LABORATORY INVESTIGATIONS ON THE EFFECT OF REJUVENATORS IN RECLAIMED ASPHALT PAVEMENT BASED STONE MASTIC ASPHALT MIXES

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

L DURGA PRASHANTH
(CV12P03)

DEPARTMENT OF CIVIL ENGINEERING

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SURATHKAL, MANGALORE-575025

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July, 2019

D E C L A R A T I O N

by the Ph.D. Research Scholar

I hereby declare that the Research Thesis entitled "***Laboratory investigation on the effect of rejuvenator in Reclaimed Asphalt Pavement based Stone Mastic Asphalt Mixes***" which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Civil Engineering** *is a bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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Department of Civil Engineering

Place: NITK-Surathkal
Date: 12/07/2019

C E R T I F I C A T E

This is to certify that the Research Thesis entitled "***Laboratory investigation on the effect of rejuvenator in Reclaimed Asphalt Pavement based Stone Mastic Asphalt Mixes***" submitted by L **DURGA PRASHANTH**, (Register Number: **121200CV12P03)** as the record of research work carried out by him is accepted as the Research Thesis submission in partial fulfillment of the requirements for the award of degree of Doctor of Philosophy.

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ABSTRACT

The present study discusses the characteristics of Reclaimed Asphalt Pavement (RAP) materials in bituminous mixtures. RAP is a material extracted from worn out or distressed pavement. These materials possess a valuable component such as aggregates and aged bituminous binder which has a potential to be reused or recycled. At present the field engineers are facing lot of problems to get quality aggregate for road construction. Due to the scarcity of this material, the cost is escalating. The government of India is insisting to use marginal or reclaimed materials in road construction based on investigations in the laboratory.

These materials are incorporated as a replacement to conventional bitumen binder and also the aggregates in both coarse and fine fractions. The mix design for conventional and RAP based Stone Matrix Asphalt (SMA) mixes are optimised to obtain sufficient strength, durability based on the standards suggested by relevant codes to be used as a bituminous layer in flexible pavement. The RAP materials are incorporated at different replacement levels (0%, 30%, 50%, and 70% by weight of total aggregate gradation content in the mix). Various mechanical, durability and performance properties are studied in detail and compared to conventional SMA mix.

It was found that the RAP based SMA Mix displayed better strength when compared to that of conventional mixes. Whereas, the durability and fatigue performance was found to decrease with the increase in RAP content. To overcome the problems of durability and fatigue performance of RAP materials, rejuvenators were used. The rejuvenators used in the present study are bio based and another petroleum based viz., Waste Cooking Oil (WCO) and Waste Engine Oil (WEO). The rejuvenators are added to reduce the stiffness and viscosity with improved workability. The test results of rejuvenated RAP based SMA Mix exhibited better strength than the conventional mix. The durability and fatigue performance of the rejuvenated mix also improved even at higher levels of replacement of RAP, indicating the significance of rejuvenation and utilization of higher RAP content in the mix.

The use of rejuvenated RAP in bituminous mixes would lead to lower production cost of bituminous mixes as compared to the conventional type.

Keywords: Reclaimed Asphalt Pavement; Waste Cooking Oil; Waste Engine Oil; Mechanical and durability properties, Fatigue performance, and waste management.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

AASHTO	American Association of State Highway and Transportation Officials
AI	Asphalt Institute
AIV	Aggregate Impact Value
ARRA	Asphalt Recycling and Reclaiming Association
ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
CI	Combined Index
CM	Control Mix
CMT	Copper Mine Tailings
Co2	Carbon di Oxide.
CRMB	Crumb Rubber Modified Bitumen
DSR	Dynamic Shear Rheometer
FHWA	Federal Highway Administration
FL	Fatigue Life
FTIR	Fourier Transform InfraRed
Gmb	Bulk Density of Compacted Specimen
Gmm	Maximum Theoretical Density
HMA	Hot Mix Asphalt
IRC	Indian Roads Congress
IS	Indian Standards
ITS	Indirect Tensile Strength
J_C	Critical Strain Energy
LAV	Los Angeles Abrasion Value
LVDT	Variable Displacement Transducer
MoRTH	Ministry of Road Transport and Highways
M_R	Modulus of Resilience
MS	Marshall Stability
NCHRP	National Cooperative Highway Research Program
OBC	Optimum Binder Content

