figure 2.2 Schematic of Cold-In Place Recycling Machine (from Sherwood, 1995)

2.2.2.2 Typical Properties of RAP Materials

In this section, physical, chemical and engineering properties are discussed. Table 2.1 presents both physical and mechanical properties of the RAP materials. It should be noted that the unit weight of RAP varies between 19.4 and 23.0 kN/m^3 whereas the moisture content varied between 5 to 8%. Compaction unit weights ranged between 16.2 and 20.0 kN/m^3 and the California Bearing Ratio values ranged from 20 to 25. Chemically, a small percent of RAP material (6%) contain hardened asphalt binder and the rest is predominantly composed of natural aggregates. The asphalt binder can be of hardened type due to oxidation process during service period of asphalt pavements.

Table 2.1 Physical and Mechanical Properties of RAP Materials

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

In this research, the main focus is on the aggregate application of RAP materials to support both cement concrete and asphalt pavements. The RAP material used here is a central plant processed aggregates that are stabilized with both cement and polypropylene fibers.

2.3 Pavement Design

The basic function of any pavement structure is to distribute the imposed wheel loads over a large area of the natural soil. The shear strength of the soil in itself is usually not high enough to support the wheel load. In addition to the load distribution, the surface course of a pavement structure must provide a level, safe traveling surface. The major components of a pavement structure are:

1. Surface
2. Base
3. Subbase
4. Compacted subgrade
5. Natural subgrade

A pavement is classified to be “rigid” or “flexible” or “composite”, depending on how it distributes the surface loads. Rigid pavements are surfaced by Portland cement concrete slabs and they undergo 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 usually consist of both rigid and flexible pavements and usually flexible pavement is located above the rigid pavement. Composite pavements found most often on old rigid pavements that have had flexible pavement overlay. Typical flexible pavement overlays include hot mix asphalt pavements, open graded friction course, or rubberized asphalt concrete. The function of upper flexible layer is to serve as a thermal and moisture blanket to reduce temperature and moisture gradients within the rigid pavement section, thereby decreasing deformation of rigid pavements. The flexible layer also serves as a wearing course to reduce wearing effects of wheel loads.

The main variable in the design of a pavement structure is its thickness. The main criteria involved in the design of the pavement thickness are:

1. The magnitude of the imposed loads

   The load that is imparted primarily to pavements comes from heavy trucks. Equivalent single axle load or ESAL is used to approximate the actual truck load with an 18 kip load using a fourth power formula. Trucks with different wheel configuration impart different ESAL number when they pass over the pavements. For example, a 3k automobile exerts about 0.0001 ESAL whereas an 18-wheeler with two tandem axles and one single axle exerts ESAL equivalent to 2.44. Similar such magnitudes for loads from other types of trucks and their wheel configurations can be found in several pavement design source books.

2. The strength and resilient modulus of the subgrade soil

The strength of the subgrade is the most crucial parameter in pavement design. In the past, practitioners used California Bearing Ratio (CBR), R-value, soil support value (SSV) and triaxial strength parameters for pavement design. Most of these parameters are based on static type loading and the measured loads depend on the failure of the soil specimen in the laboratory experiment. Soon researchers and practitioners realized that these parameters do not either represent traffic loads which are of repeated load types or test conditions inducing soil failure does not occur in real field conditions since soil failures seldom occur in the field.

As a result, AASHTO (1986) recommended the use of resilient modulus as a soil parameter for pavement design. This parameter, which represents dynamic elastic modulus, is considered more appropriate since it accounts for plastic deformation in subsoils. As a result, both direct (laboratory) and indirect (charts and correlations) methods are introduced into the practice.

The input parameters required for the design of a pavement structure are:

- Design variables: The variables as performance period, traffic, reliability and environmental effects are called the design variables. These variables come into picture while designing for specific road sections.
- Performance criteria: They represent specific boundary conditions within which a pavement should perform. These include serviceability criteria, allowable rutting, aggregate loss, etc.

- Material properties: They include effective roadbed resilient modulus, effective subgrade modulus, pavement layer material characteristics, PCC modulus of rupture and layer coefficients.
- Structural characteristics: They refer to the physical characteristics as drainage load transfer, and loss of support which to some extent affect the pavement performance.
- Reinforcement variables such as jointed and flexible pavements.

2.3.1 Design of Flexible Pavements

Flexible Pavement design basically requires the determination of the layer thicknesses based on their structural support and the predicted level of traffic (18-kip equivalent single-axle load, ESAL). Flexible pavements generally consist of the surface, base and the subbase courses. The surface course of a flexible pavement is made of Asphalt concrete. The following steps briefly describe the AASHTO procedure for design of flexible pavements.

Firstly, the structural number (SN) of the pavement is determined from the design chart for flexible pavement design based on the mean values of the required input parameters. The input parameters required are the total estimated 18-kip Equivalent Single Axle 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). The design chart for determination of the structural number is as shown in the figure 2.1 below.

Once the design structural number for the pavement is arrived at from the previous step, it is necessary to select a set of layer thicknesses so that the provided SN, as computed by the equation 2.1 below is greater than the required (design) SN.

$$SN = a_1 \times D_1 + a_2 \times D_2 \times m_2 + a_3 \times D_3 \times m_3 \qquad (2.1)$$

Where,

a_1, a_2, a_3 = layer coefficients for the surface, base and subbase, respectively

D_1, D_2, D_3 = thicknesses of the surface, base and subbase, respectively

m_2, m_3 = drainage coefficients for the base and subbase courses, respectively

The layer coefficients for each layer should be determined from the resilient or elastic moduli properties of the respective layers. The correlations are as provided in the AASHTO design guide. Many combinations of the layer thicknesses could now be assumed to arrive at a SN greater than the design SN. The cost effectiveness along with the construction and maintenance constraints must be considered in arriving at the final design thickness of each layer.

2.3.2 Design of Rigid Pavements

The design guide for rigid pavements was also developed at the same time as that for flexible pavements in the AASHTO (1993) manual. Rigid pavements consist of a Portland cement concrete slab placed directly on the subgrade without a subbase or with a subbase existing between the slab and the subgrade. The design of rigid pavements requires the following steps.

The property of the roadbed soil to be used for rigid pavement design is the modulus of subgrade reaction k. Thus it is required to convert M_R to k. The figures 2.4

and 2.5 as shown below provide a method of estimating the modulus of subgrade reaction, k.

The input parameters required to estimate the value of k are the roadbed soil resilient modulus, M_R (psi), Subbase thickness, D_{SB} (inches), depth of subgrade to rigid foundation, D_{SG} (ft.) and the subbase elastic modulus, E_{SB} (psi). The figure 2.6 below presents a chart for estimating the relative damage to rigid foundations.

In order to account for the loss of support by foundation erosion or differential vertical soil movements, the effective modulus of subgrade reaction is reduced by a factor, LS. The figure 2.7 below presents the chart for the correction factor to be applied.

Once the effective modulus of subgrade reaction has been determined, the PCC slab layer thickness can be determined using the charts shown in the Figures 2.8 and 2.9. The design variables for flexible pavement design such as the traffic, reliability, environmental effects, serviceability and the standard deviation are the same for rigid pavements. The additional parameters required for the design of rigid pavements are the elastic modulus of concrete, E_c, the concrete modulus of rupture S_c, the load transfer coefficient J and the drainage coefficient C_d.

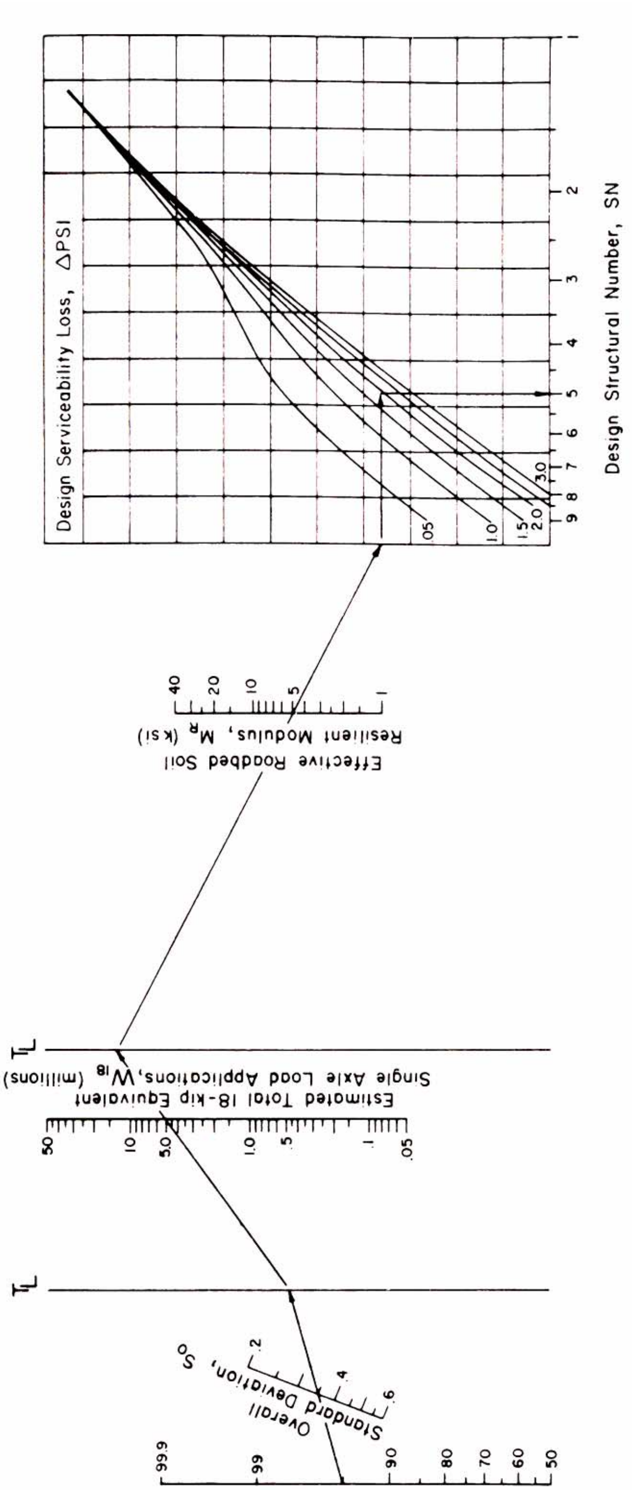


Figure 2.3 Design Chart for Flexible Pavements (AASHTO, 1993)

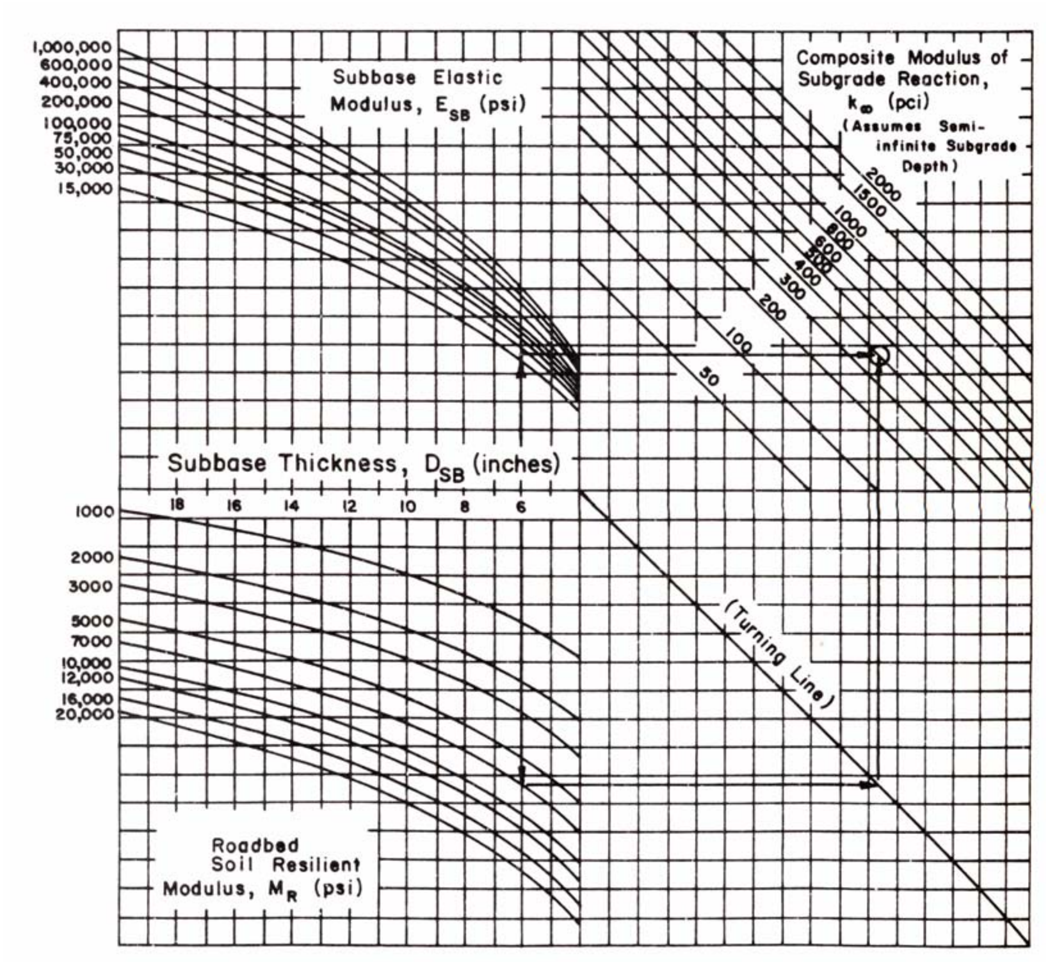


Figure 2.4 Chart for estimating modulus of subgrade reaction (AASHTO, 1993)

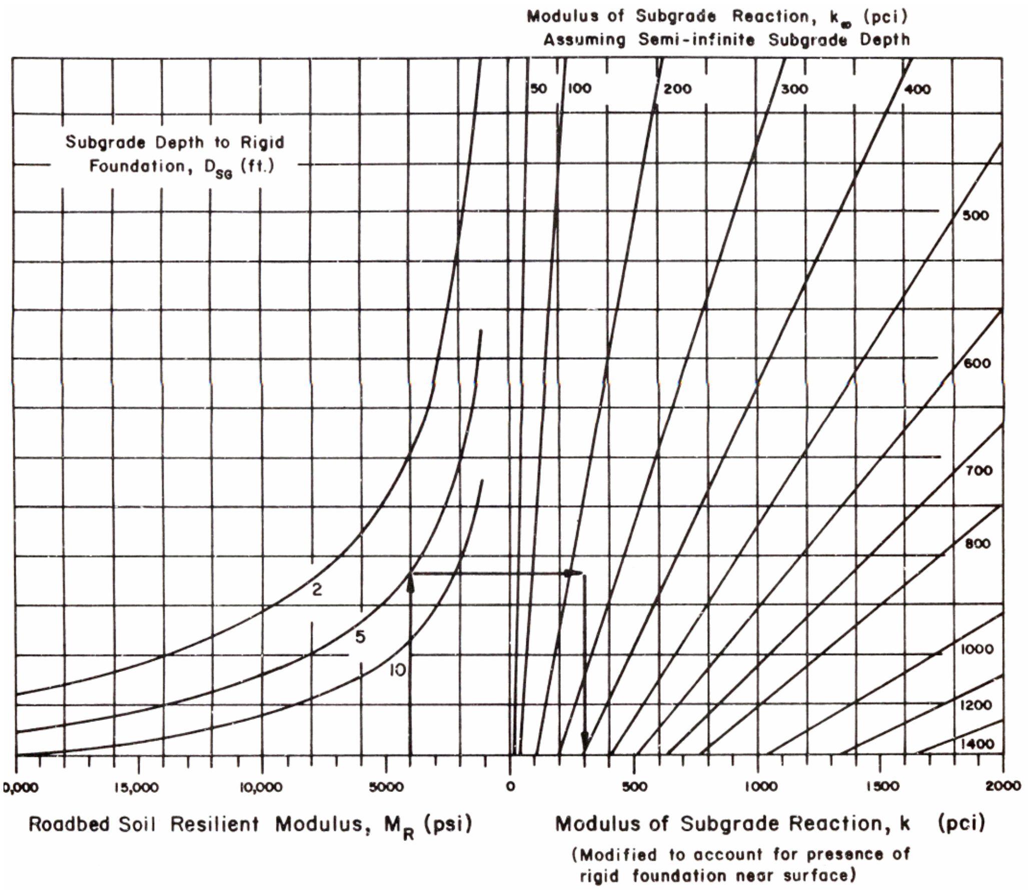


Figure 2.5 Chart for modifying modulus of subgrade reaction due to rigid foundation (AASHTO, 1993)

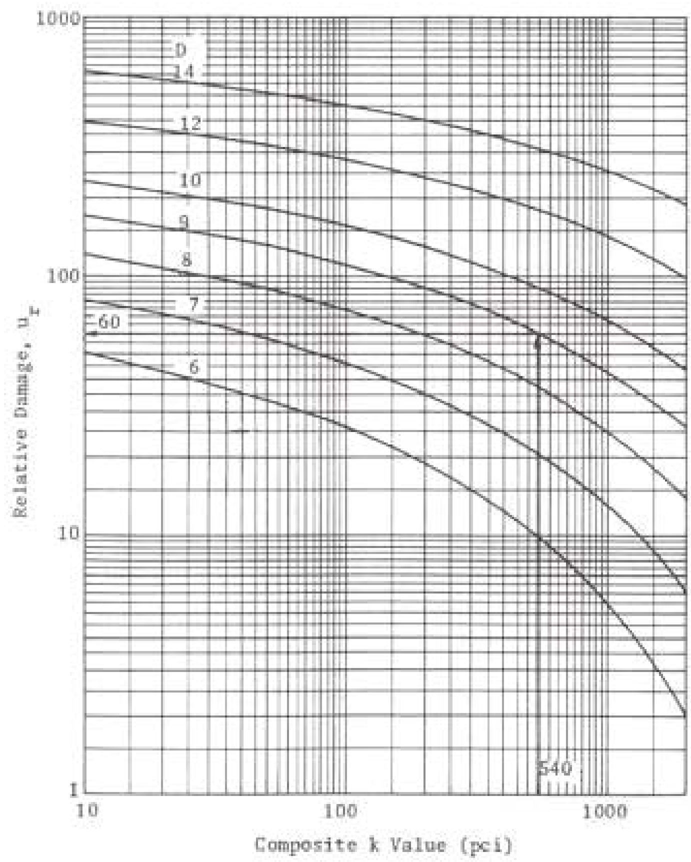


Figure 2.6 Chart for estimating the relative damage to rigid pavements (AASHTO, 1993)

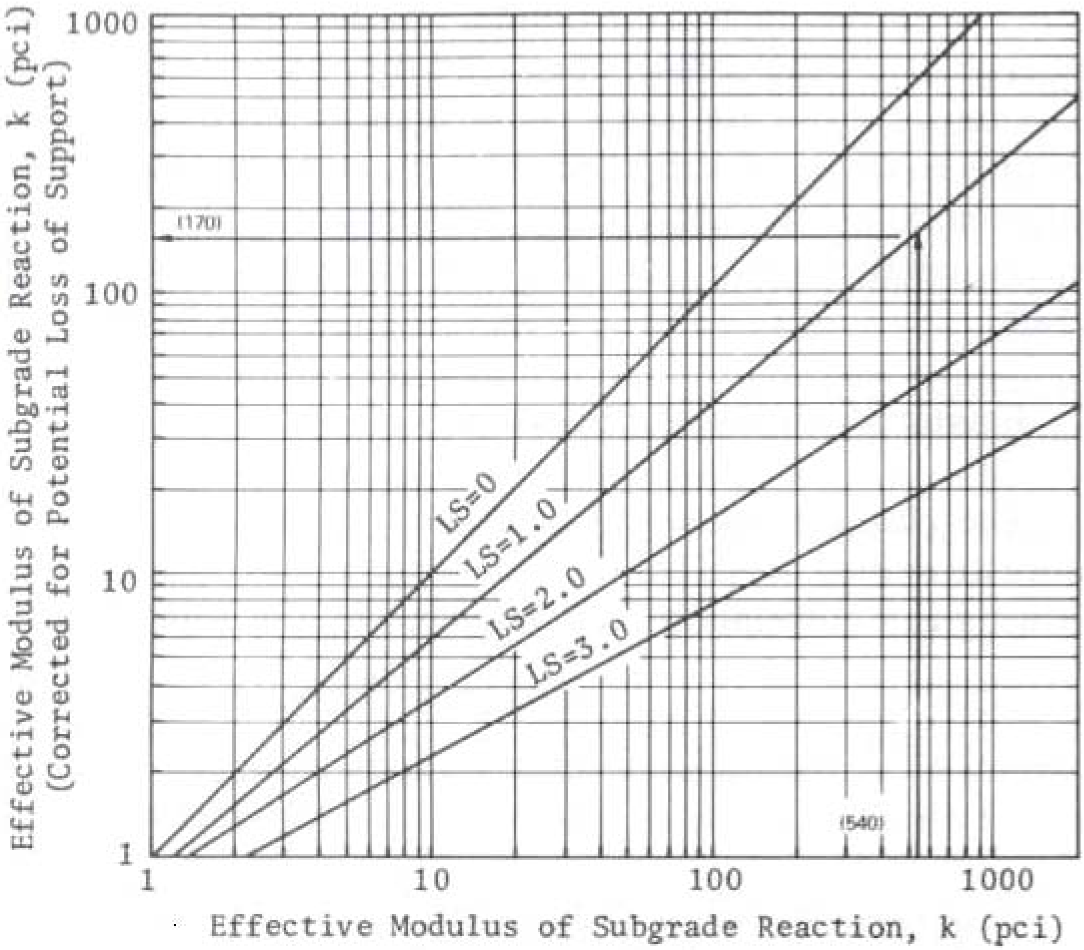


Figure 2.7 Correction for the effective modulus of subgrade reaction (AASHTO, 1993)

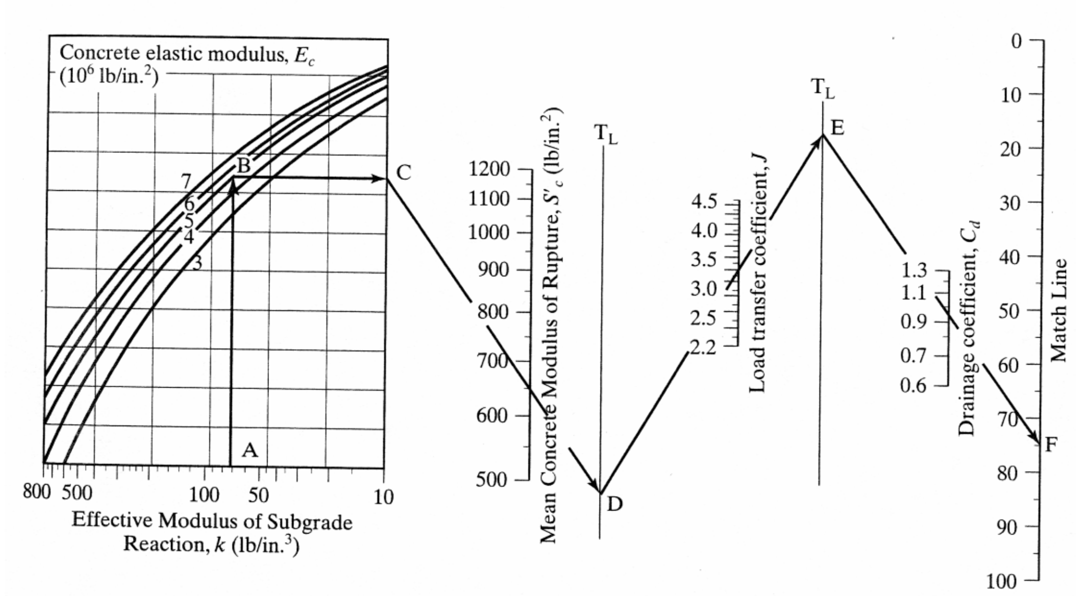


Figure 2.8 Design chart for rigid pavements (AASHTO, 1993)

As seen from the design procedures of both flexible and rigid pavements, one of the most important input parameters employed in the design is the resilient modulus (M_R). Since this research is primarily focusing on the use of cement and cement-fiber treated RAP material as a base layer of flexible pavement, it is essential to determine the resilient moduli properties of these materials and determine their structural coefficients.

