Resilient Behavior of Fly ash Treated Reclaimed Asphalt Pavements

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Department of Civil Engineering Engineering

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Dedicated

to

My Parents

Abstract

This study evaluates the use of reclaimed asphalt pavements (RAP) as a base course in flexible pavements. This study looked at the resilient behavior of RAP mixtures with addition of fly ash and virgin aggregates. The effect of fly ash dosage, aggregate content and curing period on resilient modulus were clearly studied. The reclaimed asphalt pavements material used in this study came from an ongoing project at Nellore district in Andhra Pradesh on National Highway 5 (NH5), the fly ash came from Neyveli Lignite Corporation (NLC), a thermal power station at Tamil Nadu, and virgin aggregates were taken from nearby quarry in Kandi village at Andhra Pradesh. MORTH gradation was used as a control materials.

Physical properties were determined in the laboratory in controlled environment and the whole RAP and virgin aggregates were divided according to MORTH specified sizes. Modified proctor compaction tests were performed on the mixtures prepared by maintaining MORTH gradation to determine optimum moisture content – maximum dry unit weight relationship of 100% RAP material. For mixing the fly ash in mixture two different techniques (addition technique and replacement technique) were tried and addition method is considered to be appropriate technique. The specimens were prepared with 100% RAP material with fly ash dosage from 10% to 40% in 10% interval for resilient modulus (M_r) test, unconfined compressive strength (UCS) test and California Bearing Ratio (CBR) test. After casting, the specimens were stored in a specially designed stability chamber for curing. The specimens were tested for 1, 7 and 28 day curing periods. The resilient modulus tests were performed in a fully automatic cyclic triaxial equipment in accordance with test procedure given in AASHTO T 307-99, 2003. For gaining better strength the aggregates were mixed in the mixture and the same tests were performed on all the mixtures. The effect of fly ash content on the resilient modulus of RAP and RAP – virgin aggregates (VA) were evaluated. Increase in resilient modulus was observed in both mixtures. The similar trends were observed with increase in deviatoric stress, confining stress and curing period. For evaluating the effect of virgin aggregate on resilient modulus of RAP mixtures, two different mix compositions were considered. One mix composition

consists of 80% RAP material and 20% VA material and another mix composition consists of 60% RAP material and 40% VA. A decreasing trend was observed in the resilient modulus of RAP mixtures with increase in aggregate content. It was observed that with increase in fly ash content UCS was increased. The similar trends were observed with increase in aggregate content, and curing period. The retained strength and CBR were also shown similar results. From the CBR values, the resilient modulus values were calculated using correlations given in IRC: 37, 2012 and compared with resilient modulus values which were directly determined by using fully automatic cyclic triaxial equipment. The comparison has shown that the calculated resilient modulus were showing comparatively very less resilient modulus than experimental results. From the experimental results of resilient modulus, the design parameters (layer coefficients and regression coefficients) were calculated, which are the main design inputs for the software like KENLAYER and IITPAVE for the design of flexible pavements.

Overall, it was found that the RAP cannot be used as base materials in its original composition due to lack of bonding and shearing resistance. However, better mixes can be prepared by replacing certain portion of RAP with VA. Further improvement can be achieved by stabilizing the mixes with calcium rich fly ashes.

Nomenclature

A	Aggregates
a_2	Layer Coefficient
A/D	Analog to Digital
AASHTO	American Association of State Highway and Transportation Officials
CBR	California Bearing Ratio
CDAS	Control and Data Acquisition System
CIR	Cold In-Place Recycling
CKD	Cement Kiln Dust
CSIR	Council of Scientific and Industrial Research
E	Young's Modulus
F	Fly ash
FA	Fly ash
FACT	Fully Automatic Cyclic Triaxial
FWD	Falling Weight Deflectometer
FDR	Full Depth Reclamation
IRC	Indian Roads Congress
k_1, k_2	Regression Coefficients
LVDT	Linear Variable Displacement Transducer
MDD	Maximum Dry Density
MORTH	Ministry of Road Transport and Highway
M_r	Resilient Modulus
NH	National Highway
OMC	Optimum Moisture Content
PAI	Pozzolanic Activity Index
QDMR	Queensland Department of Main Roads
R	Reclaimed Asphalt Pavements
RAP	Reclaimed Asphalt Pavements
RPM	Recycled Pavement Material

RSG	Road Surface Gravel
RUCS	Retained Unconfined Compressive Strength
TRL	Transport and Road research Laboratory
UCS	Unconfined Compressive Strength
UTS	Universal Testing System
VA	Virgin Aggregates
w	Moisture content

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Chapter 1

Introduction

1.1. Introduction

In developing countries like India infrastructure plays a crucial role, in which road network is very primary thing. The economic and social development of the nation mainly rely upon the quality of transportation system. A vast investment of money is required for construction and maintenance of roads to continuously fulfill their functions. The pavements which are poorly designed will suffer from premature failure which leads to high economic loss as the damaged pavement has to be repaired, which leads to extra maintenance and repair costs.

The pavement is generally a layered system of selected materials placed on top of the natural ground or subgrade. The flexible pavement system basically consists of an asphalt surface layer, base layer, subbase layer and subgrade (natural ground) as shown in Figure 1.1. It basically provided for water ingress and often the layer is omitted due to wear and tear between surface and vehicle wheels. Hence base layer and subbase layers plays a prominent role in flexible pavements. Base layer transfers the loads coming from the asphalt surface layer to the other layers beneath. Hence, base layer helps in distributing the traffic loads. The efficiency of distributing the loads mainly depends upon the thickness of the layer and quality of the material used as base course. Therefore, the base layer should have enough strength and stiffness to carry loads coming on to it. Traditionally good quality material like virgin aggregates were derived from variety of rocks sources to use as a base course material. But the increased usage of virgin aggregates for different purposes to build the infrastructure leads to depletion of natural resources and leads to disturbances in biodiversity. At the same time, in recent days the cost of virgin aggregates were increasing drastically. By keeping in view all the situations and aspects a number of researchers and road agencies were trying to consider more cost effective alternatives to mitigate reliance on virgin aggregates, particularly for large quantity applications like construction of granular base road substructure.

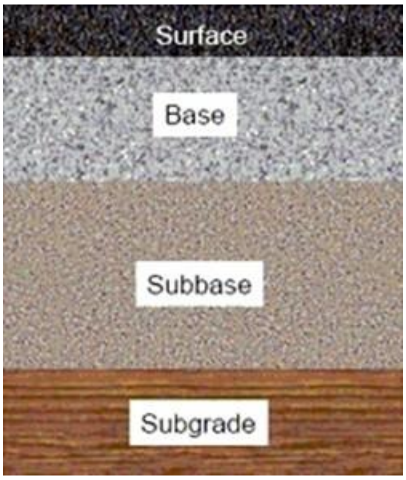

Figure 1.1: Typical Cross-Section of a Flexible Pavement System

On the other hand because of the tremendous growth in nation's infrastructure in recent years, the construction and demolishing waste is increasing day by day. This waste has to be dumped in landfills. But because of the increase in development and population, the landfills are turning as residential or industrial areas. Hence there was no space for dumping these waste materials. Thus, increased amounts of reclaimed materials such as broken glass, roofing shingles, rubber tires, pavement waste and many more are proposed to use to supplement natural aggregates in road construction.

1.2. Broken Glass

In United States about 7 percent of municipal solid waste consists of waste glass. Among recycling materials glass was considered to be second largest next to paper throughout the world. The broken glass was crushed and screened to produce recycled glass cullet as shown in Figure 1.2. This glass cullet can be used in substitution of fine aggregate materials in areas where the good quality aggregates are high in demand and expensive.

Figure 1.2: Broken Glass Bottles and Recycled Glass Cullet

Source: http://3.bp.blogspot.com/-IpKO2vb0FrI/UQ2NMWKMcAI/AAAAAAAAFNE/U_hIh87-ovc/s320/waste1.jpg, http://www.earth911.com/wp-content/uploads/2011/04/Glass-colors.jpg

Apart from using recycled glass for producing new glass items, recycled glass can also be used in construction industry in various fields. The waste glass can be used in asphalt paving mixes. Since the recycled glass has low melting point than virgin glass, it can be used in a clay as an additive and therefore, lowers the cost for production of tiles and bricks. The crushed glass can also be used as a substitute of granular soils in base layers and added as a course aggregate in hot-mix asphalt.

When glass is crushed and fractionated to the size of fine aggregates it exhibits properties similar to the sandy material which includes high stability and frictional strength due to angular nature of crushed glass [1]. The high frictional angle of well crushed glass contributes to good lateral stability for pavement structures.

1.3. Roofing Shingles

Roofing shingles, as shown in Figure 1.3, are one of the largest productions in the municipality solid waste stream. In US the production was approximately 11 million tons every year which consists approximately 90% post-consumer scrap (or tear-off shingles) and 10% containing post manufacture scrap. Typically, these shingles consists of 25% asphalt, 25% fiber glass and 50% granular of filler material. These components can be useful in production of hot-mix asphalt.

Figure 1.3: Roofing Shingles

Source:http://upload.wikimedia.org/wikipedia/commons/7/72/Failure_of_asphalt_shingles_allowing_roof_leakage.JPG, http://www.greenbuildingadvisor.com/sites/default/files/IMG_7855.JPG

Basically there are two types of roofing shingles, one is manufacturer scrap or roofing shingle scraps, which were generated during production by trimming new asphalt shingles to obtain requires sizes according to the specifications. The scraps which were created during manufacturing were mostly uniform and homogeneous. These scraps are generally free from debris. Another one is tear-off roofing shingles which were generated from construction, demolition and replacing the existing roofs. The quality of these type of scraps vary depending upon the source. These tear-off shingles may contain different types of debris such as plastic, paper, wood, nails and many more which has to be removed through processing. The aggregate in the tear-off shingles may be lost due to weathering throughout its life time. But it contains good amount of asphalt in it. Many studies concluded that roof shingles can improve the rutting and cracking resistance and organic fibers reinforce the pavement. The roofing shingles can also be used in construction of temporary roads, driveways and parking lots. These roofing shingles can also be used for a base course application which results in saving of money in buying virgin aggregates.

1.4. Waste Tires

In recent years every family has at least one two wheeler bike, which has two rubber tires. Due to were and tear of rubber tires with road surface these rubber tires become smooth and gripping will be lost which leads to slipping or skidding and finally leads to accidents. So after certain life period, these rubber tires has to be replaced by new one. Now the real problem is disposal of these waste rubber tires has become an environmental problem. First of all there was no landfill area available for disposal of these waste rubber tires. Furthermore, disposal of waste rubber tires in landfills and stockpiles increases the risk of accidental fires, which leads to uncontrolled emission of harmful gases. Rao and Dutta [2] reported that in India every year 112 million rubber tires are discarded.

Waste tires shown in Figure 1.4 can be used in several construction activities in various forms. Waste tires can be used in construction of retaining walls by stacking them on one on other, shredded tires can be used as a light weight fill material for embankments and rubber tire chips can be used in pavement layers.


Figure 1.4: Rubber Tires

Source: http://harmonicenergyinc.com/wp-content/uploads/tire-stock-pile-landfill-waste-tyres-dump-tires-illegal-scrap-mountian.jpg, http://tires2powder.com/images/20mm.jpg

1.5. Pavement Waste

In India the major road connectivity was developed in early 20th century. But those all roads were constructed without any proper design. Hence, all those roads are getting damaged because of the poor construction. Because of the fatigue cracking, rutting and reflection cracking the functionality of the roads is reducing day by day. So these all roads has to be repaired or reconstructed.

In India if there is any damage in pavement, the contractor basically over lay a new surface layer and later because of the lack of bonding between the previous existing layer and new layer with in no time again the pavement will be damaged. But in developed countries the existing damaged top layer was removed and a new layer was laid. The other benefit of doing in this is the increase in elevation of the pavement due to overlay can be prevented. But the main problem with this is the removed material has to be disposed in a landfill. Due to increasing in development and population the landfills are getting reduced gradually. It is practice that the top asphalt layer was removed and heated at high temperature. Than the bitumen and aggregates were separated and used directly in new pavement surface layer in onsite. This process of recycling method is known as hot recycling process. But the production of pavement waste is much higher than the consumption of pavement waste directly at onsite. On the other hand in hot recycling method, to use the existing pavement layer in new layer the existing layer is heating at high temperature to turn it in to liquid state. For this a very huge equipment is needed and for heating huge amount of fuel is required, which leads to spending of money.

On other hand by considering global warming and other environmental issues, it was observed that while heating the pavement waste at high temperature to separate asphalt and aggregate in hot milling process shown in Figure 1.5, a large amounts of CO_2 emissions, SO_x emissions, NO_x emissions and SPM emissions were generated. These gases are very harmful to survival of living organisms. As global warming and other environmental issues have gained greater attention, various efforts have been made to develop the techniques for reducing global warming and other environmental effects. In this prospect it was observed that pavement waste shown in Figure 1.7 which was cold milled and stockpiled can be used in base layer of flexible pavements shall be a better alternative. The material which was obtained through cold milling process is known as reclaimed asphalt pavements (RAP) shown in Figure 1.7. In cold recycling process shown in Figure 1.6, typically the asphalt pavement was removed by milling the upper surfaces or full depth removal of the entire pavement section itself. A milling machine is used to remove the top surface, whereas a rhino horn on a bulldozer is used for full depth removal of the entire pavement in several broken pieces. These broken pieces were undergone crushing, screening, and stored in a stockpiles. Basically, this whole process is performed at a central processing plant.

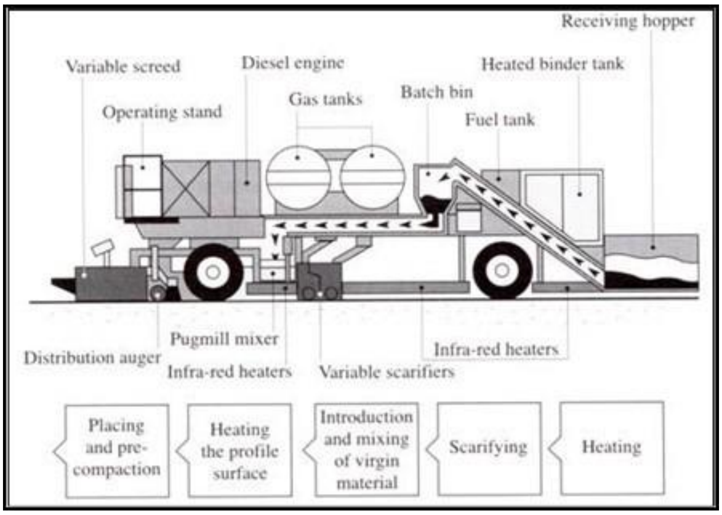

Figure 1.5: Hot In-Place Recycling Process

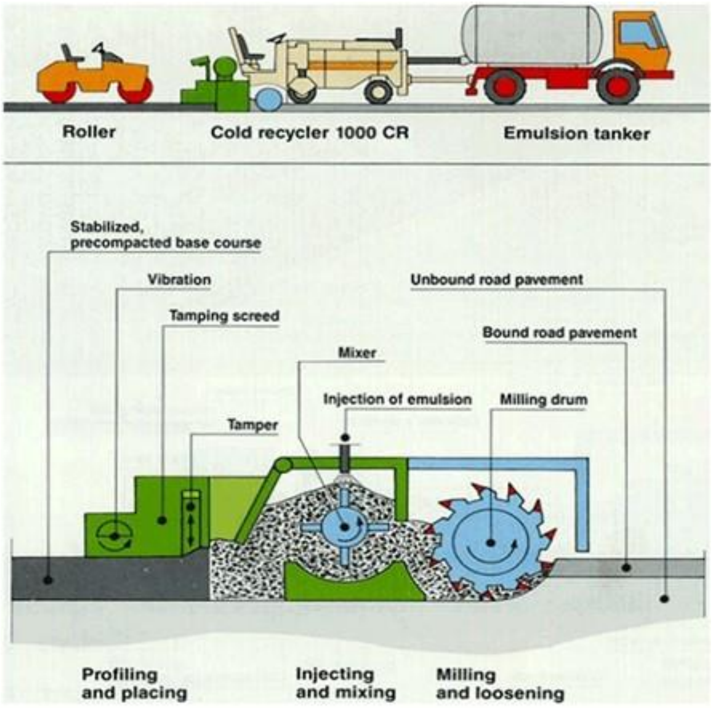

Figure 1.6: Cold In-Place Recycling Process

It has to be observed that RAP material typically contain 3 to 7% of asphalt and the remaining is aggregates. By observing the physical and mechanical properties presented in Table 1.1**,** RAP could be a best alternative for virgin aggregates in base layer of flexible pavements. So for this thesis RAP material is taken as a major material for base applications in flexible pavements.

Figure 1.7: Pavement Waste and RAP Material

Table 1.1: Typical Mechanical and Physical Properties of RAP Material

PROPERTY	TYPICAL RANGE
Unit Weight	19.4 to 23 kN/m^3
Moisture Content	5 to 8%
Asphalt Content	3 to 7%
Asphalt Penetration	10 to 80 at 25^0C
Compacted Unit Weight	16 to 20 kN/m^3
California Bearing Ratio (CBR)	20 to 25% for 100% RAP

Among all the waste materials RAP material which was obtained through cold milling process of existing damaged roads is considered to be a better alternative of virgin aggregates in base layer because this is the only material has aggregate particles in it. But because of the thick asphalt coat around the aggregates in the RAP material, it is week in binding property. So it was proposed to use a cementicious material like lime, cement or fly ash to create the binding property between the RAP particles. By considering the cost benefits fly ash is considered to be best binding material.

1.6. Fly ash

Coal is a combustible fuel which contains more than 50% of carbonaceous material by weight. Coal consists of organic equivalents of minerals in rocks which are broadly classified as reactives and inerts. Reactives obtained from woody material are called vitrinite and those obtained from plant reproductive organs leaves and stem coatings are called liptinite. The reactives increase the porosity of coal, whereas inerts increases the density. The properties of the coal are more variable when compared with other fossil fuels. The colour of coal ranges from brown to black and its hardness ranges from very fragile to very hard. In view of its varying properties it is essential to classify coal.

In general coals may be classified as anthracite coal, bituminous coal, sub-bituminous coal and lignite coal. Anthracite coal is the superior grade of coal which is a metamorphic rock formed during mountain building. These are clean, dense and hard. Hence, they are also known as hard coals. They have very high percentage of fixed carbon (about 90%) and low percentage of volatile matter. They are difficult to ignite. But once ignited they burn for a long time with a short, clean flame and it is almost smokeless. Bituminous coals are usually black in colour, they contain 75-90% of fixed carbon. These coals ignite relatively easily and burn with a long flame. Sub- bituminous coals are moist, they break up easily as they dry. They contain 60-80% of fixed carbon. When ignited they burn with medium length flame with little smoke. Lignite coal is also known as brown coal which contain very high moisture and fixed carbon in the range of 55-70%. They ignite easily and burn with little smoke.

In thermal power plants coal is used as a fuel for generating steam. In this process coal freed from impurities is pulverized and is injected into the combustion chamber, where it burns instantaneously. The resulting ash is known as fly ash shown in Figure 1.8, which is made up of molten minerals. While the ash particles move along with the flu gases, the moving air stream around the molten material gives the fly ash particles spherical shape.

Figure 1.8: Fly ash

Source: http://www.downtoearth.org.in/dte/userfiles/images/Hindal2.jpg

The ash is subjected to economizer to cool the ash. During this process temperature of the fly ash reduces suddenly and the resulting ash was composed of mostly amorphous or glassy material. It has been observed that if fly ash is subjected to economizer, it improves its reactivity and has pozzolanic activity index (PAI) of about 103%. But, if the boiler design allows gradual cooling the ash is more likely to have more crystalline material. Which was less reactive with PAI of about 94%. The fly ash is than separated from rest of the gases by using the mechanical dust collectors of electrostatic precipitators. Mechanical dust collectors separate coarser and finer fractions of fly ash. Generally, electro static precipitators consists of about 4 to 6 hoppers also known as fields. The fineness of fly ash increases with the number of fields. For example, the specific surface of the fly ash obtained from the hopper, near the boiler end is approximately 2800cm^2/gram. Whereas the specific surface area of the fly ash collected from the last field i.e. at the chimney end can be as high as 8200cm^2/gram. In recent day's utilization of fly ash is increasing gradually in various areas such as embankment and dam construction, mining filling, back filling, structural fills, road construction, soil stabilization, mass concreting, grouting, ceramic industry, floor and wall tiles and many more.

Hence, among the number of waste materials, in this study RAP is chosen as main material and fly ash is chosen as additive because, RAP consists of aggregate particles, from where the real strength will come. Since, the RAP material is coated with bitumen and due to lack of angularity of aggregate particles in RAP material, there is a week bondage between the RAP particles. So to create the binding property within the mixture, some cementitious material has to be used. Hence, the fly ash is considered to be cheapest and abundantly available material compared to cement and lime. For this thesis, fly ash is taken as additive. The required experiments were carried out to achieve the minimum requirements given by IRC in terms of strength and stiffness.

1.7. Objective and Scope of the Study

The objective of this study is to understand the performance of treated reclaimed asphalt pavements as a base course under cyclic loading.

In the scope of the study, Following aspects are given priority:

- To understand the resilient behavior of fly ash treated reclaimed asphalt pavements as a base course under repeated traffic loading conditions.
- To understand the resilient behavior of fly ash treated reclaimed asphalt pavements – virgin aggregates as a base course under repeated traffic loading conditions.
- To know the strength of the treated and non-treated reclaimed asphalt pavements and treated and non-treated reclaimed asphalt pavements – virgin aggregates in terms of California Bearing Ratio and Unconfined Compressive Strength.
- To know the retained strength in the treated and non-treated reclaimed asphalt pavements and treated and non-treated reclaimed asphalt pavements – virgin aggregates specimens after resilient modulus test, which tells weather the structure will survive till the end of design life or not.
- Comparison of resilient modulus determined from experimental study and calculated resilient modulus from the correlations followed by IRC: 37- 2012 [3].

1.8. Thesis Organization

Chapter 2 provides the results of an existing literature work of various factors influencing resilient behavior of fly ash treated reclaimed asphalt pavements. Strength parameters of reclaimed asphalt pavements have been discussed in brief. In addition available correlations between the California Bearing Ratio and Resilient Modulus were discussed in brief.

Chapter 3 describes the material characterization of reclaimed asphalt pavements and fly ash, tests performed on the materials. Besides, in this section detailed discussion is done on loading pattern and test methodology carried during testing.

In ***Chapter 4*** detailed discussion is carried on to understand the resilient behavior of fly ash treated 100% reclaimed asphalt pavements mixtures and the influence of various variables on resilient modulus. In addition initial and retained unconfined compressive strength were also briefly studied.

In ***Chapter 5*** detailed discussion is carried on to understand the resilient behavior of fly ash treated reclaimed asphalt pavements – virgin aggregate mixtures and the influence of various variables on resilient modulus. In addition initial and retained unconfined compressive strength were also briefly studied.

Chapter 6 describes the resistance of reclaimed asphalt pavements mixtures with addition of fly ash and aggregates against the loads coming onto them. In addition resilient modulus values were also calculated by using the correlations followed by IRC: 37 – 2012.

In ***Chapter 7*** detailed discussion is carried on the combined results from ***Chapter 4, Chapter 5, and Chapter 6*** on various aspects and optimum mix composition was checked for minimum requirements given by IRC.

Conclusions were drawn in ***Chapter 7*** based on the results obtained in previous chapters and Future work is suggested from the present research.

Chapter 2

Background

2.1. Introduction

Roads provides the arterial network to facilitate trade, transport, social integration and economic development. Roads facilitates specialization, extension of markets and exploitation of economies of scale. Transportation by roads has many advantages because of its easy accessibility, flexibility of operations, door-to-door service and reliability.

The total road network in India increased more than 11 times during the last 62 years between 1951 and 2014. From 3.99 lakh kilometers as on 31 March 1951, the road length increased to 46.90 lakh kilometers as on 31 March 2014, which was considered to be world's second largest road network after United States of America having 65.86 lakh kilometers of road network [4, 5].