OPC	Ordinary Portland Cement
PMB	Polymer Modified Bitumen
R-1	Reclaimed Asphalt Pavement from Source 1
R-2	Reclaimed Asphalt Pavement from Source 2
RAP	Reclaimed Asphalt Pavement
RGMB	Reclaimed Geomembrane Modified Binder
RPM	Rotation Per Minute
RSM	Response Surface Methodology
RTFO	Rolling Thin Film Oven
SCB	Semi Circular Bending
SGC	Superpave Gyratory Compactor
SMA	Stone Matrix Asphalt
S-N	Stress – Number of cycles
SR	Stress Ratio
TSR	Tensile Strength Ratio
UCS	Unconfined Compressive Strength
VCA	Voids in Coarse Aggregates
VG	Viscosity Grade
VMA	Voids in Mineral Aggregates
V_V	Volume of Voids
WCO	Waste Cooking Oil
WEO	Waste Engine Oil
WMA	Warm Mix Asphalt
WP	Waste Plastics

CHAPTER 1

INTRODUCTION

1.1 GENERAL

A good transportation infrastructure is essential and most important for the development of any nation. Deficiency of proper transportation facilities sector retards the growth and progress of any country. Of all the available transportation systems, road network is the most utilized mode as it offers easy access, more flexibility and freedom to the road users. (MoRT&H 2012). Moreover, road network alone connects the remotest areas to central business district. Most of the developed countries have focused on development of road infrastructure in order to boost their economy by providing proper road connectivity. Road network facilitates the safe and economic conveyance of goods between the source and the business hubs. An extensive road network is one of the most important elements to promote the growth and development of any country.

India, being one of the fastest developing nations has focused on the development of large scale road networks. With around 4.9 million km road network, India has the second-largest road network in the world. Indian road network is constituted of 0.09 million km national highways, 0.14 million km of state highways and 4.65 million km of major district roads and rural roads, which also include other district roads and village roads. Roads in India account for about 85% of the passenger traffic and 60% of the freight traffic (MoRT&H 2014)

Road projects need to be economically and ecologically sustainable apart from being safe so as to benefit from the huge investments made in road infrastructure projects. Roads in India are subjected to overloading due to the rapid growth of passenger vehicular traffic in addition to a considerable increase in freight traffic. This has led to the premature performance failure of highway pavements (Sharma et al. 1995). Moreover, maintenance of pavements is not carried out periodically, thus causing inconvenience to the users, along with higher maintenance costs. The demand for construction of new highways, reconstruction, and maintenance of prematurely failed pavements has also resulted in depletion of naturally available road materials specially the aggregates. To overcome this, there is a need to find out alternatives to construct roadways that are eco-friendly and sustainable at the same time.

1.2 FLEXIBLE PAVEMENTS

Majority of the road network including the urban roads i.e., Arterial roads, sub arterial roads, collector streets and rural roads i.e., National Highways (NH), State Highways(SH), Major District Roads (MDR) and Other District Roads (ODR) are generally flexible pavements. Bituminous roads are usually preferred for their excellent performance. They are quiet, smooth and durable. Unlike the cement concrete pavements, construction of bituminous pavements does not require long duration and offers easy maintenance resulting in minimum traffic delays. Highways in India are subjected to heavy traffic in terms of the number of commercial vehicles, axle loads and variations in seasonal and daily temperatures. All these factors lead to premature failure of bituminous pavements. These problems are prevalent for a long period over the length of road network across the country.