An experimental program was hence undertaken to accomplish this research objective. Also, an attempt was made to collect and compile the available research studies undertaken in the world on the resilient properties of RAP aggregates used as base materials. The next section describes a few of these studies and their results.

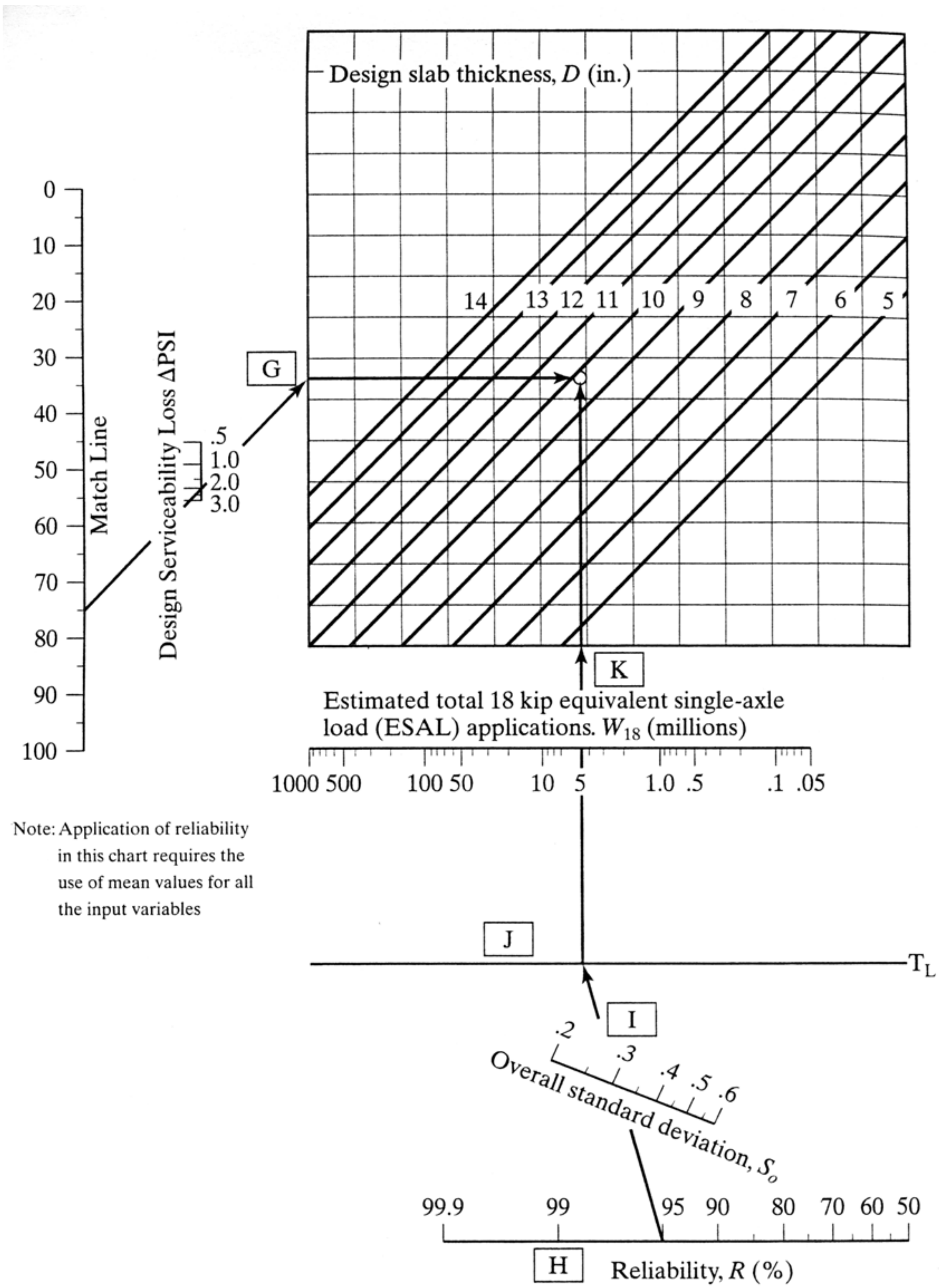


Figure 2.9 Design chart for rigid pavements (AASHTO, 1993).

2.4 Resilient Properties of Recycled Materials

One of the earliest studies in the dynamic characterization of base and subbase materials was undertaken by Lofti and Witczak (1985). Resilient moduli of five cement-treated base materials used by the Maryland State Highway Administration were determined and evaluated in this study. Specific values of layer coefficients based on the material moduli were then evaluated for use in the design of flexible pavements. The M_R testing was performed at a range of stress levels varying from 40 to 320 psi. The range of these resilient moduli is presented in Table 2.2. It should be noted however that the material used in this case is a natural aggregate and not a recycled/reclaimed aggregate, which is the main focus of this research.

In a separate study conducted for the New Hampshire Department of Transportation (NHDOT), Janoo (1994) experimented with the use of reclaimed asphalt concrete as a base material. Test sections of different RAP materials were built by NHDOT near Concord off Interstate 89. Falling Weight Deflectometer (FWD) tests and other tests were conducted on the test sections and the deflections were then used to back-calculate the layer modulus. The layer moduli were then used with the established relationships for determining the layer coefficients in the 1993 AASHTO guide for design of pavement structures. Table 2.2 below also presents the layer coefficients for the New Hampshire base courses.

In another study conducted by Taha et al. (2002), RAP/Virgin aggregate mixtures were tested with different cement dosages. Compaction and Unconfined compression strength (UCS) tests were conducted in the study. The modulus values were arrived at from the UCS results using correlations between M_R and UCS. No resilient modulus tests were conducted in the laboratory environment. The layer coefficient charts included in the AASHTO guide for design of flexible pavements were used for in obtaining the values. The results of this study are also presented in the same table.

Table 2.2 Structural Layer Coefficients from Different Studies

Reference	**Type of Recycled Material Tested**	**Tests Conducted**	**Stress Levels**	**Resilient Modulus**	**a_2**
Lofti and Witczak	Cement-Treated Dense Graded Aggregate, which includes Limestone	Resilient Modulus (M_R)	0.28 to 2.28 MPa of bulk stresses	1260 MPa (4.5% cement)	0.27
Janoo (1994)	Reclaimed Stabilized Base	Back Calculation from Layer Modulus (FWD)	NA	NA	0.15 - 0.19
Janoo (1994)	Reclaimed Stabilized Base	CBR	NA	NA	0.13
Taha et al. (2002)	Cement Stabilized RAP Aggregates	Unconfined Compression Strength Tests	NA	3,726 MPa (7% cement)	0.13
Gnanendran and Woodburn (2003)	Cement Stabilized RAP Aggregates	Resilient Modulus (M_R), CBR and UCS tests	0 to 140 kPa	310 to 590 MPa (0% to 3% cement)	NA

Gnanendran and Woodburn (2003) conducted series resilient modulus, CBR and UCS tests on cement, lime and fly ash stabilized reclaimed. These tests provided typical resilient moduli values of these aggregates, and enhancements in moduli values with respect to each of the chemical treatments. This is the only study currently available to the author in which similar stabilized RAP materials were used and tested in repeated load triaxial test environment. Hence, the moduli of these materials were used for evaluating the reliability assessments.

Although reclaimed aggregate materials are widely used in various pavement applications, neither sufficient numbers of resilient modulus laboratory tests were conducted nor field FWD studies were attempted in determining the resilient modulus values. Also, it should be noted that each kind of the recycled material is distinct with respect to the others (basing on its source and other constituents involved) and hence comprehensive experimental characterizations using resilient modulus tests are analyzed for its qualification in pavement applications.

2.5 Summary

This chapter first covers various recycled materials used in pavement systems, followed by a description of various recycled material used in the highway construction. Among the recycled materials, the reclaimed asphalt pavement is considered one of the promising materials to be used as a base material. Hence, a complete section is devoted to this material. This is followed by two sections describing both pavement material characterization and pavement designs. Both rigid and flexible pavement design concepts and charts are covered. Since the focus of this research is on RAP material use in flexible pavements, the last section describes various research studies that cover both resilient moduli properties and structural coefficients.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Introduction

This experimental program was designed and conducted to test and determine the resilient properties of the fiber-reinforced RAP base material specimens at a given gradation and different dosage levels of Portland cement (Type I/II). RAP base specimens with no fibers (control specimens) have been tested at 0%, 2% and 4% cement contents and those with fibers (fiber-reinforced) have been tested at 2%, 4% and 6% of cement content. The following sections describe physical and chemical properties of the control soil and testing materials used in this research, types of laboratory tests performed, test equipment used and the test procedures followed.

3.2 Properties of the Test Material – RAP Base

The base material used in this research is a bonded base and subbase material produced by the process of blending crushed recycled construction/demolition waste/debris, to specified gradation requirements and bonding these with a fine silica Portland cement matrix at optimum moisture content for compaction density. A series of basic and engineering tests have been conducted on this RAP base material. The basic tests included grain size distribution tests, specific gravity, and Proctor compaction tests. The specific gravity of the material was found to be 2.43. Resilient Modulus tests using the cyclic triaxial setup were also conducted on the compacted RAP base specimens. All of the basic testing was done in accordance with the current TxDOT and ASTM standard testing procedures.

3.2.1 Basic Material Properties

All the basic soil properties were determined at the beginning of the experimental program. The particle size distribution was first determined using the sieve analysis. The sieve analysis indicates that about 99% of the material was retained on No. 200 sieve. Since the percent of material passing No. 200 sieve is 1%, no Hydrometer analysis was further performed. Figure 3.1 presents the grain size distribution curve of the RAP base material.

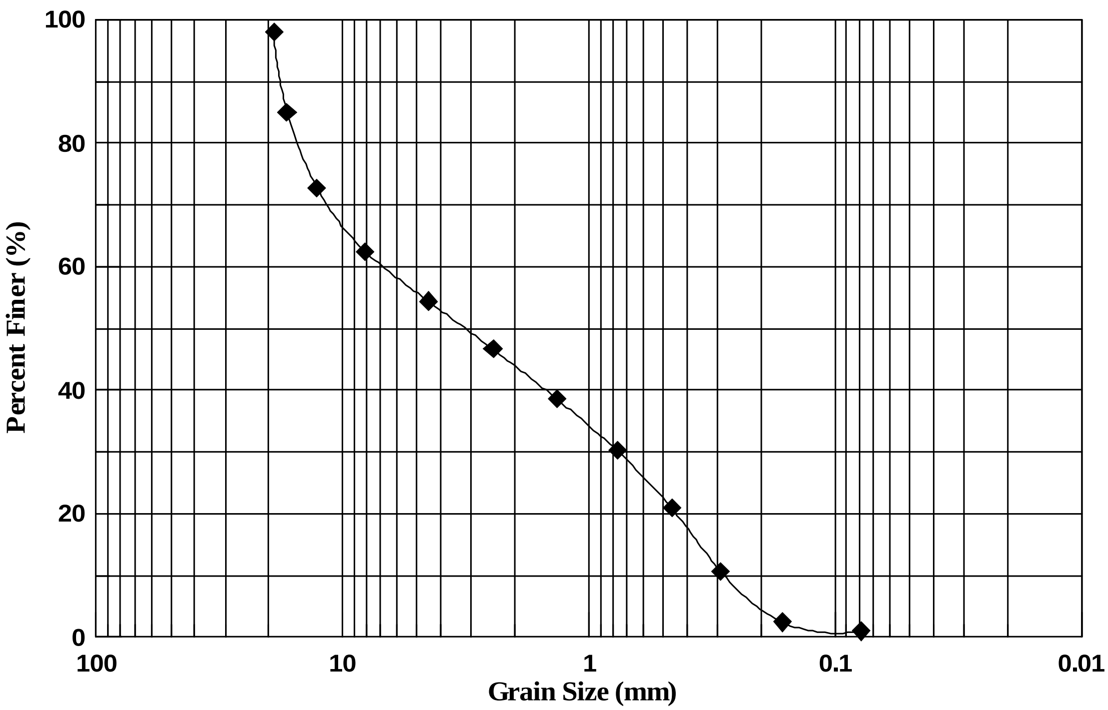


Figure 3.1 Grain Size Distribution Curve of the RAP Base Material

Soil Compaction tests were conducted on the RAP base material to establish the optimum moisture content and dry unit weight relationships. Tests were conducted as per the TxDOT procedure (Tex-113-E) for determining the laboratory compaction characteristics and moisture-density relationship. This procedure requires a compactive effort of 13.26 ft-lb/in^3. Based on this requirement, for a 4.54 kg (10 lb) weight of hammer and a height of drop of 0.46 m (1.5 ft), it was determined to compact the specimen in three layers with 17 blows per layer for a specimen size of 10 cm in diameter and 11.6 cm in height. Table 3.1 presents the compaction parameters adopted for aggregate specimen preparation. Figure 3.2 below presents the compaction dry unit weight and moisture content relationships of the RAP base material at 0, 2, 4, and 6% cement treatment. The results of this compaction test were adopted in preparing the samples at the optimum moisture content and maximum dry unit weight.

Table 3.1 Compaction Parameters

Required Compactive Effort (ft-lb/in^3)	13.26
Weight of Hammer (kg)	4.54
Height of Drop (m)	0.46
Diameter of Sample (cm)	10.16
Height of sample (cm)	11.63
Volume of Molded Specimen (cm^3)	943.06
No. of Layers	3
Drops per Layer	17
Applied Compactive Effort (ft-lb/in^3)	13.29

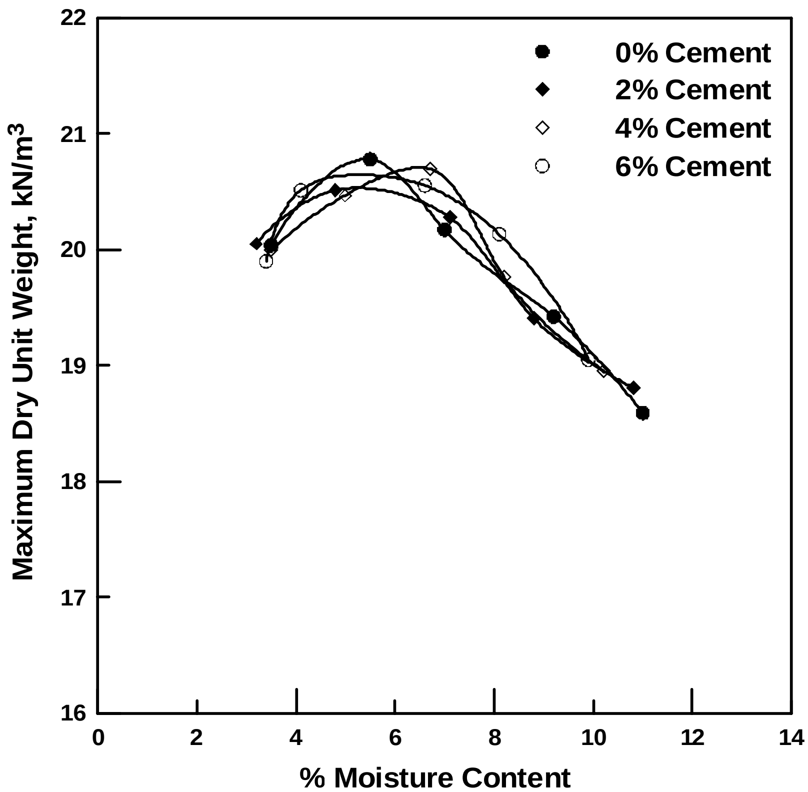


Figure 3.2 Compaction Test Results for the Untreated Aggregate Material

3.2.2 Engineering Properties - Resilient Modulus Test Procedure

The Resilient Modulus Test using the Cyclic Triaxial test equipment is designed to simulate the traffic wheel loading on the in situ soils by applying a sequence of repeated or cyclic loading on the sample specimens. In this thesis research, the standard method of testing for determining the resilient modulus of soils and aggregate materials – AASHTO Designation T 307-99 has been employed. The stress levels used for testing the specimens are based upon the location of the specimen within the pavement structure as standardized by AASHTO for Base/Subbase materials.

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

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

Tests were conducted on the RAP base specimens (both with and without fibers) compacted at the optimum moisture content, and at different dosage levels of the Portland cement. RAP base specimens without fibers are tested at 0%, 2% and 4% of the cement dosage levels, whereas the specimens with fibers are tested at 2%, 4% and 6% of the cement dosage.

3.2.2.1 Soil Specimen Preparation Procedure

RAP base specimens for the resilient modulus tests have been compacted at the optimum moisture content and the maximum dry unit weight**.** The samples were compacted in three layers, with 17 drops per layer in a 10 cm in diameter by 11.6 cm in height mold, conforming to the required compactive effort (13.26 ft-lb/in^3) as specified by TxDOT. The samples were compacted using the automatic compactor. After compaction, the specimens have been extruded and kept for curing for 7 days. The cylindrical specimens were then subjected to testing immediately after the curing period.

Table 3.2 Resilient Modulus Testing Sequence

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

3.2.2.2 Research Variables

All of the samples were prepared and compacted at the optimum moisture content densities. The samples without fiber reinforcement have been tested at 0, 2 and 4% cement treatment. However, the samples with fiber-reinforcement were tested at 2, 4 and 6% cement contents. Thus, the samples were studied for variations in their resilient moduli values with varying amounts of cement content.

Also, the effects of fiber reinforcement on the resilient moduli properties have been studied for samples with the same percent of cement content. The percent of fiber content employed in the specimens was not varied and was kept at 0.15%. Hence, the quantitative effects of fiber-reinforcement could not be studied. All of the specimens were consistently tested at a 7-day curing period.

The Table 3.3 below presents various research variables studied in the present research. As stated in the table, each specimen was tested at five different confinements and at each confining pressure the specimen was again subjected to three different deviatoric stresses. All the stresses applied are in accordance with the values recommended by AASHTO guide for design of flexible pavements, as shown in Table 3.2.

Table 3.3 Research Variables Studied

Reclaimed Pavement Aggregate Material	**% Cement Content**			
	0%	**2%**	**4%**	**6%**
Without Fibers	3	3	3	_
With Fibers	_	3	3	3

<u>3.3 Equipment Employed for the Resilient Modulus Testing</u>

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

3.3.1 Loading Frame

The loading frame consists of a heavy flat base plate, supported on four leveling screws. Two threaded rods support the crosshead beam and provide height adjustment. The frame is of heavy construction to limit deflection and vibrations that could influence the accuracy of measurements during dynamic repeated loading tests. The loading forces are applied through the shaft of a pneumatic actuator mounted in the centre of the crosshead. Sensitive, low friction displacement transducers attached to the crosshead enable measurement of the permanent and small resilient deflections of the specimen during loading. The loading frame is as shown in the figure 3.3 below.

Figure 3.3 The Loading Frame and Triaxial Cell

3.3.2 The pneumatic loading system

The UTM pneumatic system is an air compressor controller unit used to control both load and pressures applied on soil specimens. For asphalt tests, only the vertical force pneumatics are required, while the unbound tests on soils require both confining and axial deviatoric pressure pneumatics. The system requires a filtered clear air supply at a minimum supply pressure of 800 kPa. Lower supply pressures will prevent the system from achieving the maximum specified stresses or forces, as selected by the operator. Figure 3.4 shows the Pneumatic system at the UTA geotechnical lab facility.

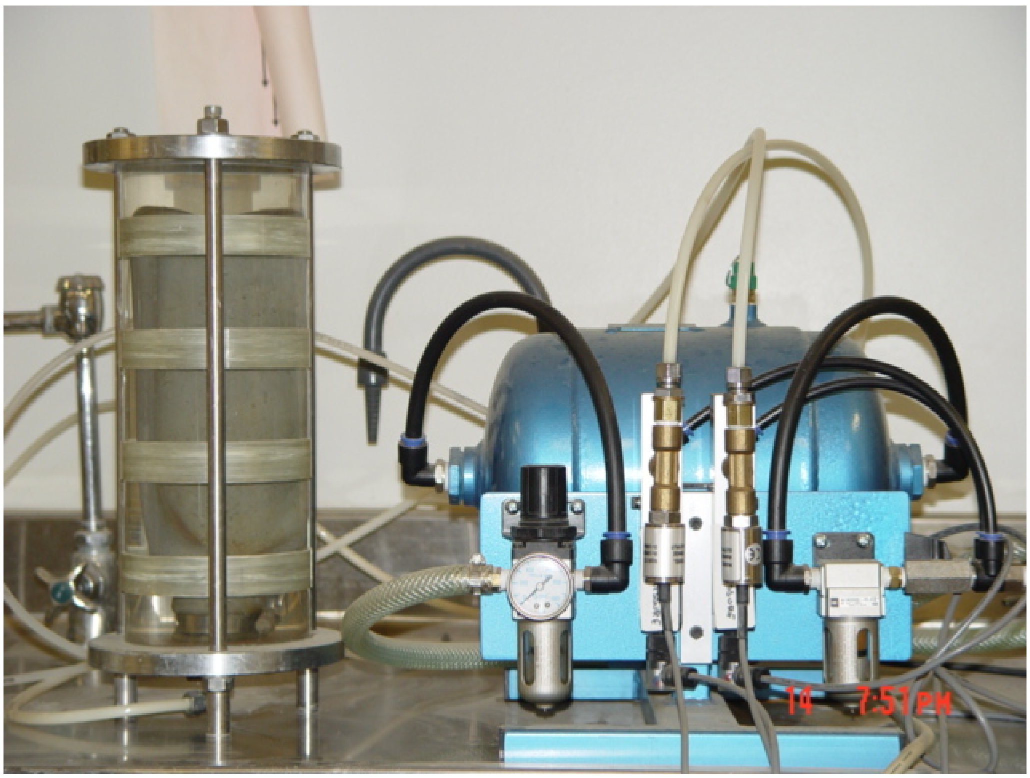


Figure 3.4 The Pneumatic System

3.3.3 Triaxial Cell

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

3.3.4 Control and Data Acquisition System

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

The Feedback Control module has three normalized input channel controls. These channels are dedicated to the actuator position, actuator force and general purpose input (Aux) for on-specimen transducers. This module has a dedicated communication interface of its own that provides for an uninterrupted, simultaneous communication with the PC enabling increased speed of operation and flexibility. The figure 3.5 below shows the control and data acquisition system.

3.3.5 Linear Variable Displacement Transducers (LVDTs)

Based on the AASHTO testing procedure T 307-99, high resolution LVDTs are needed to measure the soil displacements. Two LVDTs are used to record the vertical displacements. This external displacement transducer is easy to install and provides a simplified procedure to reset the initial zero reading. The LVDTs are placed on the top cover of the cell and fitted to the load shaft. The maximum scale stroke for these two LVDTs is ±5 mm, with a resolution of 0.001 mm accuracy. The output from each LVDT is monitored independently and compared to the output of the other LVDTs. Figure 3.6 shows the external transducer assembly employed in this project.