In India, road infrastructure is used to transport over 60 percent of total goods and 85 percent of total passenger traffic [6].The Ministry of Road Transport and Highways encompasses within its fold, Road Transport and Highways which includes construction and maintenance of National Highways (NHs), administration of Motor Vehicle Rules 1989, formulation of broad policies relating to road transport, environmental issues, automotive norms, fixation of user fee rate for use of National Highways etc. besides making arrangements for movements of vehicular traffic with neighboring countries [7]. So these are resembles how important the road network for India's economy. Since roads directly contribute to the economic growth of the country it is extremely necessary that the roads are well laid out and strong. Thus, design of pavement becomes a herculean task, considering importance of stability in road and accelerated rate at which road network is increasing in India. Thus, it is desirable that the base layer which acts as a mediator between surface layer and subgrade should possess sufficient strength and stiffness. Since India is a developing country, it was estimated that in coming 10 years the length of road network is going to increase in tremendous way. For this to happen a huge quantities of virgin aggregates (VA) are required which are derived from quarries. Because of extensive use of aggregates, these quarries are getting depleted gradually which leads to increase in cost of virgin aggregates and unbalance in biodiversity. By considering the upcoming problems, new materials were encouraged by government authorities to replicate the virgin aggregates in base layers. An extensive research has been carried out to understand the resilient behavior of stabilized reclaimed asphalt pavements (RAP) as a base coarse material in flexible pavements.

This chapter deals with the work carried out by various practitioners and researchers on reclaimed asphalt pavements applications in pavement structures. However, there are several studies available on reclaimed asphalt pavements, only those which are important studies were included as the key focus of this study. Primarily this chapter is subdivided into following sections based on literature studies on stabilized pavement structures.

- Studies on Reclaimed Asphalt Pavements
- Studies on Treated Reclaimed Asphalt Pavements
- Studies on Resilient Modulus
- Studies on correlations between resilient modulus and CBR

2.2. Studies on Reclaimed Asphalt Pavements (RAP)

Although some form of pavement recycling has been practiced as early as 1915 [8], the first sustained efforts to recover and reuse old asphalt paving materials were conducted during 1974 in Nevada and Texas [9]. Bolstered by the sponsorship of the Federal Highway Administration, (FHWA), more than 40 states performed and documented RAP demonstration projects between 1976 and 1982.

2.2.1. In-Situ Pavement Recycling

An alternative to common methods of pavement reconstruction is to recycle the existing pavement material. In-situ recycling is a pavement rehabilitation method in which the material from the existing pavements were used for construction of new pavement structure. In-situ recycling has become popular and attractive because of the potential reduction in costs and consumption of natural resources. Additional benefits of in-situ recycling include conservation of energy, waste reduction, and reduction of greenhouse gas emissions [10].

There are three different types of in situ recycling in pavement rehabilitation, hot in-place recycling (HIR), cold in-place recycling (CIR), and full-depth reclamation (FDR). The three in-situ recycling methods are typically classified according to the procedures used for recycling, and the materials to be recycled into the new pavement. Because of their similarity, however, the nomenclature for in situ recycling is often used interchangeably.

2.2.2. Hot In-Place Recycling

Hot in-place recycling (HIR) is an in situ pavement rehabilitation process where a fraction of the existing asphalt course is used in the new asphalt surface. The existing asphalt is softened by applying heat, mechanically removed, blended with a chemical additive and virgin aggregates or asphalt if needed, and then replaced onto the pavement structure [11]. HIR is typically used to correct for pavement distress, such as rutting, corrugations, thermal cracking, raveling, flushing and loss of surface friction [12]. HIR is an attractive alternative for pavement rehabilitation because it has been shown to reduce construction costs and energy consumption by as much as 25% and 30%, respectively, when compared with conventional methods [13].

2.2.3. Cold In-Place Recycling

Cold in-place recycling (CIR) is similar to hot in-place recycling, but without heat. CIR can be performed either partially or to the full depth of the existing pavement structure. Recycled asphalt pavement (RAP), the material obtained by pulverizing the existing asphalt layer, is reused for the new pavement. Typical depths for CIR range from 50 to 100 mm [14]. CIR consists of pulverizing the existing asphalt layer to a specified depth, mixing the recycled asphalt pavement (RAP) aggregates with an emulsion, compacting the material to the desired density, and letting the material cure. The recycled layer is typically used as a base layer that is surfaced with a thin layer of wearing course. However, CIR has been used for surface course for roadways with low to medium traffic volume [15]. Typical chemical additives used in CIR include soft asphalt cements, cutback asphalt, foamed asphalt cements, and emulsions combined with cement, fly ash, or lime [16].

2.2.4. Full-Depth Reclamation

Full-depth reclamation (FDR) consists of pulverizing and mixing the existing asphalt layer with the underlying aggregate base, and sometimes subgrade, to form a recycled base layer for a new asphalt pavement. This method is also referred to as full-depth cold in-place recycling. A primary difference between FDR and CIR is the depth of pulverization of the existing pavement. FDR extends 100 to 300 mm deep, depending on the dimensions of the existing pavement structure [14]. In contrast, CIR consists of depths only 50 to 100 mm. The material generated from FDR, comprised of existing RAP and underlying base and subgrade materials, is referred to as recycled pavement material (RPM) [17]. RPM can be used as base course for a new pavement [18]. In practice, however, RPM is often mixed with a binder or admixture to enhance the strength and stiffness [17, 19, 20, 21, 22]. RPM can be improved by adding good quality granular material, or by blending with Portland cement, hydrated lime, fly ash, or bituminous agents (slow or medium set asphalt emulsions) [10]. FDR is also used to upgrade unpaved pavements to asphalt pavements [23]. The existing road surface gravel is blended with fly ash and reused as the base course of a new pavement.

2.3. Studies on Treated Reclaimed Asphalt Pavements

The effect of RAP content on strength and stiffness may be an impediment for using recycled materials as base course for a new pavement [24, 25, 26]. An alternative is to enhance the mechanical properties of recycled materials by adding cementicious fly ash. Cementicious fly ashes have been used to effectively improve the mechanical properties of soft subgrades [27] [28]. However, enhancing the mechanical properties of granular materials through fly ash addition is largely undocumented in the literature.

Li et al. [17] evaluated the use of recycled asphalt pavement blended with fly ash as base course during the reconstruction of a 0.5-km section of asphalt pavement in Waseca, Minnesota. The recycled base layer was obtained by pulverizing the existing asphalt pavement and underlying materials to a depth of 300 mm, removing the uppermost 75 mm of recycled pavement material (RPM), uniformly spreading Class C fly ash (10% by dry weight) on the surface, and mixing the fly ash and RPM with water to a depth of 150 mm. CBR tests were performed to evaluate the resistance of RPM through fly ash addition. CBR of RPM increased significantly with the addition of fly ash, ranging from 3 to 17 for RPM (laboratory) and from 70 to 94 for RPM with fly ash (laboratory). The RPM did not meet the CBR typically required for base course (CBR $\geq$ 50), whereas fly ash addition increased the CBR of RPM beyond 50. Field specimens exhibited CBRs approximately two thirds lower than laboratory specimens, but still had CBR significantly larger than RPM alone.

Guthrie et al. [29] investigated the influence of reclaimed asphalt pavements on the mechanical properties of recycled base materials. For this, he taken RAP from two different sources and performed California Bearing Ratio (CBR) test, free- free resonant column test, and tube suction tests to measure strength, stiffness and moisture susceptibility. The results indicate that, on average, CBR values decrease between 13% and 29% with each 25% increase in RAP. For stiffness testing at the optimum moisture content determined for each blend, the general trend was a decrease in stiffness from 0 to 25% RAP, followed by a steady increase in stiffness as the RAP content was increased from 25% to 100%.

A laboratory study was undertaken by Stephen et al. [30] to evaluate the effect of fly ash content on cold in-place recycling (CIR). Reclaimed asphalt pavement (RAP) was mixed with 3, 7, 11, and 15 percent Type C fly ash and the fatigue life, durability, freeze-thaw resistance, and thermal cracking potential of laboratory-compacted samples were evaluated. RAP mixed with asphalt emulsion and asphalt emulsion with hydrated lime were evaluated as well. The results indicated that 7 to 11 percent Type C fly ash provided optimal laboratory freeze-thaw and moisture sensitivity performance. Increasing the fly ash content resulted in a brittle fatigue behavior as well as an increased thermal fracture temperature. AASHTO T283 [31] is recommended for selecting the optimum fly ash content.

Felipe et al. [32], Berthelot [33] performed a similar laboratory studies on recycled pavement material and natural aggregates by treating with fly ash. California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) tests were performed and results shown that CBR of stabilized RAP material has 11 times the CBR of unstabilized material alone. The CBR of RAP material increased with increase of fly ash content. The UCS of RAP material increases with increase in fly ash content and curing period. A similar study was performed by Jeremy et al. [34] on cement kiln dust treated recycled asphalt pavement material and a similar trends were observed.

Crovetti [21] conducted falling weight deflectometer (FWD) tests on pavement test sections to evaluate the structural capacity of pavements containing recycled pavement material blended with fly ash (7% by dry weight) and asphalt emulsion (application rate of 7 L/m2).

Field structural capacity was computed from moduli defined from FWD tests. The test section containing recycled pavement materials blended with fly ash had the highest structural capacity, yielding increase in lifespan of 58% when compared to the control, and 28% when compared to the section with emulsified asphalt. No surface distresses were encountered in any of the test sections after one year of service. In a similar study, Wen et al. [35] reported no surface distresses for test sections containing recycled pavement materials blended with fly ash after two years of service. Moreover, back calculated FWD data indicated that the structural capacity of the test section containing fly ash increased 49% after 1 year of service.

Addition of fly ash can also have detrimental effects on pavements. A series of cold in-place recycling (CIR) test sections using Class C fly ash were constructed by the Kansas Department of Transportation. Test sections with higher fly ash contents exhibited more initial cracking than those with lower fly ash contents. Cross and Young [36] evaluated the durability, fatigue, and thermal cracking potential of laboratory-prepared samples of the CIR materials blended with Class C fly ash. Fatigue testing indicated an increase in brittleness with increasing fly ash content, which would yield a pavement structure with greater propensity for fatigue and thermal cracking. Thus, using more Class C fly ash than the necessary is not recommended.

2.4. Studies on Resilient Modulus

Stiffness is the most important mechanical characteristic of materials in pavements. The relative stiffnesses of the various layers dictate the distribution of stresses and strains within the pavement system. It may seem odd that stiffness rather than strength is considered the most important material property for pavements. Pavement structural design is usually viewed as ensuring sufficient load-carrying capacity for the applied traffic providing sufficient pavement strength. However, the stress levels in well-designed asphalt pavement are well below the strength of the materials, and thus failure under any given load application is not an issue. The preferred method for characterizing the stiffness of pavement materials is the resilient modulus which is defined as the unloading modulus in cyclic loading. The AASTHO Design Guides beginning in 1986 [37] have recommended the resilient modulus for characterizing subgrade support for flexible and rigid pavements and for determining structural layer coefficients for flexible pavements. The resilient modulus is also the primary material property input for materials in the NCHRP 1-37A Design Guide for both flexible and rigid pavements [38]. In this study resilient modulus is considered to be a major property of reclaimed asphalt pavements to use as base course in flexible pavement, so an extensive research was conducted. To know the basic thumb rules and to get an idea to start, a number of studies ware revised.

Li et al. [17] evaluated the stiffness of recycled asphalt pavement blended with fly ash as base course during the reconstruction of a 0.5-km section of asphalt pavement in Waseca, Minnesota. Stiffness was measured by resilient modulus (Mr) tests. Field-mix specimens were prepared by collecting fly ash treated RPM and compacting the mixture into Mr molds. Laboratory-mix specimens were prepared from fly ash and RPM samples obtained during construction. These specimens were prepared to mean field water contents and dry unit weights. RPM-only specimens were prepared in a similar manner. Addition of fly ash increased the Mr of laboratory RPM specimens appreciably (2.2 times, on average), whereas Mr of field specimens were 25% lower, on average, than the Mr of laboratory specimens.

Brian et al. [39] conducted a study to determine the resilient modulus of two recycled roadway materials: recycled pavement material (RPM) and road surface gravel (RSG) with and without cement and cement kiln dust (CKD) stabilization. The results showed that the RSG blended with CKD at 28 days of curing had the highest resilient modulus (1340 MPa). For 0.30 m thick layers, the modulus of RPM with 4% cement after 28 days of curing was 2.4 times higher than unstabilized RPM, while RPM with 10% CKD was 2.1 times greater. The modulus of RSG with cement increased by a factor of 4.6 compared to unstabilized RSG, and by a factor of 6.1 for RSG with CKD. The stabilized base materials continued to increase in stiffness between curing times of 7 and 28 days, with the exception of RPM blended with cement. RPM and RSG blended with CKD gained greater stiffness compared to cement, although the cement stabilization resulted in a higher 7 day modulus.

Kang et al. [40] evaluated the resilient modulus of 17 mixtures of 4 recycled materials with aggregates relative to 100% virgin aggregate. Recycled materials tested were recycled asphalt pavement (RAP), recycled concrete material (RCM), fly ash (FA) and foundry sand (FS). The study concluded that addition of RAP (coarser than aggregates), RCM (same as aggregates) and FA+RAP (very fine and coarser than aggregates) to aggregates increased resilient modulus values. At any given RAP content, increasing the FA content from 5 % and 15% in FA-RAP-aggregate mixture slightly lowered the MR values. Addition of FS (fine material) to aggregate decreased MR values relative to that of 100% aggregates.

Mohamed Attia et al. [41] investigated the effect of moisture content on the resilient modulus of base layer containing reclaimed asphalt pavements material. For this samples were compacted at different moisture contents to achieve maximum dry density. All evaluated

RAP samples had higher resilient modulus value than the typical base material. Moisture content had a clear impact on the resilient modulus value of the base layer containing RAP. As the moisture content increased, the resilient modulus decreased.

Puppala et al. [42] conducted a series of resilient modulus tests on cement treated reclaimed asphalt pavement material. MR values of untreated and cement-treated RAP aggregates ranged from 180 to 340 MPa and 200 to 515 MPa, respectively, which reveal the enhancements with cement treatment. The results obtained by Puppala et al. [42] were presented in Figure 2.1, Figure 2.2 and Figure 2.3.

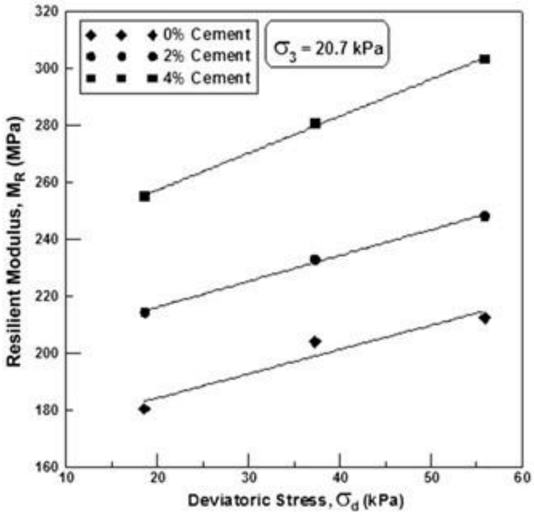

Figure 2.1: Variation of Resilient Modulus with Deviatoric Stress at 20.7 kPa Confining Stress

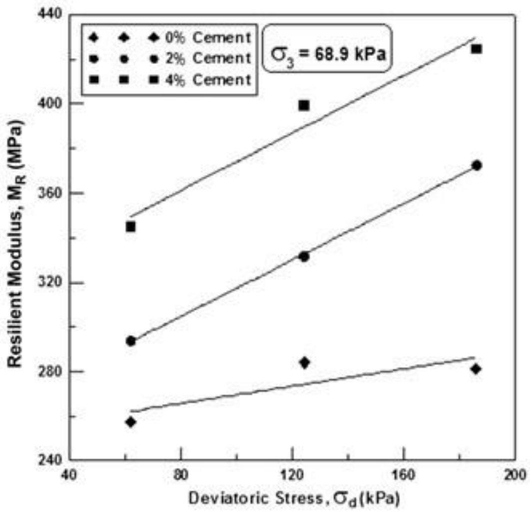

Figure 2.2: Variation of Resilient Modulus with Deviatoric Stress at 68.9 kPa Confining Stress

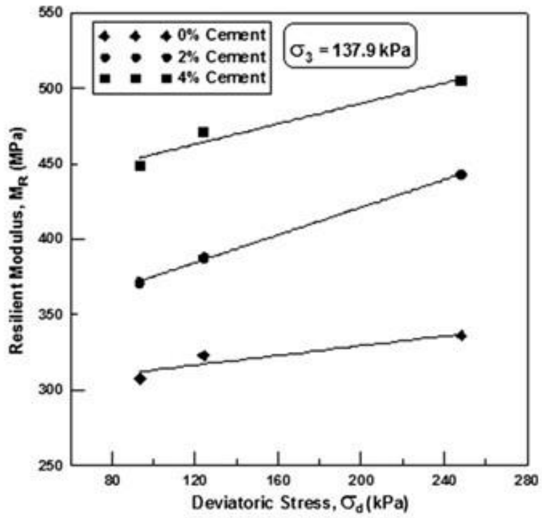

Figure 2.3: Variation of Resilient Modulus with Deviatoric Stress at 137.9 kPa Confining Stress

Edil et al. [43] investigated two field projects, where cementicious fly ashes (10% by dry weight) and water were mixed to stabilize recycled pavement materials and road-surface gravel to form a base during reconstruction of a city street in Waseca, MN, and construction of a flexible pavement in a segment of gravel country road, CR 53 in Chisago County, MN, respectively. Addition of fly ash improves the stiffness and strength of the base materials significantly. A resilient modulus of minimum 50 MPa appears safe to assume irrespective of the base material at the end of construction due to fly ash stabilization. However, moduli of 100 MPa or more can also be achieved.

Lav et al. [44] conducted the repeated load indirect tensile and repeated load triaxial (cyclic triaxial) tests to investigate the effects of stabilization on resilient behavior of fly ash as pavement material. The results shows that stabilized fly ash is a stress dependent material and cyclic triaxial results showed that an apparent relationship between resilient modulus and the first stress invariant (the sum of the three principal stresses). Therefore, the resilient modulus of the material increases with the increasing magnitude of the first stress invariant. It should be noted that throughout the testing program, after removing the confining stresses, the strains under confining pressures were recovered. This proved that the samples were not subjected to significant permanent strains, hence in in-situ applications it is recommended that this material should be designed in thicker layers than conventional pavement layers to keep strains lower. Otherwise, it may end up with premature cracking over shorter times, which significantly reduces pavement life.

Fakhri et al. [45] investigated the effects of the loading history parameters such as the waveform, loading time and the ratio of rest period to loading time on the resilient modulus of the control and SBS-modified mixtures, experimentally. The study determined 9 as the minimum ratio of the rest period to loading time for measuring Mr accurately, especially for square waveforms. The results obtained from the study confirmed that the resilient modulus under square loading can be predicted when the resilient modulus under haversine loading is known by means of a calibrated quadratic polynomial with zero intercept. It was also observed that the beneficial effect of SBS-modified mixtures greatly depends on temperature, loading waveform and loading frequency. Finally, it was shown that the concept of master curve could be used successfully to represent resilient moduli of an asphalt mixture at a wide range of temperatures and loading frequencies.

2.5. Studies on Correlations between Resilient Modulus and CBR

It is a vague idea to correlate the resilient modulus (M_r) and California Bearing Ratio (CBR) because these two parameters is different in nature. Resilient modulus is determined based on the permanent strains from dynamic load tests, whereas CBR value corresponds to the peak resistance that is developed to a monotonic shear failure. Since the test equipment used for conducting resilient modulus test is quite expensive and high skilled technicians are required for conducting the experiment, it is not preferred by a vast majority of transportation agencies. On other hand CBR had become a popular test for characterizing the subgrade strength because of its simplicity and efficiency. So it was deemed necessary to correlate the CBR with the resilient modulus. The earliest of such correlations was developed by Heukelom and Klomp [46] [Eq. 1].

E (MPa) = 10 x CBR ...1

The equation was developed on the basis of Rayleigh Wave and dynamic Impedance testing which was derived from the results of wave propagation testing conducted at very low strain levels in the Netherlands and the UK. The results were modified according to Poisson's Ratio and the modulus was correlated to a series of CBR values. The equation was originally developed for a modulus range of 2-200 MPa.

A similar equation was developed by the US Army Corps [47] by slightly modifying the results to account for the fact that the wave propagation was done at very low strain levels.

E (MPa) = 37.3 x CBR0.71 ...2

The South African Council on Scientific and Industrial Research (CSIR) adopted modified equations of the form E = k x CBR, where k is the factor that accounts for local factors [48]. Even though there are a number of equations emerging out from huge number of studies, the equation developed by Heukelom and Klomp was considered to be preferred relationship.

The Transport and Road Research Laboratory (TRL), Crowthorne, UK also adopted an equation [49]

E (MPa) = 17.6 x CBR0.64 ...3

In the course of time, other researchers such as Angell [50] decided that the Heukelom and Klomp equation was not accurate because the test data indicate that the equation underestimates the modulus for CBR values less than 5, and overestimates the same for CBR values greater than 5. In this regard Main Roads Department, Queensland (QDMR) adopted the following relationship [51]:

E (MPa) = 21.2 × CBR0.64 (CBR < 15), and

E (MPa) = 19 × CBR0.68 (CBR > 15) ...4

The Indian Roads Congress (IRC, 2012) [3] adopted a relationship by combining Heukelom and Klomp equation and the TRL equation:

E (MPa) = 10 x CBR (CBR < 5),

$E (MPa) = 17.6 \times CBR^{0.64} (CBR > 5)$

2.6. Summary

Initial literature study gives an outlook of the work carried out to understand reclaimed asphalt pavements, and effect of repetitive loading on reclaimed asphalt pavements. Some of the important consensuses are drawn from literature review.

- Reclaimed Asphalt Pavements material is obtained through cold milling process of existing damaged flexible pavement.
- 100% Reclaimed Asphalt Pavements material cannot be used as a base course material in flexible pavements.
- Treated Reclaimed Asphalt Pavements material can be used as base coarse material in flexible pavements.
- Class C fly ash can be used as a stabilizer.
- Resilient Modulus is an essential design parameter of the material to use in flexible pavements.
- There are no proper correlations between Resilient Modulus and CBR to derive the resilient modulus value from CBR data.

Though literature covers major aspects of Reclaimed Asphalt Pavements, a very little attempt was made in India because of the cost of equipment used to determine resilient modulus and lack of awareness on the advantages of recycling the pavement materials especially asphalt pavements.

In view of this, following chapters encompass experimental evaluation of reclaimed asphalt pavements and treated reclaimed asphalt pavements under repetitive loading.

Chapter 3

Materials and Methods

3.1. Introduction

As discussed in chapter 1 and 2, extensive experimental program was designed and conducted to find the strength and stiffness properties in terms of resilient modulus and California Bearing Ratio of the fly ash treated reclaimed asphalt pavements (RAP) with and without – virgin aggregate mixtures at a given gradation for pavement applications. For this the samples were prepared with different dosages of fly ash i.e. 10%, 20%, 30%, and 40% and stored in a specially designed stability chamber for 1, 7 and 28 day testing periods. The following sections describes the physical and chemical properties of the materials used in this research (RAP, fly ash and virgin aggregates), types of laboratory tests performed, test equipment used and the test procedures followed.

3.2. Reclaimed asphalt pavements (RAP)

The cold in-place reclaimed asphalt pavements was sampled from an ongoing project at Nellore district in Andhra Pradesh on National Highway 5 (NH5). The milled RAP material has been transported to the laboratory and a series of basic tests and engineering tests were performed. Physical properties of RAP depends upon the properties of constituent materials, type of recycling and type of asphalt concrete mix from which they are milled. The basic tests include grain size distribution tests, specific gravity, and Proctor compaction tests. Resilient Modulus tests using fully automatic advanced cyclic triaxial testing apparatus and California Bearing Ratio tests were also performed on the compacted stabilized RAP mixtures with different dosages of fly ash from 10% to 40% with 10% increment for 1, 7, and 28 day curing periods. All the basic tests were performed in accordance with Indian standard codes and AASHTO standard testing procedures.

3.2.1. Gradation

The basic tests were performed on the RAP material at the beginning of the experimental program. The particle size distribution of the RAP material was first determined in accordance with IS: 2720 – 4 – 1985 [56]. It was observed that about 99% of the material was retained on the 75 microns sieve, so the hydrometer analysis for RAP material was not performed.