The bituminous pavement layer consists of aggregates and bitumen. Bitumen is costly and non-renewable pavement material that forms to be a very important part of the flexible pavement system mainly because of its ability to bind the materials and hold them together. Majority of the pavements constructed in India have bituminous material in both the binder and wearing courses. VG 30 (Viscosity Grade) or bitumen with a penetration grade of 60/70 is most commonly used type of bituminous binder in the bituminous layers of pavement structure. To cater to the increased vehicular traffic and the need for better performance of highways there has been a significant development in the ways the roads are constructed. The materials used, construction techniques adopted, and the amount of cost involved has necessitated these changes.

From the mid-1990's use of modified bituminous binders have attracted road contractors because of their advantages such as better strength, flexibility, durability, and provision for use of alternate materials into the binder. The neat binders can be modified based on the requirements and purpose of application. Several implementation programs or projects have been found to be successful across the country. Materials like rubber and Elastomeric polymers have been preferred by the highway contractors. Crumb rubber modified bitumen (CRMB) and polymer modified bitumen (PMB) is also used extensively. In the revised edition of guidelines for design of flexible pavements (IRC:37-2012), use of VG 40 binder and other modified binders are recommended and encouraged.

The bound and unbound granular layers of flexible pavement structure constitute to around 95% of aggregates. Considering the scope for road construction projects in future across the country, the amount of aggregates required is quite enormous. With the current rate of development, natural aggregates may no longer be available within a few decades. The quality of bituminous pavements mainly depends on quality of the aggregates used. Hard, durable, and angular aggregates are preferably used for road construction. The aggregates and bitumen used should be hydrophobic. Of all these properties, gradation of aggregates tips all the other requirements as a primary and most important property. Depending on the usage, i.e., Low volume and high volume roads, the roads may be constructed with different bituminous mixture gradations. Generally, dense graded, open-graded and gap graded type of bituminous mixtures are considered for construction depending on the requirement. Out of these, the dense-graded is more widely accepted and adopted type of bituminous mix across the country. This is simply because of the availability of well developed, clearly defined and proven mix design guidelines by the central highway authorities (MoRT&H 2013). The other type of mixes such as gap graded mixtures and an open graded mixture is generally not preferred by the road contractors. This is due to non-availability of proper user guidelines to the contractor and field engineers. Of late, in the European and American countries, use of gap graded and open-graded mixtures along with alternate materials have gained appreciation based on the trial stretch performances. Due to the variety of advantages these mixtures possess and with proper guidelines to the implementation authorities would witness revolutionary changes in the highway constructions industry.

1.3 RECLAIMED ASPHALT PAVEMENT (RAP)

Over the service life of pavements, repair and maintenance works are carried out on a regular basis to keep the roads in top condition. Road repair and maintenance generates substantial waste. When a Road is removed during resurfacing and maintenance work, the material known as asphalt pavement waste is produced. This material consists of aggregates coated with asphalt which is termed as RAP (Reclaimed Asphalt Pavement). In the past, these RAP materials had been re-used mainly for temporary access and as a lower layer sub-base material in road construction which is not good enough. These materials are often very useful when properly processed. Asphalt has always been a recyclable material and in fact, it ranks second in the world next to recyclable water. It is a valuable commodity that can be used right back into the hot mix asphalt (HMA) without compromising on the performance. Some of the issues related to its usage is, the hauling distance of the RAP material from the hot mix asphalt plant and processing. However, banking on the environmental and economic benefits that these materials have, every penny spent on asphalt recycling seems to be worth investing.

Historically RAP materials were used in many ways, such as in shoulder backing right next to the road, trucking and equipment yards, haul roads, dust control on dirt roads and also in base layers of the pavement structure (Abdelrahman et al. 2011). All of these applications were found to be of lower value for such a valuable material. Hence, researchers across the globe have given these materials a higher value as these materials have binder characteristics and considered them as a valuable asset.