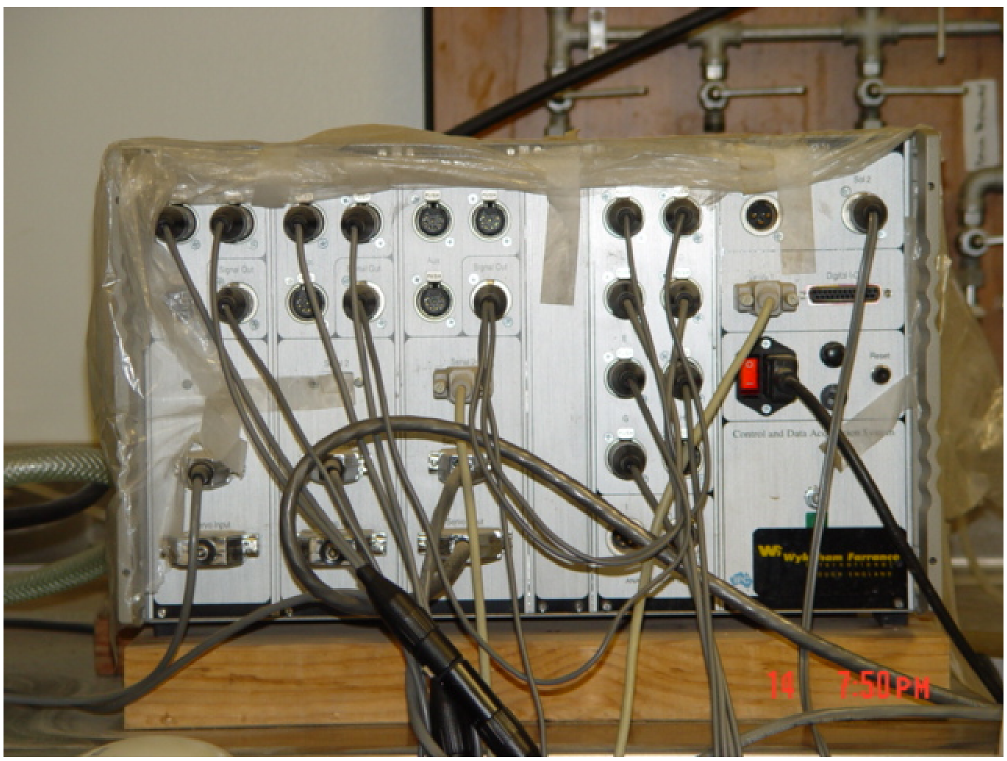


Figure 3.5 The Control and Data Acquisition System

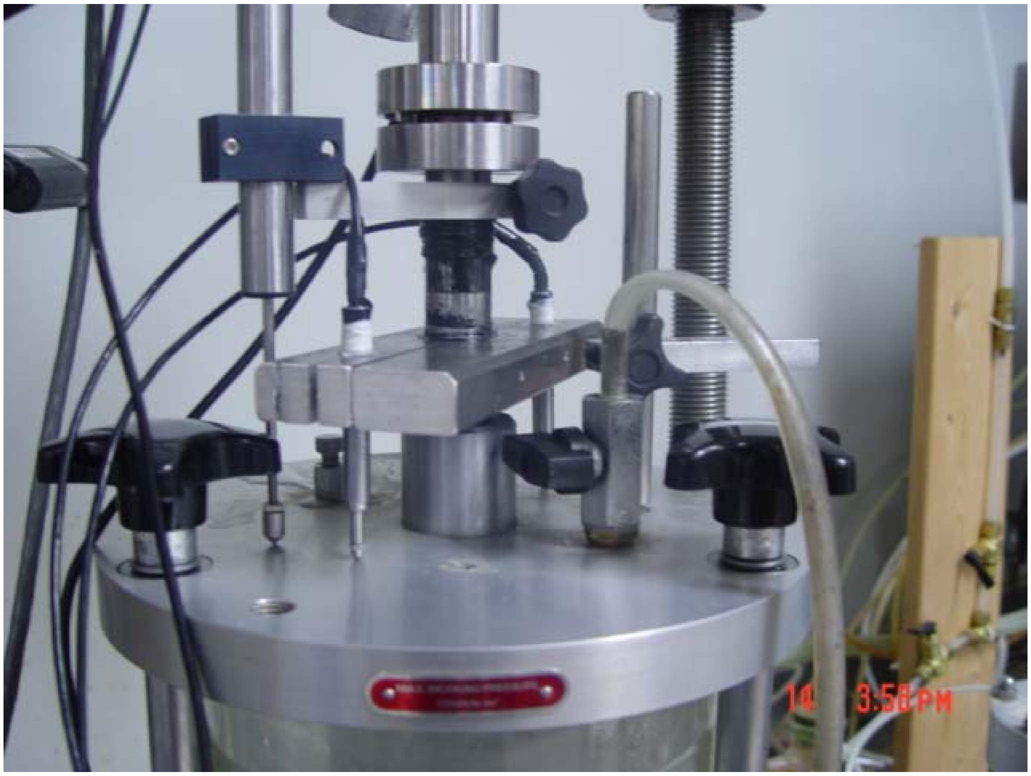


Figure 3.6 External LVDTs Assembly

3.3.6 Software

The UTM software is used for equipment control and data acquisition operations. In this software, there are programs available for several test procedures, which include unconfined compressive strength test, resilient modulus test, unconsolidated undrained test, consolidated undrained test, consolidated drained test and a provision for user defined programs. The user program is a program that is provided for operators to create their own testing methods and protocols. In this Research, the AASHTO T 307-99 program for the determination of resilient modulus of aggregate base materials has been used. The figure 3.7 below shows a sample test data window during the test.

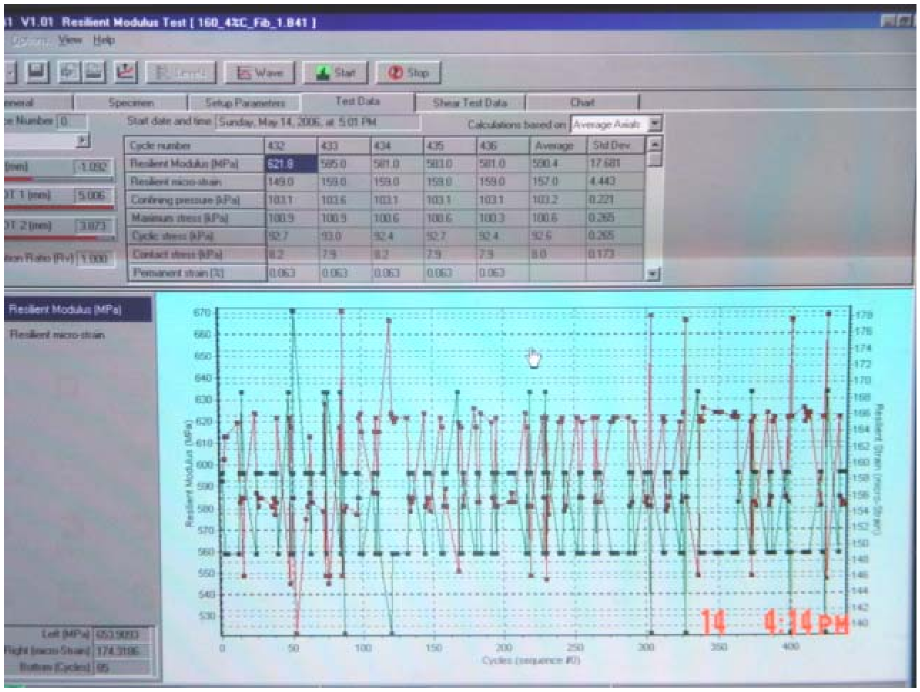


Figure 3.7 Software Window Showing the Test Data

3.4 Summary

This chapter provides a summary of basic properties of selected RAP base material, experimental program, test procedures and equipment used in this research. Also, the notations used to present these test results in a simple format have been explained. Details of the resilient modulus test procedure employed in this research have also been presented.

CHAPTER 4

ANALYSIS OF RESILIENT MODULUS TEST RESULTS

4.1 Introduction

This chapter presents the resilient modulus test results of the reclaimed asphalt pavement material. The specimens have been tested at different dosages of the Portland cement with and without fiber-reinforcement. The standard AASHTO test procedure, T 307-99 was followed for the determination of the resilient modulus of the base/subbase materials. The Repeated Loading Triaxial (RLT) test device was used for the resilient modulus tests. The resilient modulus test results are analyzed and discussed with respect to the percent cement content, confining and deviatoric stresses employed in the test. Explanations are based on the majority of the trends noted in the test results.

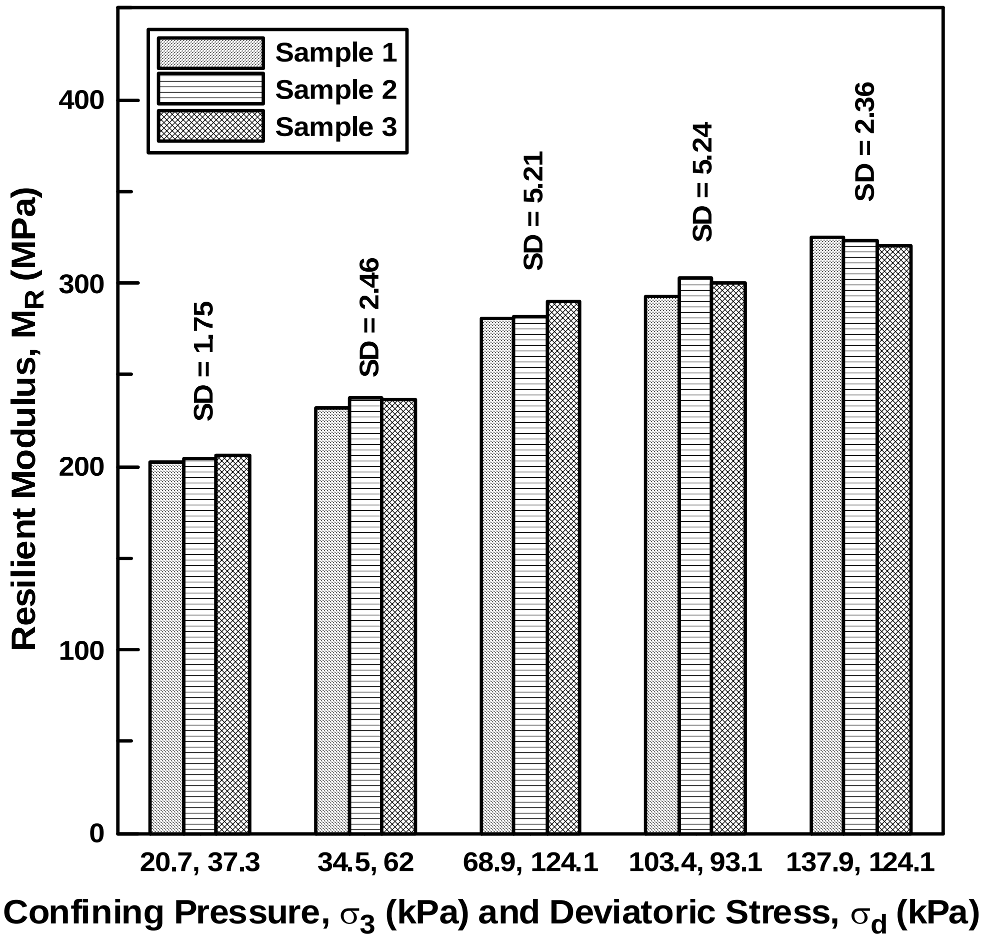
4.2 Resilient Modulus Test Results

The AASHTO standard test procedure, T 307-99 has been employed for the determination of resilient moduli of the aggregate specimens. The combinations of various deviatoric and confining stresses applied in the test sequence have been tabulated in Table 3.2 presented in Chapter 3. In each test sequence, the specimen was subjected to five different confining stresses with three levels of deviatoric stresses applied at each confinement. A haversine loading wave with a frequency of 10 Hz was used to simulate the traffic wheel loading. Each loading cycle subjects the specimen to 0.1 sec of deviatoric or repeated loading and 0.9 sec of relaxation. During the test, the average total vertical deformation was monitored and recorded using two linear variable displacement transducers (LVDTs) placed on top of the triaxial cell. The internal load transducer placed inside the triaxial chamber recorded the deviatoric stress applied to the soil specimen.

In an attempt to evaluate the repeatability and reliability of the resilient modulus test results, tests were conducted on similar aggregate specimens with identical conditions.

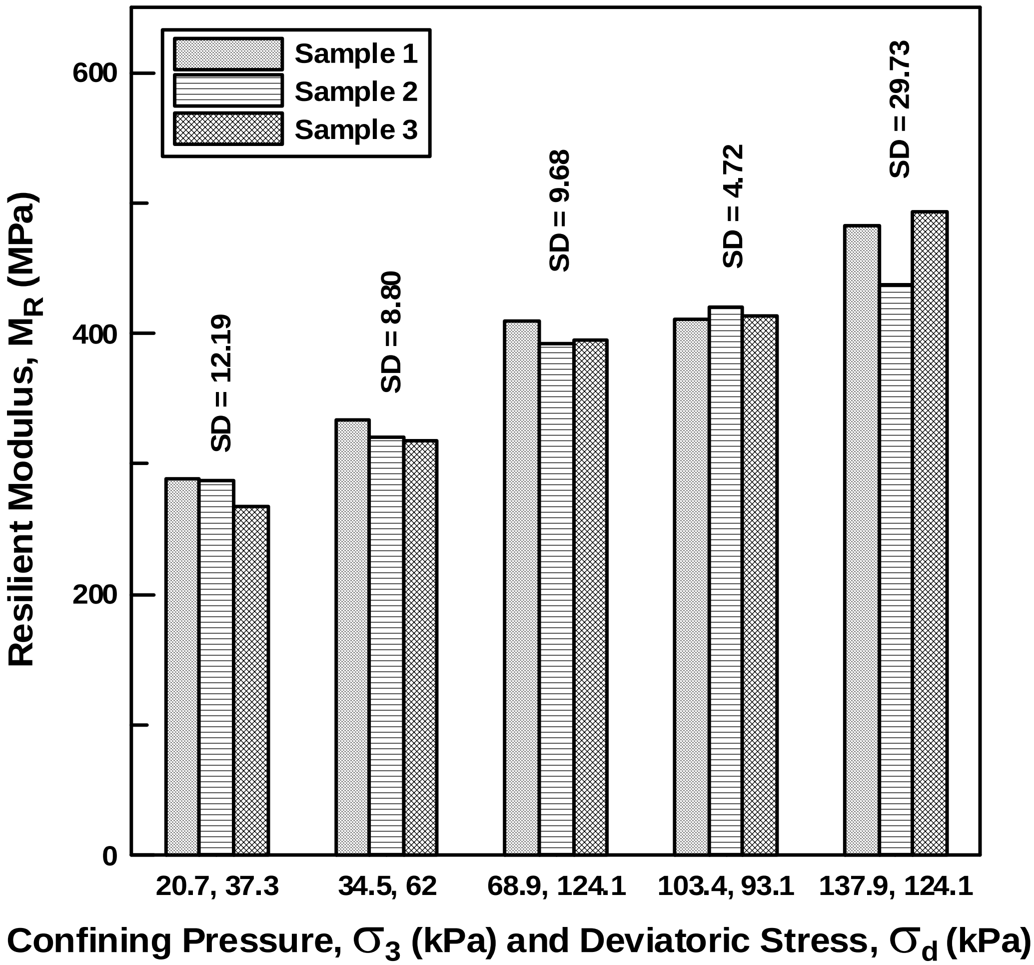
A total of three identical specimens were tested in this assessment. Results were statistically analyzed to determine both standard deviations and coefficients of variation. As seen from the results presented below in figures 4.1 and 4.2, the tests provided for excellent repeatability with standard deviations ranging from 1.8 to 5.2 MPa for untreated aggregate materials, and from 4.7 to 30 MPa for cemented aggregates.

High standard deviations were recorded at high resilient moduli and hence overall coefficients of variations are still low. This clearly indicates that the present resilient modulus test is providing good repeatable results when tests were conducted on identical specimens.



Note: SD in kPa

Figure 4.1 Resilient Modulus Test Results of Untreated Aggregates: Repeatability



Note: SD in kPa

Figure 4.2 Resilient Modulus Test Results of Cement Treated Aggregates: Repeatability

In order to address the reliability of the test results, the moduli results obtained from the present tests are compared with the results obtained from previous research studies performed on similar specimens using repeated load triaxial test equipment. Figure 4.3 presents the variation in M_R with respect to the bulk stress of various untreated reclaimed asphalt pavement materials from different studies including the present study. From the comparison of test results as outlined in Figure 4.2 below, it can be mentioned that the present measurements on untreated aggregates from this study can be termed as reliable.

Figure 4.4 compares the resilient modulus test results of cemented aggregates from this research with the research results on similar cemented aggregate specimen from an independent study conducted by Gnanendran (2003) at the University of New South Wales in Australia. From the plots, it is clear that the ranges of the results from both the studies are close to each other, thus establishing that the present test results on cemented aggregate specimens are also reliable.

The reclaimed asphalt pavement material specimens have been prepared at 0, 2 and 4% of cement content for specimens without fiber-reinforcement and at 2, 4 and 6% of cement content for specimens with fiber-reinforcement. The test results and discussions are as reported in the following sections.

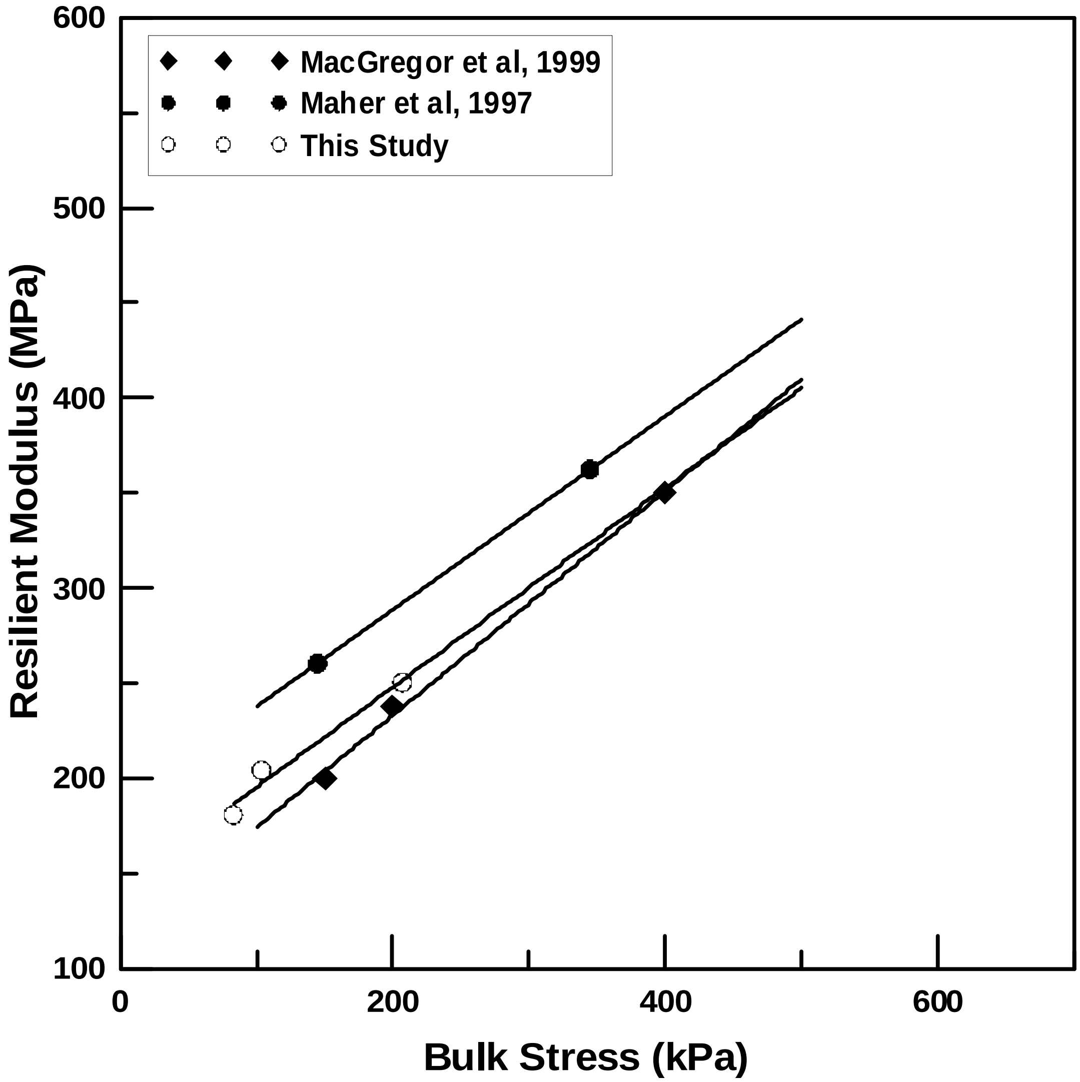


Figure 4.3 Resilient Modulus Test Results of Untreated Aggregates: Reliability

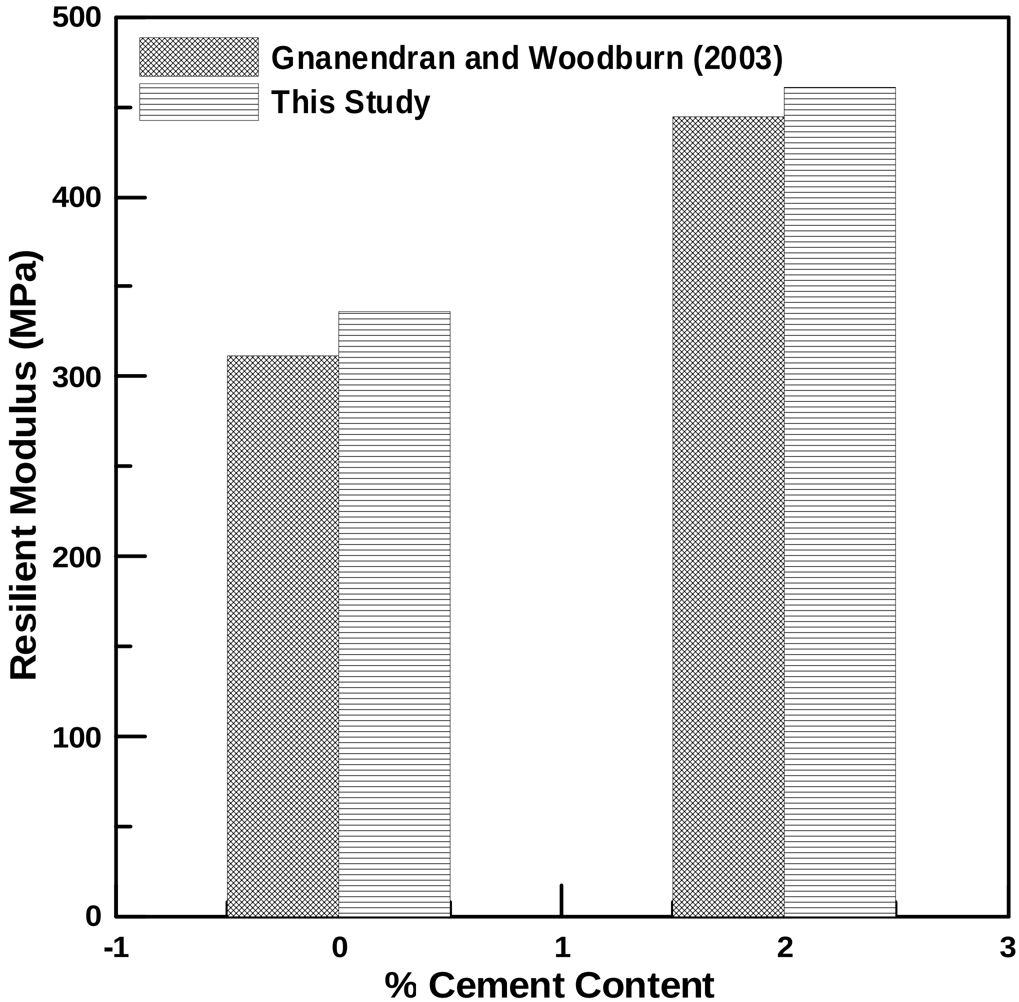


Figure 4.4 Resilient Modulus Test Results of Cement Treated Aggregates: Reliability

<u>4.3. Resilient Modulus Test Results for Untreated Specimens</u>

The resilient modulus test results for the control or untreated aggregate specimen subjected to a 7-day curing period are presented in the figure 4.5 below. From the plot, it can be mentioned that the M_R for the aggregate specimen increased with an increase in confinement. This behavior could be attributed to the fact that increasing confinements of the aggregate specimen tends to get denser and stronger specimens thereby exhibiting greater stiffnesses and hence higher resilient moduli. Also, for the same confining pressure applied, the M_R value increased with an increase in the deviatoric stress. This might be attributed to the fact that dense compacted specimens when subjected to higher axial loading, tend to get hardened, thereby yielding low axial strains and exhibiting high M_R values.