For the material to use in base layer of flexible pavements in India, the gradation of the material has to meet the requirements laid down by the Ministry of Road Transport and Highway (MORTH). Since the gradation of the RAP material obtained from Nellore district in Andhra Pradesh on National Highway 5 (NH5) is not falling within the MORTH specified upper and lower limits, the whole RAP material was initially divided according to specified sizes and stored separately. Later, the samples were prepared by mixing specified amounts by weight to maintain the MORTH specified gradation within the sample. Figure 3.1 shows the grain size distribution of the RAP material obtained from NH-5 and the gradation curves of MORTH upper and lower limits for the material to use in base layer of flexible pavements in India.

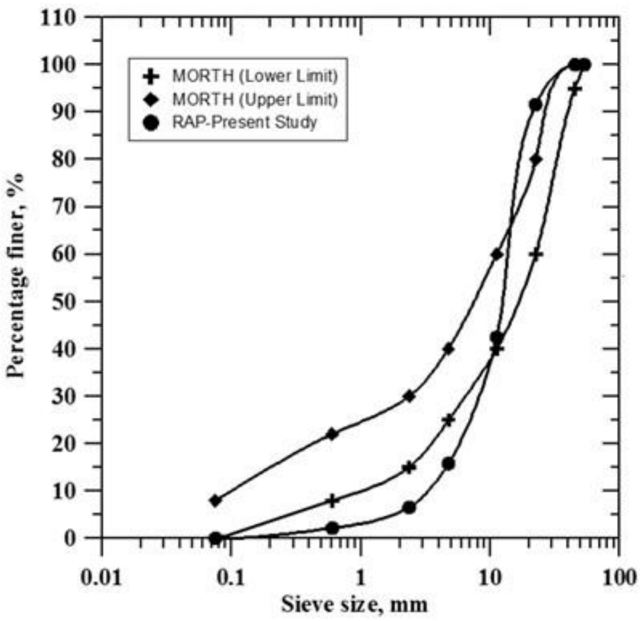

Figure 3.1: Grain Size Distribution Curves of the RAP, Upper and Lower Gradations of Base Material as per MORTH.

3.2.2. Asphalt Content

In the design mixture that incorporates high percentage of RAP, it is important to determine the asphalt content, this can be only done by separating asphalt from RAP. For this purpose solvent extraction method was used in which a solvent such as benzene, toluene, ethylene chloride or trichloroethylene can be used to dissolve and separate asphalt from RAP material. Asphalt content is calculated as difference in mass before and after the extraction in accordance with ASTM D2172 [52]. In this regard, RAP material of known weight is taken and soaked in benzene for 24 hours and the solution is passed through a filter paper, so that no fines are lost. Later aggregates are oven dried and weighed. Asphalt content is calculated by using formula given below. Table 3.1 shows the obtained asphalt content of RAP material.

$$\text{Asphalt Content} = \frac{\text{Weight loss}}{\text{Initial weight}} \text{ x } 100$$

Table 3.1: Asphalt Content of RAP

	Trail I	Trail II	Trail III
Initial weight of RAP, grams	120.9	134.2	117.8
Weight of aggregates after socking in the solvent, grams	115.8	128.5	112.8
Obtained asphalt content, %	4.21%	4.24%	4.24%
Average asphalt Content,%	4.23%		

3.2.3. Moisture Content

The moisture content (w) of a soil sample is equal to the mass of water divided by the mass of solids. The moisture content of the RAP material was determined in accordance with IS: 2720 (Part II) – 1973 [53]. For this initially 500 grams of sample was taken and kept in an oven for 24 hours at 110^0C. After 24 hours of oven dry the sample was taken out of the oven and covered with lid to prevent the entrance of moisture in to the sample. Now the dry weight of the sample was taken. By using the below given formula, moisture content of the RAP material was determined. Table 3.2 shows the obtained moisture content of RAP material.

$$\text{Moisture content} = \frac{[W_2 - W_3]}{[W_3 - W_1]} * 100\%$$

Where: W_1 = Weight of empty container in grams

W_2 = Weight of container + wet soil in grams

W_3 = Weight of container + dry soil in grams

Table 3.2: Moisture Content of RAP

	Trail I	**Trail II**	**Trail III**
W_1, grams	274	297	246
W_2, grams	774	797	746
W_3, grams	763	787	734
Water Content, %	2.25	2.04	2.45
Average Water Content,%	2.25		

3.2.4. Specific Gravity

Specific gravity is the ratio of the density of a substance to the density (mass of the same unit volume) of a reference substance. Specific gravity of RAP material was determined in accordance with IS: 2386 (Part III) – 1963 [54] by using wire basket having 3mm finer mesh. For this initially some required amount of RAP material was taken and washed gently with water to remove the dust particles. Than the sampled was dried by keeping the sample in oven for 3 hours at 105^0C and then immersed in basket containing water for 24 hours at room temperature. After completion of 24 hours the sample was removed from the water, rolled in a dry absorbent cloth to remove the visible water drops. Then the saturated surface dry sample weight was taken and immediately the sample was placed in a wire basket, its weight was measured in water. Finally by using the below correlation specific gravity of RAP material was determined. Table 3.3 shows the obtained moisture content of RAP material.

$$\text{Specific Gravity} = \frac{A}{(B-C)}$$

Where: A = weight of oven-dry specimen in Air, g

B = weight of saturated surface-dry specimen in air, g

C = weight of saturated specimen in water, g

Table 3.3: Specific Gravity of RAP

	Trail I	Trail II	Trail III
A, grams	3000	3000	3000
B, grams	3015	3017	3024
C, grams	1912	1910	1921
Specific Gravity	2.72	2.71	2.72
Average Specific Gravity	2.72		

3.2.5. Compaction Characterization

Compaction tests were performed on the RAP material to obtain the optimum moisture content and maximum dry density in accordance with IS: 2720-8 [55] for determining the laboratory compaction characteristics. This procedure requires a compactive effort of 2703 kJ/m^3. In this prospect compaction tests were performed in 150mm diameter mould having 125mm height in 5 layers, each layer receiving 55 blows. For this, initially the material was taken in accordance with MORTH specified gradation and mixed thoroughly by mixing some ideal moisture content to start. Than the mixture is equally divided into 5 parts, one part of the mixture is poured into the mould and then 55 blows were given with 4.5kg rammer falling from 450mm height. Than in the same manner the remaining parts also compacted one after another. After completion of the compaction, the collar is removed and by using the straight edge, the top surface was leveled. Now the weight of the soil in the mould was determined and later small amount of soil was taken to determine moisture content. The same procedure was continued by keep on adding 2% of water to the same mixture until it reached the optimum dry density. After 24 hours optimum moisture content was determined. The optimum moisture content and maximum dry density were determined for RAP material. Table 3.4 shows the parameters adopted for compaction test. Figure 3.2 shows the obtained relation between the dry density and moisture content for RAP material.

Table 3.4: Compaction Parameters

Compactive Effort (kJ/m^3)	2703
Weight of Rammer (kg)	4.5
Height of Drop (mm)	450
Diameter of Mould (mm)	150
Height of mould (mm)	125
Volume of Mould (mm3)	2208932.335
No. of Layers	5
Blows per Layer	55

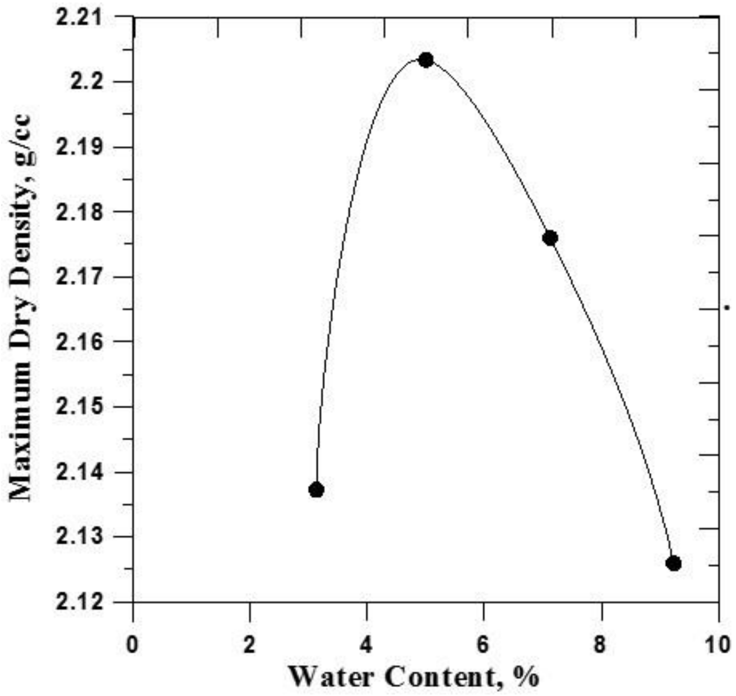

Figure 3.2: Maximum Dry Density – Water Content Relationship for RAP

3.3. Fly ash

The fly ash was sampled from Neyveli Lignite Corporation (NLC), a thermal power station from Tamil Nadu state, which was formed by burning lignite coal which contains very high moisture and the presence of fixed carbon is in the range of 55 – 70%. The fly ash was directly collected from the hopper without any treatment. The fly ash was transported to the laboratory and a series of basic tests were performed. The basic tests include grain size distribution tests, specific gravity, and Proctor compaction tests.

3.3.1. Gradation

The particle size distribution of the fly ash is performed in accordance with IS: 2720 (Part 4) – 1985 [56]. The material passing 75 microns sieve was analyzed by using hydrometer analysis and the coarser material retained on 75 microns sieve was analyzed by mechanical sieve analysis. Fine soil collected on pan is taken in a beaker and 125ml of dispersing agent is added, which was prepared by mixing 40 grams of sodium hexa-meta-phosphate in 1000ml distilled water. Later the solution was stirred gently till the sample is completely wet. The soil was left for 10 minutes for soaking. During this process 125ml of dispersing agent was taken in controlled cylinder and the cylinder was filled with distilled water till it reaches the 1000ml mark. The soil slurry present in the beaker was transferred in to 1000ml cylindrical flask and distilled water is added till it reaches the 1000ml mark. The open end of the cylinder was closed with stopper and then the cylinder was turned upside down for approximately 30 times in a minute. Then the cylinder was placed on a flat table without any disturbances. Immediately the time was recorded and hydrometer was inserted carefully for the first reading. The reading were taken after 2, 5,8,15,30, 60 minutes, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24 hours. The gradation of the fly ash is also found out using particle size analyzer to cross verify the results obtained from hydrometer analysis. The results obtained from both the methods are shown in Figure 3.3.

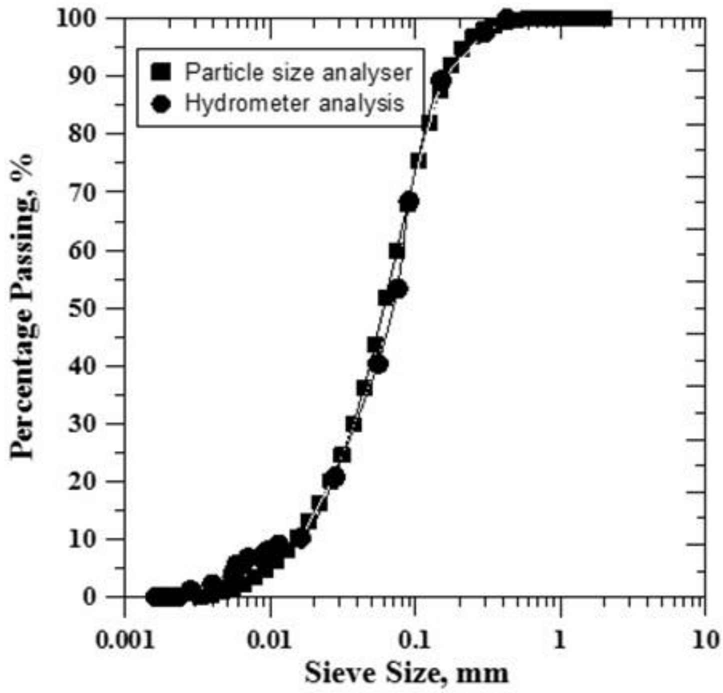

Figure 3.3: Grain Size Distribution Curve of the Fly ash from hydrometer analysis and particle size analyzer

3.3.2. Specific gravity

Specific gravity is the ratio of the density of a substance to the density (mass of the same unit volume) of a reference substance. Specific gravity of fly as is determined in accordance with IS 2720 (Part 3/Sec 1) – 1980 [57]. In this aspect a density bottle with stopper was taken and its dry empty weight was determined. Now, the bottle was filled with fly ash to 1/3rd of its height and weight was determined. Then kerosene was poured in bottle till it reaches the neck and the open end was closed with stopper. Now the sample was allowed for partial vacuum suction using mechanical suction motor for 10 minutes. After ensuring that all the air pockets removed from the sample the bottle was filled with kerosene till its neck and the weight was determined. Now the density bottle was cleaned and dried, density bottle was filled with only kerosene till the neck and weight was determined. Finally with the below mentioned formula specific gravity was determined. Table 3.5 shows the obtained moisture content of RAP material.

$$\text{Specific Gravity, G} = \frac{(W_2 - W_1)}{(W_4 - W_1) - (W_3 - W_2)}$$

Where: W_1 = Weight of density bottle, grams

W_2 = Weight of density bottle and dry soil, grams

W_3 = Weight of density bottle, soil and kerosene, grams

W_4 = Weight of density bottle and kerosene, grams

Table 3.5: Specific Gravity of Fly ash

	Trail I	**Trail II**	**Trail III**
W_1, grams	52.33	52.33	52.33
W_2, grams	77.78	101.35	88.58
W_3, grams	145.32	161.47	152.80
W_3, grams	127.64	127.64	127.64
Specific Gravity	2.22	2.20	2.21
Average Specific Gravity	2.21		

3.3.3. Compaction Characterization

Compaction tests were performed on fly ash to determine the dry density – moisture content relationship in accordance with IS 2720 (Part 7) 1980 [58]. In this regard the compaction test was performed in a mould having 100mm diameter having 127mm height. The compaction was performed in 3 layers, each layer giving 25 blows. In this aspect a rammer of weight 2.7kg having a drop height of 300mm was taken. In this process the energy released per blow is 596KJ/m^3. For compaction test, initially the considerable amount of material was taken by assuming some density and mixed thoroughly by mixing some ideal moisture content to start. Than the mixture is equally divided into 3 equal parts, one part of the mixture is poured into the mould and then 25 blows were given with 2.7kg rammer falling from 300mm height. Than in the same manner the remaining parts also compacted one after another. After completion of the compaction, the collar is removed and by using the straight edge, the top surface was leveled. Now the weight of the fly ash in the mould was determined and later small amount of fly ash was taken to determine moisture content. The same procedure was continued by keep on adding 2% of water to the same mixture until it reached the optimum dry density. After 24 hours optimum moisture content was determined. The optimum moisture content and maximum dry density were determined for fly ash. Figure 3.4 shows the obtained relation between the dry density and moisture content for fly ash.

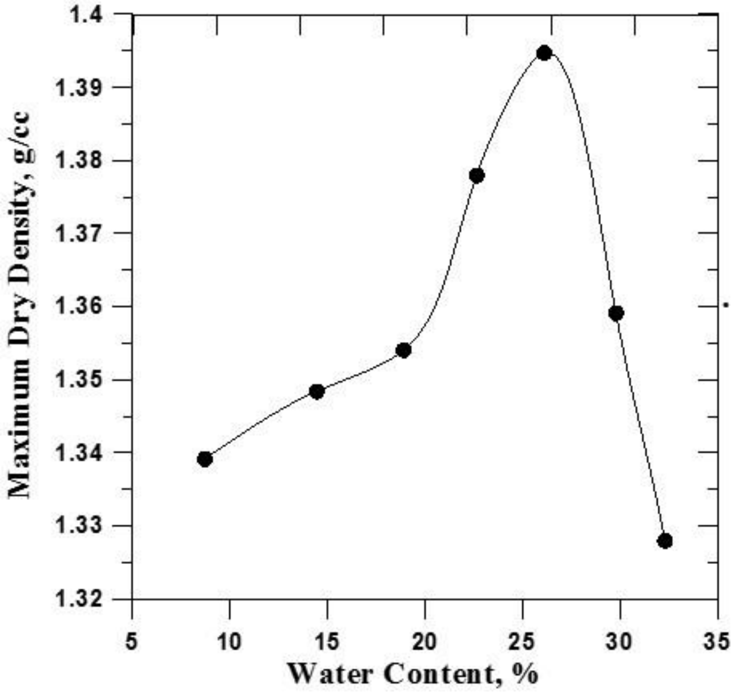

Figure 3.4: Maximum Dry Density – Water Content Relationship for Fly ash

3.3.4. Chemical Composition

The chemical composition of the fly ash depends upon many factors such as coal deposits deciding its quality, the composition of the parent coal, the process of combustion of coal, the additives used for flame stabilization, corrosion control additives used, hopper position, flow dynamics of the precipitators and the removal efficiency of the pollution control devices. Fly ash that is taken from same source with similar chemical composition may have significantly different mineralogy depending upon the coal combustion technology used, which affects the hydration properties of the fly ash. The mineral groups present in coal such as hydrated silicates (kaolinite, montmorillonite e.t.c.), carbonates (calcite, siderite and dolomite), silicates (quartz, feldspar e.t.c), sulphates (gypsum anhydrate), sulphides (pyrite and marcasite), phosphates (apatite) and their varying proportions play a crucial role in deciding the chemical composition of the fly ash. When the pulverized coal is subjected to combustion, the clay minerals undergo thermal chemical transformations. During this process, sillimanite ($Al_2O_3.SiO_2$) and mullite ($3Al_2O_3.SiO_2$) may crystallise as slender needles along with glass formation. Pyrites and other iron bearing minerals form iron oxides, and calcite gets transformed into CaO. The glassy phase formed renders pozzolanity to the fly ash. The major components of fly ash are silica (SiO_2), alumina (Al_2O_3) and ferric oxide (Fe_2O_3). Oxides of calcium, magnesium, sulpher, titanium and sodium are also present in fly ash in small amounts. Some of the carbon particles do not burn in the furnace and hence, fly ash may contain some amount of unburnt carbon particles.

As per IS: 1727 [59], chemical characterization of fly ash can be found out by using reagents method, which is time consuming. So the chemical analysis of the fly ash was performed by using X-Ray Florescence (XRF) in which fluorescent X-rays were emitted from a material which has been excited by bombarding with high-energy X-rays or gamma rays. The chemical analysis of the fly ash from XRF is tabulated in Table 3.6.

Table 3.6: Chemical analysis of fly ash obtained from XRF

Chemical Compound	**Quantity (%)**
Silicon Dioxide (SiO_2)	40.625
Calcium Oxide (CaO)	11.929
Iron Oxide (Fe_2O_3)	9.614
Aluminum Oxide (Al_2O_3)	32.342
Magnesium Oxide (MgO)	1.854

3.4. Mix Design

RAP material cannot be used directly for base application because of the thick asphalt coating around the aggregates in the RAP material which is responsible for response of RAP material towards binding property. So in order to create the bonding between the aggregate particles in RAP material, fly ash from Neyveli Lignite Corporation (NLC), a thermal power station from Tamil Nadu state is taken which acts as a binder between the aggregate particles in RAP material, because fly ash is a self cementicious material as calcium compounds are present in it. In this aspect samples were prepared with different dosages of fly ash (10%, 20%, 30%, and 40%) for resilient modulus test and California Bearing Ratio (CBR) test. To prepare the optimum samples, initially two different mixing methods were proposed for mixing fly ash in the RAP material.

- Replacement method
- Addition method

3.4.1. Replacement method

Replacement method is a method where the fly ash is added to the mixture by removing a proposed amount of RAP by weight and replacing with the same amount of fly ash by weight. For example, for the case of RAP treated with 10% fly ash represent replacement of 10% RAP with 10% fly ash by weight of RAP to constitute 100% RAP - fly ash mixture. It is important to note that in replacement method at higher percentage of fly ash, the percentage of coarse grained particles, which are primary responsible for strength and structural support, are getting reduced corresponding to the fly ash replacement.

3.4.1.1. Specimen Preparation

For conducting resilient modulus and unconfined compressive strength tests on fly ash treated RAP material, specimens were prepared in a cylindrical split mould having 100mm diameter and 200mm height. The gradation was adopted according to MORTH specifications. MORTH has specified a minimum and maximum gradation for the material to be used in base/sub-base of a flexible pavement. Average of the minimum and maximum was considered for the present study. For this initially the whole RAP was sieved according to MORTH specified sizes and stored in separate bins. For preparing specimen, the amount of RAP material required was calculated from obtained compaction results. In calculations the whole required material was further divided up to the specified percentages of each size of particles and its proportionate weights were calculated. The material was taken in a pan according to the MORTH gradation by weight. Now assumed percentage of fly ash was taken, let us consider 10% dosage of fly ash. Before mixing the fly ash in the RAP material, 10% of RAP material by weight of whole RAP material in the pan was taken out from the pan and same 10% of fly ash was mixed in RAP material in pan. Hence, the mixture in the pan contains 90% of RAP material and 10% of fly ash. Now, the obtained optimum moisture content from compaction test performed on this mix composition was taken and mixed properly to create a homogeneous mixture. After mixing, the material is compacted in five layers with 25 blows on each layer with 4.9kg rammed having a free fall of 450mm. The blows were given in such a way that all 25 blows are equally spread all over the surface of the layer. The top surface was smoothened to create a horizontal surface by using straight edge. The sample was retained in the mould for 24 hours. After 24 hours of an initial setting time the specimen was carefully removed from the cylindrical split mould and is stored in a stability chamber for curing, where a uniform temperature and relative humidity were maintained at 25^{0}C and 70 respectively.

3.4.2. Addition method

Addition method is a method wherein the fly ash is added in addition to a proposed amount of RAP by weight. For example, for the case of RAP treated with 10% fly ash represent addition of fly ash equivalent to the weight of 10% RAP to 100% RAP to constitute 110% RAP - fly ash mixture. It is important to note that in addition method even at higher percentage of fly ash, the percentage of coarse grained particles, which are primary responsible for strength and structural support, are retained in the mixture. A caution should be exercised when higher percentages of fly ash has been proposed for the mixtures. For instance, for 40% fly ash treated RAP mixture, it is advisable to reduce the RAP percentage and fly ash percentage proportionately to avoid a waste of 40% mixture.

Similar sample preparation procedure explained in Section 3.4.1.1 has been adopted even for addition method. However, the modified percentage of fly ash and RAP materials were added according to the proposed dosages to avoid material wastage.

3.5. Mix Composition

The samples were prepared with different mix proportions for California Bearing Ratio and Resilient modulus tests on the basis of trial and error method in order to achieve strength and stiffness in terms of California Bearing Ratio and Resilient Modulus (20 and 450MPa) as specified by Indian Roads Congress (IRC:37-2012) and Ministry of Road Transport and Highway (MORTH). Various mix proportions evaluated in this study are presented in Table 3.7.

Table 3.7: Various Mix Proportions Evaluated in This Thesis

S.No.	Designation of the mix	Quantity of RAP (%)	Quantity of virgin aggregates (%)	Quantity of fly ash (%)
1	100R:0A+10F	100	0	10
2	100R:0A+20F	100	0	20
3	100R:0A+30F	100	0	30
4	100R:0A+40F	100	0	40
5	80R:20A+10F	80	20	10
6	80R:20A+20F	80	20	20
7	80R:20A+30F	80	20	30
8	80R:20A+40F	80	20	40
9	60R:40A+10F	60	40	10
10	60R:40A+20F	60	40	20
11	60R:40A+30F	60	40	30
12	60R:40A+40F	60	40	40

3.6. Test Procedures

3.6.1. Compaction Test

Modified Proctor compaction tests were performed in accordance with IS: 2720-8 [55] on all design mixtures shown in Table 9 to obtain the relationship between maximum dry density and optimum moisture content. For compacting the mixture containing the coarse material up to 37.5 mm size, 150mm diameter mould is used. Mixture is compacted in 5 layers each layer being given 55 blows with 4.9kg rammer. The blows were distributed uniformly over the surface of the each layer to maintain the uniform compaction over the surface. After completion of compacting the 5 layers, the collar was removed and the surface was levelled exactly up to the top edge of the mould using straight edge. For this initially some known moisture was added to start up with and corresponding dry density was found out. Later the same procedure was repeated by increasing water content by 2% intervals till the maximum dry density and optimum moisture content was obtained. The water added for each stage of the test should be such that a range of moisture contents is obtained which includes the optimum moisture content.