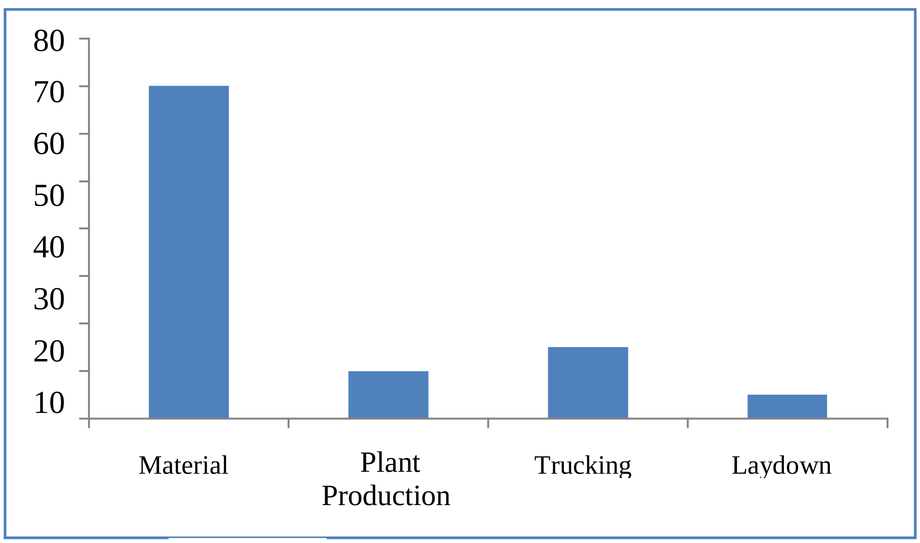
With large scale construction and infrastructure projects being carried out in recent years, the production of Hot Mix Asphalt mixtures has increased rapidly with the consumption of natural resources. The demand for aggregates has increased resulting in the depletion of natural rock beds, mountains, and river beds leading to severe ecological imbalance. In order to meet the increase in demand for aggregates and to protect the aggregates for future, there is a need to identify ways in the use of alternative materials at large scale.

Recycling of asphalt pavements dates back to around 1915 in the United States of America, but it was not considered as a common implementation practice until the early 1970’s when the cost of asphalt binder increased exponentially as a result of Arab oil embargo. Thus 1970’s period marked the beginning of extensive utilization of RAP in asphalt pavements across the United States. In addition to this, some field trials were constructed containing RAP materials and were tested to evaluate its feasibility as a road construction material. These trial test results were found to be successful in RAP usage up to a certain extent. As a result, to begin with many highway agencies incorporated lower content (percentage by weight of total mix) of RAP materials in hot mix asphalt (HMA). This may have been attributed to the fact that, mixtures containing higher RAP contents could result in increased "blue smoke" emissions from plants since the RAP materials were fed directly into the path of hot gasses. It is also important to note that with the modern design and technology used in new plants; this is no longer a major concern (Putman and Amirkhanian 2004). Also, based on field experience, the industry has developed very effective techniques to introduce proper proportion of RAP into asphalt mixtures.

In the era of environmental, economic and sustainability issues the use of RAP material on a larger scale has gained importance. Federal Highway Administration (FHWA) states in their recycling policy that "The same materials used to build the original highway system can be re-used to repair, reconstruct, and maintain them. Where, appropriate recycling of aggregates and other highway construction material makes sense in terms of economy, environment, and engineering aspects.

Generally, there are four major cost categories with respect to asphalt mixture production including materials, plant production, trucking, and field construction (lay down). Of all these four categories, the category of materials is considered to be the most expensive one. In majority of the cases, about 70% of cost is incurred in materials to produce bituminous mixtures as shown in figure 1. In any bituminous mixture, binder is the most expensive material compared to others. Apart from being costlier, the material is an exhaustible resource. Hence, the use of RAP in surface layers of flexible pavements replacing a portion of aggregates and binder is considered to be effective in terms of economy and also proves to be environmental friendly.

When super pave mix design procedure was first implemented in 1990's, the specifications had no provision for incorporating RAP in new asphalt mixtures. Therefore, majority of the highway agencies were unwilling to allow contractors to use RAP in asphalt pavements. This was the scenario until researchers and engineers began to develop procedures to account for the utilization of recycled materials.