The increase in the M_R with an increase in the deviatoric stress, for the same confinement, seems to be moderate at higher confinements. This implies that the influence of deviatoric stress on the M_R values is less at higher confinements. This is because at higher confinements first stiffens the aggregate specimens and thus specimens do not exhibit any additional stiffening to higher deviatoric stresses. From the figure 4.5, the maximum M_R achieved for the control aggregate specimen is 335 MPa, which is found to be consistent with the range of values reported from other research studies such as those reported by MacGregor et al. (1999), Maher et al. (1997) and Gnanendran and Woodburn, (2003).

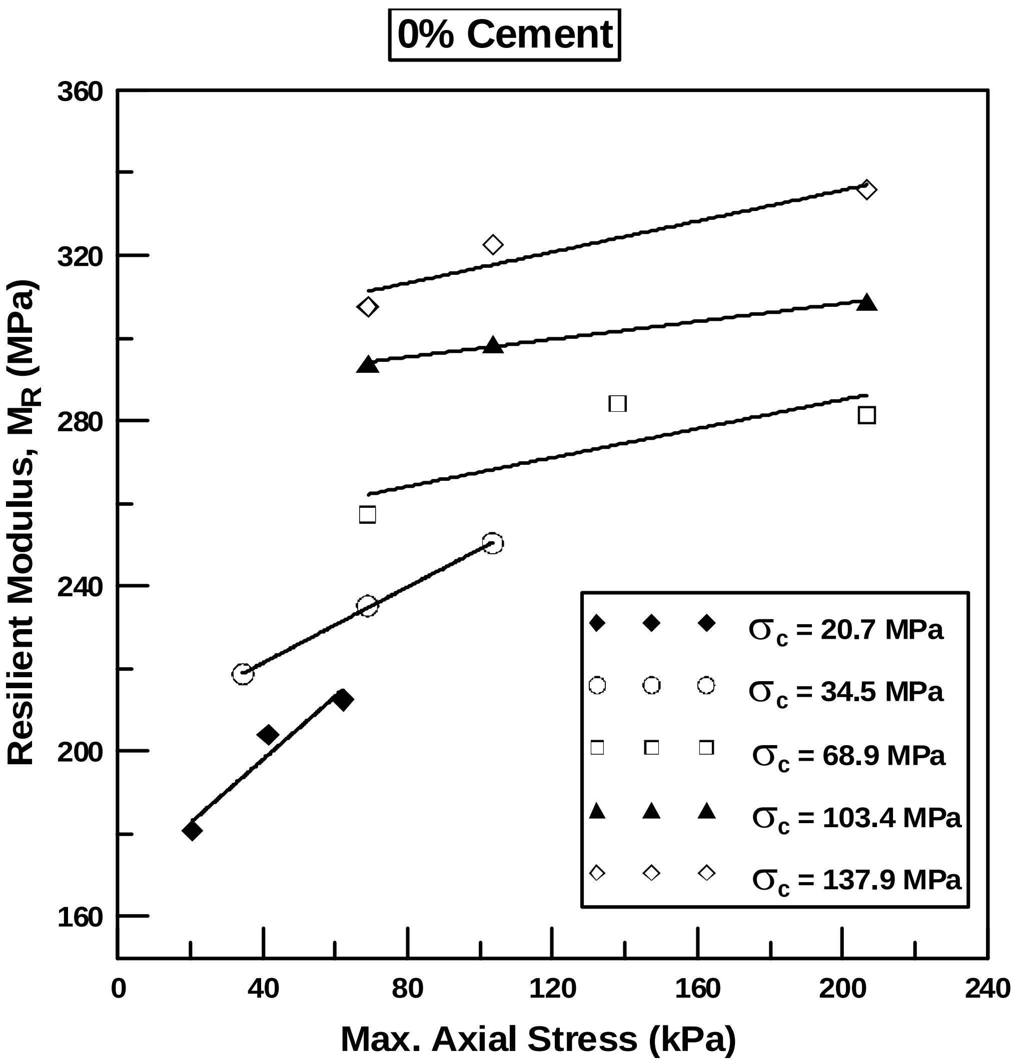


Figure 4.5 Resilient Modulus Test Results for Control Specimen

4.4 Resilient Modulus Test Results for Cement Treated Aggregate Specimens

The resilient modulus results for the cement treated specimens showed similar trends with respect to the changes in confining and deviatoric stresses as in the case of untreated/control specimens. Figures 4.6 to 4.15 below present the M_R results for the cement treated specimens both with and without fiber-reinforcement. Explanations of cementation and confining as well as deviatoric stresses on the resilient moduli are explained in the later sections.

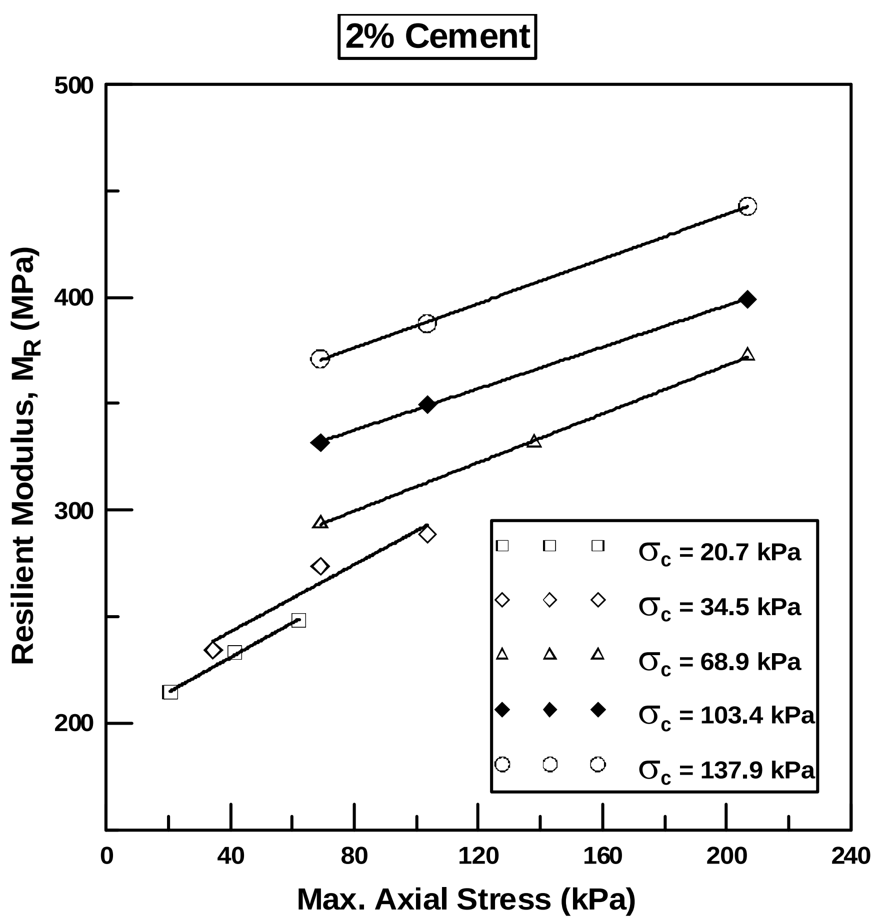


Figure 4.6 Resilient Modulus Test Results of 2% Cement Treated Specimens

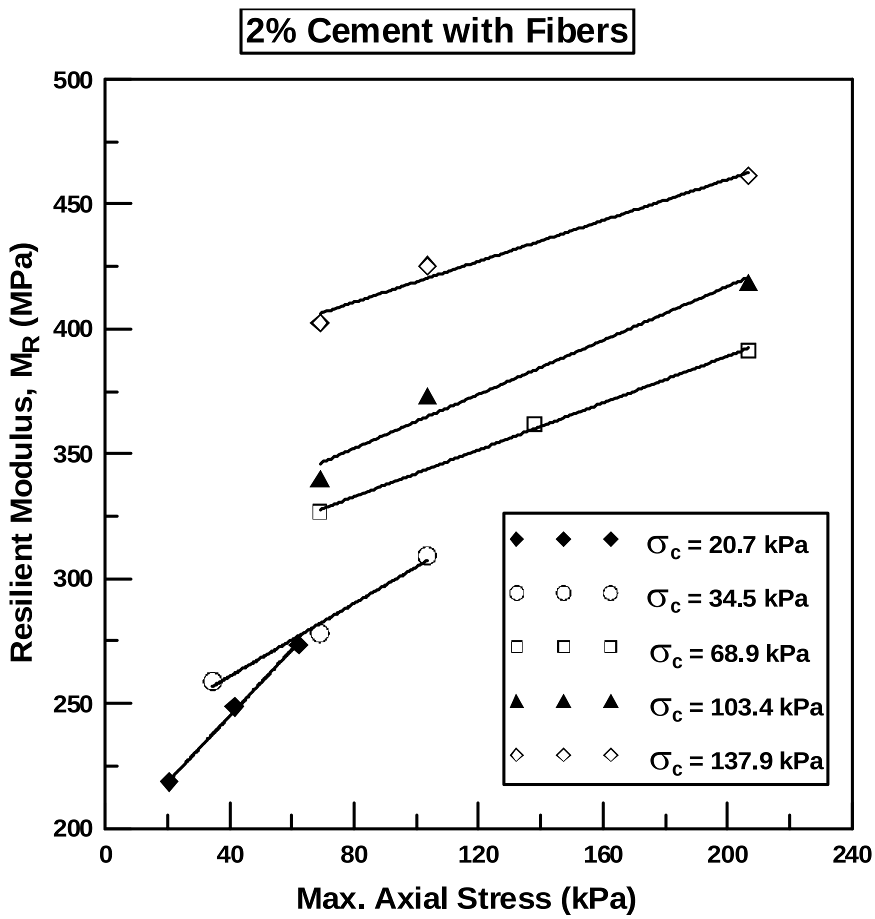


Figure 4.7 Resilient Modulus Test Results of 2% Cement-Fiber Treated Specimens

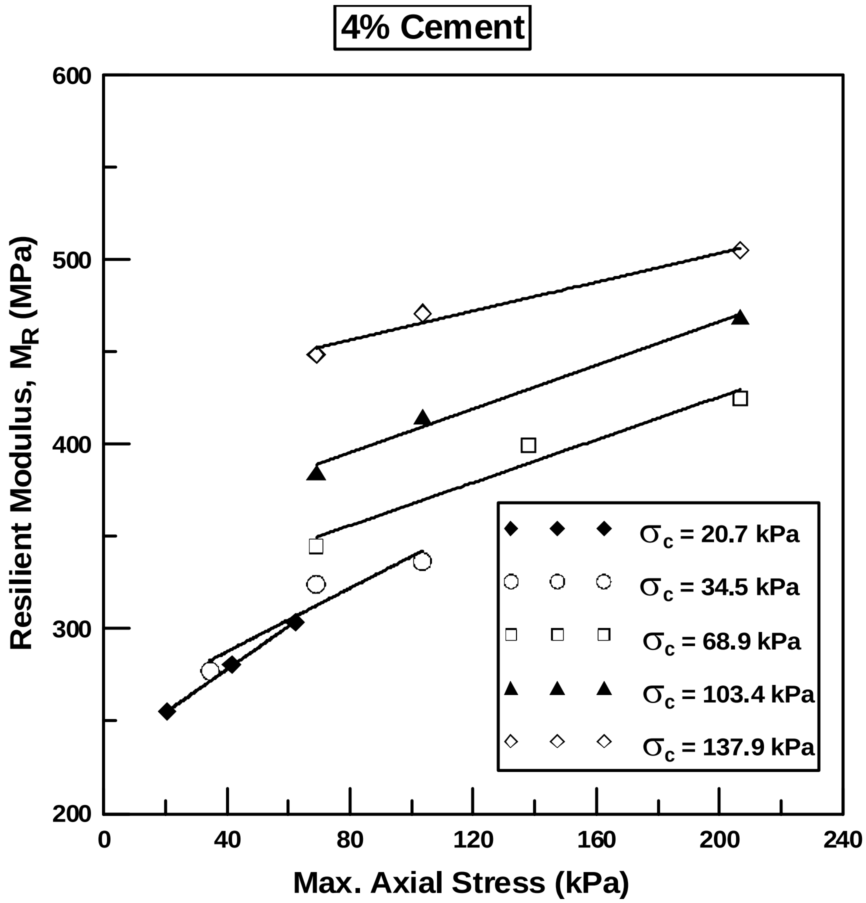


Figure 4.8 Resilient Modulus Test Results of 4% Cement Treated Specimens

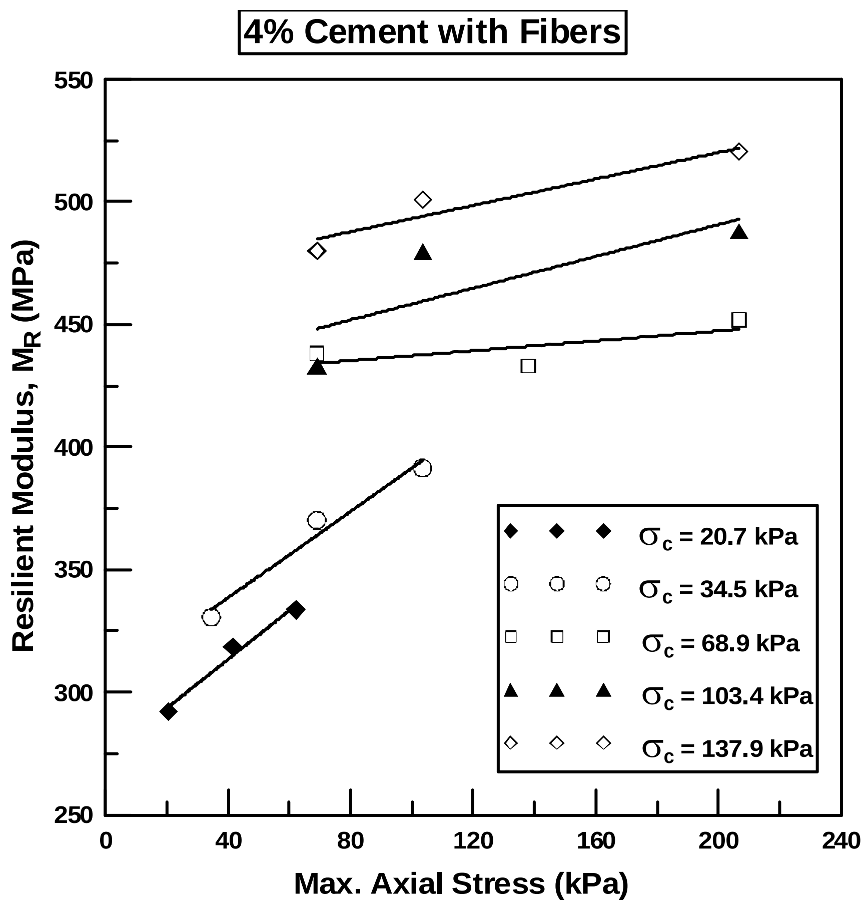


Figure 4.9 Resilient Modulus Test Results of 4% Cement-Fiber Treated Specimens

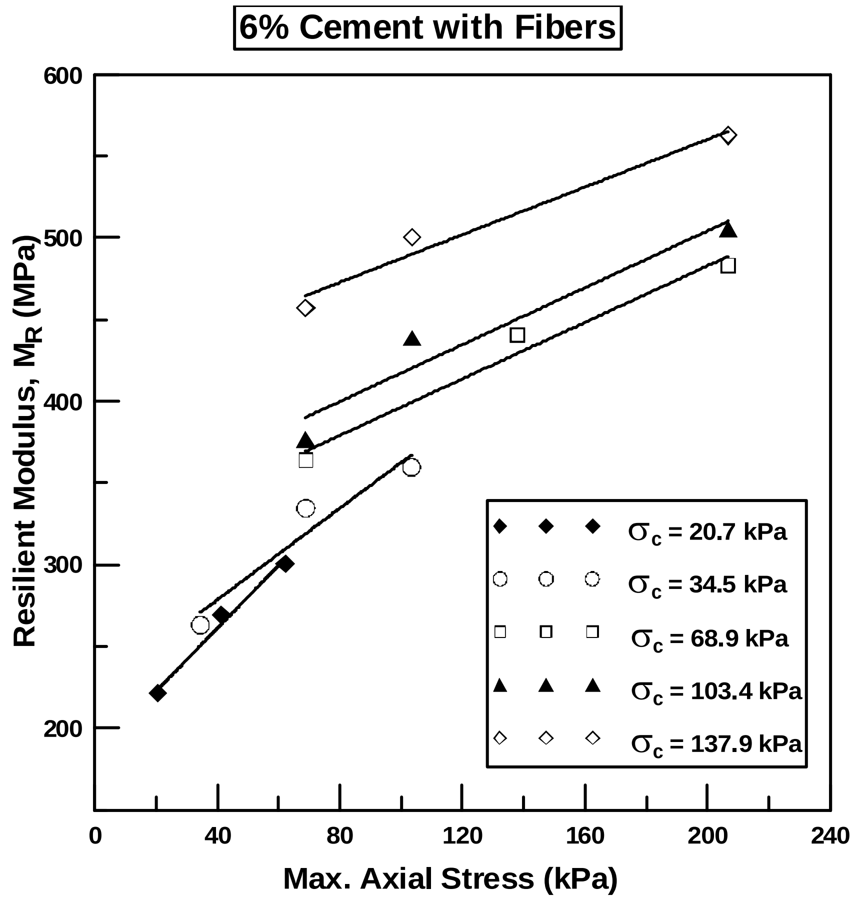


Figure 4.10 Resilient Modulus Test Results of 6% Cement-Fiber Treated Specimens

4.5 Effects of Confining and Deviatoric Stresses on M_R

From figures 4.6 to 4.15, it can be observed that both confining and deviatoric stresses have a significant effect on the resilient modulus of the reclaimed aggregate base materials. With an increase in the deviatoric stress, the modulus of the material increased due to stress hardening of the specimen. This effect is more pronounced even at lower confinements. As explained in the section 4.3, this behavior could be attributed to the fact 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 could be noted that the modulus of the cement aggregate material increased with increasing confinements. The increase in the resilient modulus with the increase in confinements is not as pronounced in specimens at higher cement contents. This is because at higher cement contents, the material is stiff and strong and hence is not influenced by the higher confinements. This is similar to loading a weak concrete specimen, which will be unaffected by the confinements.

4.6 Effects of Cement Content on M_R

The resilient modulus characteristics of the cement stabilized specimens, determined using the repeated load triaxial testing are summarized in the Figure 4.16 below. The figure 4.16 presents the resilient modulus values for the cement treated specimens tested over a range of confinements as proposed by AASHTO. It can be observed that the resilient modulus increases appreciably with increasing percent of cement at every confinement. For a maximum confining pressure of 137.9 kPa, the addition of 2% cement increased the M_R by 32% when compared to the same resilient modulus of untreated specimens.

For the same confinement, the addition of 4% cement increased the M_R by about 50% when compared to the same of untreated specimen. The maximum value of the resilient modulus achieved for a specimen treated with 4% cement is about 505 MPa. Thus cement appears to be an effective stabilizer for stabilizing the reclaimed asphalt pavement materials in achieving high strength and hence high resilient characteristics.