3.6.2. Resilient Modulus, M_r

Resilient modulus is the elastic modulus based on the recoverable strain under repeated loads. In other words it is the ratio of applied deviator stress to recoverable or resilient strain. Resilient modulus is a key granular material characterization parameter which indicates the elastic response of a material. It is a measure of material stiffness and provides a mean to analyze stiffness of material under different stress conditions. Resilient modulus is typically determined through laboratory tests by measuring stiffness of a cylindrical specimen subjected to a cyclic loading using fully automatic advanced cyclic triaxial testing apparatus.

The resilient modulus test was performed by using cyclic triaxial test equipment in which it was designed to simulate the traffic wheel loading coming on to the specific pavement layer. For this thesis research, the standard testing method for determining the resilient modulus of soils and aggregate materials, AASHTO designation T 307-99 2007 [60] was employed. The specimens were tested at a different stress levels based upon the location of the specimen within the pavement structure as specified by AASHTO for Base/Subbase materials. Table 3.9 presents the testing sequences applied in the test procedure. The test sequences mainly consists of 5 confining pressures and each confining pressure having different axial deviatoric stress. Confining pressure basically represents the overburden pressure of the specimen location within the pavement layer. The axial deviatoric stress is basically composed of two components, cyclic stress and contact stress, in which cyclic stress is the applied deviatoric stress and contact stress represents the seating load which was applied by placing a vertical load on the sample to maintain a positive contact between the specimen cap and the specimen. The contact stress is 10% of total axial stress. A haversine shaped wave loading pulse as shown in Figure 3.5 was applied as the traffic wheel loading on the sample. A loading period of 0.1sec is used, which is the time interval the sample is subjected to a cyclic stress. A relaxation period of 0.9sec was adopted.

Table 3.8: Resilient Modulus Testing Sequence

Sequence No.	Deviator Stress, kPa	Confining Stress, kPa	No. of Cycles
0	103.4	103.4	1500
1	20.7	20.7	100
2	41.4	20.7	100
3	62.1	20.7	100
4	34.5	34.5	100
5	68.9	34.5	100
6	103.4	34.5	100
7	68.9	68.9	100
8	137.9	68.9	100
9	206.8	68.9	100
10	68.9	103.4	100
11	103.4	103.4	100
12	206.8	103.4	100
13	103.4	137.9	100
14	137.9	137.9	100
15	275.8	137.9	100

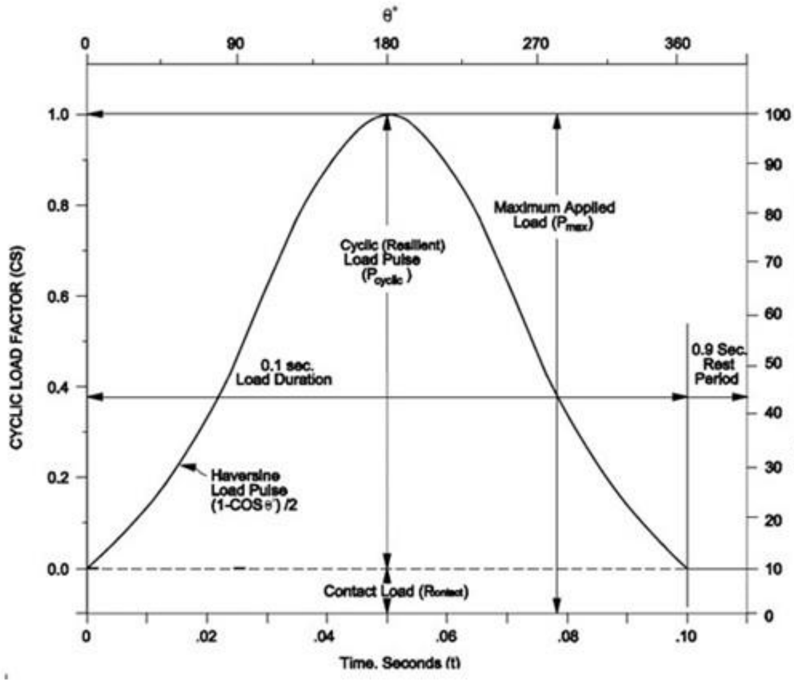

Figure 3.5: Haversine Load Pulse Wave

3.6.2.1. Cyclic Triaxial Apparatus

The resilient modulus test is a cyclic load test where the stiffness of the material changes with loading. These changes are formed due to the nonlinear stiffness behavior of the material for different stress states during cyclic loading. Since the cyclic loading of the system depends on the stiffness of the material, most systems fail to apply the correct load throughout the test [61]. Hence, in this thesis resilient modulus test was performed by using Fully Automatic Cyclic Triaxial System (FACT) shown in Figure 3.6. The FACT is a closed loop, servo control, material testing machine. The major components of FACT are loading frame, Pneumatic loading system, Triaxial pressure cell, Control and Data acquisition system, Linear Variable Displacement Transducers (LVDTs).

Figure 3.6: Fully Automatic Cyclic Triaxial System

3.6.2.1.1. Loading Frame

The loading frame is a stiffer version of standard geotechnical load frame consists of heavy base plate. The loading frame is of stiff enough to limit the deformation and vibrations which may influence the test results during dynamic repeated loading tests. The loading was applied through the pneumatic actuator mounted in the center of the crosshead. Very sensitive displacement transducer was attached to the actuator to measure the displacements in the sample while testing. The loading frame was shown in Figure 3.7.

Figure 3.7: The Loading Frame

3.6.2.1.2. Pneumatic loading system

The pressures and the loads applied on the specimen in FACT system was controlled by the air compressor controller unit, the system requires a clear air supply without any moisture in the air. So the moisture filters were provided at the exit point of the compressor. These filters will clean the air before sending it in to the system. The cell was made with Licite-type material in such a way that it can bear the pressure exerted with in the cell. The cell was designed to contain liquid material to provide confining pressure and the use of any compressible gas may lead to accident. The pneumatic system was shown in Figure 3.8.

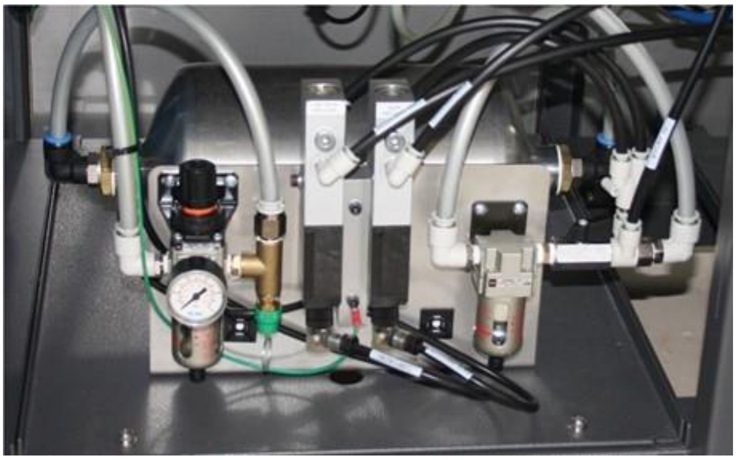

Figure 3.8: The Pneumatic System

3.6.2.1.3. Triaxial cell

The triaxial pressure cell used in this equipment is suitable to test the specimens having diameter up to 100mm and height 200mm. This triaxial cell is rated to a maximum confining pressure of 1000kPa. The triaxial cell was shown in Figure 3.9.

Figure 3.9: The Triaxial Cell

3.6.2.1.4. Control and Data Acquisition System

The Universal Testing System (UTS) control and Data Acquisition System (CDAS) is a self-contained unit which provides all the facilities for determining the resilient modulus at different stress states of material beneath flexible road pavements subjected to moving wheel loads. The CDAS consists of an acquisition module and a feedback control module. 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. The confining pressure applied through air is controlled from 0 to 1000kPa. The feedback control module has three normalized input channel controls, where one id dedicated to the actuator position, another one is for actuator force and the remaining one is for general purpose input. The system has its own communication system for providing uninterrupted, simultaneous communication between PC and the UTS system. The transducer assembly was shown in Figure 3.10.

Figure 3.10: The Control and DAQ System

3.6.2.1.5. Linear Variable Displacement Transducers (LVDTs)

According to the AASHTO T 307-99 (2007) [60], high resolution LVDTs are required to measure the displacements occurred in the sample while test is in progress. One LVDT which was placed below the actuator to load shaft of the Universal Testing System to measure the vertical displacement of the actuator. Two LVDTs are placed with in the cell to record the displacements in middle portion of the specimen. The maximum scale stroke for these two LVDTs is +5mm, with a resolution of 0.001mm accuracy. The output data was continuously monitored individually for further calculations. The LVDTs were shown in Figure 3.11.

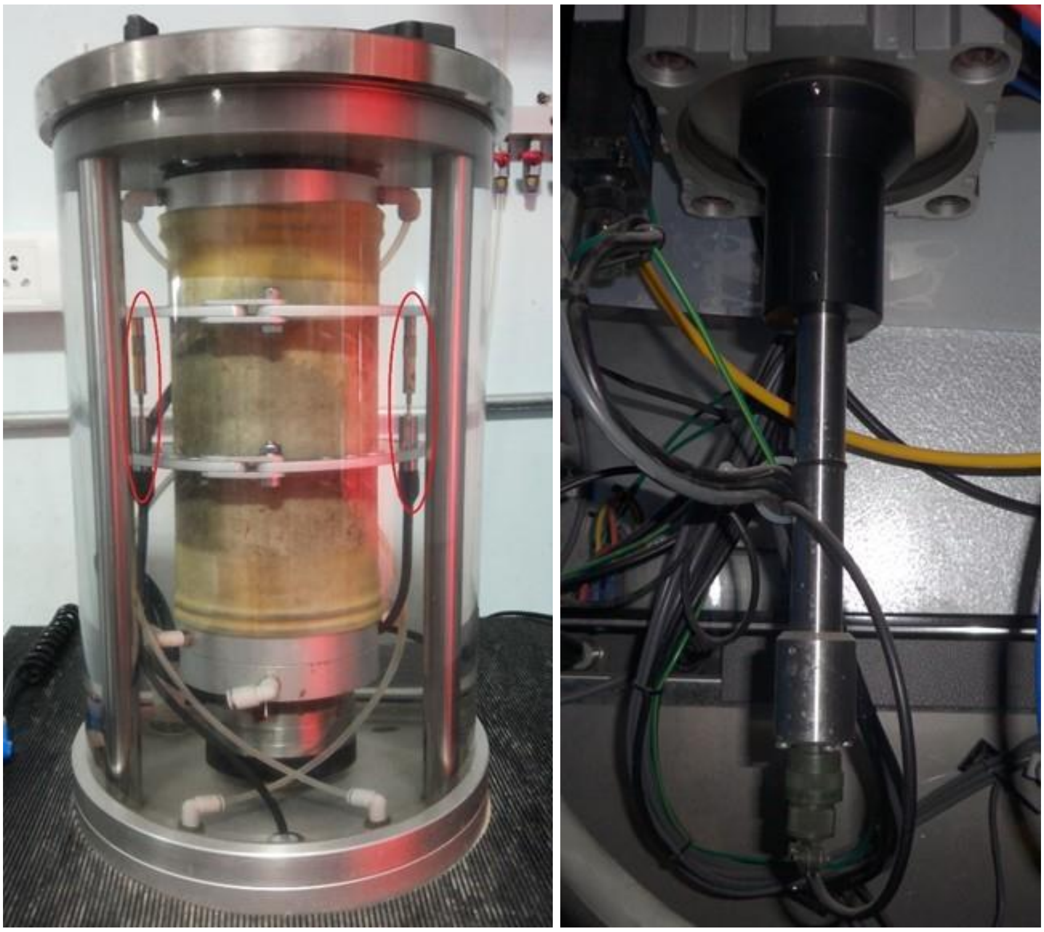

Figure 3.11: The External LVDTs

3.6.2.1.6. Software

Since the UTS is fully automated, the whole equipment control and data acquisition operations were performed through UTS software. In this software all the predefined programs were installed for different test procedures such as unconfined compressive strength test, resilient modulus test, unconsolidated undrained test, consolidated undrained test, consolidated drained test and etc. This software also proved a user defined programs in which a user can create their own testing method and protocol. In this thesis, the AASHTO T 307-99 [60] program for the determination of resilient modulus of aggregate base materials has been used. The Figure 3.12 below shows a sample test data window during the test.

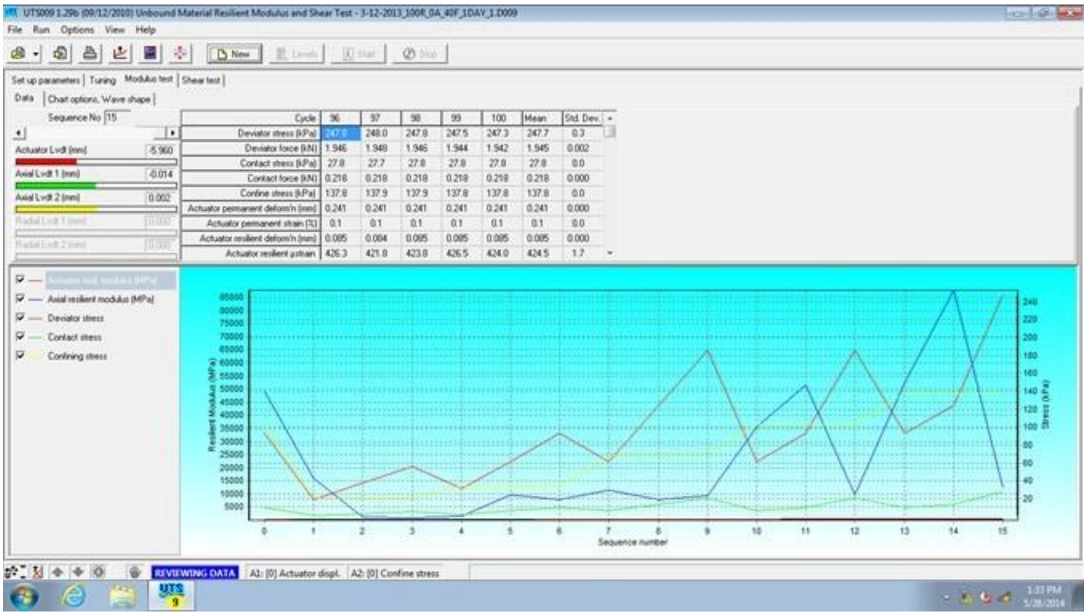

Figure 3.12: Software Window showing the test data

3.6.3. Unconfined Compressive Strength

The unconfined compressive strength is the measure of the resistance of the composites to external loading in single axial loading when the sample is not subjected to any confining pressure. Unconfined compressive strength test is the most widely used laboratory test in pavement application and it is the very simple and quick test for determining the shear strength of the cohesive soils which was conducted in accordance with test procedure given in ASTM D5102 [62]. The result obtained may be used as one of the design parameters of pavement layers.

Pavements are subjected to several load repetitions in their design life. It is always important to know how much strength is retained after repeated loading. The retained strength, after some number of loading cycles, plays a key role in designing the layer thickness. IRC: 37-2012 [3] recommends usage of original UCS for designing layer thickness, in which case the designed thickness may not be sufficient after certain load repetitions. In such cases, pavements may fail even before reaching their design life. In this thesis retained strength is considered as the unconfined compressive strength of the specimen after testing it for resilient modulus (M_r). Indian roads congress design method for flexible pavements specifies a permissible value of the UC strength of a base/sub-base layer to be 1.7 MPa at 28 day curing period.

3.6.4. California Bearing Ratio (CBR)

The California bearing ratio is basically a penetration test to evaluate the strength of pavement layers. It was developed by the California Department of Transportation before World War II. The test measures the load required to penetrate the plunger of standard diameter in to the soil sample. The harder the surface, the higher the CBR value. A CBR of 3 equals to tilled form land, a CBR of 4.75 equals to turf or moist clay, while moist sand may have a CBR of 10. High quality crushed rock has a CBR over 80. The standard material for this test is crushed California limestone which has a value of 100. The CBR test mainly determines the resistance of the pavement layer, which undergo deformation under the load from vehicle wheels. The higher the CBR value, the higher the strength of the pavement layer, so the lesser the thickness of the pavement layer, which gives a considerable cost savings. For this thesis CBR test was performed in accordance with test procedure given in AASHTO T 193 – 13 [63] on all design mixes because the Indian Roads Congress (IRC) design for pavements completely follows the CBR based design.

3.7. Summary

This chapter provides the detailed explanation on basic properties of the RAP material and Fly ash used in this study. Also, the details of the tests performed on the materials are briefly explained and the notations used for test results to present in a simple format is explained. The test equipment used to determine resilient modulus value is also explained.

Chapter 4

Resilient Behavior of Fly ash Treated 100% RAP Material

4.1. Introduction

This chapter presents the resilient modulus test results of 100% reclaimed asphalt pavement (RAP) treated with different proportions of fly ash. It is required to achieve a minimum resilient modulus value for the proposed RAP mix to be used as a base/subbase material as per Indian Roads Congress's (IRC) design methodology for flexible pavements [3]. In brief, the resilient modulus of the RAP specimen was determined in accordance with the AASHTO standard test procedure, T 307-99(2007) [60]. A fully automatic cyclic triaxial test equipment was employed for conducting repetitive loading test to determine resilient modulus of the specimens as discussed in Section 3.6.2. Samples were tested after being cured for required curing periods. The results were analyzed with respect to dosage of fly ash, curing period, confining and deviatoric stresses. Layer coefficients and regression coefficients were calculated from the trends of resilient modulus of RAP mixes. These coefficients are useful for design of flexible pavements. These coefficients are important input parameters in KENPAVE and IITPAVE softwares, which are developed on the basis of finite element analysis for flexible pavement designs according to AASHTO and IRC respectively. Unconfined compressive strength and retained UC strengths of the specimens before and after the resilient modulus tests were also determined. Strain rates for the UC tests ranging from 0.5% to 2.1% per minute are suggested in ASTM D 5102 [62]. However, slower rates are optional for stiffer materials. All specimens were loaded at a strain rate of 0.5% per minute. The UC strength of RAP mixes at 28 day curing period is crucial for the performance of flexible pavement as per IRC: 37 – 2012 [3] and IRC SP: 20-2002 [68].

4.2. Compaction Characteristics of RAP-Fly ash Mixes

To cast the specimens for resilient modulus and UC strength tests, a priory, modified compaction tests (Section 3.2.5) were performed on 100% RAP stabilized with different dosages of fly ash i.e. 0%, 10%, 20%, 30%, and 40%. Both replacement and addition methods of mixing were adopted as discussed in Section 3.4. The compaction test results in terms of optimum moisture content (OMC) and maximum unit weight are respectively presented in Figures 4.1 and 4.2.

It was observed that as the percentage of fly ash content in the mix increased, from 0% to 40%, the optimum moisture content gradually increased in both the cases. This may be due to high specific surface area of fly ash compared to the aggregates and hence absorbs more moisture. On the other hand, it was observed that as the fly ash content increased from 0% to 40%, dry unit weight reduced. As the dosage of fly ash in the mix increases, the average specific gravity of the total mix decreases. Hence, the unit weight of specimens having more fines is less than the specimens with more coarse aggregate. Overall, the mixes prepared using addition method performed better in terms of OMC and maximum dry unit weight when compared to the replacement method.

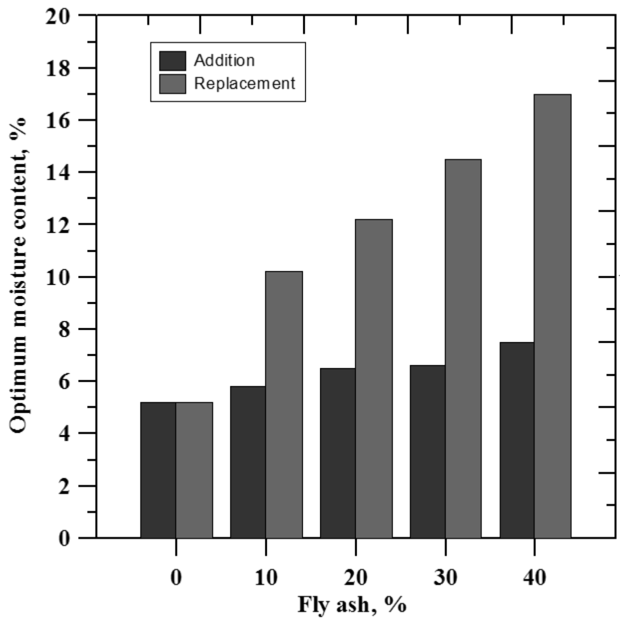

Figure 4.1: Variation of OMC with dosage of fly ash

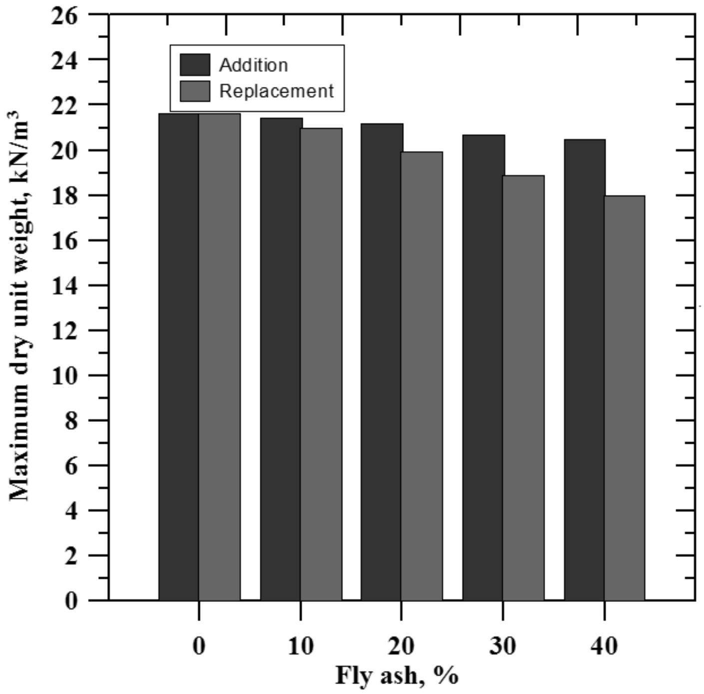

Figure 4.2: Variation of MDD with dosage of fly ash

4.3. Analysis of Test Results

In the following sections, results are presented in terms of resilient modulus with respect to dosage of fly ash, deviatoric and confining stresses applied, and curing periods for both replacement and addition methods of mixing.

4.3.1. Effect of Dosage of Fly ash on Resilient Modulus

Figures 4.3 and 4.4 presents the variation of resilient modulus with fly ash for replacement and addition methods respectively. It was observed from Figure 4.3 that as the dosage of fly ash increases from 10% to 30%, the resilient modulus increases, but further increase in percentage of fly ash decreases the resilient modulus. Similar trend was observed for specimens tested at 1, and 7 day curing periods. The decrease in resilient modulus is due to increase in fines content at higher percentages of fly ash which would bind the aggregate particles and increase the stiffness of the specimen. In addition, at this proportion, the effective aggregate content reduces in replacement method which will lead to low structural support. Hence, it was observed that at higher dosages of fly ash in replacement method the resilient modulus has decreased.

In contrary to this observation, in addition method of sample preparation, the resilient modulus has increased with increase in percentage of fly ash even up to 40% (Figure 4.4).

This could be attributed to the method of mixing. In addition method, as discussed in Section 3.4.2.