*Source: FHWA-HRT-11-021

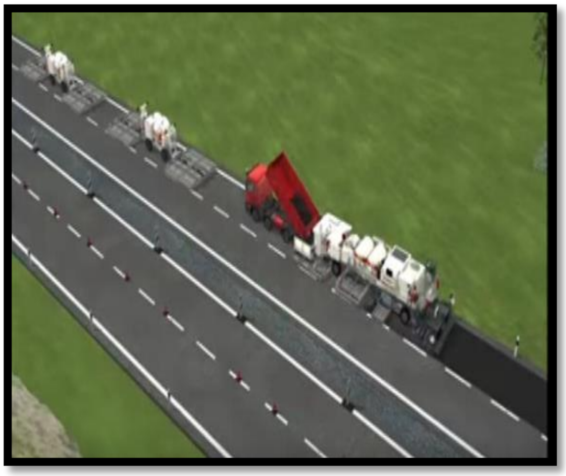
Figure 1.1 Production cost (%) for a typical highway project

The National Cooperative Highway Research Program (NCHRP) accomplished this goal to a certain extent by providing guidelines for use of RAP content. These guidelines were being relatively conservative. However, usage of RAP in maintenance and construction of new pavements gradually increased across various state transportation departments across the United States.

Utilization of RAP material in asphalt paving mixtures is considered to outperform the native aggregates in many cases through several studies. (Das and Swamy 2014; Pradyumna and Jain 2016) RAP is an unavoidable material obtained as the pavement reaches its service life or if the pavement deteriorates prematurely. The use of a higher content of RAP has been discouraged for many years because of its brittleness and stiffness caused leading to the development of cracks in the asphalt mixture (Watson et al. 2008). However, problem of stiffness in the RAP mixture can be countered by the addition of rejuvenators to bring back the flexibility of mix within the acceptable limits (Zaumanis et al. 2014). This encouraged many researchers across the globe to check for means and ways to utilize higher percentages of RAP in new HMA mixes with minimal wastage.

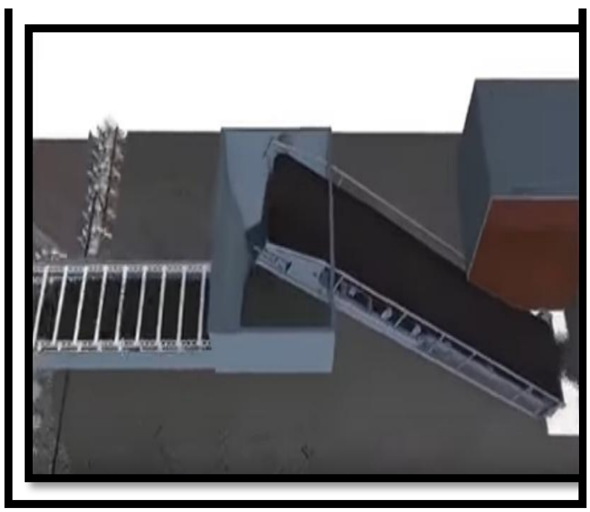
In the 21st century the asphalt recycling has become a common highway construction practice in many countries, including the United States of America (USA), Australia, the European Union, and China. In the United States about 85% of RAP material generated annually goes back into the pavement layers. Some of the materials that are not used in that particular season are stockpiled and eventually reused at a later stage. In India, use of RAP material in pavement layers is still in cradle stage and gaining importance recently in the light of depleting natural resources. All reclaimed road material goes into the landfill or dump yards and thereby increase the risk of environment degradation. The appropriate utilization of RAP material in HMA mixtures can lower these environmental impacts along with the reduction in valuable landfill space. The utilization of RAP is very limited in Indian road sector. Research in this regard and development of proper guidelines in the usage of RAP suiting local conditions is found to be a requirement for developing a sustainable road construction practice.