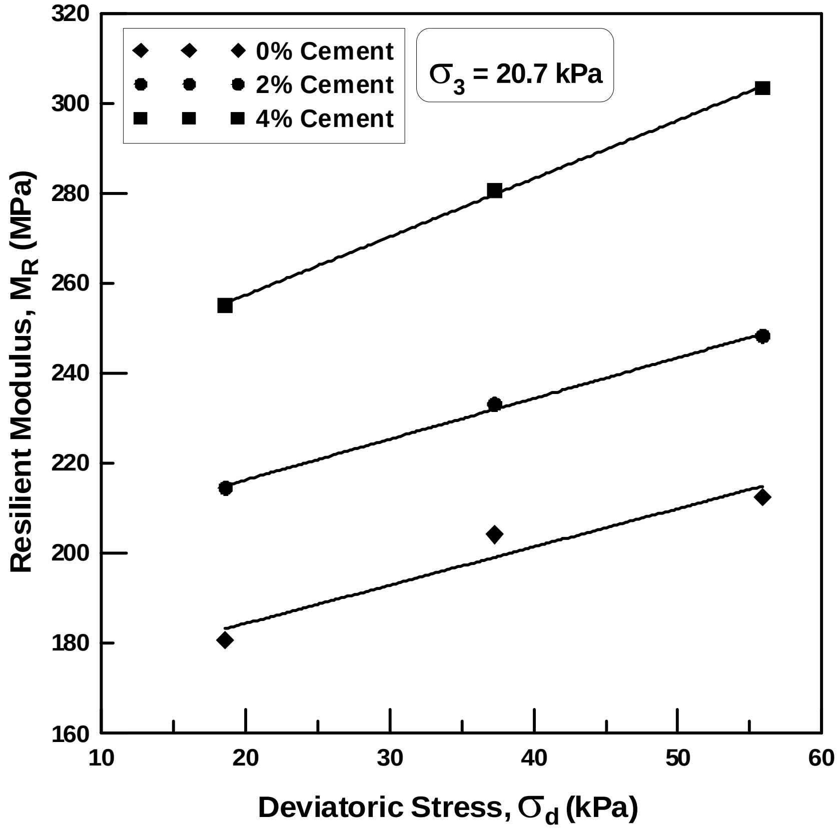


Figure 4.11 Influence of %Cement on Resilient Modulus Test Results (σ_3 = 20.7 kPa)

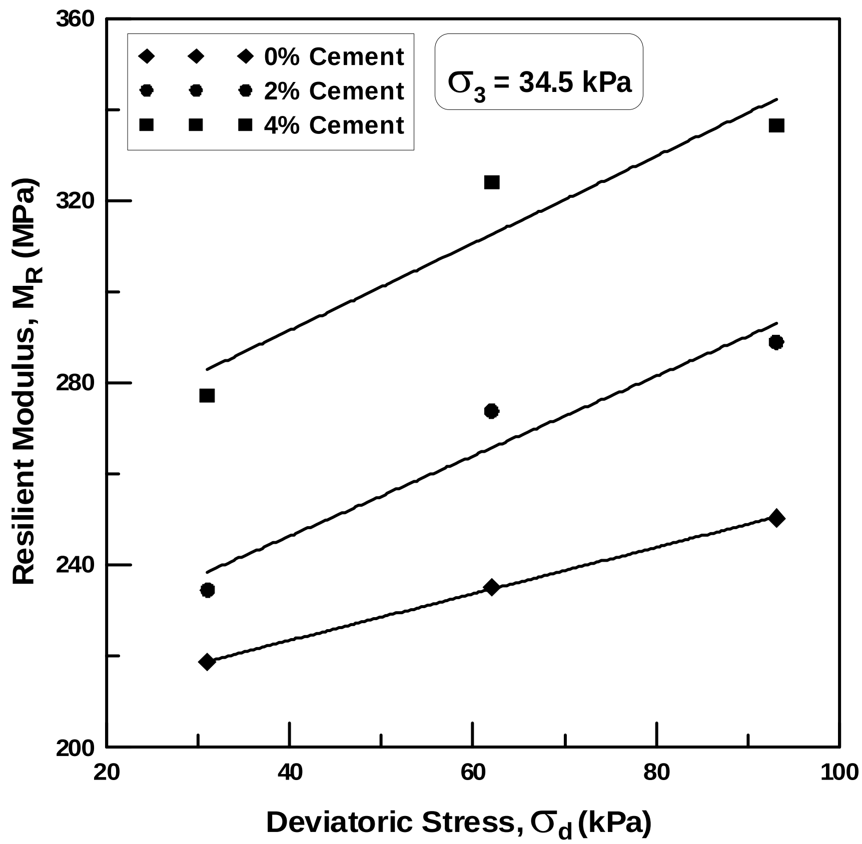


Figure 4.12 Influence of %Cement on Resilient Modulus Test Results (σ_3 = 34.5 kPa)

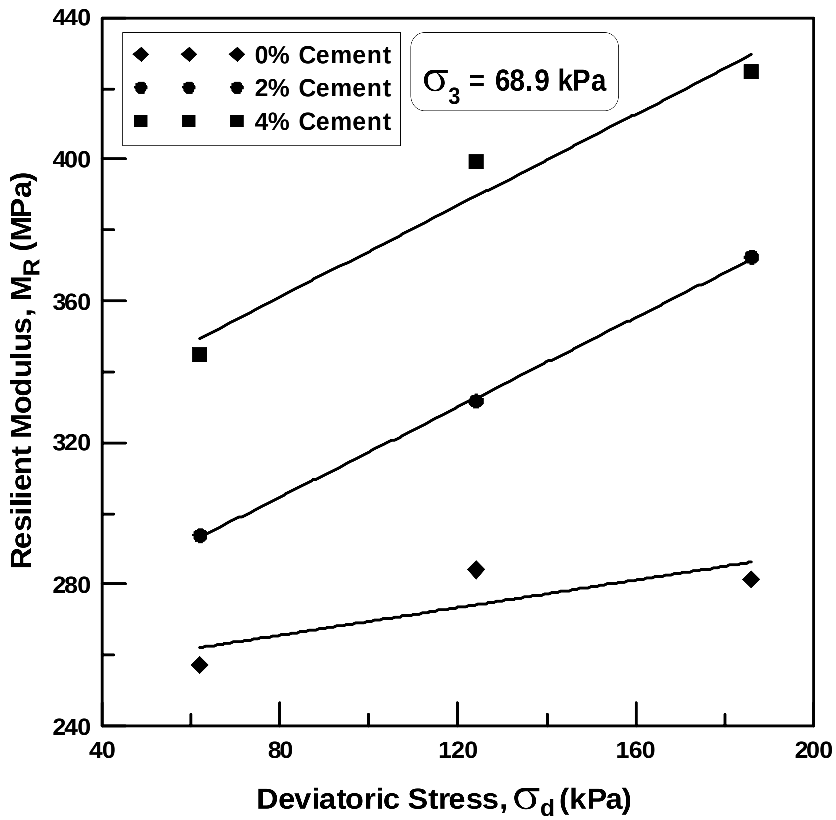


Figure 4.13 Influence of %Cement on Resilient Modulus Test Results (σ_3 = 68.9 kPa)

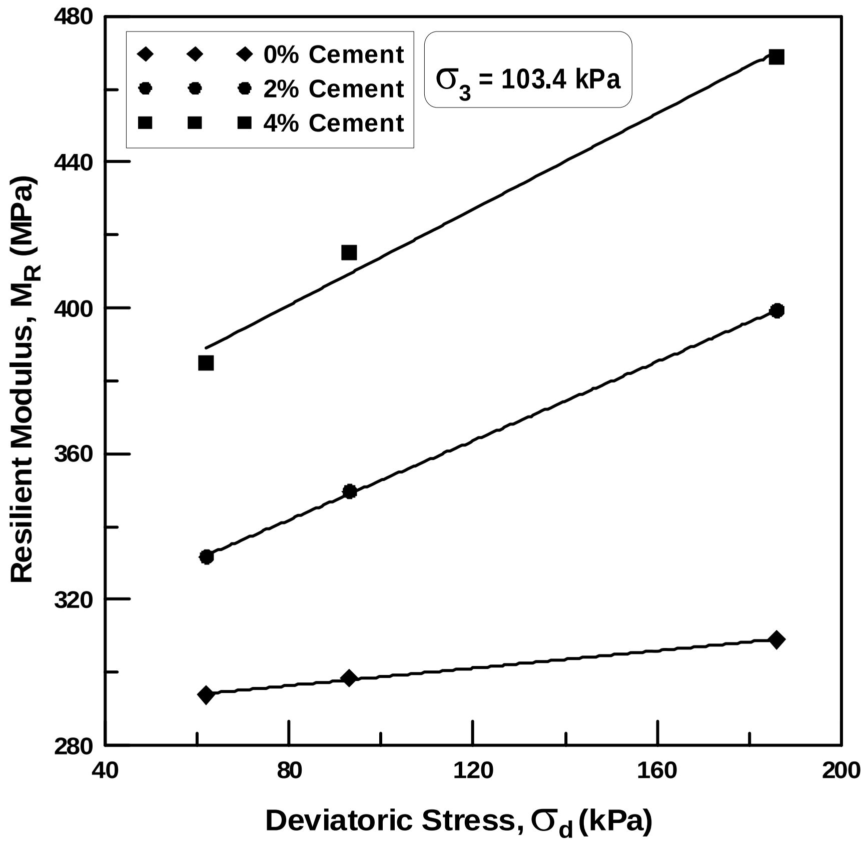


Figure 4.14 Influence of %Cement on Resilient Modulus Test Results (σ_3 = 103.4 kPa)

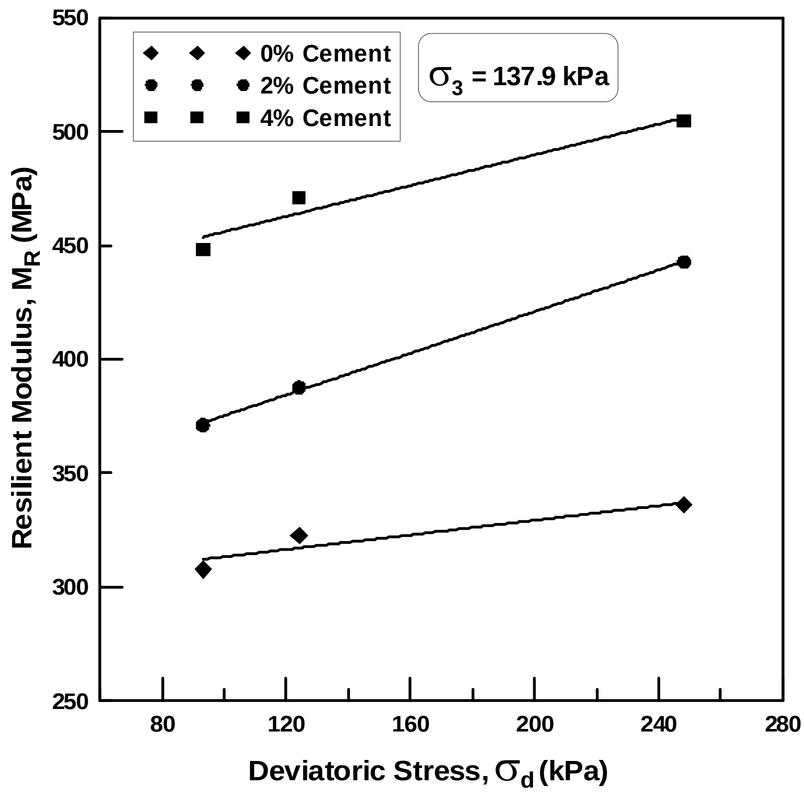


Figure 4.15 Influence of %Cement on Resilient Modulus Test Results (σ_3 = 137.9 kPa)

Cement treated Samples with fiber reinforcements also showed the same trends, as those without fiber-reinforcement. Figures 4.17 to 4.20 presents these results for combined cement and fiber treated specimens.

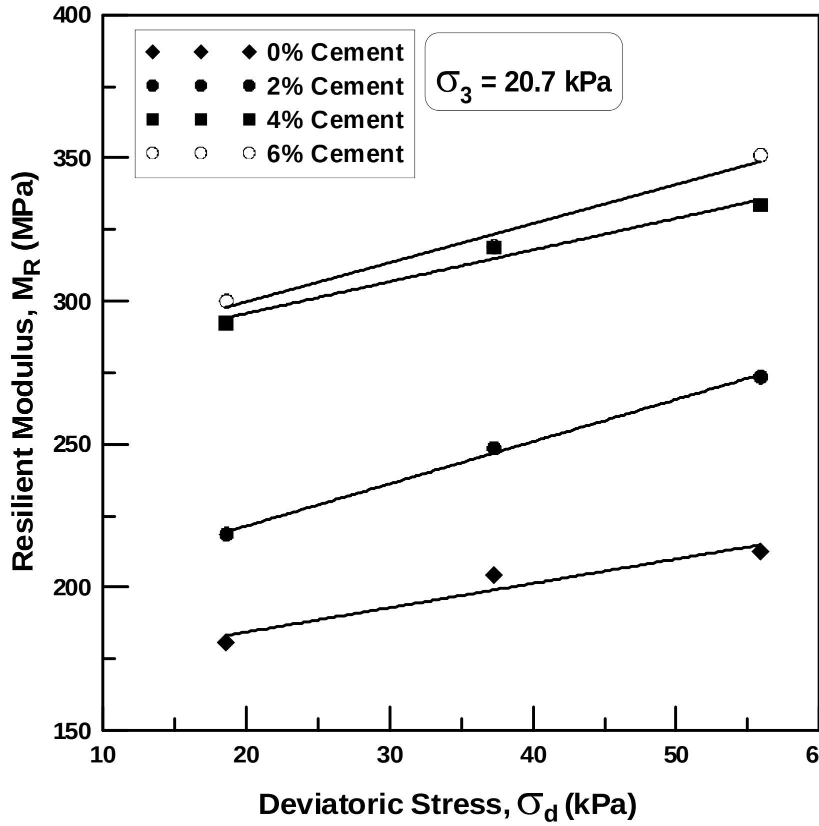


Figure 4.16 Influence of %Cement-fiber on Resilient Modulus Test Results (σ_3 = 20.7 kPa)

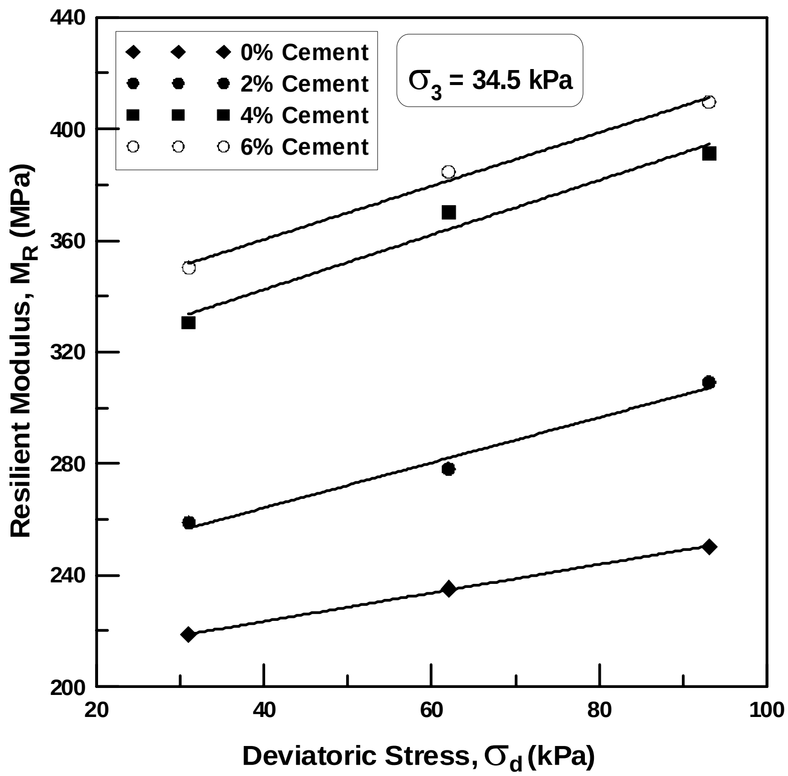


Figure 4.17 Influence of %Cement-fiber on Resilient Modulus Test Results (σ_3 = 34.5 kPa)

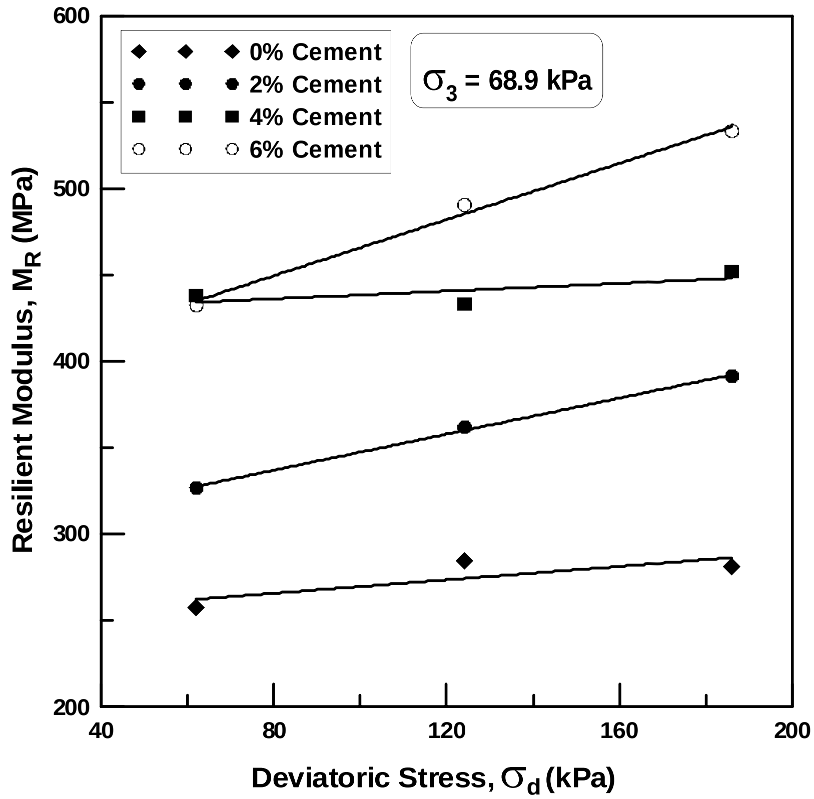


Figure 4.18 Influence of %Cement-fiber on Resilient Modulus Test Results (σ_3 = 68.9 kPa)

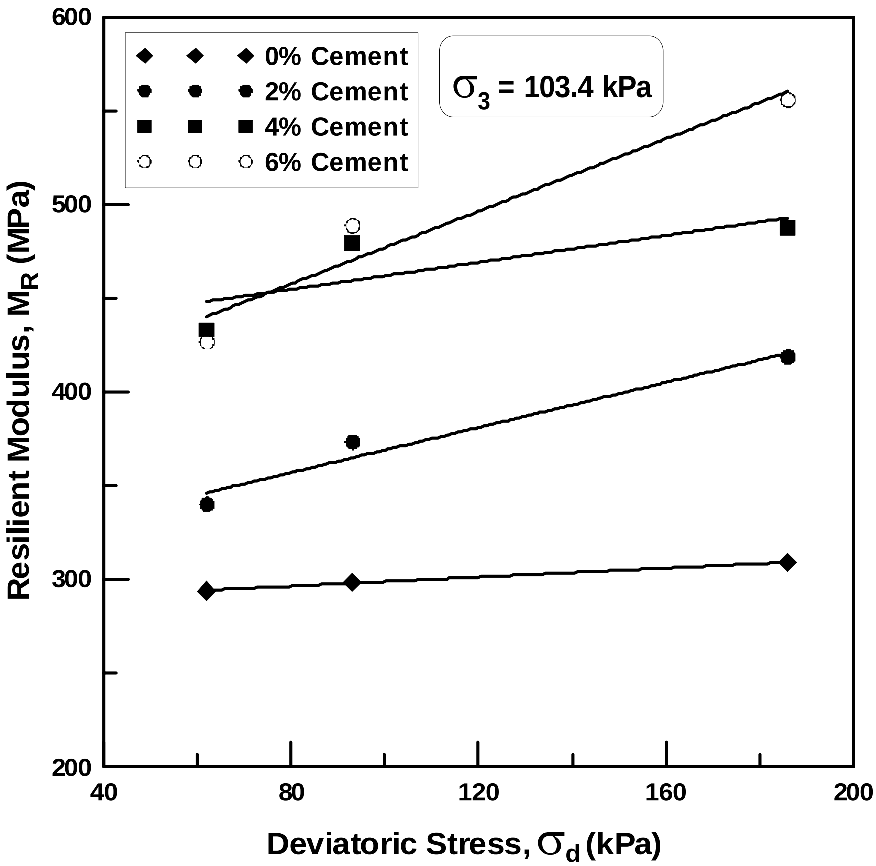


Figure 4.19 Influence of %Cement-fiber on Resilient Modulus Test Results (σ_3 = 103.4 kPa)

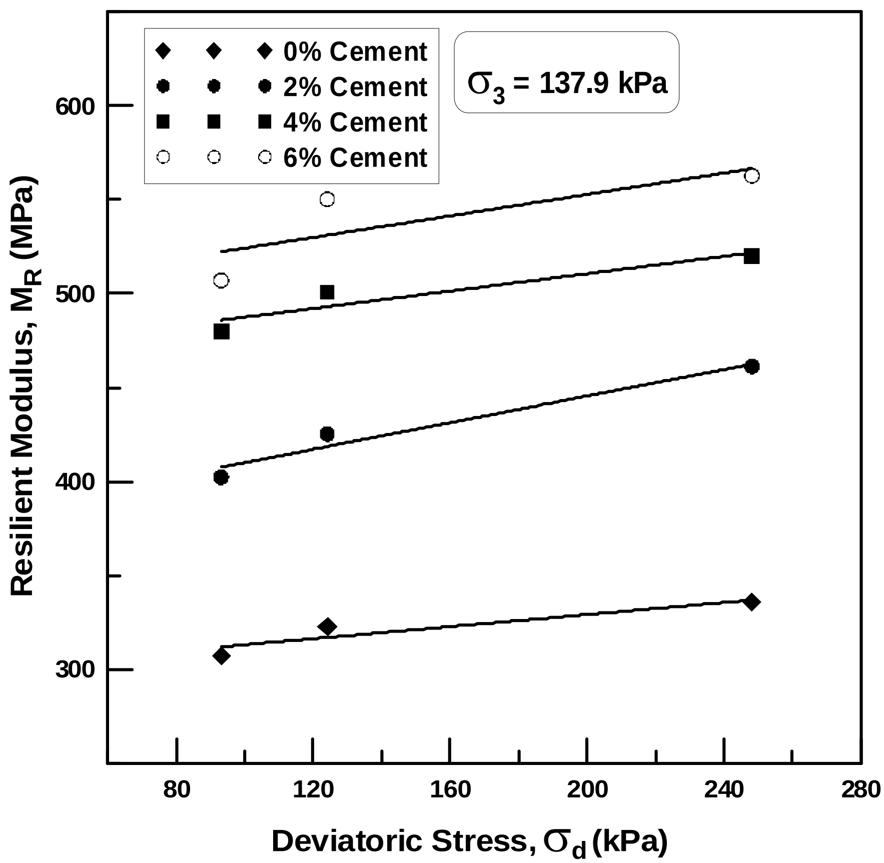


Figure 4.20 Influence of %Cement-fiber on Resilient Modulus Test Results (σ_3 = 137.9 kPa)

4.7 Statistical Analysis

The method of analysis used here is statistical comparison test, t-test. The main intent of this analysis is to evaluate whether cement and cement-fiber treatments of the present RAP aggregates provided statistically significant enhancements to their resilient moduli properties. In the t-test, the mean values of resilient modulus of natural or untreated aggregates and cement or cement-fiber treated aggregates are compared. A statistical program was used to perform all these analyses in this research. A p-value of 0.05 was used, which means that there is less than a 5% chance that the average moduli values of treated aggregates are not truly different from those of the untreated aggregates. The following describes the basic hypotheses used in this research.

$H_0 : \mu_1 = \mu_2$ (The means of the M_R of untreated and treated aggregates are the same)

$H_1 : \mu_1 \neq \mu_2$ (The means of the M_R of untreated and treated aggregates are different)

Where μ_1 = Mean of the resilient moduli of control aggregate specimens

μ_2 = Mean of the resilient moduli of treated aggregate specimens

When significant differences in moduli are found, the effectiveness of either cement or cement-fiber treatment in enhancing the resilient properties can be explained by comparing the treated moduli properties with the untreated aggregate moduli. However, if the statistical analysis does not show any significant difference, then it can be concluded that the present cement and cement - fiber treatments have not resulted in any enhancements to moduli properties of aggregate specimens.

Table 4.1 below presents the t-test results. As can be seen from the table below, there is no statistically significant difference between the control/untreated specimen and the 2% cement treated specimen. This implies that, by treating the aggregate specimen with 2% cement, there is not any significant increase in the modulus of the specimen material. Also from the table 4.1, it can be mentioned that the addition of fibers in the 2% cement treated aggregates resulted in a significant increase in the modulus of the specimen when compared to the control specimen. Thus the inclusion of fibers had a positive influence on the reclaimed aggregate material.

Other t-tests concluded that the addition of both cement and cement-fibers to the aggregates resulted in enhanced moduli, which are statistically significantly higher than those of untreated aggregates. Hence, overall, it can be concluded that cement treatment and cement - fiber treatment provided resilient moduli enhancements. Fiber enhancements were noted at lower cement dosages (2%) than at higher cement dosage (4%). This can be attributed to the fact that higher cement dosage results in higher moduli and hence any improvements thereafter are not considerably significant.

To further understand the effects of fiber treatments, several t-tests were conducted between cement treated aggregate groups and cement-fiber treated aggregate groups. These results are reported in the Tables 4.1 (cement treated group) and 4.2 (cement-fiber treated group).

Table 4.1 presents the test results comparing the cement treated specimens with the control specimen. The addition of 2% cement did not provide any significant enhancements in the moduli of the material. However, the addition of fibers for the same cement content (2%) resulted in a statistically significant difference in the moduli of the same materials when compared to the moduli of control specimen. Higher cement contents (4% and 6%), both with and without fiber reinforcement, exhibited a significant improvement in the moduli of the material over the control aggregate specimen.

Table 4.2 compares the cement-fiber treated specimens with the cement treated specimens. Also, there was no significant difference in the moduli of the material with the addition of fibers for the same cement content.