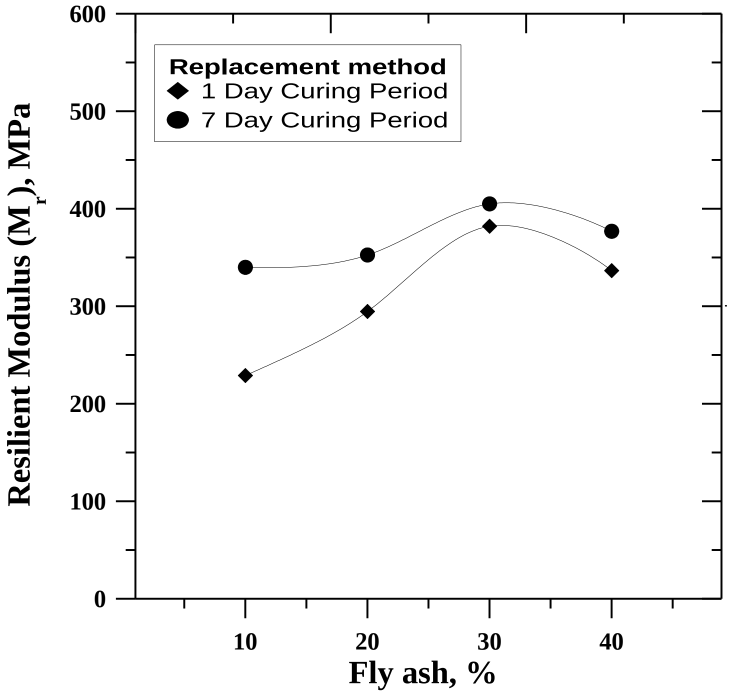

Figure 4.3: Variation of Resilient Modulus with Dosage of Fly ash

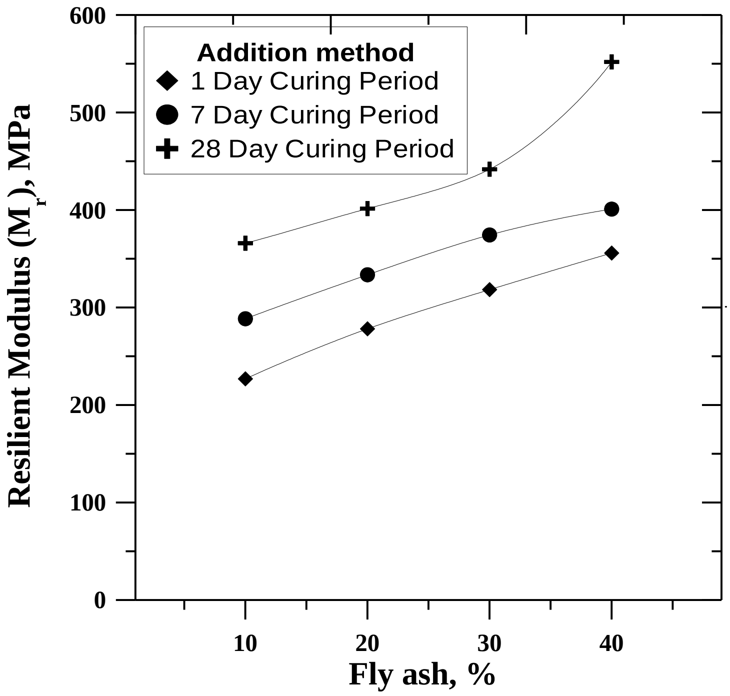

Figure 4.4: Variation of Resilient Modulus with Dosage of Fly ash

4.3.2. Effect of Confining and Deviatoric Stresses on Resilient Modulus

Figure 4.5 shows the influence of confining stress on the resilient modulus of 100% RAP treated with fly ash; and the influence of deviatoric stress can be seen in Figure 4.6. The Figures 4.5 and 4.6 show that both confining and deviatoric stresses have a considerable influence on the resilient modulus of fly ash treated RAP. With an increase in the deviatoric stress, the resilient modulus of the mix increased owing to stress hardening of the specimen. The stress hardening most likely occur in granular materials at lower confinements [69]. Similarly, at higher confining stresses, the influence of deviatoric stress is minimal due to the fact that the specimens are much stiffer at the conditions. Similar trends can be seen for addition method as presented in Figures 4.7 and 4.8. These variations are necessary in obtaining the bulk stresses which will be used to determine the regression coefficients for further analysis.

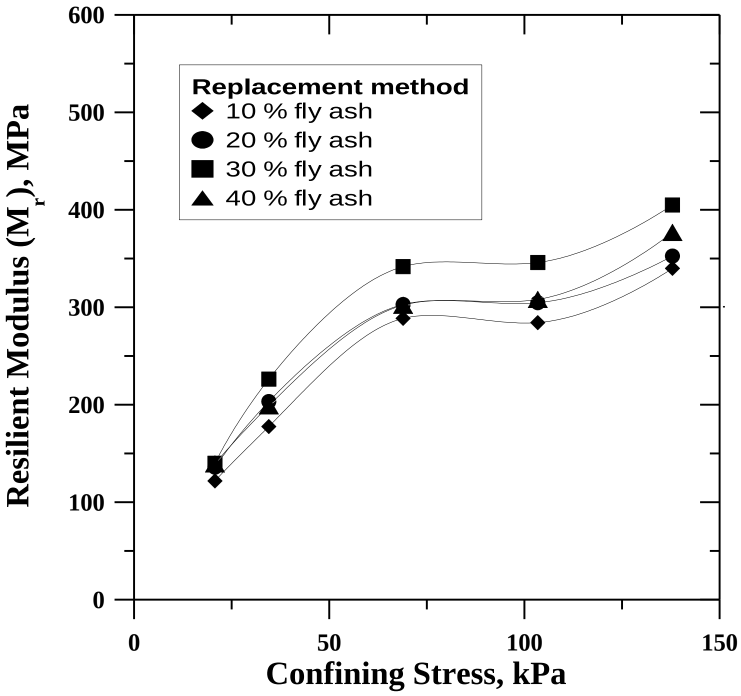

Figure 4.5: Variation of Resilient Modulus with Confining Stress at 7 Day Curing Period

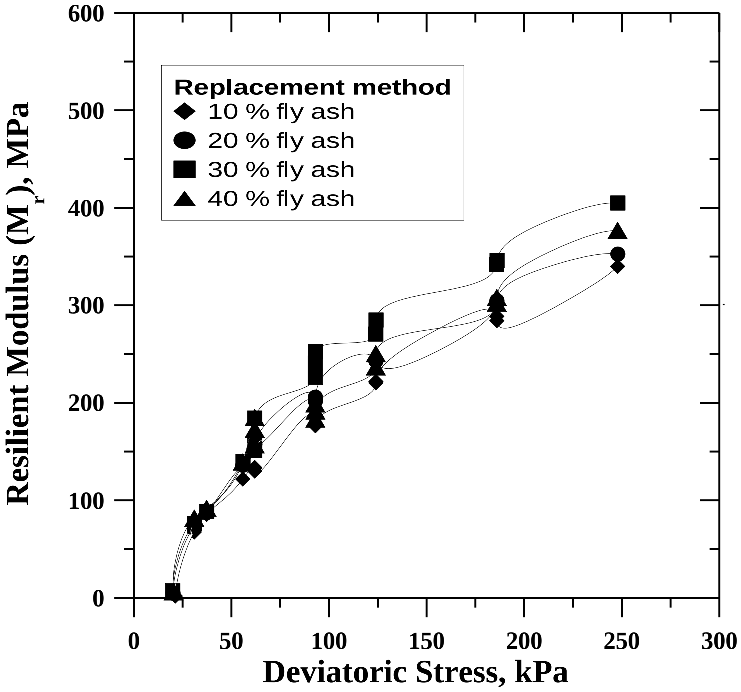

Figure 4.6: Variation of Resilient Modulus with Deviatoric Stress at 7 Day Curing Period

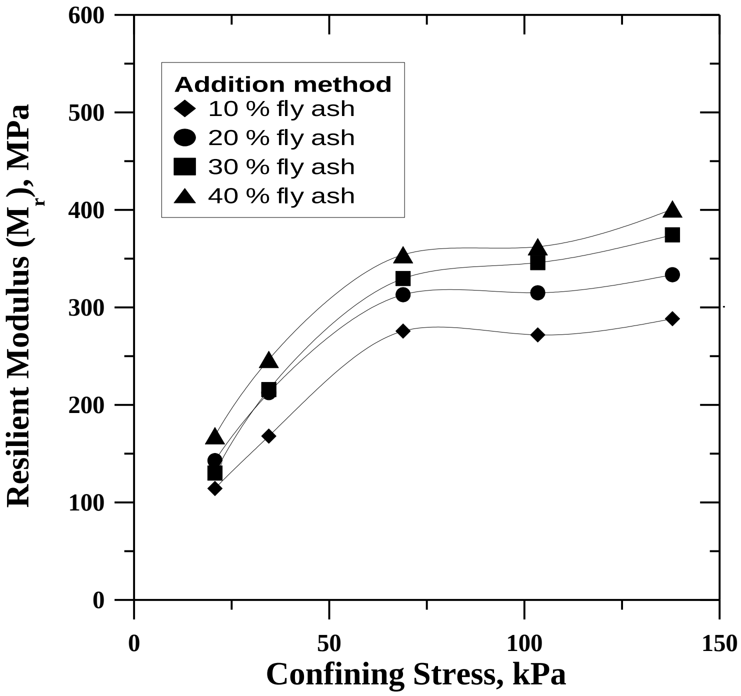

Figure 4.7: Variation of Resilient Modulus with Confining Stress at 7 Day Curing Period

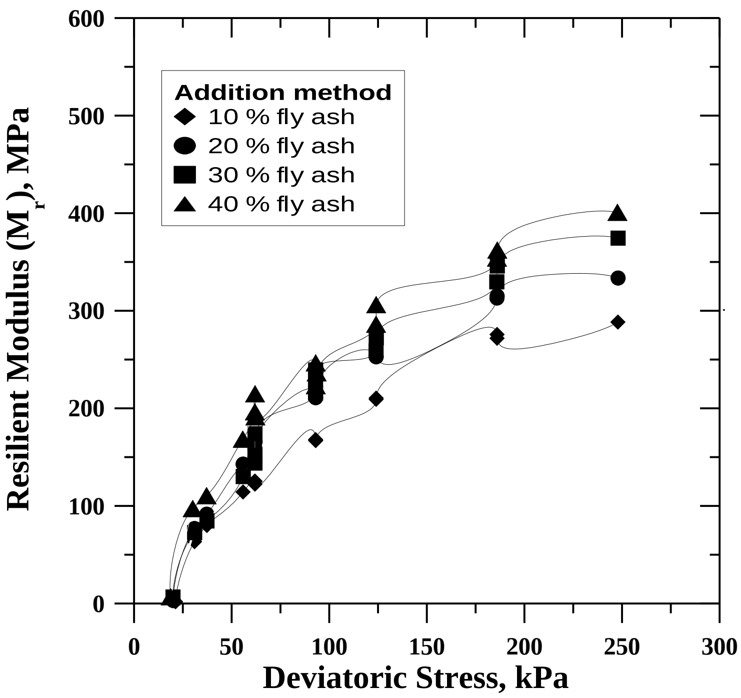

Figure 4.8: Variation of Resilient Modulus with Deviatoric Stress at 7 Day Curing Period

4.3.3. Effect of Curing Period on Resilient Modulus

As we know that the curing period plays a prominent role in cementicious material which contributes to the stiffness parameters, the specimens were tested at 1 and 7 day curing periods. The results are presented in Figures 4.9 and 4.10 respectively for replacement and addition methods of sample preparation. From the results it can be observed that as the curing period increases, the resilient modulus increases. The similar trend was noticed for all percentages of fly ash treated RAP samples. The increase in resilient modulus of RAP is higher for lower dosages of fly ash (up to 30%) and marginal thereafter. However, higher resilient behavior was observed at 28 day curing period. The resilient modulus corresponds to 28 day curing period is crucial for fly ash stabilized bases as recommended by IRC. The higher performance at 28 day curing period can be attributed to the presence of higher pozzolanic products (calcium-silicate-hydrate gel) in the specimens. Overall, it is to be noted that the resilient behavior of RAP – fly ash mixes is superior for addition method of mixing compared to replacement method. Hence, addition method of material mixing has been adopted for further testing.

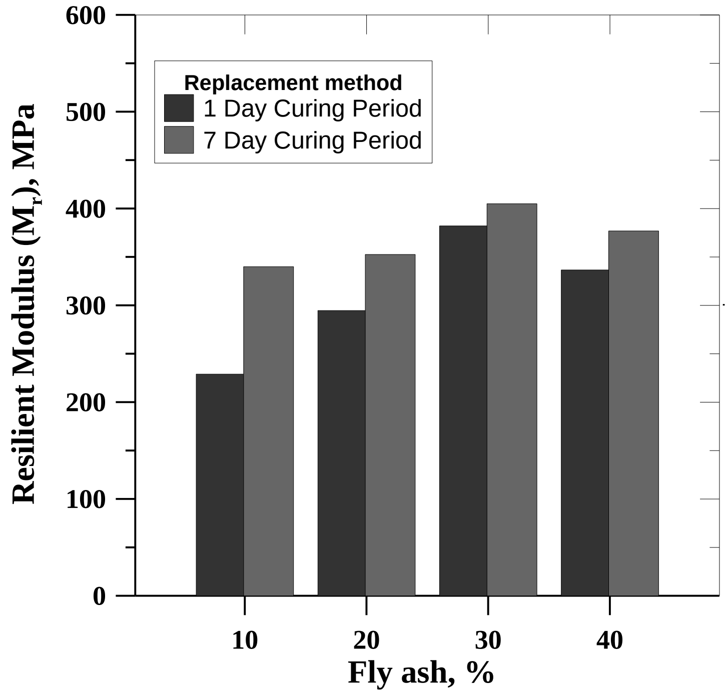

Figure 4.9: Variation of Resilient Modulus with Curing Period

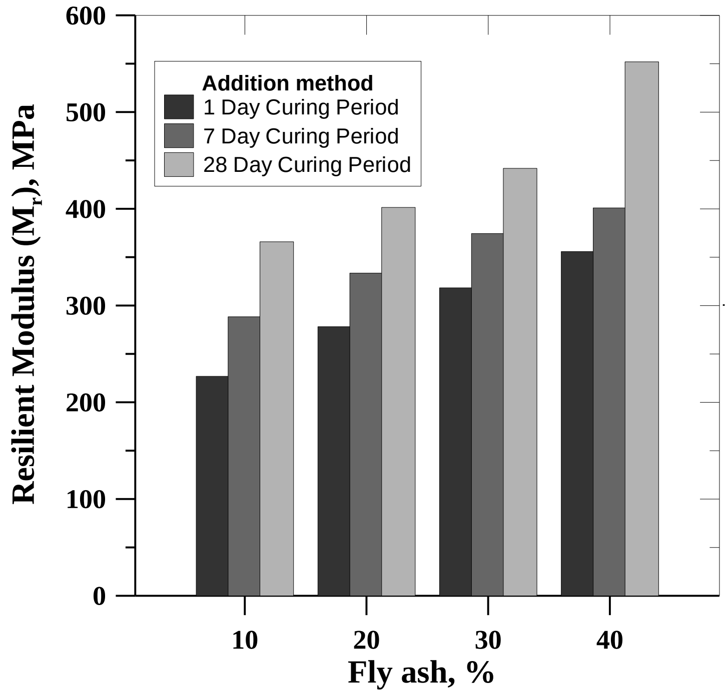

Figure 4.10: Variation of Resilient Modulus with Curing Period

4.4. UC Strength of 100% RAP – Fly ash Mixes

Unconfined compressive strength tests of fly ash treated RAP bases at 28 day curing period is one of the crucial parameter for the design of flexible pavements as per IRC: 37-2012 [3]. However, the retained strength of the newly proposed base materials would give an insight about the extent of design life after a prescribed value. Hence, UC strength tests have been performed after conducting the resilient modulus tests on the design mixes. Unconfined compressive strength and retained UC strength of all the specimens prepared using addition technique were determined in accordance with the test procedure prescribed in ASTM D5102 [62]. The retained strength after resilient modulus test was determined on all the specimens of 1, 7, and 28 curing periods and the results are presented in Figure 4.11. It can be seen that the retained UC strength has gradually increased with increase in fly ash content and curing period. A 100% increase in retained strength can be seen from 10% fly ash content to 40% fly ash content. However, approximately a 25% reduction in UC strength has been noticed for all the dosages of fly ash after the specimen was subjected to repeated loading.

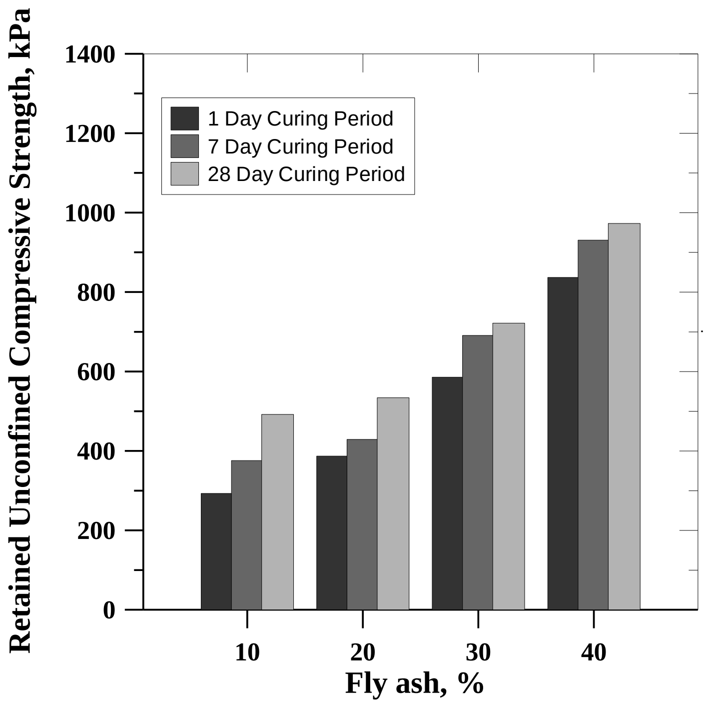

Figure 4.11: Variation of Retained Unconfined Compressive Strength with Fly ash at 1, 7, and 28 Curing Periods

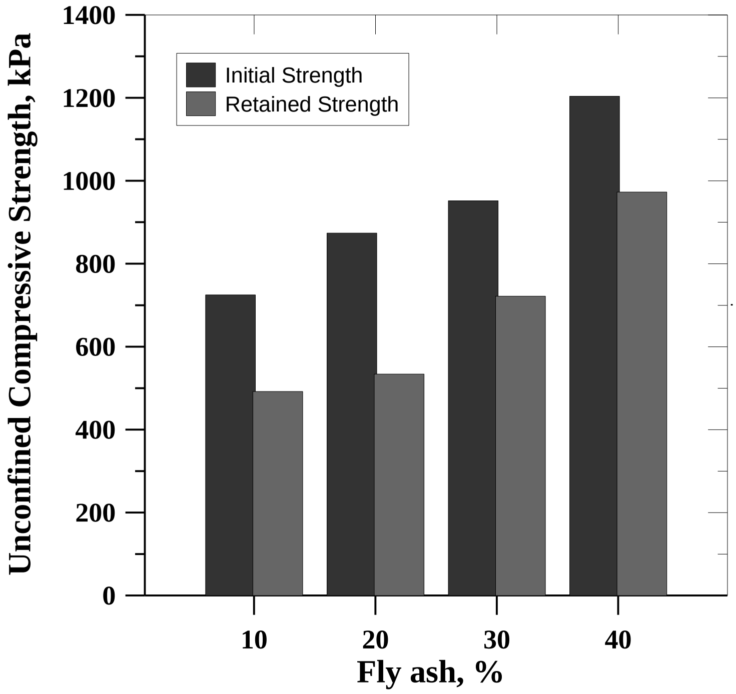

Figure 4.12: Variation of Unconfined Compressive Strength with Fly ash at 28 Curing Period

4.5. Layer Coefficients

Layer coefficients (a_2) are required for each pavement layer to design their thickness based on AASHTO design guidelines for flexible pavements. This section describes how to obtain the layer coefficients of different mixes proposed in this research from resilient modulus values using the correlations given in AASHTO guide for design of pavement structures 1993 [64]. A coefficient is assigned to each pavement layer in the pavement structure in order to convert actual layer thicknesses into a corresponding structural number (SN). The correlation between layer coefficient and resilient modulus given by AASHTO was presented below. The variation of layer coefficients with dosage of fly ash added to the RAP material are presented in Figure 4.13.

$$a_2 = 0.249\ (\log_{10} M_r) - 0.977 \qquad [1]$$

Where, a_2 = Layer coefficient

M_r = Resilient modulus

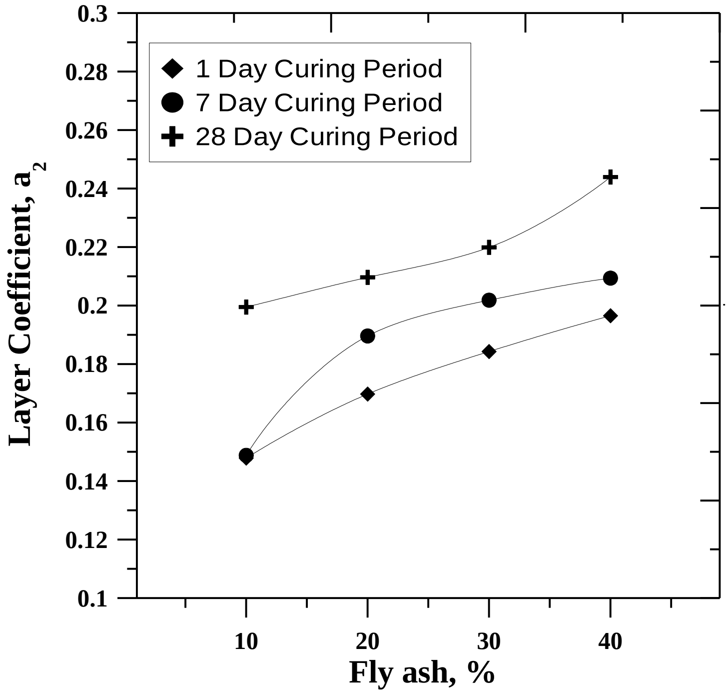

Figure 4.13: Variation of Layer Coefficient with Fly ash

4.6. Regression Coefficients

Regression coefficients were also derived from the resilient modulus values, which are the functions of material type. Regression coefficients, k_1 and k_2, represent the y-intercept and slope, respectively, of a regression line on a log-log plot of resilient modulus verses bulk stress. The calculated regression coefficients of all mix compositions were presented in Table 4.1. These coefficients are input parameters for pavement analysis software such as KENPAVE and IITPAVE. Using these coefficients, the rutting strain and fatigue strain values of different design mixes can be obtain using the software.

Table 4.1: Regression Coefficients for 100% RAP Mixes

S.No.	Mix Composition	Regression Coefficients	
		k_1	k_2
1	100R:0A+10F	235	0.60
2	100R:0A+20F	225	0.44
3	100R:0A+30F	186	0.43
4	100R:0A+40F	110	0.52

4.7. Summary

In this chapter the resilient modulus of specimens prepared with 100% RAP material treated with different dosages of fly ash were analyzed and discussed in different aspects. The effect of fly ash content, deviatoric stress, confining stress and curing period on resilient behavior of 100% RAP were clearly presented. In addition, the two different methods of mixing fly ash to the RAP material were evaluated. For the mixing methods considered, the resilient behavior of fly ash treated 100% RAP mixes has increased with percent of fly ash. In replacement method, the resilient modulus decreased after 30% fly ash dosage. However, the resilient modulus has increase for addition methods of mixing even at higher dosages of fly ash. Hence, from these results it was proposed that the addition method would be a suitable method for mixing fly ash to the RAP bases. For further series of tests, samples were prepared only by addition method. It was also observed that the UC strength of fly ash treated RAP has increased with increase in curing periods. A 25% reduction in UC strength was noticed after the specimen has been subjected to repeat loading prior to the UC testing. Design parameters like layer coefficients and regression coefficients of all the mixes were calculated from the determined resilient modulus values by using the correlations given by American Association of State Highway and Transportation Officials (AASHTO) [64].

Chapter 5

Resilient Behavior of Fly ash Treated RAP – Virgin Aggregate Mixes

5.1. Introduction

In chapter 4, resilient behavior of 100% RAP material was explained and observed that the resilient behavior was influenced by the percentage of fly ash addition and curing period. However, the mixes exhibited limited performance in terms of resilient modulus and UC strength due to a thin amorphous asphalt coating around the aggregate. In this chapter, the resilient modulus test results of RAP and virgin aggregates (VA) mixes treated with fly ash are presented. For mixing fly ash in the mix only addition method was chosen as discussed in Chapter 4. Quantity of VA was taken on trial and error basis. This chapter mainly focusses on two mix compositions, 80R:20A and 60R:40A. The samples were tested after being cured for required curing periods as discussed in Chapter 4. The results were analyzed with respect to dosage of fly ash, curing period, confining and deviatoric stress. Layer and regression coefficients were calculated using the correlations in AASHTO design guide lines for flexible pavements. Unconfined compressive strengths of the specimens before and after resilient modulus test were also presented.

5.2. Compaction Characteristics of RAP-VA Mixes

To cast the specimens for resilient modulus and UC strength tests modified compaction tests (Section 3.2.5) were performed on RAP – VA mixes stabilized with different dosages of fly ash i.e. 10%, 20%, 30%, and 40%. For this series of tests, addition method was adopted for mixing fly ash. The compaction test results in terms of OMC and maximum dry unit weight are respectively presented in Figures 5.1 and 5.2.

When fly ash content in 80R:20A mix increased from 0% to 40%, a 26% increase in OMC and a 3.2% decrease in maximum dry unit weight was observed. Whereas in 60R:40Amix, 18% increase in OMC and 2.7% decrease in Maximum dry unit weight was observed. From the results, a very slight change in OMC and Maximum dry unit weight was observed when two mixes (80R:20A and 60R:40A) were compared. In other words, when percentage of VA increased, the increase in OMC decreased and decrease in maximum dry unit weight also decreased. The reason being in both cases the fly ash dosage is same and coarse aggregate content is same. The only change is higher percentage of RAP particles were replaced with VA in 60R:40A mixes than 80R:20A mixes. The slight change is due to low specific gravity and moisture absorption capacity of RAP than VA because of thin asphalt coating around aggregate particles in RAP material.

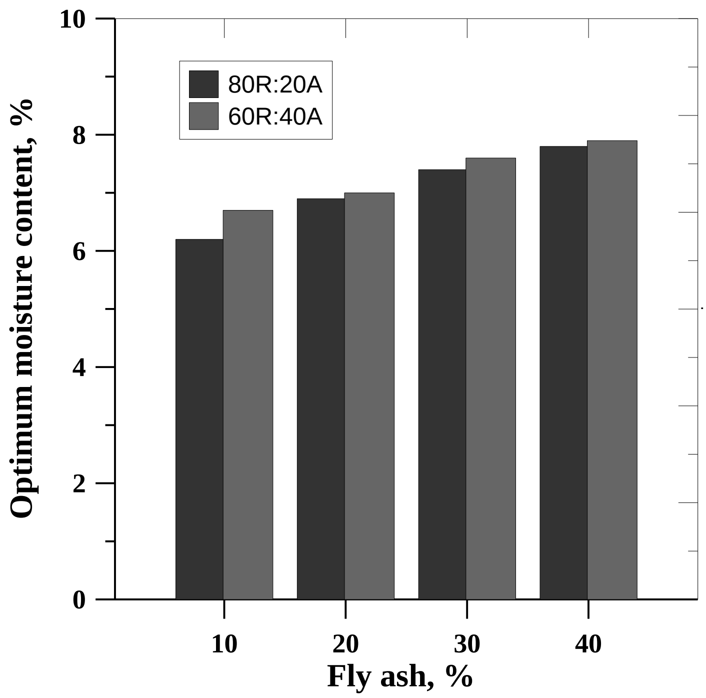

Figure 5.1: Variation of OMC with dosage of fly ash

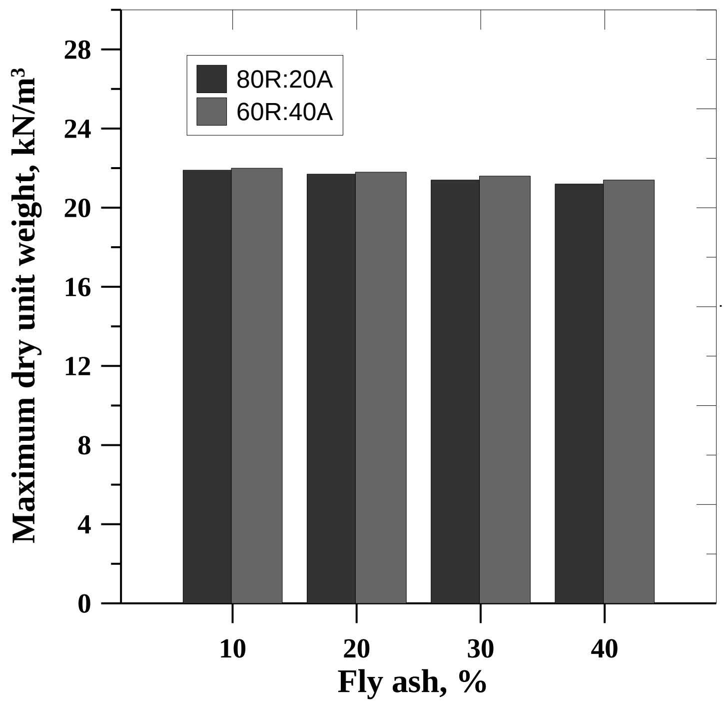

Figure 5.2: Variation of Maximum Dry Unit Weight with dosage of fly ash

5.3. Analysis of Test Results

In the following sections, results are presented in terms of resilient modulus with respect to dosage of fly ash, deviatoric and confining stresses applied, and curing periods for both mixes (80R:20A and 60R:40A).

5.3.1. Effect of Dosage of Fly ash on Resilient Modulus

Figures 5.3 and 5.4 presents the variation of resilient modulus with fly ash for 80R:20A and 60R:40A mixes respectively. From the results, it is observed that M_r increases with increase in dosage of fly ash from 10% to 40. The reason may be at lower dosages of fly ash, the voids in the mix is very high, which leads to permanent deformations compared to mixes with higher dosages of fly ash. The similar trends were observed in both the mixes.

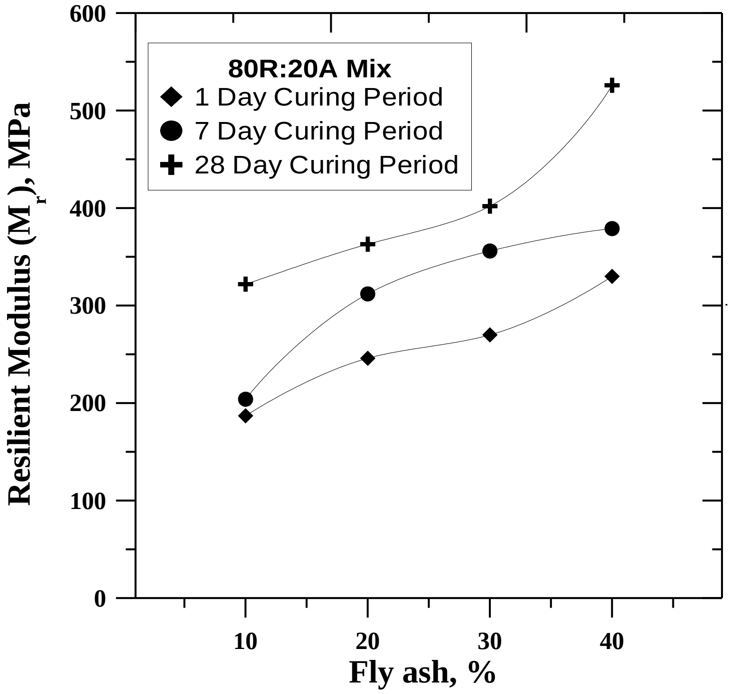

Figure 5.3: Variation of Resilient Modulus with percentage of Fly ash

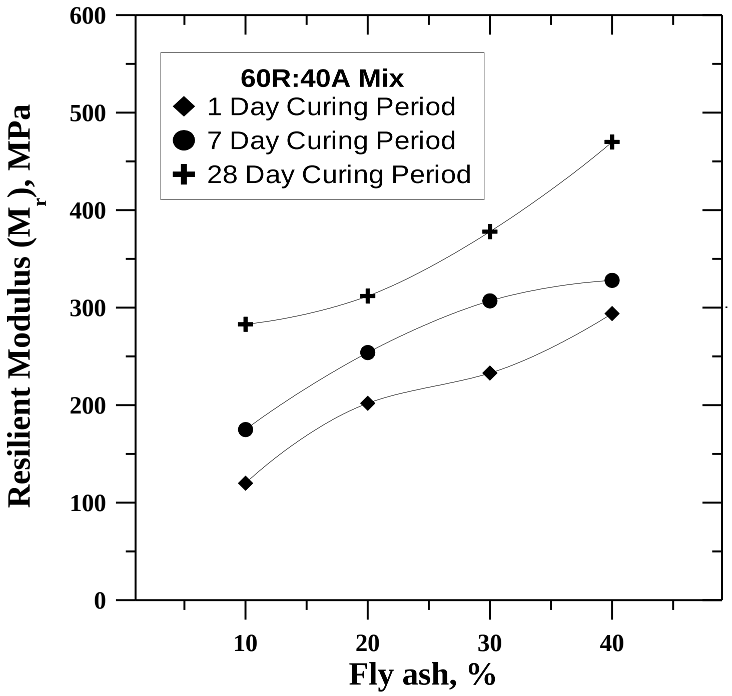

Figure 5.4: Variation of Resilient Modulus with Dosage of Fly ash

5.3.2. Effect of Confining and Deviatoric Stresses on Resilient Modulus

Figures 5.5 and 5.6 shows the influence of confining stress on the resilient modulus of 80R:20A and 60R:40A mixes treated with fly ash; and the influence of deviatoric stress can be seen in Figures 5.7 and 5.8 respectively. The Figures 5.5 to 5.8 show that both confining and deviatoric stresses have a considerable influence on the resilient modulus of fly ash treated RAP – VA mixes. With an increase in confining stress, the resilient modulus owing to stress hardening of the specimen. Similarly, the resilient modulus increases with increase in deviatoric stress. Similar observations were made by Richard et al. [70] while performing tests on cemented soils. They explained that the resilient modulus test begins initially at higher confining stress, which causes a considerable amount of water to exit the sample. There will be a little capillary exists in the sample at these higher stresses. Hence, the sample has a tendency to swell as the stresses are lowered. As a result, negative pore pressures (capillary forces) develop in the specimen. These capillary forces are tensile in nature which pull the individual particles together. This implies that the sample is much stiffer than the initial. Since the RAP has been treated with high dosage of fly ash up to 40%, increase in resilient modulus can be attributed to the same reason.

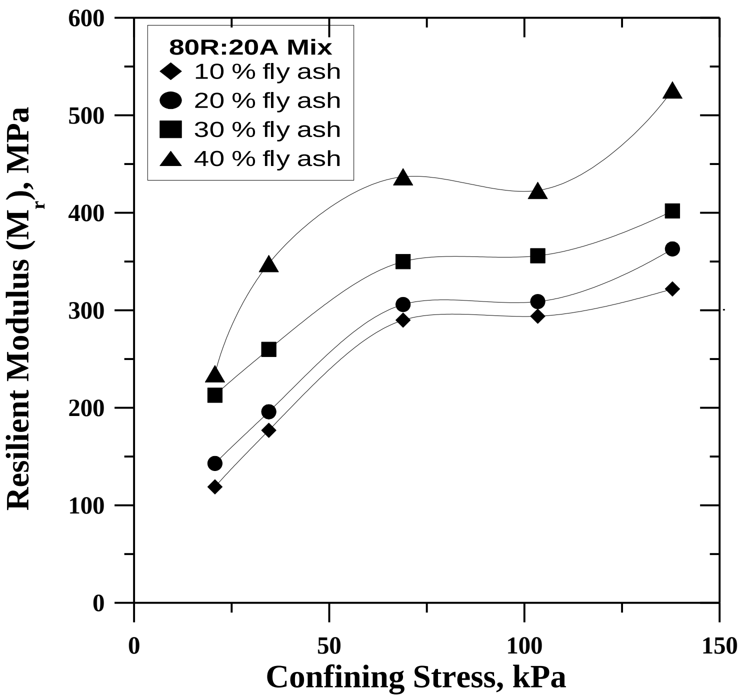

Figure 5.5: Variation of Resilient Modulus with Confining Stress at 28 Day Curing Period

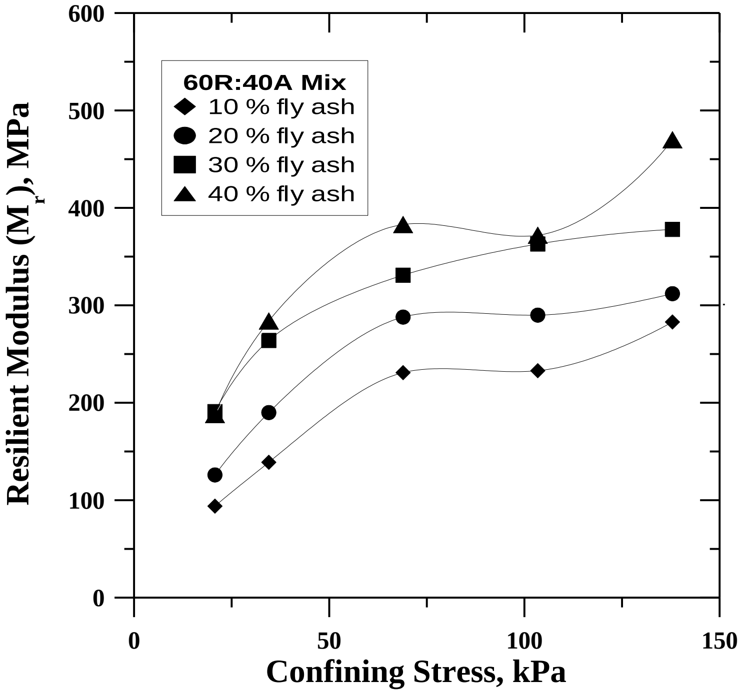

Figure 5.6: Variation of Resilient Modulus with Confining Stress 28 Day Curing Period

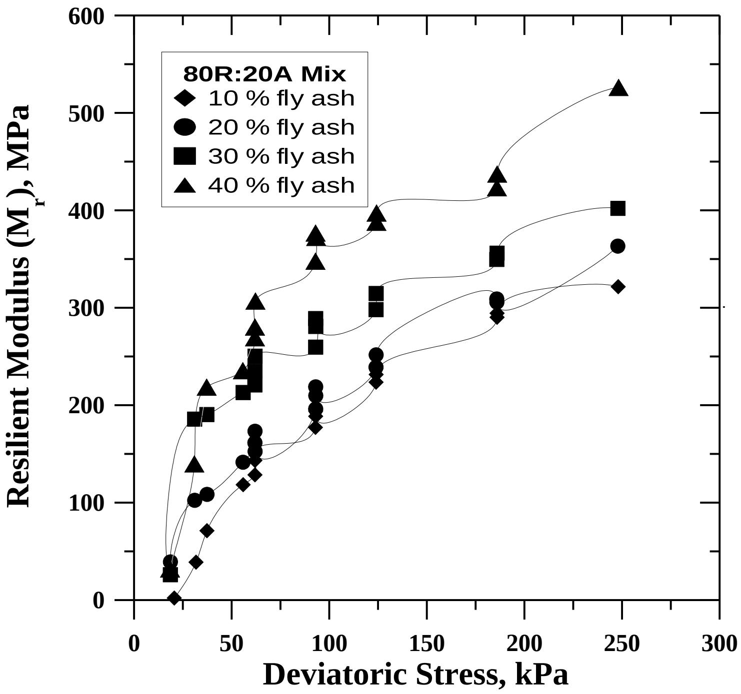

Figure 5.7: Variation of Resilient Modulus with Deviatoric Stress at 28 Day Curing Period

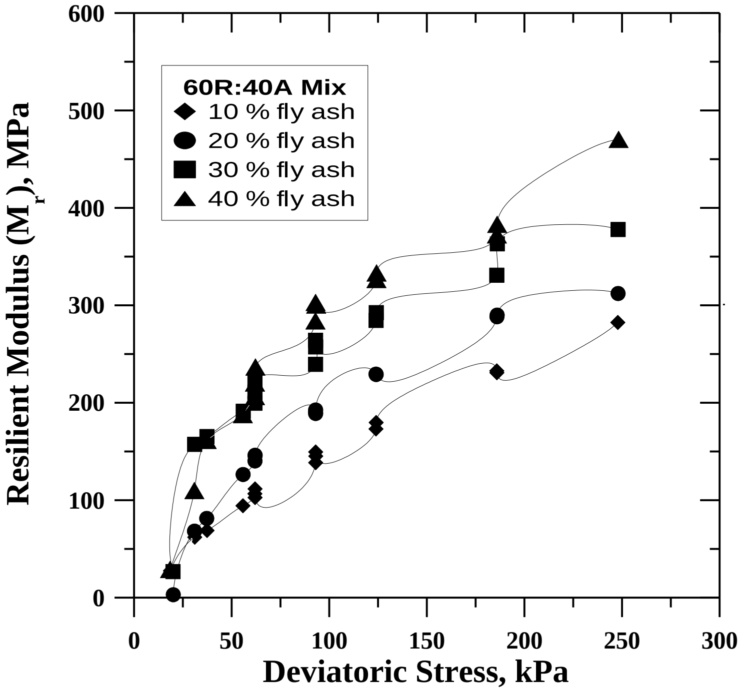

Figure 5.8: Variation of Resilient Modulus with Deviatoric Stress at 28 Day Curing Period

5.3.3. Effect of Curing Period on Resilient Modulus

As the curing period plays a prominent role in cementicious materials which contributes to the stiffness parameters, the specimens were tested at 1, 7, and 28 curing periods. The results are presented in Figures 5.9 and 5.10 respectively for 80R:20A and 60R:20A mixes. The resilient modulus corresponds to 28 day curing period is crucial for fly ash stabilized bases as recommended by IRC 37-2012 [3]. From the results, it can be observed that as the curing period increases, the resilient modulus increases by 59% on an average for both the mixes at 40% fly ash addition. The increase in resilient modulus is due to increase in pozzolanic products (calcium-silicate-hydrate gel) in the specimens with increase in curing period.

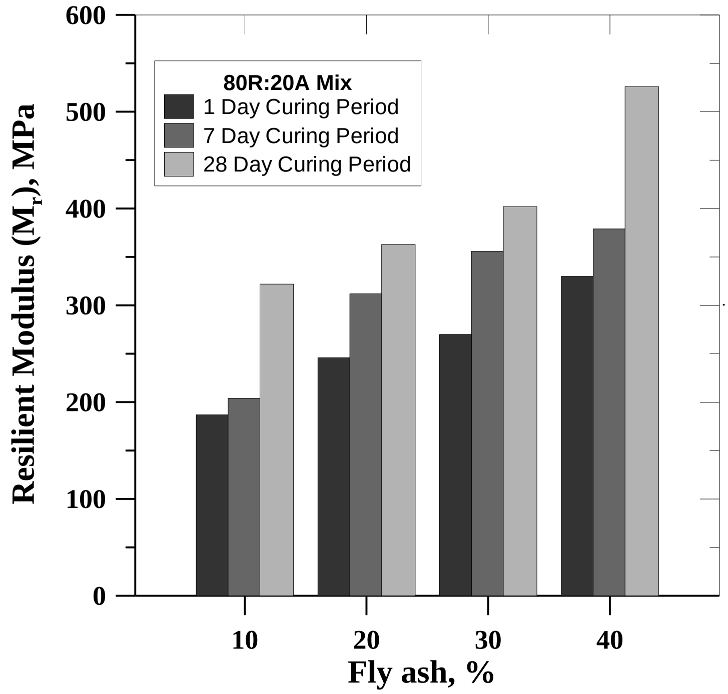

Figure 5.9: Variation of Resilient Modulus with Curing Period

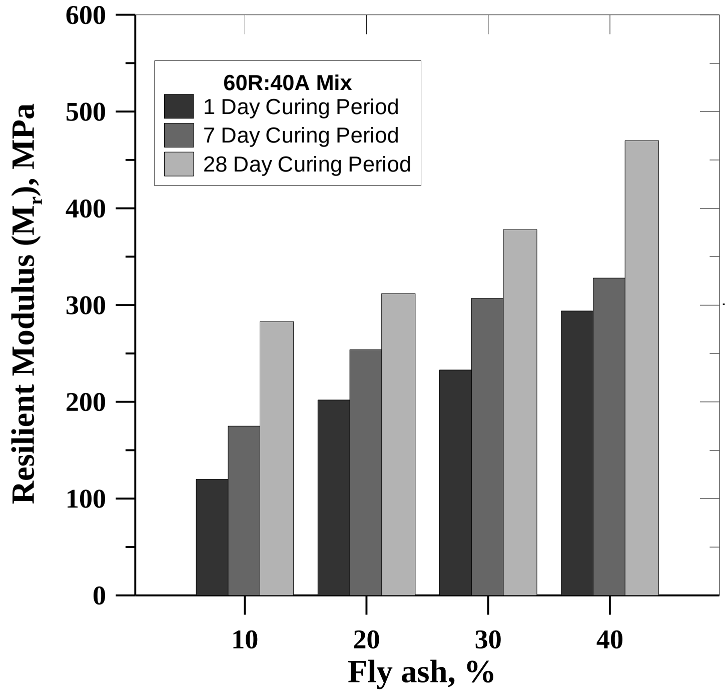

Figure 5.10: Variation of Resilient Modulus with Curing Period

5.4. UC Strength of RAP – VA Mixes

Unconfined compressive strength tests of fly ash treated RAP – VA bases at 28 day curing period is one of the important parameter for the design of flexible pavements as per IRC: 37-2012 [3]. However, the retained strength of the newly proposed base materials would give an insight about the extent of design life after a prescribed value. Hence, UC strength tests have been performed after conducting resilient modulus tests on the design mixes. Unconfined compressive strength and retained UC strength of all the specimens of RAP – VA mixes were determined in accordance with the test procedure prescribed in ASTM D5102 [62]. The retained UC strength tests after resilient modulus tests were performed at all curing periods considered and the results are presented in Figures 5.11 and 5.12. With increase in curing period, a 33% increase in retained strength was observed for the 80R:20A+40F mixes. Whereas in 60R:40A+40F mix an increase of 60% retained strength was observed. From Figures 5.11 to 5.14, it is observed that there was only 23% and 16% reduction in strength in 80:20 and 60:40 combination of RAP and VA at 40% fly ash specimens after resilient modulus test respectively.