Table 4.1 t-test Results on Untreated and Cement Treated Aggregates

t-test Groups	**p value**	**Significant Difference (Yes/No)?**	**E - Effective, NE – Not Effective**
Control or Untreated Aggregates Versus 2% Cement Treated Aggregates	0.054	No	NE
Control or Untreated Aggregates Versus 4% Cement Treated Aggregates	< 0.0001	Yes	E
Control or Untreated Aggregates Versus 2% Cement - Fiber Treated Aggregates	0.0031	Yes	E
Control or Untreated Aggregates Versus 4% Cement - Fiber Treated Aggregates	< 0.0001	Yes	E
Control or Untreated Aggregates Versus 6% Cement - Fiber Treated Aggregates	< 0.0001	Yes	E

Table 4.2: t-Test Results on Cement Treated and Cement-Fiber Treated Aggregates

t-test Groups	**p value**	**Significant Difference (Yes/No)?**	**E - Effective, NE – Not Effective**
2% Cement Treated Aggregates Versus 2% Cement - Fiber Treated Aggregates	0.428	No	NE
4% Cement Treated Aggregates Versus 4% Cement - Fiber Treated Aggregates	0.148	No	NE

4.8 Resilient Modulus Modeling

4.8.1 Theta Model (Two-Parameter)

The AASHTO test procedures recommend analysis of resilient modulus test results by using different regression models such as bulk stress model and deviatoric stress model. Since the present research is conducted on aggregate materials, bulk stress modeling is used here to analyze the present test results. Bulk stress model can be presented in the following equation 1:

$$M_R = k_1 \times \theta^{k_2} \tag{1}$$

The logarithmic form of the same expression can be listed as:

$$\log(M_R) = \log(k_1) + k_2 \times \log(\theta) \tag{2}$$

Where,

M_R = Resilient Modulus

θ = Bulk stress

k_1 and k_2 = Theta model parameters

The present research results were analyzed with the linear statistical regression program to determine both log k_1 and k_2 parameters. Regression results of the present test results are showed in Figures 4.21 (cement treated aggregates) and 4.22 (cement fiber treated aggregates). The theta model constants, log k_1, k_2 and the coefficient of determination values are presented in Table 4.3.

The coefficient of determination values of all test results when analyzed with 'Theta model' ranged from 0.97 to 1.00, suggesting that a very good correlation was obtained with the statistical regression analysis. The constant parameter, log k_1, which is an indicator of resilient moduli magnitudes, varied between 3.00 to 3.58 and the k_2 parameter, which denotes or represents the non-linearity nature of the stress dependency, varied from 0.81 to 1.00.

For highly cemented materials (except for 4% cement-fiber treated aggregates), the resilient moduli appears to follow close a linear variation with respect to bulk stress. Though log k_1 trend was difficult to explain with respect to cement and cement – fiber treatment, it should be noted that the final resilient moduli properties should require both model constants for determining the moduli values.

Table 4.3 Regression Analysis of Theta Model

Notation	**Log** k_1	k_2	**Coefficient of Determination,** R^2
Untreated Aggregate	3.36	0.82	0.98
2% Cement Treated Aggregate	3.01	0.99	0.98
4% Cement Treated Aggregate	3.15	0.96	0.98
2% Cement-Fiber Treated Aggregate	3.00	1.00	1.00
4% Cement-Fiber Treated Aggregate	3.58	0.81	0.96
6% Cement-Fiber Treated Aggregate	3.30	0.92	0.97

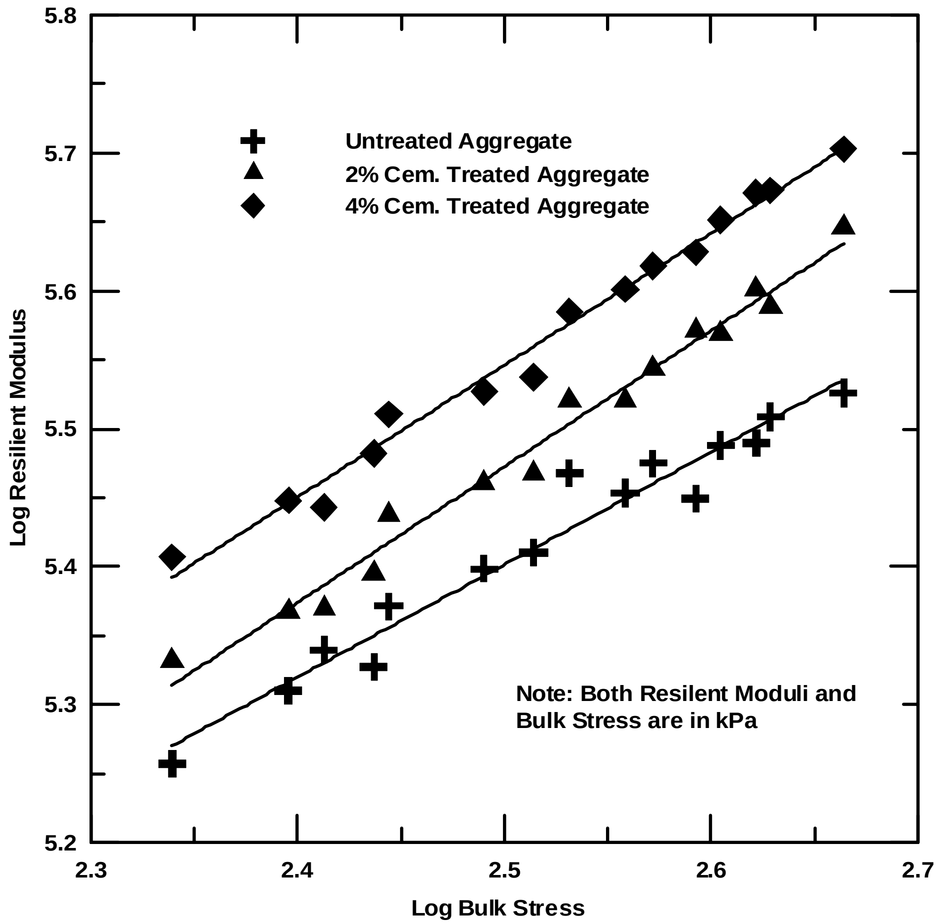


Figure 4.21 Theta Model Analysis: Cement Treated Aggregates

Limitations of the bulk stress models are that they do not account for individual confining and deviatoric stresses and the two model constants are too simple to fully account for exact variations of the resilient moduli values. Hence, more rigorous resilient property correlations are developed in the literature (Barksdale et al 1990). Hence, further analysis was conducted using such comprehensive resilient moduli models. Details of this analysis are presented in the next section.

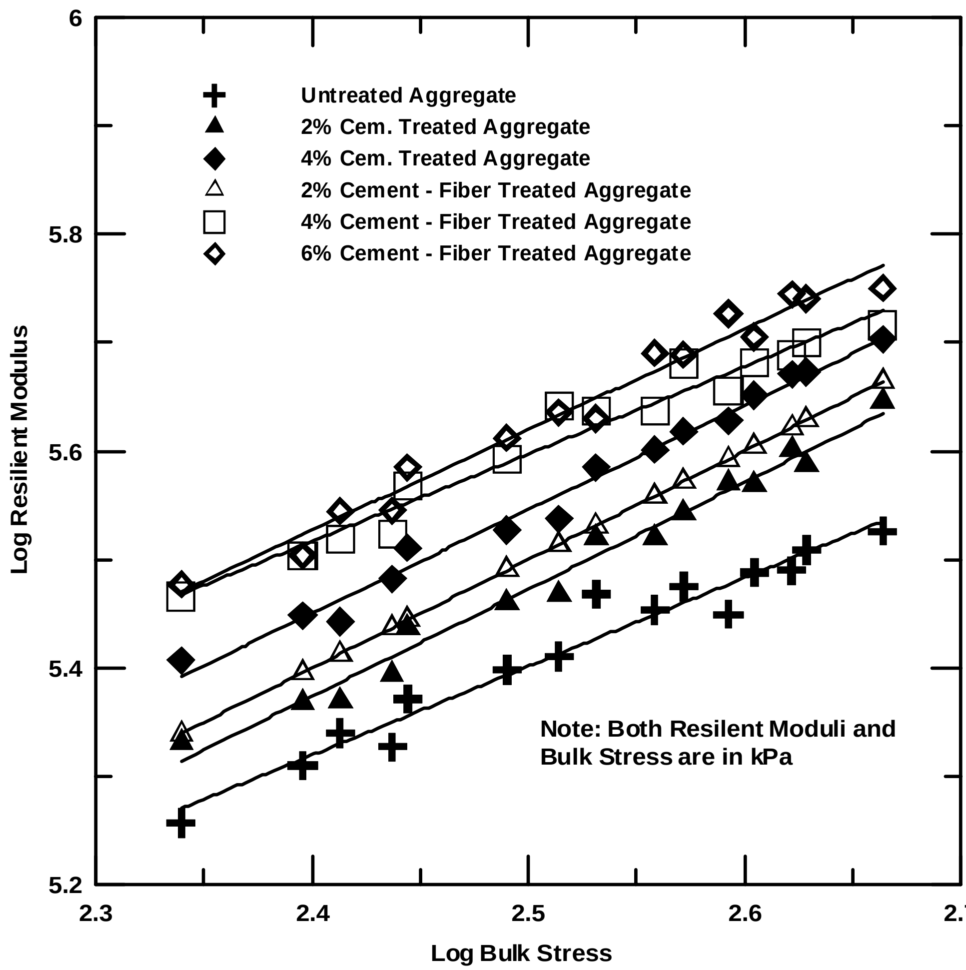


Figure 4.22 Theta Model Analysis: Cement-Fiber Treated Aggregates

4.8.2 Three-Parameter Resilient Modulus Model

The following equation 3 presents a three parameter resilient modulus model that accounts for both confining and deviatoric stresses (Puppala et al. 1997):

$$\frac{M_R}{\sigma_{atm}} = k_3 \times \left(\frac{\sigma_3}{\sigma_{atm}}\right)^{k_4} \times \left(\frac{\sigma_d}{\sigma_{atm}}\right)^{k5} \quad (3)$$

Applying logarithmic form on both sides of the equation results in the following form:

$$\log\left(\frac{M_R}{\sigma_{atm}}\right) = \log(k_3) + k_4 \times \log\left(\frac{\sigma_3}{\sigma_{atm}}\right) + k_5 \times \log\left(\frac{\sigma_d}{\sigma_{atm}}\right) \quad (4)$$

Where

σ_{atm} = atmospheric pressure

σ_3 = confining pressure

σ_d = deviatoric stress

k_3, k_4, k_5 = three parameter model constants.

Since this Equation has more than one parameter, multiple linear regression modeling analysis was attempted to analyze the present test results. It should be noted that the model constant parameters are non-dimensional since stress normalization was used in the above correlation. Table 4.4 presents the regression analysis results including model constant parameters and coefficient of determination values.

A close scrutiny of the present regression model analysis revealed the following important observations:

- High coefficient of determination values were obtained for all aggregate samples, indicating that the present three parameter formulation provided a good simulation of both confining and deviatoric stress effects on the resilient moduli values.

Table 4.4 Regression Analysis of Three Parameter Model

Notation	**log k_3**	**k_4**	**k_5**	**R^2**
Untreated Aggregate	3.47	0.20	0.09	0.98
2% Cement Treated Aggregate	3.55	0.19	0.15	0.97
4% Cement Treated Aggregate	3.62	0.19	0.14	0.96
2% Cement-Fiber Treated Aggregate	3.58	0.20	0.15	0.97
4% Cement-Fiber Treated Aggregate	3.66	0.19	0.09	0.98
6% Cement-Fiber Treated Aggregate	3.69	0.17	0.15	0.97

- The constant parameter of the model correlation, log k_3 varied from 3.47 to 3.69, with a low value being reported for untreated aggregates and high values being obtained for both cement and cement-fiber treated aggregates.
- The variation between log k_3 parameter between cement treated and cement-fiber treated aggregates is small (less than 0.04) and always higher value was obtained for cement-fiber treated aggregates. This trend is consistent with the present resilient moduli results showing higher moduli properties for cement-fiber treated aggregates than corresponding cement treated aggregates.
- The k_4 parameter is close to 0.19, indicating the resilient moduli results are showing a non-linear type confining pressure dependency. It is interesting to note that both cement and cement-fiber treatments resulted in no major variation in this constant parameter.
- The k_5 parameter, on the other hand, varies between 0.09 to 0.15, with a low value of 0.09 was being obtained for untreated aggregate specimens and value close to 0.15 was obtained for cement treated aggregates with the exception of 4% cement-fiber treated aggregates.
- Since the k_5 value is a positive value, it can be mentioned that stress hardening is taking place in the present aggregate materials. This is expected since granular aggregate materials in general tend to display or undergo stress hardening phenomenon, i.e. an increase in resilient moduli with an increase in deviatoric stress under the same confining pressure.

Comparisons between both two-parameter theta and three parameter resilient moduli model clearly showed that the more comprehensive three parameter model provided better simulation and explanation of both confining and deviatoric stress effects. Author recommends the use of this three parameter model for future estimation of resilient properties of the present aggregate materials at different sets of confining and deviatoric stresses.

4.9 Summary

This chapter describes the resilient moduli properties of reclaimed asphalt pavement materials stabilized with cement and cement-fibers. Effects of cement content, fibers, confining and deviatoric stresses on the resilient properties are explained. Statistical analyses using t-test are conducted to evaluate the stabilization effectiveness of cement and cement-fiber treatments in statistical significant terms. The final section covers the regression modeling analysis of the resilient moduli results using both two parameter theta model and a three parameter confining pressure and deviatoric stress model.

CHAPTER 5

FLEXIBLE PAVEMENT DESIGN CHARTS

5.1 Introduction

This chapter presents various methods to determine the structural coefficients of both untreated and cement treated aggregates. This determination is based on the resilient moduli magnitudes determined from the experimental testing. Then several flexible pavement design examples are provided in which base layer thicknesses are determined for different RAP materials under different traffic related ESAL conditions and subgrade conditions.

5.2 Structural Coefficients

As noted earlier, the AASHTO standard test procedure, T 307-99 has been employed for the determination of resilient modulus of the test specimens. The combinations of deviatoric and confining stresses applied in the test sequence have been used to determine various average subgrade resilient moduli for different confining pressure conditions. If specific confining and deviatoric stresses of aggregate bases under pavement loading conditions are known, one can directly use the measured moduli from the same conditions. For the present research, average moduli, from the measured moduli at three different deviatoric pressures, is calculated for each confining pressure condition. The same step is repeated for each cement and cement–fiber dosage contents. These results can be seen in Tables 1 (untreated and cement treated) and 2 (cement-fiber treated). In order to determine the structural coefficients, the following AASHTO (1993) equation 1 was used:

$$a_2 = 0.249 \times \log M_R - 0.977 \quad (1)$$

Where a_2 is structural coefficient; M_R is the resilient modulus in psi. This equation was used along with the average resilient moduli to determine the a_2 values, which are included in the same tables 1 and 2.

The structural coefficient values ranged from 0.13 to 0.24 and this range is in agreement with those materials reported by Janoo (1994) for New Hampshire DOT. As expected, the structural coefficient values increase with the confining pressure and they are higher for cement and cement-fiber treated aggregates.

It should be noted that the structural coefficients determined by the above procedure still need to be verified with other methodologies including the field falling weight deflectometer measurements on both untreated and cement treated aggregate materials.

5.3 Flexible Pavement Design

A flexible pavement cross-section would generally consist of an asphalt surface, a base layer, a subbase layer and a subgrade. The subbase layer is not adopted in some cases.

Table 5.1 Average Resilient Moduli of Untreated and Cement Treated Aggregates

Notation	Confining Pressure (kPa)	Average Resilient Moduli (MPa)	Structural Coefficient, a_2
Untreated	20.7	199	0.13
	34.7	235	0.15
	68.9	274	0.17
	103.4	300	0.18
	134.7	321	0.19
2% Cement Treated	20.7	231	0.15
	34.7	265	0.16
	68.9	332	0.19
	103.4	360	0.20
	134.7	400	0.21
4% Cement Treated	20.7	247	0.16
	34.7	282	0.17
	68.9	360	0.20
	103.4	377	0.20
	134.7	430	0.22

Table 5.2 Average Resilient Moduli of Cement-Fiber Treated Aggregates

Notation	**Confining Pressure (kPa)**	**Average Resilient Moduli (MPa)**	**Structural Coefficient, a_2**
2% Cement-Fiber Treated	20.7	280	0.17
	34.7	313	0.18
	68.9	390	0.21
	103.4	423	0.22
	134.7	475	0.23
4% Cement-Fiber Treated	20.7	315	0.18
	34.7	364	0.20
	68.9	441	0.22
	103.4	467	0.23
	134.7	500	0.23
6% Cement-Fiber Treated	20.7	323	0.19
	34.7	381	0.20
	68.9	485	0.23
	103.4	490	0.23
	134.7	540	0.24

In this present study, the flexible pavement design analysis was undertaken by using the reclaimed asphalt pavement aggregates stabilized with cement and fibers as a base material. A few conditions were assumed and the properties for the asphalt surface, and the subgrade layers were held constant in the analysis. The subbase layer was not adopted in the present study. The traffic and material properties assumed for the analysis are presented in Tables 5.3 and 5.4.

Table 5.3 Traffic Variables for the Three Types of Highway System

Variable Type	**Interstate Highway**	**State Highway**	**City Road**
ESALs (in millions)	1, 10 and 40	1, 10 and 20	0.1, 1, 10
Reliability (%)	90	85	80
Standard Deviation	0.45	0.45	0.45
Initial Serviceability	4.5	4.5	4.5
Final Serviceability	2.50	2.25	2.00

Table 5.4 Material Variables for the Three Types of Highway System

Variable Type	**Interstate Highway**	**State Highway**	**City Road**
Asphalt Pavement, Structural Coefficient	0.40	0.40	0.40
Resilient Modulus (MPa)	5, 10 and 20 ksi	5, 10 and 20 ksi	5, 10 and 20 ksi

The design analysis undertaken in this study has been dealt with in three subgroups and each subgroup tackles traffic conditions expected for interstate (high volume traffic), state highway (medium to low volume) and the city roads (low volume). The factors differentiating these groups are reliability, standard deviation, and change in serviceability indexes, which are provided by the AASHTO design guide. Different values of reliability, standard deviation, change in serviceability indices have been used depending on the class of highways under pavement design. The following steps have then been followed in the flexible pavement design of the different classes of highways.

- The resilient modulus for the subgrade soils has been assumed for three types of subgrade soil conditions and the structural number has then been determined based on the assumed subgrade modulus and the traffic levels for the above mentioned pavement conditions.
- The reclaimed aggregate base material modulus determined from the repeated load triaxial testing has been used to determine the structural layer coefficient for the base layer. The correlation (a) as shown above and recommended by AASHTO (1993) guide for design of Flexible pavements was used in determining the base layer coefficient. The base layer thicknesses have then been determined from the structural number, the base layer coefficient, the asphalt layer properties and the assumed traffic levels (18-kip ESALs). The base layer thicknesses have thus been arrived at for different base layer moduli.
- Design charts with base layer moduli on one axis and the arrived at base layer thickness on the other have been prepared for different traffic levels.

Three design charts have been prepared for each class of highway considered here and for three different subgrade soil moduli conditions. Each chart provides base layer thickness for different base layer moduli (those correspond to the present researched moduli properties) and different traffic volume in terms of ESAL conditions.

Tables 5.5, 5.6 and 5.7 below present the base layer thicknesses for the respective highways class considered in this research, corresponding subgrade and base layer moduli. For each subgrade moduli condition, the base layer thickness was calculated for three different assumed traffic levels (ESALs). The WinPas program for the design of flexible pavements was used in arriving at the required base layer thicknesses. Design charts are presented for the above mentioned variables in the Tables 5.5, 5.6, and 5.7. They are also presented in the form of design charts in Figures 5.1, 5.2 and 5.3.

From these tables and figures, the following observations can be made:

- For the same traffic variables and asphalt layer coefficient, an increase in base moduli and resilient moduli resulted in a decrease of base layer thickness.
- For the same material properties and highway variables, an increase in ESAL resulted in an increase in base layer thickness.
- Typical base layer thicknesses in practice vary between 24 and 30 in. Higher thicknesses are recommended here since no subbase layer is considered. If the practitioner plans to reduce the base layer thickness, options available are either use a much stronger asphalt layer with higher structural coefficient or use a subbase layer. The minimum base layer thickness of 6 in. is considered for practical purposes as often practiced.

Table 5.5 Design Table for Interstate Traffic Conditions

Base Moduli (MPa)	Structural Coefficient, a_2	Base Layer Thickness (in.) (Subgrade moduli, 5 ksi)			Base Layer Thickness (in.) (Subgrade moduli, 10 ksi)			Base Layer Thickness (in.) (Subgrade moduli, 20 ksi)		
		I	II	III	I	II	III	I	II	III
190	0.12	20	32	40	12	22	31	6*	15	21
220	0.14	16	27	35	10	19	26	6*	12	18
256	0.16	14	23	31	9	17	22	6*	11	16
310	0.18	12	21	27	8	15	20	6*	10	14
370	0.20	11	18	24	7	13	18	6*	9	12
431	0.22	10	17	22	6	12	16	6*	8	11
540	0.24	9	15	20	6	11	15	6*	7	10

Note : I = ESAL of 1 E +06; II = ESAL of 10 E +06; III = ESAL of 40 E +06; Reliability = 90%; Standard Deviation = 0.45; Asphalt Structural Coefficient = 0.4; Asphalt Layer Thickness = 4 in.; Initial Serviceability = 4.5, Terminal Serviceability = 2.5; Base layer thicknesses are rounded to the nearest inch; * = Minimum Base Layer Thickness of 6 in.

Table 5.6 Design Table for State Highway Traffic Conditions

Base Moduli (MPa)	Structural Coefficient, a_2	Base Layer Thickness (in.) (Subgrade modulus, 5 ksi)			Base Layer Thickness (in.) (Subgrade modulus, 10 ksi)			Base Layer Thickness (in.) (Subgrade modulus, 20 ksi)		
		I	II	III	I	II	III	I	II	III
190	0.12	17	28	33	10	20	23	6*	13	16
220	0.14	14	24	28	9	17	20	6*	11	14
256	0.16	13	21	24	8	15	17	6*	10	12
310	0.18	11	19	22	7	13	15	6*	9	11
370	0.20	10	17	19	6	12	14	6*	8	10
431	0.22	9	15	18	6*	11	13	6*	8	9
540	0.24	8	14	16	6*	10	12	6*	7	8

Note : I = ESAL of 1 E +06; II = ESAL of 10 E +06; III = ESAL of 40 E +06; Reliability = 85%; Standard Deviation = 0.45; Asphalt Structural Coefficient = 0.4; Asphalt Layer Thickness = 4 in.; Initial Serviceability = 4.5, Terminal Serviceability = 2.25; Base layer thicknesses are rounded to the nearest inch; * = Minimum Base Layer Thickness of 6 in.

Table 5.7 Design Table for City Road Traffic Conditions

Base Moduli (MPa)	Structural Coefficient, a_2	Base Layer Thickness (in.) (Subgrade modulus, 5 ksi)			Base Layer Thickness (in.) (Subgrade modulus, 10 ksi)			Base Layer Thickness in.) (Subgrade modulus, 20 ksi)		
		I	II	III	I	II	III	I	II	III
190	0.12	15	23	34	10	17	26	6	12	19
220	0.14	13	20	29	9	15	22	6*	10	17
256	0.16	11	17	25	8	13	20	6*	9	15
310	0.18	10	15	23	7	11	17	6*	8	13
370	0.20	9	14	20	6	10	16	6*	7	12
431	0.22	8	13	19	6*	9	14	6*	7	11
540	0.24	8	12	17	6*	9	13	6*	6	10

Note : I = ESAL of 1 E +06; II = ESAL of 10 E +06; III = ESAL of 40 E +06; Reliability = 80%; Standard Deviation = 0.45; Asphalt Structural Coefficient = 0.4; Asphalt Layer Thickness = 2 in.; Initial Serviceability = 4.5, Terminal Serviceability = 2.0; Base layer thicknesses are rounded to the nearest inch; * = Minimum Base Layer Thickness of 6 in.