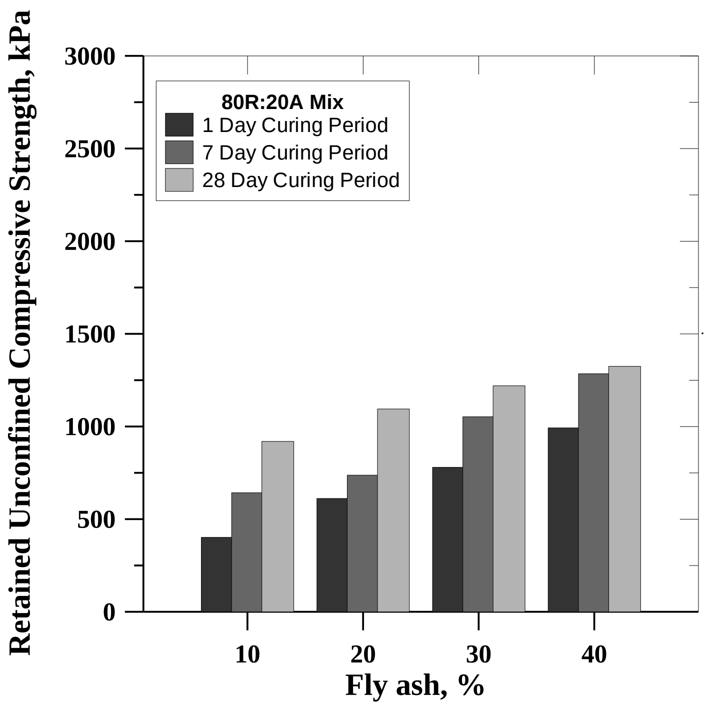

Figure 5.11: Variation of Retained Unconfined Compressive Strength with Fly ash at 1, 7, and 28 Curing Periods

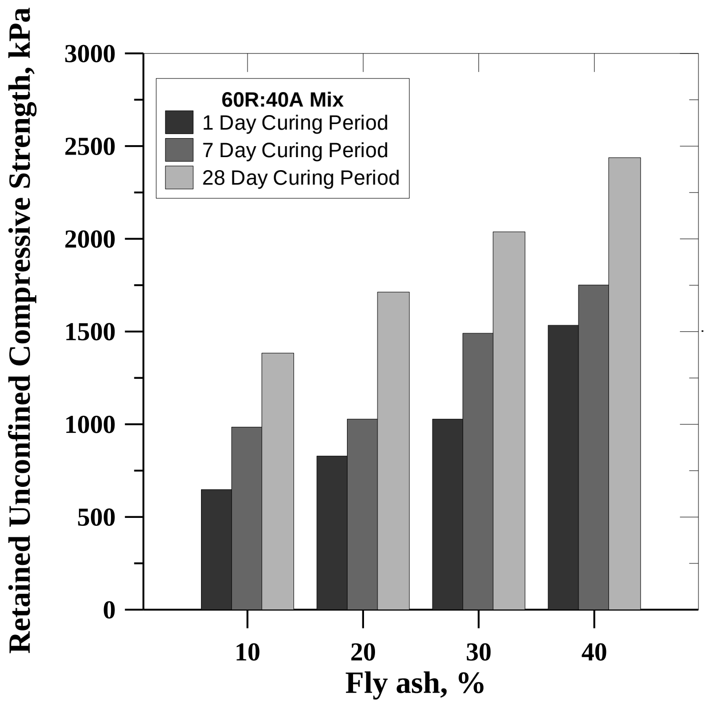

Figure 5.12: Variation of Retained Unconfined Compressive Strength with Fly ash at 1, 7, and 28 Curing Periods

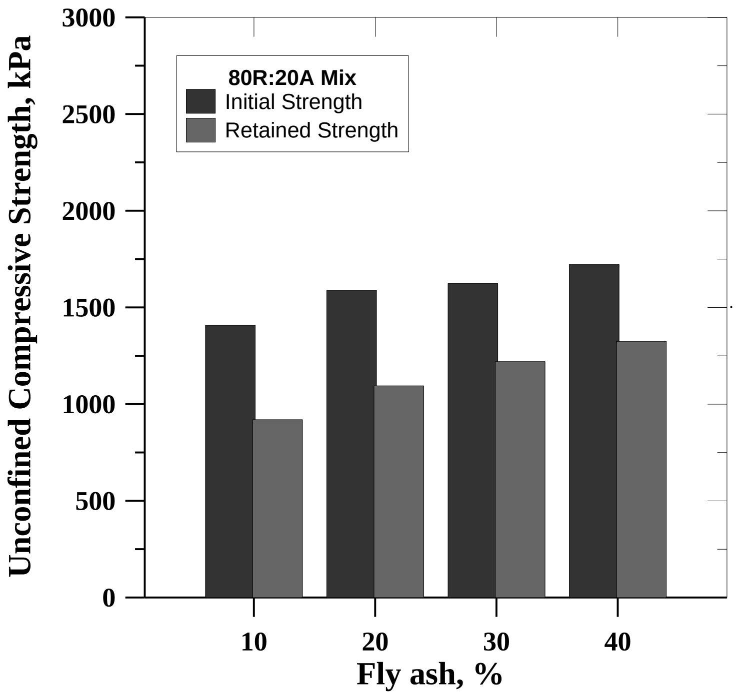

Figure 5.13: Variation of Unconfined Compressive Strength with Fly ash at 28 Curing Period

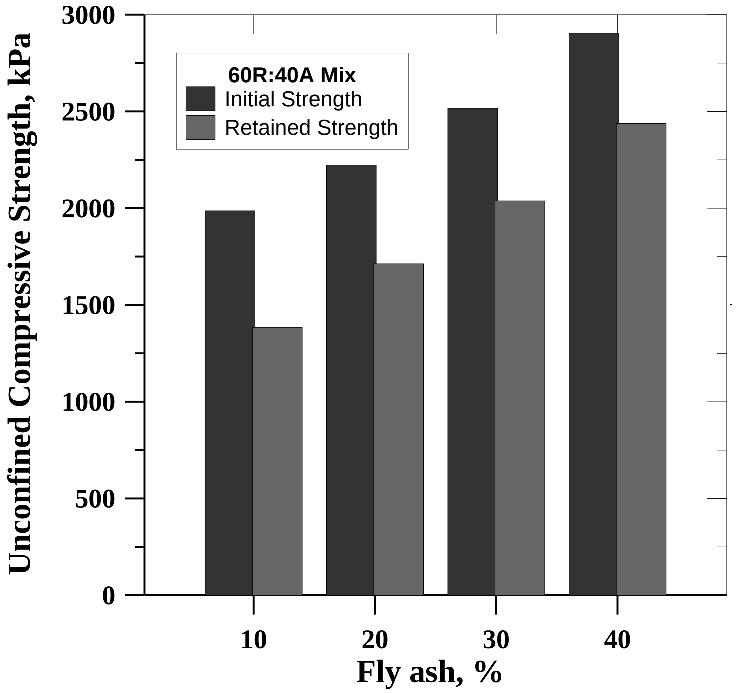

Figure 5.14: Variation of Unconfined Compressive Strength with Fly ash at 28 Curing Period

5.5. Layer Coefficients

Layer coefficients (a_2) are required for each pavement layer to design their thickness based on AASHTO design guidelines for flexible pavements [64]. This section describes how to obtain the layer coefficients of different mixes proposed in this research from resilient modulus values using the correlations given in AASHTO guide for design of pavement structures 1993 [64]. A coefficient is assigned to each pavement layer in the pavement structure in order to convert actual layer thicknesses into a corresponding structural number (SN). The correlation between layer coefficient and resilient modulus given by AASHTO was presented below. The variation of layer coefficients with dosage of fly ash added to the RAP material are presented in Figures 5.15 and 5.16. It is evident that the layer coefficients increase with increase in fly ash content and curing period. The increase in layer coefficient would reduce the thickness of a particular pavement layer considerably.

$$a_2 = 0.249\ (\log_{10} M_r) - \ 0.977 \qquad [1]$$

Where, a_2 = Layer coefficient

M_r = Resilient modulus of that particular pavement layer

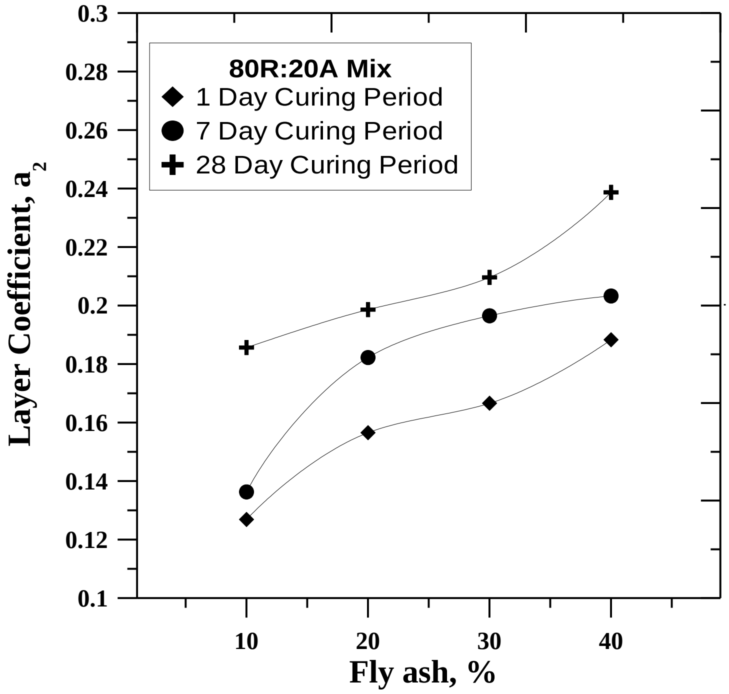

Figure 5.15: Variation of Layer Coefficient with Fly ash

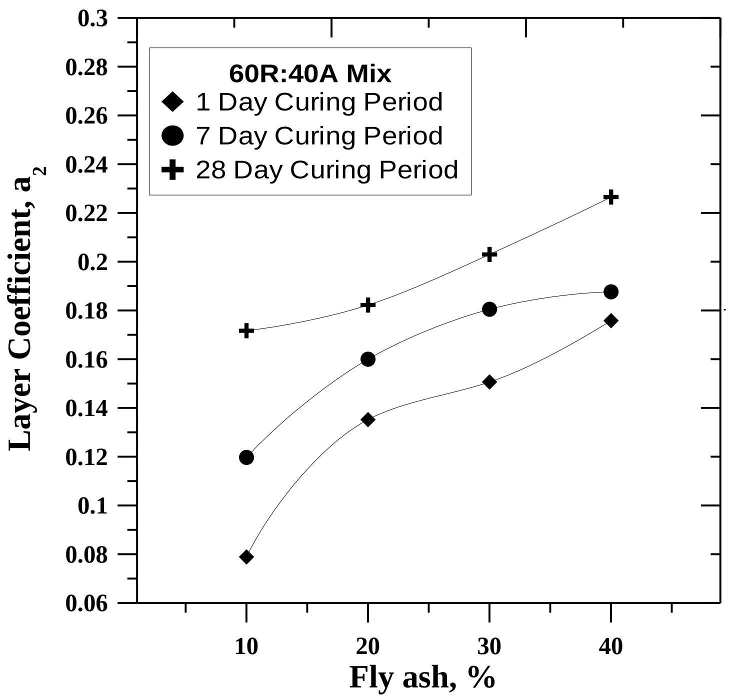

Figure 5.16: Variation of Layer Coefficient with Fly ash

5.6. Regression Coefficients

Regression coefficients were also derived from the relation between resilient modulus values and bulk stresses, which can be obtained from Figures 5.5 – 5.8. Regression coefficients, k_1 and k_2, represent the y-intercept and slope, respectively, of a regression line on a log-log plot of resilient modulus verses bulk stress. The calculated regression coefficients of all mix compositions were presented in Table 5.1. These coefficients are input parameters for the pavement analysis software such as KENPAVE and IITPAVE. Using these coefficients, the rutting strain and fatigue strain values of different design mixes can be obtained directly to check the feasibility of the design mixes in a proposed pavement structure.

Table 5.1: Regression Coefficients for RAP – VA Mixes

S.No.	Mix Composition	Regression Coefficients	
		k_1 (MPa)	k_2
1	80R:20A+10F	213	0.60
2	80R:20A+20F	185	0.43
3	80R:20A+30F	110	0.51
4	80R:20A+40F	95	0.48
5	60R:40A+10F	160	0.60
6	60R:40A+20F	177	0.42
7	60R:40A+30F	111	0.43
8	60R:40A+40F	65	0.44

5.7. Summary

In this chapter the resilient modulus of specimens prepared with two different mixes of RAP and VA (80R:20A and 60R:40A) treated with fly ash were analyzed and discussed in different aspects. The effect of fly ash content, deviatoric stress, confining stress and curing period on resilient behavior of RAP – VA mixes were explained in detail. For this addition technique of fly ash mixing was adopted in preparation of all the specimens. It was observed that a very slight reduction in strength after resilient modulus test and an appreciable increase in strength with fly ash content and curing period. Design parameters like layer coefficients and regression coefficients of all the mixes were calculated from the determined resilient modulus values by using the correlations given by American Association of State Highway and Transportation Officials (AASHTO) [64].

Chapter 6

California Bearing Ratio of Different RAP Mixes

6.1. Introduction

In the previous chapters (4 & 5), the results obtained from resilient modulus test are presented for the design of flexible pavements. Even though the resilient behavior of design base mixes are important for the longevity of the pavement systems [64], the IRC's design is still relay on California Bearing Ratio (CBR) test results. Though there are some correlations available between CBR and M_r, no suitable correlations can be developed between resilient modulus and California Bearing Ratio [65] because these two parameters are significantly different from one another. Resilient modulus is determined based on the permanent strains from dynamic load tests, which is only a fraction of the total strain that is induced. Whereas the California Bearing Ratio value corresponds to the peak resistance that is developed to a monotonic shear failure. However, the resilient modulus test is not encouraged in India from the beginning because the test equipment used for determining resilient modulus is very costly and lack of knowledge on resilient modulus and its mention in codes.

Even though the IRC method [3] did not incorporate the CBR values of base/subbase layers of high volume roads in the design directly, IRC: SP 20-2002 [68] recommends to use the CBR value of base/subbase layers in determining the pavement layer thicknesses of low volume roads. In addition, the resilient modulus values of base/subbase layers can be obtained from the corresponding CBR values using certain correlations. In this chapter the unsoaked and soaked CBR values of fly ash treated RAP and RAP: VA mixes at different curing periods are presented. From the test data, the resilient modulus values for all the mixes are calculated by using the correlations given by Heukelom and Klomp.

6.2. Sample Preparation

For conducting CBR tests on 100R, 80R:20V, 60R:40V treated with 0 to 40% fly ash specimens were prepared in a cylindrical CBR moulds having 150mm diameter with 175mm height. The quantity of the material and water content required for preparing the specimen were taken according to the moisture – density relationships for different mix compositions. The material was mixed thoroughly to obtain the homogenous Mix. For casting specimen, initially a spacer disc having 148mm diameter and height 50mm was placed in the mould. Now the Mix was compacted in the mould in 5 identical layers, each layer giving 55 blows uniformly spreading all over the surface. The mould was detached from the frame and it was inverted along with the specimen in it. The weigh placed in the mould was removed and one annular metal weight and several slotted weights weighing 2.5 kg each, 147 mm in diameter, with a central hole 53 mm in diameter was placed on the specimen to prevent the change in volume of the specimen. Similar procedure was carried out for preparing the specimens with different mix compositions as mentioned in Table 3.8. All these specimens were tested after 1, 7 and 28 day curing periods.

6.3. Analysis of Test Results

The CBR tests were performed on the specimens prepared with different mix compositions for different curing periods. For conducting the soaked CBR test, the 1 day curing period specimens were soaked for 4 days in a curing tank under water and allowed to drain for 15 minutes prior to test. All the 7 day curing period specimens were stored in a stability chamber for 3 days and kept for soaking for 4 days in curing tank under water, 28 day curing period specimens were stored in a stability chamber for 24 days and kept for soaking for 4 days in curing tank under water. After completion of specified curing periods the specimens were taken out and the tests were performed.

The results presented in Figures 6.1 to 6.3 show that there is a considerable increase in trend in CBR with increase in fly ash dosage. The reason for this may be at lower percentages of fly ash, the voids are very big in the sample which leads to easy penetration of plunger in to sample. But, as the fly ash (fines) content increases these voids between the aggregate particles are filled will fly ash and thus tries to obstruct the plunger to penetrate. From the results it has to be observed that there was a tremendous growth in CBR with curing period. This is because of the hardening of the sample due to fly ash which is a cementicious material. As the curing period increases the hydrated products will increase and further leads to stronger specimen. For better understanding of the experimental results, all the CBR values were tabulated in Table 6.1.

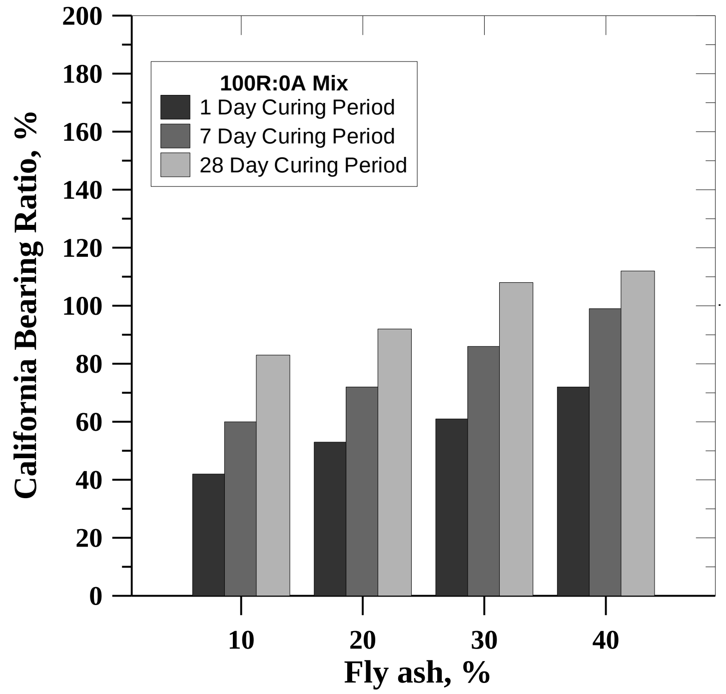

Figure 6.1: Variation of CBR with Dosage of Fly ash at Different Curing Periods

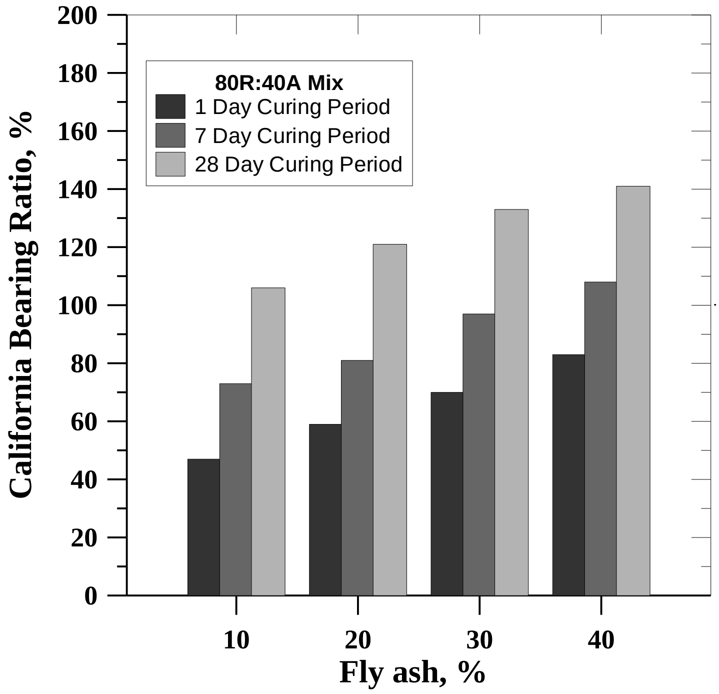

Figure 6.2: Variation of CBR with Dosage of Fly ash at Different Curing Periods

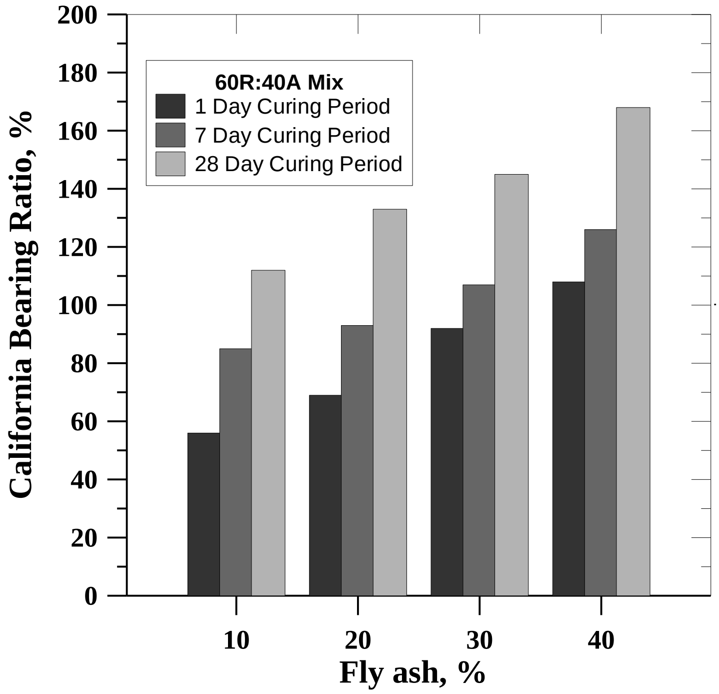

Figure 6.3: Variation of CBR with Dosage of Fly ash at Different Curing Periods

6.4. Derived Resilient Modulus

Resilient modulus values were derived from the correlations given by Heukelom and Klomp [Eq. 6.1 and Eq. 6.2] and which were also been followed by IRC for several years.

E (MPa) = 10 x CBR (CBR < 5) …..6.1

E (MPa) = 17.6 x $CBR^{0.64}$ (CBR > 5) …..6.2

Since all the CBR values determined in this study are greater than 5, equation 6.2 is considered for deriving resilient modulus. The derived resilient modulus values are presented in Table 6.1.

Table 6.1: CBR and Calculated Resilient Modulus (M_r) Values for All Mix Compositions

S.No.	Mix Composition	1 Day Curing Period		7 Day Curing Period		28 Day Curing Period	
		CBR	M_r	CBR	M_r	CBR	M_r
1	100R:0A+10F	42	192	60	242	83	298
2	100R:0A+20F	53	223	72	272	92	318
3	100R:0A+30F	61	244	86	305	108	352
4	100R:0A+40F	72	272	99	333	112	361
5	80R:20A+10F	47	207	73	274	106	348
6	80R:20A+20F	59	239	81	293	121	379
7	80R:20A+30F	70	267	97	329	133	403
8	80R:20A+40F	83	298	108	352	141	418
9	60R:40A+10F	56	231	85	302	112	361
10	60R:40A+20F	69	264	93	320	133	403
11	60R:40A+30F	92	318	107	350	145	425
12	60R:40A+40F	108	352	126	389	168	467

6.5. Summary

In this chapter, the CBR results of specimens prepared with 100R, 80R:20V, 60R:40V treated with 0 to 40% fly ash were determined. In all the mix compositions, the CBR kept on increasing as the fly ash dosage increasing, hence it clearly indicates that the increase in strength mainly depends on dosage of cementicious material to the mix. Further, the curing period also plays a crucial role in gaining the strength. It was observed that at high dosages of fly ash, curing period plays a prominent role. With the addition of virgin aggregates, the CBR value of RAP mix has increased. In this chapter resilient modulus values were also calculated from the CBR values by using Heukelom and Klomp correlations

Chapter 7

Results and Discussions

7.1. Introduction

To qualify a material as a base/subbase material for flexible pavement system, it has to meet certain requirements in terms of strength and stiffness as per the design methodology adopted. If the material found inferior, these properties can be improved by stabilizing the base material. In Indian context, Indian Roads Congress (IRC) allows the use of stabilized bases and specifies in Annex-VIII of IRC: 37-2012 [3] that the cemented base material supposed to meet a minimum strength, UCS ≥ 4.5 MPa and a resilient modulus, $M_r \geq 450$ MPa. This chapter presents the analysis of results from resilient modulus and UC strength tests conducted on various combinations of RAP and VA treated with fly ash (results from Chapter 4 & 5) to verify the suitability of these mixes as a base/subbase material for flexible pavements.

7.2. Resilient Modulus of RAP and RAP – VA Mixes

The results obtained from resilient modulus tests on 100% RAP, 80% RAP:20% VA, and 60% RAP:40% VA treated with different dosages of fly ash are compared in Figure 7.1. The results pertaining to 100% RAP depicts that the resilient modulus increases with increase in fly ash content and curing periods (Figure 4.10). However, From the Figure 7.1, it can be observed that there is a reduction in resilient modulus with an increase in virgin aggregate content. This percentage reduction in resilient modulus decreases with an increase in fly ash content. In addition, it can be seen that the 80R:20A mixes treated with 40% fly ash are only meeting the requirements with respect to M_r as per IRC-37 [3]. Even though 100% RAP treated with 40% fly ash meets this requirement, it is important to note that virgin aggregates are added to the RAP stabilized with 0 to 40% fly ash to meet the strength (UCS) criteria in addition to meet the permissible value of the resilient modulus.

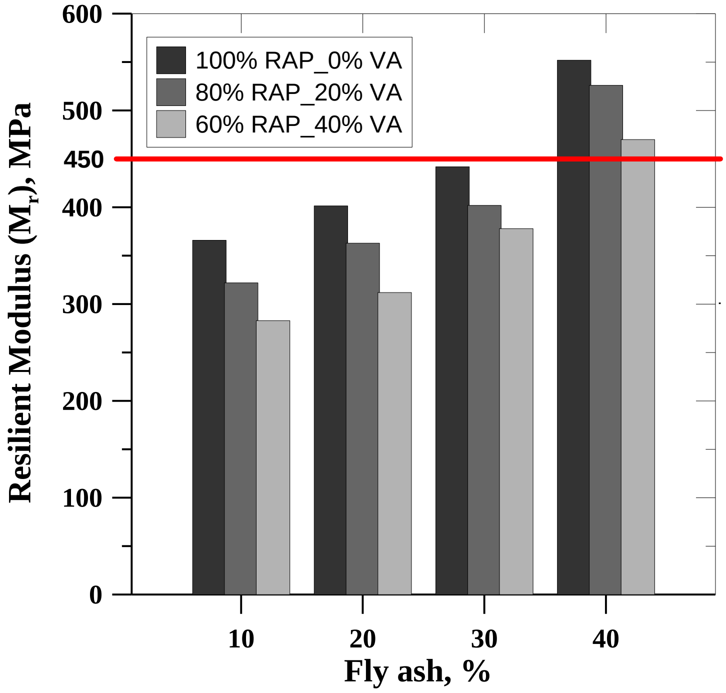

Figure 7.1: Variation of Resilient Modulus with Fly ash

These results are in accordance with the study conducted by Crovetti [66] for cold in-place reclaimed asphalt pavements treated with small dosages of fly ash. Crovetti [66] treated the RAP material with 5.5 percent, 7 percent, and 8.5 percent of fly ash by weight. But, it has to be noted that for determination of resilient modulus, Crovetti [66] did not used cyclic triaxial test equipment and the specimens were prepared by using standard Marshall Compaction equipment. Besides, it also be kept in mind that the MORTH gradation was followed for preparing the specimens in the present study, however, there was no mention of the same by Crovetti [66] regarding the gradation of the mix.

The reduction in resilient modulus with increase in virgin aggregate content is similar to the study conducted by Cameron et al. [67] on the specimens prepared with recycled clay bricks by adding different percentages of aggregates. Cameron et al. [67] gave a similar reason for decrease in resilient modulus.

7.3. Unconfined Compressive Strength of RAP and RAP – VA Mixes

As has been discussed earlier, the design mix should meet the UC strength criteria as well to meet the quality of base materials [3]. It is to be noted that the UC strength of 100% RAP with 40% fly ash was about 1.0 MPa (Figure 4.11). Hence, to increase the UC strength of the proposed RAP mixes, virgin aggregates have been amended with RAP in 80:20 and 60:40 (RAP:VA) proportions by weight of RAP material. The UC strengths of these mixes treated with 40% fly ash and cured at 28 days are compared in Figure 7.2.

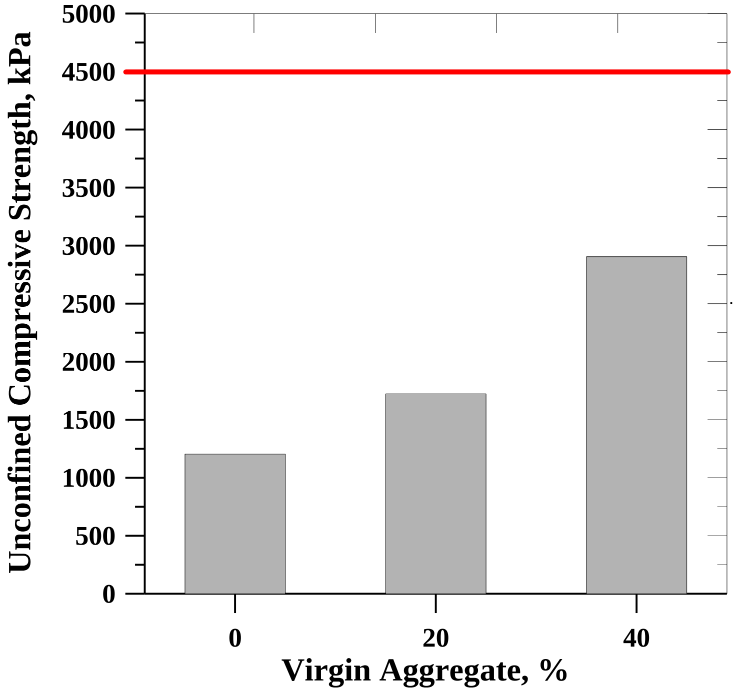

Figure 7.2: Variation of Resilient Modulus with VA Content

From the Figure 7.2, it can also be observed that there was a tremendous increase in the strength with increase in virgin aggregate content in the mix. Guthrie et al. (2007) [29] observed similar results in their study on RAP:VA mixes treated with cement. It was noticed that there was a decrease in UC strength of RAP with an increase in RAP content due to the asphalt cement coating around RAP particles prohibits the formation of bonds between the cement paste and the aggregate surfaces. That is, with increasing RAP content, more of the aggregate surface area in a given specimen is coated with asphalt cement and is therefore less able to develop strong bonds with the cement paste. At cement contents of 0.0% and 0.5%, the differences in UCS between specimens having different RAP contents is less pronounced because little or no cement is available to stabilize the material.

The IRC: 37 [3] recommends a minimum UC strength of 4.5 MPa for cemented base material. However, for the present proposed mixes, the highest UC strength is observed to be 1.72MPa for 60R:40A+40F mix. Further, higher strengths can be obtained by increasing the fly ash content in the mix. However, further increase in fly ash dosage could reduce the structural support offered by the base material for repeated traffic loading on the pavement, since, higher dosage of fly ash content can highly alter the gradation of the mix.

The feasibility of using these mixes (especially 80R:20A+40F mix) as a base/subbase layer in flexible pavements is verified by IRC: 37 [3] and IITPAVE software to check whether the proposed mix can produce rutting and fatigue strains well within the prescribed valued proposed in a design example.

7.4. California Bearing Ratio of RAP and RAP – VA Mixes

The CBR values obtained for various mixes are presented in Figure 7.3. The variation of CBR with fly ash dosage shows an increase in CBR with an increase in fly ash dosage as well as with an increase in VA content. The increase in CBR value with an increase in fly ash content at 28 days of curing period can be attributed to the maximum UC strength obtained by the specimen because of the high pozzolanic reactions with in the mix. On the other hand, since the RAP material is coated with thin layer of asphalt, and subjected to prior high traffic loading, the edges of the RAP particles have become rounded. When a good quality virgin aggregates with high angularity are added to the mix, these virgin aggregates increase the internal friction angle of the total mix and hence, a better interlocking between the particles is achieved, which increase the shear strength of the material. Hence, an increased trend was observed in CBR with an increase in virgin aggregate content.

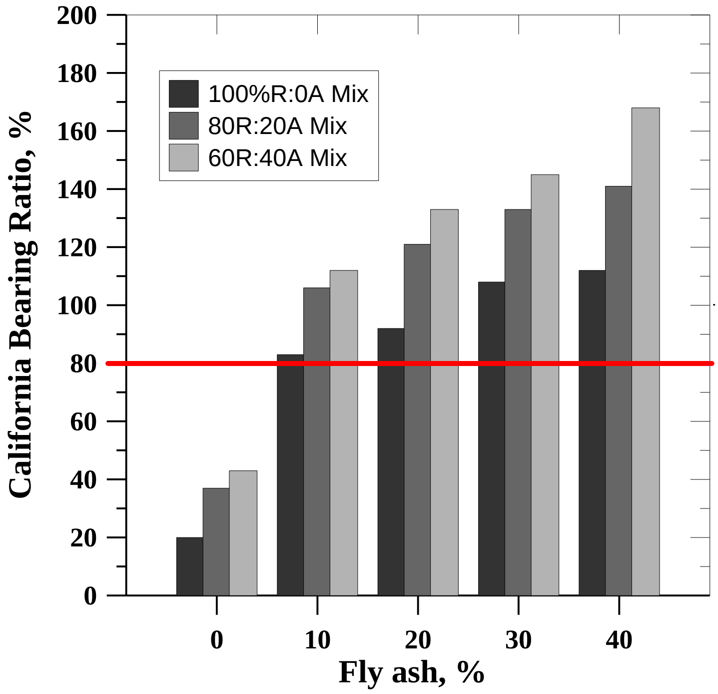

Figure 7.3: Variation of CBR with Fly ash Dosage

Taha et al. [24] determined the CBR of different mix compositions of RAP and aggregates. A low CBR value of 11 percent was determined for 100 percent RAP aggregate. As the percentage of virgin aggregate in the mix increases, the CBR value increases. When 20 percent virgin aggregate is added to RAP, the CBR value increases to 26. Possible reasons for this increase in CBR may be due to better load transfer between particles of the virgin aggregate and the slip surfaces developed between the asphalt-coated particles of the RAP. In the present study, the base CBR for 100% RAP is 20% and increased up to 40% when 20 percent virgin aggregates are added. This difference may be attributed to the variability of the RAP materials and its gradation.

In addition, the CBR data for different RAP:VA mixes with varying dosages of fly ash (Figure: 7.3) is also useful in determining the required CBR of base/subbase mixes for low volume roads. The IRC: SP-20-2002 presents a design methodology to be adopted for low volume roads. According to this method, to determine a base/subbase layer thickness, a minimum CBR of 80% required. From Figure 7.3, it can be observed that the 100% RAP with 10% fly ash mix is meeting this requirement.

7.5. Prediction of Resilient Modulus of RAP Mixes

From the determined CBR values, the resilient modulus values were predicted by using the correlations given by Heukelom, Klomp and Transport and Road Research Laboratory (TRL), Crowthorne, UK. The IRC: 37 [3] follows these equations for predicting resilient modulus values from CBR values (Page-12, Section 5.3). But, the experimental date from this study seem to indicate that the correlations underestimate the resilient modulus in some cases and overestimate the resilient modulus in some cases (Figures 7.4 to 7.6).

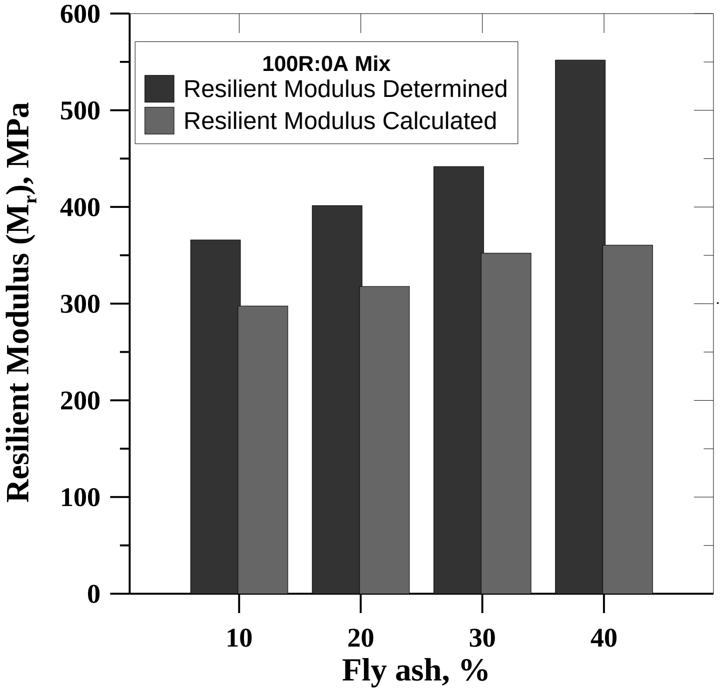

Figure 7.4: Variation of Resilient Modulus with Fly ash Dosage

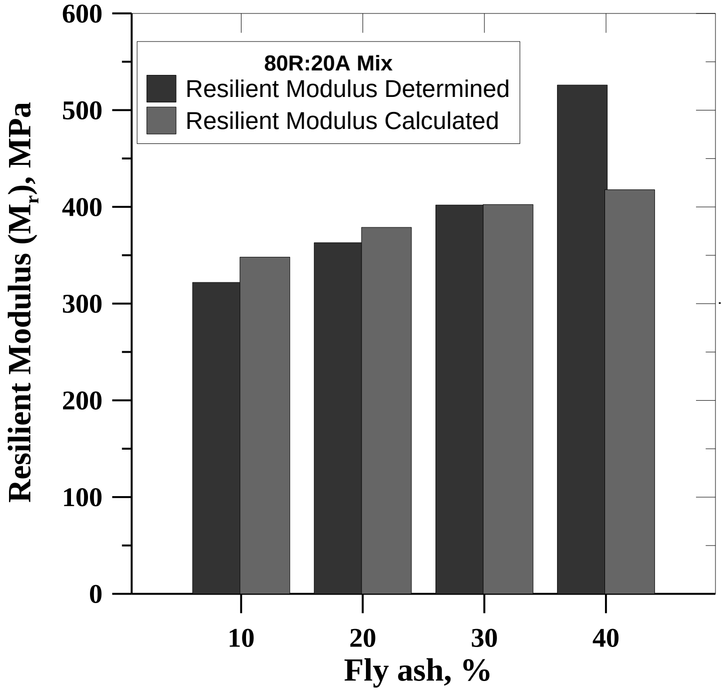

Figure 7.5: Variation of Resilient Modulus with Fly ash Dosage

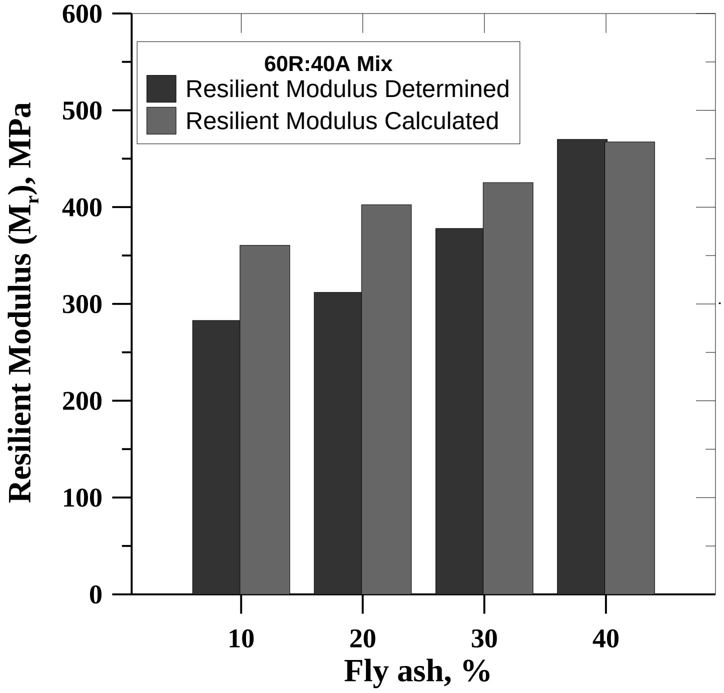

Figure 7.6: Variation of Resilient Modulus with Fly ash Dosage

Angell [50] conducted an experimental study on base coarse materials and predicted the resilient modulus values from the correlation proposed by Heukelom and Klomp [46]. Angell [50] found that the equation was not accurate, since the correlation either underestimated or overestimated the resilient modulus values.

7.6. Design Example

From the experimental tests conducted on RAP material by varying fly ash dosage and aggregate content, 80:20+40 mix has been showing consistent results. However, the UCS of this mix is not meeting the minimum requirement as per IRC: 32-2012 [3]. But, it is to be observed that in the design of flexible pavements, the UCS was considered directly. The main aim of IRC design is to have the rutting and fatigue strains obtained from the proposed mix should be well within the permissible limits. To demonstrate whether the proposed mix meets the design requirements, a design example has been taken up. Initially, the design thickness of each pavement layer was obtained from choosing an appropriate CBR Plate presented in IRC: 37-2012. To obtain the fatigue and rutting strains, a multi layered model was designed in IITPAVE software and further these fatigue and rutting strains were compared with the allowable strains proposed in IRC: 37-2012.

Problem definition

This problem is considered as a three layer elastic structure consisting of bituminous surfacing, cementicious granular base and subbase and the subgrade layers. The fatigue strain is calculated at the bottom of the bituminous surface layer under the wheel load and rutting strain is calculated above the subgrade under the same wheel load.

Design problem by using 80R:20A+40F as a base course in flexible pavements

The flexible pavement was designed for a traffic of 150msa (million standard axles) and by assuming an average wheel load of 40kN, contact radius of 150mm and tyre pressure of 550 kPa. The properties of material used are given below:

Subgrade:

CBR (%):	**10**	(IRC: 37 – 2012, Page: 37, ILLUSTRTION)
E (MPa) =1.76 x $CBR^{0.64}$:	77	(IRC: 37 – 2012, Page: 12, Section 5.3, Eq: 5.2)
Poisson's Ratio:	0.4	

Unit Weight (kN/m^3):	18	
Bituminous Layer:		
Thickness (mm):	100	(IRC: 37 – 2012, Page: 37, PLATE 19)
E (MPa):	3000	(IRC: 37 – 2012, Page: 37, ILLUSTRTION)
Poisson's Ratio:	0.35	
Unit Weight (kN/m^3):	22	
Subbase/Base:		
Thickness (mm):	**410**	(IRC: 37 – 2012, Page: 37, PLATE 19)
E (MPa):	526	
Poisson's Ratio:	0.36	
Unit Weight (kN/m^3):	21.2	
Regression Coefficients:	k_1 (kPa)	: 95000 (Thesis Table: 5.1)
	k_2	: 0.48 (Thesis Table: 5.1)

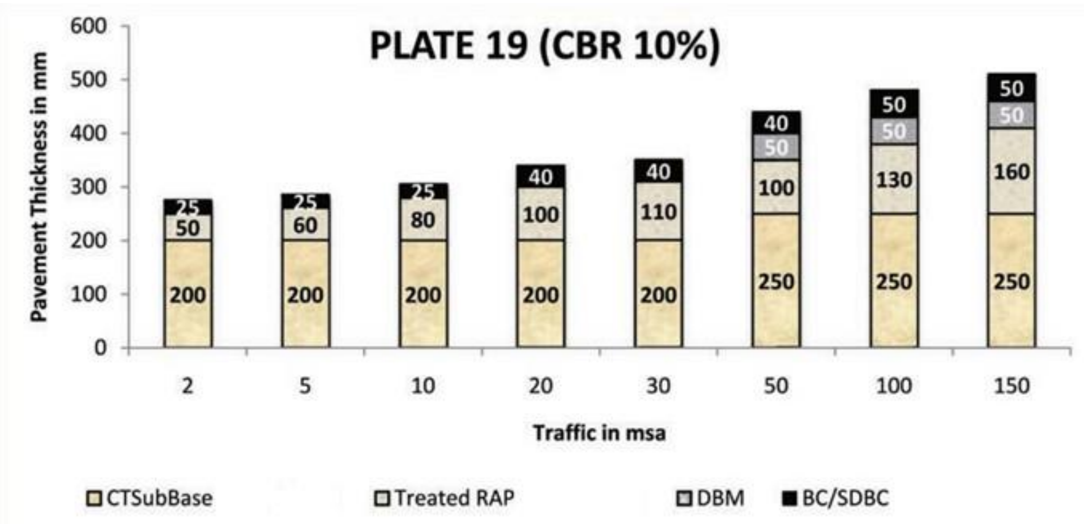

Figure 7.7: Design Plate from IRC: 37-2012 (reproduced)

The obtained thicknesses were incorporated in IITPAVE software to obtain the fatigue and rutting strains.

Permissible Limits:

Fatigue Strain:	0.153×10^{-3}	(IRC: 37 – 2012, Page: 38)
Rutting Strain:	2.91×10^{-4}	(IRC: 37 – 2012, Page: 38)

IIT PAVE

Fatigue Strain:	0.148×10^{-3} (< permissible limit)
Rutting Strain:	3.00×10^{-4} (≈ Permissible limit)

From the calculated fatigue and rutting strains, it was observed that the strains which are calculated are within the permissible strains given by IRC. So it can be said that the RAP material of 80R:20A+40 combination is suitable to use as a base course in high volume roads. Even though the material is not meeting the minimum requirements in terms of strength, from IITPAVE software it was observed that the material is suitable for using in high volume roads. Besides, the design mix is meeting the minimum requirements of IRC SP20-2012: Design of Low Volume Roads. Hence, this mix can be directly used in low volume roads.

7.7. Summary

In this chapter, the stiffness and strength of specimens prepared with different combinations of RAP, VA and fly ash were analyzed and discussed. The results were supported by previous studies performed by researchers. From the results it was observed that 100% RAP with 40 fly ash mix was showing required resilient modulus value specified by IRC: 37 – 2012, however, it is not meeting the required strength. Hence, the mixes were prepared by adding some amount of VA on the basis of trial and error to meet the required strength. It was observed that there was a decrease in resilient modulus with an increase in VA. Besides, the strength of the mix tremendously increased with addition of VA. However, the strength of the mix doesn't meet the minimum requirements. But, the mix of 80% RAP – 20% VA – 40% fly ash is meeting the requirements for low volume roads. It was also observed that the correlations given in IRC:37 – 2012 for calculation of resilient modulus value from CBR is overestimating or underestimating the resilient modulus of RAP mixes.

Chapter 8

Conclusions and Recommendations

8.1. Preamble

In this research, an attempt has been made to utilize huge quantities to reclaimed asphalt pavement (RAP) materials as a base/subbase material in flexible pavements. Virgin aggregates along with cementitious fly ash have been added to RAP material to improve the mechanical properties. Several index and engineering tests have been conducted on the proposed RAP mixes to verify the suitability of the mix as a base/subbase material as per IRC: 37-2012. Following section summarized the important conclusions derived from this study.

8.2. Conclusions and Recommendations

Compaction test results have shown that, with increase in fly ash content, there is an increase in OMC by 25% and decrease in maximum dry unit weight by 3% and with increase in virgin aggregate content the OMC and MD increased by 5.3% and 17% respectively on an average.

Resilient modulus test results shown that, with increase in fly ash content, there is an increase in resilient modulus. With increase in virgin aggregate content, there is a decrease in resilient modulus and with increase in curing period there is an increase in resilient modulus. Similar trends were observed in all the series.

Even though, an appreciable results were observed at 28 day curing period of 100% RAP mixture of 40% fly ash dosage, the UCS was not shown an expected results. With addition of virgin aggregates by 20% an appreciable UCS value was obtained. At the same time, CBR results were also shown a significant improvement, by showing an increase in trend with increase in fly ash, virgin aggregate content, and curing period.

Some of the excerpt from the study are listed below:

- Preparing an intact specimens with 100% RAP material is almost impossible.
- Addition method of mixing fly ash in the mixture is a better technique.
- 100% RAP material mixtures have good stiffness but very low strength.
- 80% RAP – 20% VA mixes have good stiffness and strength.
- 80% RAP – 20% VA – 40% fly ash mixture can be considered as an optimum mixture having resilient modulus of 526 MPa, Unconfined Compressive Strength of 1.72MPa, retained strength of 1.33MPa and California Bearing Ratio of 141%.
- Increase in virgin aggregate content leads to lower stiffness and higher strength. But, higher addition of virgin aggregates should not be recommended because the main aim is to reduce the use of virgin aggregates.
- Increase in fly ash content leads to higher stiffness and higher strength up to certain limit. But, higher dosages of fly ash should not be recommended because it requires more water for compaction.
- The design parameters: layer coefficients and regression coefficients can be directly used by any pavement designer for the similar materials.

8.3. Future Scope of the Work

The present study has given emphasis on reclaimed asphalt pavement material. An attempt has been made to understand the resilient behavior of fly ash treated reclaimed asphalt pavements mixtures. Following are recommendations for scope of future work.

- Future studies can be carried out with small percentage of lime or cement to activate the fly ash and to gain required strength and stiffness at lower percentage of fly ash.
- Permeability studies may be carried out on various mixtures of RAP material to verify the drainage properties of these mixes.
- Durability Studies may be carried out on various mixtures of RAP material to verify the longevity of the base layer.
- Future studies may be carried out on micro structure of the mixtures, to validate the results in micro level.
- Field tests may be performed by laying a road of desired length using RAP material as a base course.
- Numerical models may be developed to develop the better correlations between CBR and resilient modulus with latest experimental data.
- Studies can be carried out on various waste materials.
- More studies can be done for various load patterns and stress states.

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List of Publications from this Research

Journal

1. Sireesh Saride, Deepthi A, **Sarath Chandra Prasad J**, Anand J. Puppala and Hoyos. L.R (2014) "Evaluation of Fly ash Treated Reclaimed Asphalt Pavements for Base/Subbase Applications", Indian Geotechnical Journal, Special Issue on Transpiration Geotechnics. Paper ID IGTJ-D-14-00010. (Under review)

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1. Sireesh Saride, Deepthi A, Someshwara Rao T, **Sarath Chandra Prasad J**, and Dayakar R (2014) " Evaluation of Fly ash Treated RAP for Sustainable Design of Pavement Bases" An Indian Context, Geocongress 2014: Geo-Characterization and Modeling for Sustainability, American Society of Civil Engineers, Special technical publication, GSP, Atlanta, Gorgia, Feb. 23-26, 2014.
2. **Sarath Chandra Prasad.J**, Sireesh Saride "Performance of Fly ash Treated Reclaimed Asphalt Pavements as Base Layer", Indian Geotechnical Conference 2014, Indian Geotechnical Society, Kakinada, JNTU Kakinada, Andhra Pradesh, December 18-20, 2014. Paper Id: T04P18. (Under review).
3. Anu M George, **Sarath Chandra Prasad**, Sireesh Saride "Sustainability of Low Volume Roads Using Fly ash Treated RAP as Base Material", Indian Geotechnical Conference 2014, Indian Geotechnical Society, Kakinada, JNTU Kakinada, Andhra Pradesh, December 18-20, 2014. Paper Id: T04P10. (Under review).