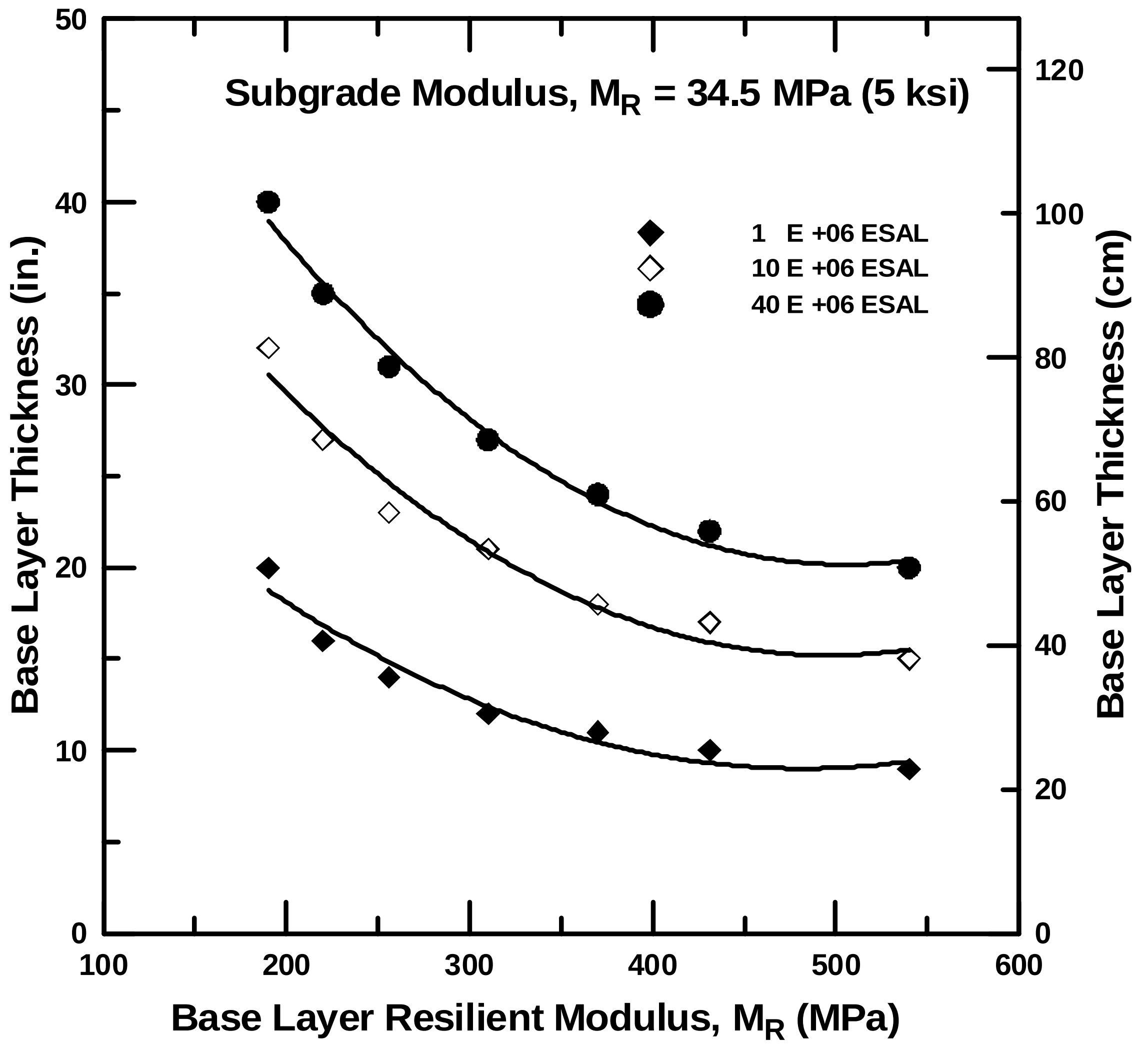


Figure 5.1 Design Chart for Determining RAP Base Thickness for Interstate Highways

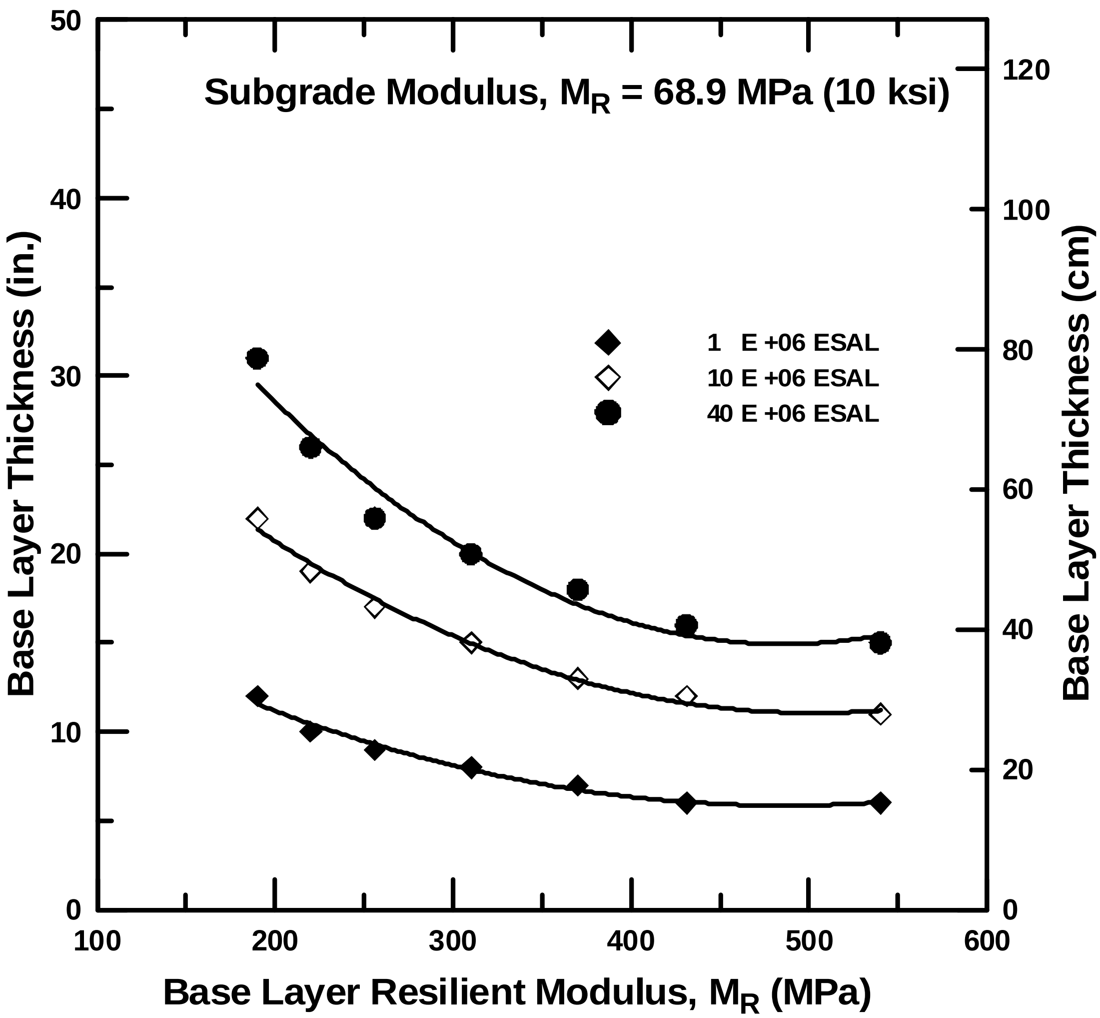


Figure 5.2 Design Chart for Determining RAP Base Thickness for Interstate Highways

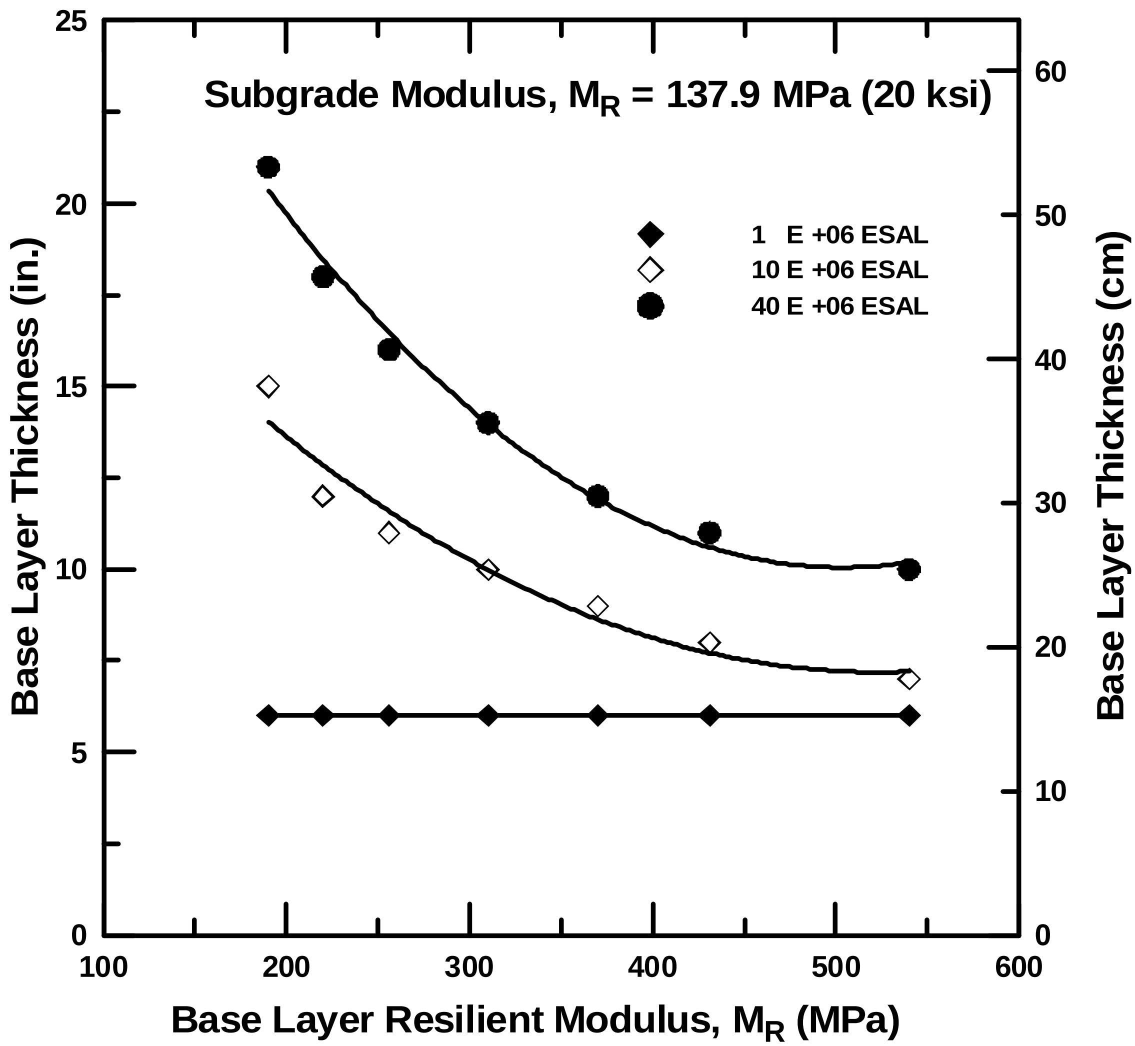


Figure 5.3 Design Chart for Determining RAP Base Thickness for Interstate Highways

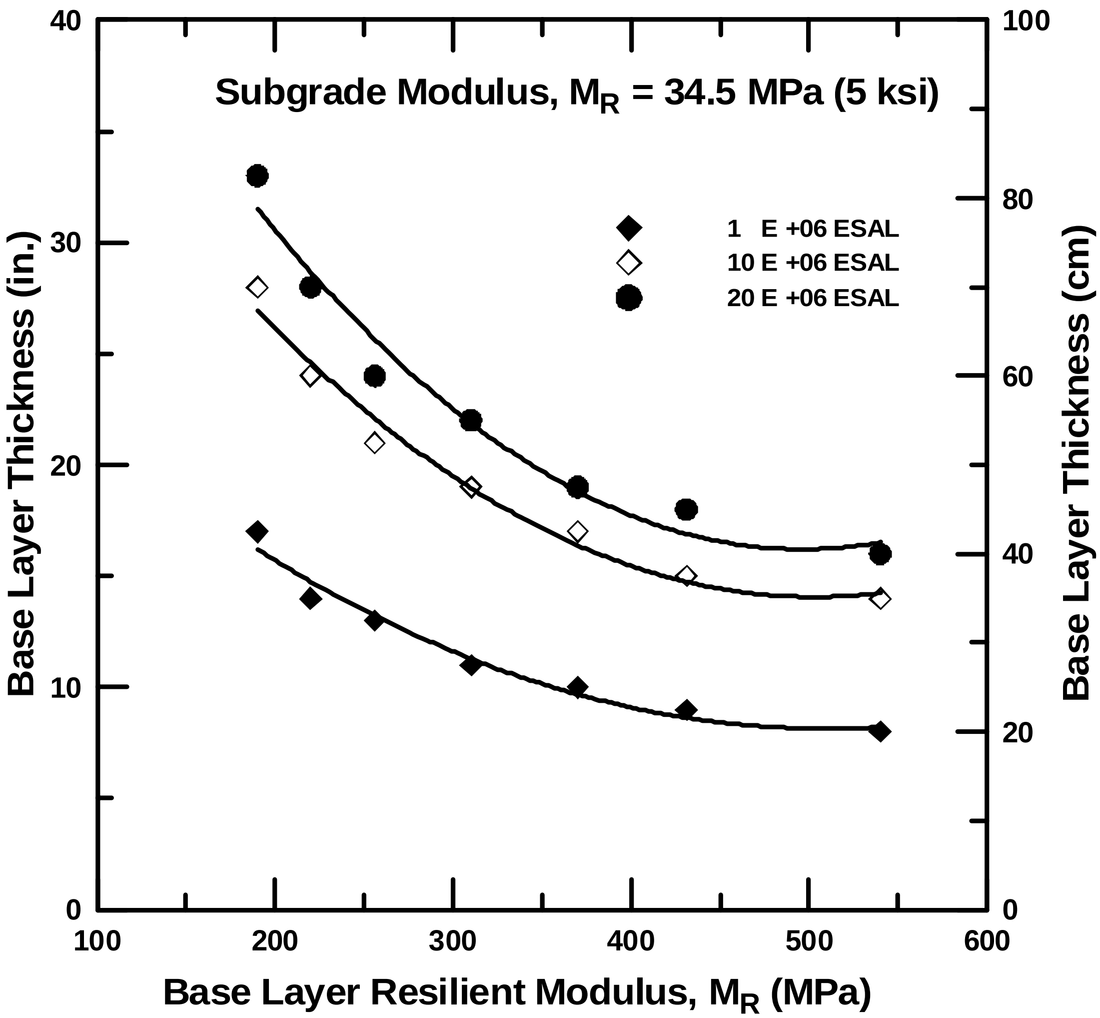


Figure 5.4 Design Chart for Determining RAP Base Thickness for State Highways

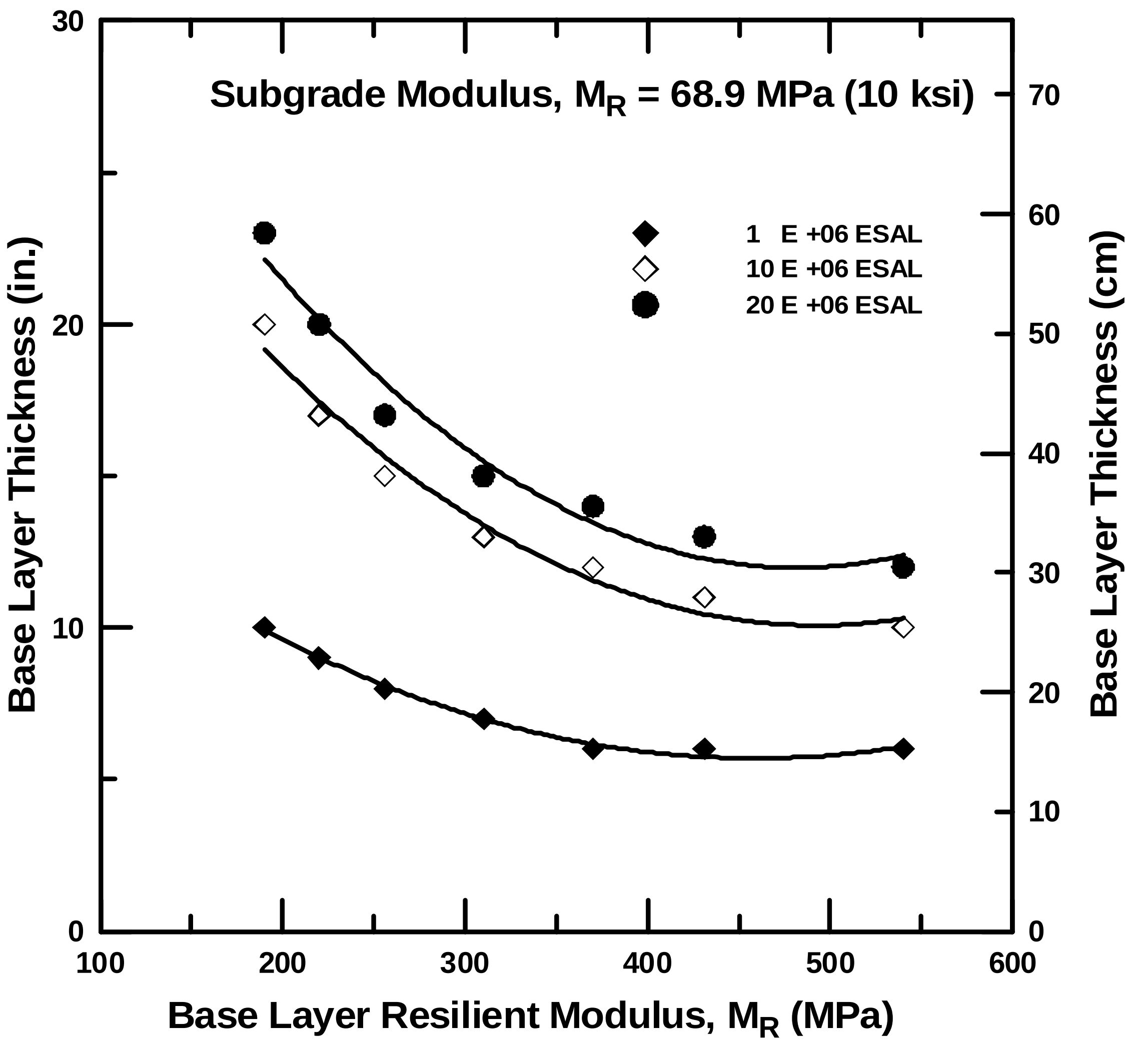


Figure 5.5 Design Chart for Determining RAP Base Thickness for State Highways

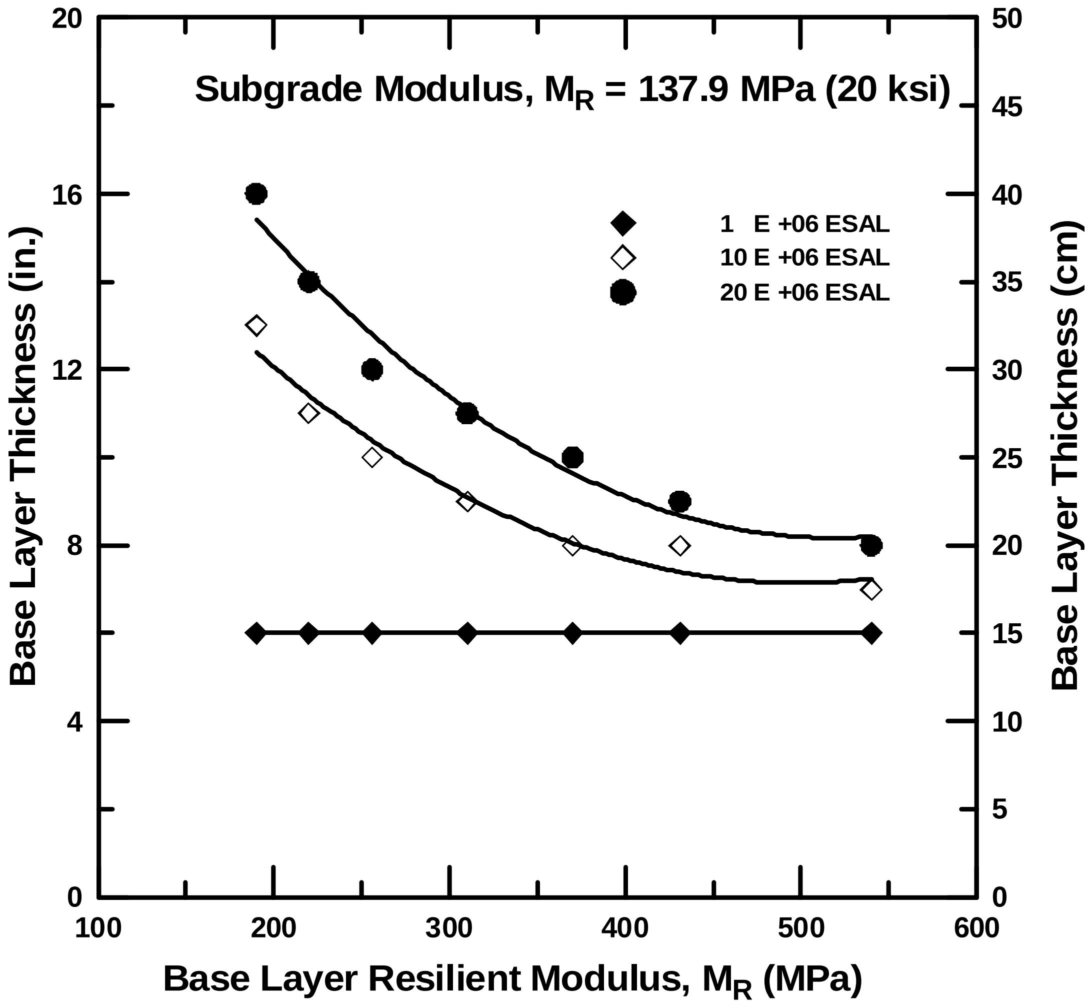


Figure 5.6 Design Chart for Determining RAP Base Thickness for State Highways

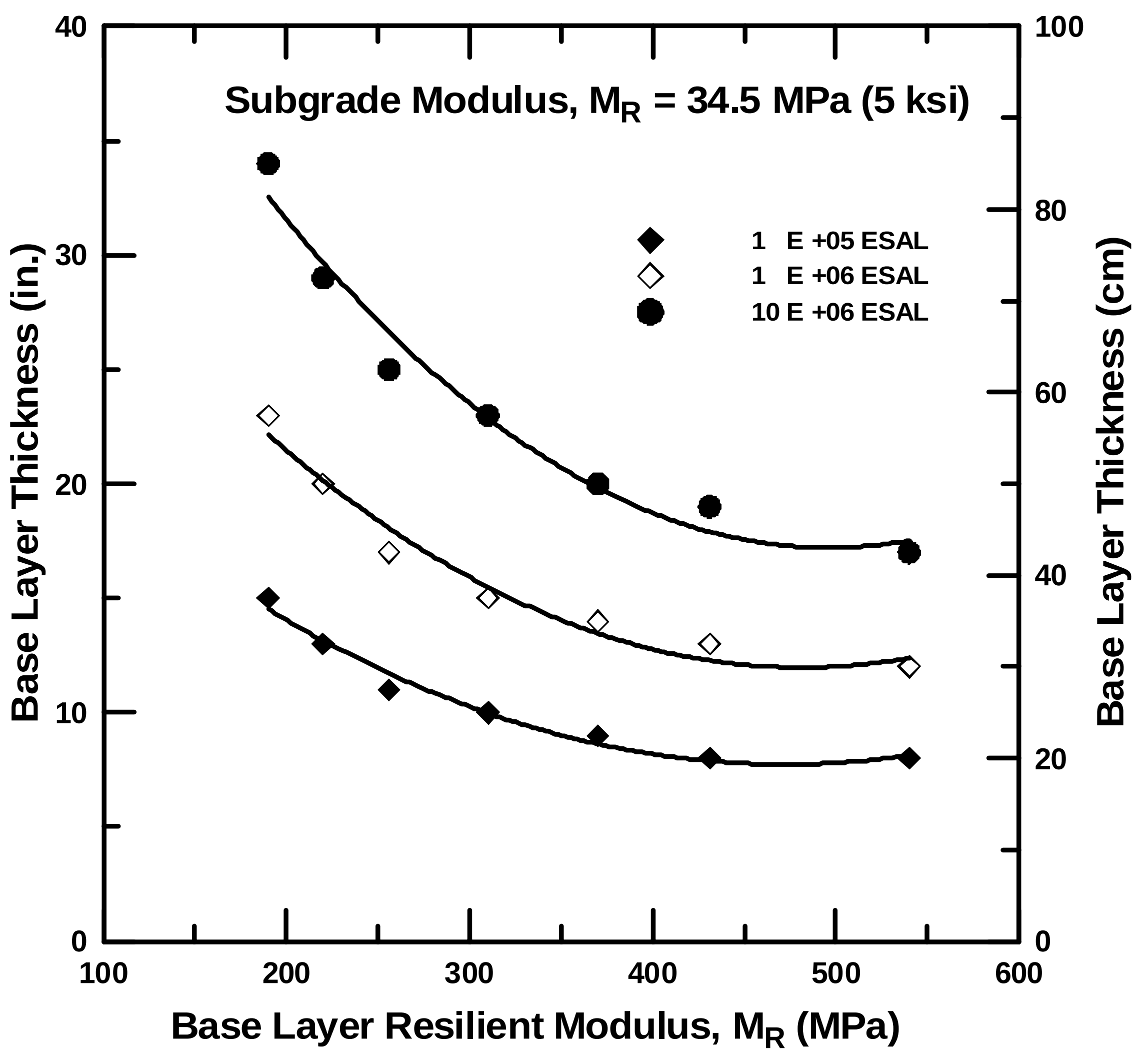


Figure 5.7 Design Chart for Determining RAP Base Thickness for City Roads

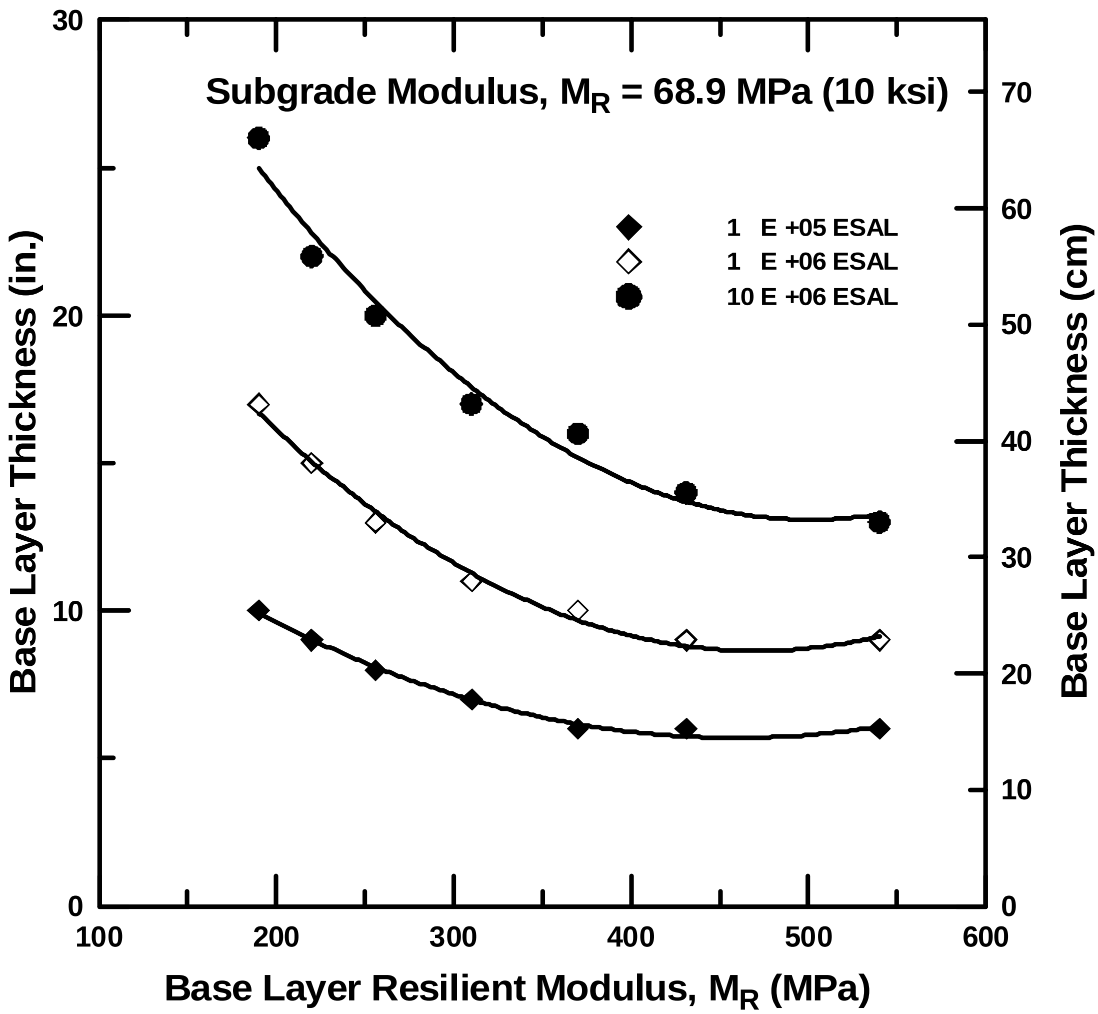


Figure 5.8 Design Chart for Determining RAP Base Thickness for City Roads

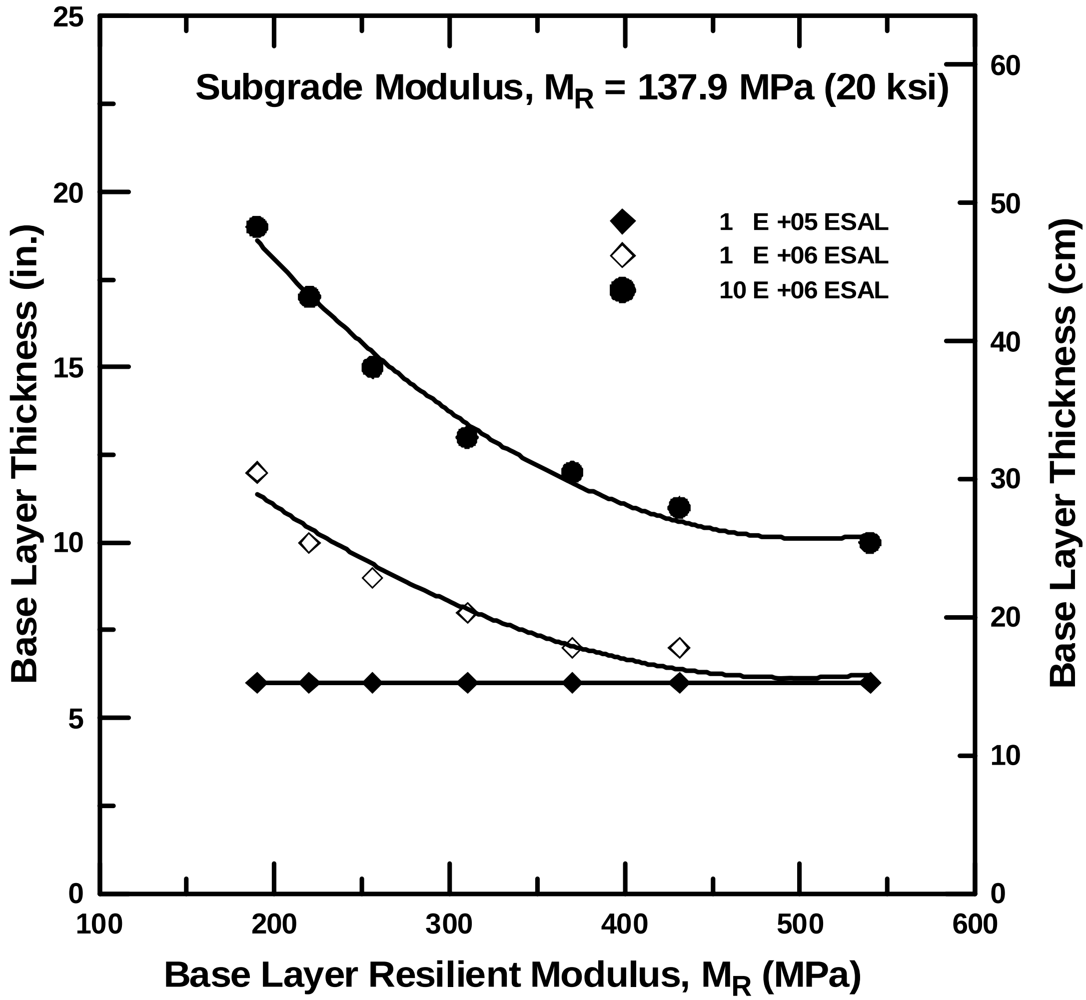


Figure 5.9 Design Chart for Determining RAP Base Thickness for City Roads

5.3.1 Flexible Pavement Design Example

Example: Determine the base layer thickness for the following pavement conditions:

- Class of Highway: State Highway
- Subgrade Soil Modulus: 10 ksi
- Base material to be employed: Reclaimed Asphalt Pavement Material Stabilized with 4% Cement and Fibers
- Design Traffic Level in ESALs: 10 millions

Solution:

The class of highway to be designed is the State Highway. The following parameters were assumed to be used in the design as recommended by AASHTO design of flexible pavements.

Reliability = 85%

Standard Deviation = 0.45 (for design of new pavement structures)

Initial Serviceability = 4.5

Terminal Serviceability = 2.25

Asphalt surface layer parameters have been assumed to be:

Asphalt layer structural coefficient = 0.4

Asphalt layer thickness = 4 in.

The next step is to assume or consider the base layer modulus and base layer coefficient (a_2). If the present cement or cement-fiber treated aggregate is considered, user can determine or establish both moduli and structural coefficient from this chapter (Tables 1 and 2).

For the given base layer material type (4% cement fiber treated aggregate), Table 2 results are used to establish the average resilient modulus of base at a confinement pressure of 34.7 kPa is 364 MPa. The last step is to determine the base layer thickness. Table 6 results can be used to determine base layer thickness for a subgrade modulus of 10 ksi and traffic ESALs of 10 E +06. By interpolating the base layer thickness for the required base layer modulus of 364 MPa, the required base layer thickness is 12.1 in. To be conservative and for a safe design, a base layer thickness of 13 in. could be adopted for the present case.

The asphalt surface properties could be varied, thus arriving at different values of the base layer thickness. For the above conditions, users can refer to the present tables or design charts. For different layer properties, users are recommended to use the pavement design software. Hence, for different asphalt layer thicknesses, one can determine various sizes of base layers. The final pavement configuration depends on a design that meets the structural support criteria (i.e. satisfying the structural number as required by traffic conditions and subgrade moduli support) and project cost criteria (i.e. cost of the pavement materials is reasonable and are locally available).

In summary, the developed design charts and tables could be used for the design of flexible pavement systems using the chemically stabilized reclaimed asphalt pavement aggregates. It should be noted that the design values arrived in this research are valid only when the same type of base material is used in practice. For materials and design variables that differ from those studied in this research, new design charts can readily be developed and adopted for the design of flexible pavements after characterizing the new materials.

5.4 Summary

This chapter describes the development of design tables and charts for determining the reclaimed asphalt base layer thickness for a variety of highway and traffic conditions. Both traffic and material parameters assumed in this analysis are mentioned. A simple case study is used to illustrate how to use the design tables to determine the base layer thickness. Also, design directions with different materials and different design variables are provided.

CHAPTER 6

SUMMARY, CONCLUSIONS, AND FUTURE RESEARCH RECOMMENDATIONS

6.1 Introduction

The main objective of the present research was first to characterize resilient properties of recycled/reclaimed asphalt pavement aggregate materials and then develop design charts for flexible pavements in which these materials can be used as bases. These objectives were accomplished and the results of this research are presented in Chapters 3, 4 and 5. Some of the salient research findings of this research are summarized in the following section.

6.2 Summary and Conclusions

In this research, a locally produced reclaimed asphalt pavement material was selected as a control/untreated base material. This material was then subjected to stabilization with cement and cement-fibers. A resilient modulus based experimental program was then designed and followed to test untreated RAP base materials, cement treated RAP base materials and cement-fiber treated RAP base materials. Type1 Portland cement and fibrillated polypropylene fibers were used as additives for stabilization. Basic tests such as standard proctor test were conducted on all test materials and these results were used to establish compaction moisture contents and dry unit weights, which were close to optimum dry unit weight conditions. Based on the experimental data and analyses the following conclusions are drawn:

1. Standard Proctor tests conducted on RAP aggregate materials indicated that both compaction moisture content and dry unit weight relationships were not influenced by the cementation process. Both properties and their ranges are close to each other.
2. Resilient moduli results were statistically analyzed to determine both standard deviations and coefficients of variation. The present test results showed an excellent repeatability, with standard deviations ranging from 1.8 to 5.2 MPa for untreated aggregate materials, and from 4.7 to 30 MPa for cemented aggregate materials. High standard deviations were only recorded at the highest resilient moduli properties measured in this research. This clearly indicates that the present resilient modulus test is providing repeatable results.
3. In reliability assessments, the moduli results of untreated RAP materials measured from the present research are compared with those measured from previous research studies. The M_R variations with respect to the bulk stress of all these studies including the present study are in agreement with each other. In the case of cement treated materials, the present moduli results closely match with those reported by Gnanendran and Woodburn (2003). This shows that the repeated load triaxial test provided reliable measurements of resilient moduli of both untreated and cement treated aggregate materials.

4. The present moduli tests showed that both confining and deviatoric stresses have shown a major influence on the resilient moduli values of the untreated, cement treated and cement-fiber treated reclaimed aggregate base materials. An increase in the deviatoric stress resulted in an increase in the resilient modulus of the material, which is attributed to stress hardening of the aggregate specimen at high deviatoric stresses. This deviatoric stress effect on moduli is more pronounced at low confining pressures than at high confining pressures. This is because, at high confining pressures, the granular cemented specimen is strong and hence does not respond to increased axial deviatoric stresses as it does at low confining pressures.
5. The resilient modulus of the cement aggregate materials increased with an increase in the applied confining pressure. Also, this increase in the resilient modulus value with respect to confining pressure is not noted in cement treated aggregate specimens, particularly those treated with higher cement contents. This is because the cemented aggregate material is strong and stiff at high cement contents and as a result they behave similar to a weak concrete material. Such materials will not be unaffected by the applied confining pressures.
6. For a maximum test confining pressure of 137.9 kPa, an addition of 2% cement treatment increased the M_R value by 32% when compared to the same of untreated aggregate specimen properties and with the addition of 4% cement, the M_R value was increased by about 50% when compared to the resilient moduli of untreated specimen. The percent moduli increase with respect to cement treatment of the present materials can be regarded as moderate at best.

7. Statistical comparison t-tests performed on experimental moduli values proved that the addition of both cement and cement-fibers to the aggregate materials resulted in enhanced resilient moduli, which are statistically and significantly higher than those of untreated aggregates. Hence, overall, it can be concluded that cement treatment and cement – fiber treatment provided resilient moduli enhancements, which are statistically significant. For a particular case of 2% cement treated specimens, they did not provide significant enhancements in the moduli when compared to those of untreated specimens. However, the same 2% cement treated specimens when reinforced with fibers yielded a significant enhancement in the moduli values of the material when compared to the untreated aggregate specimens.
8. A two parameter theta model is used to model and analyze the present experimental resilient moduli results. The regression modeling type statistical analysis yielded very good modeling with high coefficients of determination values. The model constant parameter, log k_1, which is an indicator of resilient moduli magnitudes, varied between 3.00 to 3.58 and the k_2 parameter, which denotes or represents the non-linearity nature of the stress dependency, varied from 0.81 to 1.00. For high cemented aggregates, the model constants indicate that the resilient modulus property showed a linear dependency of bulk stress values.
9. The three parameter formulation also provided a good simulation of both confining and deviatoric stress effects on the resilient moduli values. Multiple

linear regression analysis yielded high coefficients of determinations. The constant parameter of the model correlation, log k_3 varied from 3.47 to 3.69, with a low value being reported for untreated aggregates and high values being obtained for both cement and cement-fiber treated aggregates. The k_4 parameter is close to 0.19, indicating the resilient moduli results are showing a non-linear type confining pressure dependency.

10. The structural coefficient, a_2, values of the present treated and untreated aggregates ranged from 0.13 to 0.24 and this range is in agreement with those of similar type materials reported by Janoo (1994) for New Hampshire DOT. As expected, the structural coefficient values increase with an increase in the confining pressure and these values are higher for cement and cement – fiber treated aggregates.
11. Design charts and tables for flexible pavements are developed to directly determine the RAP material thickness for different subgrade conditions, traffic ESALs and types of highways. This method can be confidently used to determine the aggregate layer thickness for the known subgrade and traffic variables. If the conditions are different from those used in the development of design charts and tables, then one should utilize the recommended structural coefficients in either commercial pavement design software or a manual design procedural steps using the subgrade and traffic conditions.

6.3 Future Research Recommendations

The following recommendations will further advance the state-of-understanding of the resilient properties of RAP aggregate bases.

1 Effects of fiber dosages on the resilient moduli characteristics of cement treated aggregates should be investigated. Additionally, their influence on shrinkage cracks of the aggregate specimens should be examined.

2 Resilient moduli of cement stabilized aggregates at higher cement dosages should be further tested and verified with other test methods including echo pulse test.

3 Both resilient moduli and structural coefficients of the materials should be evaluated by performing Falling Weight Deflectometer (FWD) studies on the test sections with same type of materials as bases in field conditions.

4 Utilization of RAP materials with other traditional base materials including virgin aggregates as well as utilization of other cementing agents including fly ash and ground granulated blast furnace slag should be investigated.

APPENDIX A

SPECIMEN AND EQUIPMENT USED

Figure A.1. Compacted RAP Aggregate Material Specimens

Figure A.2. Specimen Placed on the Triaxial cell for Repeated Load Triaxial Testing

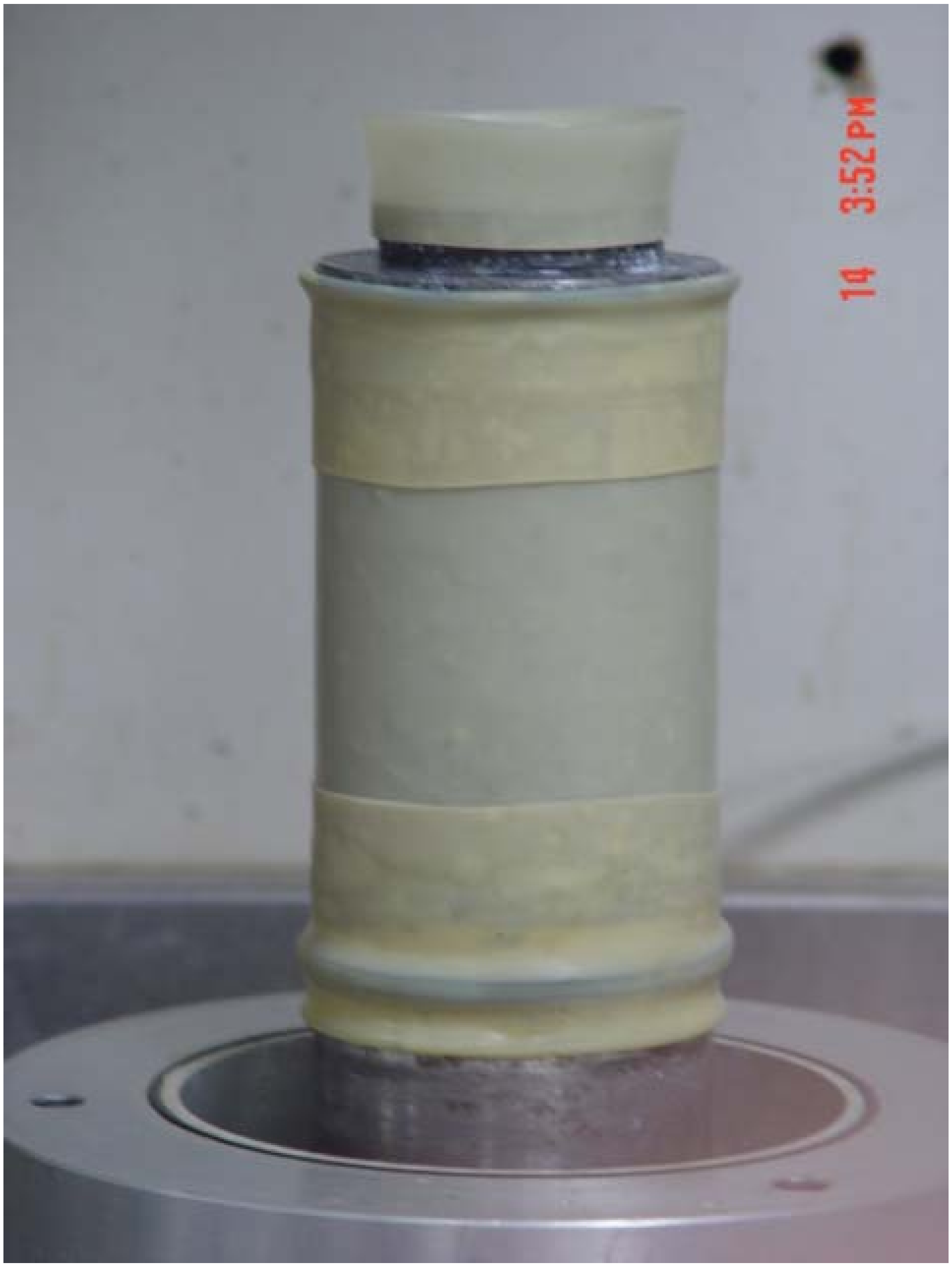


Figure A.3. Specimen Wrapped with a Membrane and Sealed with O-Rings

Figure A.4. Specimen Inside the Triaxial Cell

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