Recycling of RAP in new HMA mixes can be achieved in two ways. In situ recycling and HMA plant recycling. The recycling technique can be adopted through both hot and cold processes depending on applications of the mix. In hot in-place recycling technique, the preheaters transfer the thermal energy into pavement surface and the underlying layers. This preheater unit is attached to a milling machine that removes the first layer of preheated and softened asphalt surface. This process is 99% recyclable as it does not require a hot mix plant or large stockpiles of rock. This significantly reduces the damage incurred to the local roads and bridges caused by haul trucks transporting construction materials. The process of milling is continued until the target depth is reached. Each milling unit is outfitted with a grade control system to ensure consistent milling depth. Further, the milled material is transferred to the next unit where the required quantity of rejuvenators and virgin materials are added to produce a new recycled mix and in turn transferred to paver unit attached to the machine. This results in a newly paved surface at the site by utilizing the same materials that were used before. This technique requires heavy machinery units that are quite expensive and requires skilled manpower for handling these machines. This leads to the disruption of traffic during the process as well.

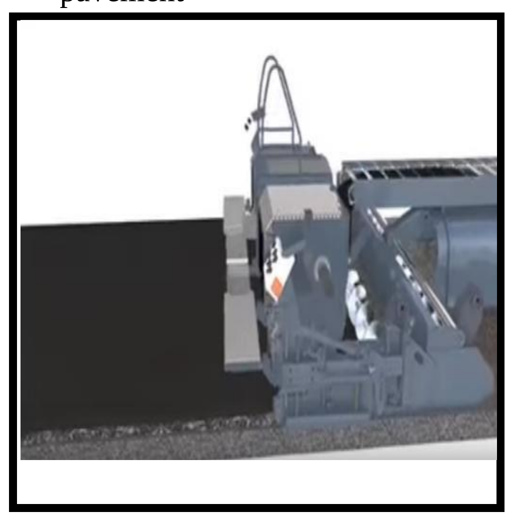


a. Preheater and Milling Units

b. Milling of the top surface of the pavement



c. Feeding of deficient virgin materials



d. Feeding of recycled mix into the paver system

Figure 1.2. Hot In Place Recycling Process

*Sourcehttps://www.wirtgen-group.com/searchfrontend/en-n/?q=recycling

The other technique of recycling the RAP material at plant gains a lot of importance during this decade as the distressed pavement can be milled and brought to the plant, stockpiled and that can be used in later stages. These materials can be checked for its properties, potential enough for reusing. The asphalt mixtures are degraded and its gradation is checked. The binder is extracted by any available means, usually with a centrifuge extractor and the properties of these materials are assessed and ascertained for further usage (Aravind and Das 2007). If the binder recovered is found to have lost its ductility due to ageing, rejuvenators are used to bring back the lost flexibility, making it a potential material for reuse. The required dosage of the rejuvenating agent is added and mixed by adding the deficient grade of aggregates and can be utilized in the same site or in any new highway construction site.

Figure 1.3 RAP stockpile at Hot Mix Asphalt Plant

*Sourcehttps://www.wirtgen-group.com/searchfrontend/en-n/?q=recycling

1.4 REJUVENATORS

Usually, the RAP binder obtained by milling of distressed pavements would have lost its useful ductile property through short term and long term ageing. This makes the RAP binder stiff and reduces its capability to coat and bind the aggregates. This stiffness in the binder leads to premature cracking in asphalt mixtures if it is used directly without treating the same. To ensure that the aged bituminous binder regains the lost flexibility, asphalt rejuvenators are added (Xie et al. n.d.) Asphalt rejuvenators are designed to replace the chemicals that are lost during the asphalt's aging process and to provide a protective seal against erosion, wear and tear. This aging of asphalt is predominantly due to oxidation process in which the sun rays, water and air remove the light oils from the surface of pavement over the years and appears to be bleached. This is why asphalt appears to be light colored as it ages.

Once an asphalt rejuvenator is introduced into the aged asphalt binder it does not form a separate layer and wears off, instead, it penetrates and gets mixed in the asphalt replacing the chemicals that are lost due to aging (Zaumanis et al. 2014). The rejuvenator in asphalt binder reverses its age by lowering the viscosity of the whole material and by increasing the flexibility for years to come. The rejuvenators penetrate into the asphalt providing all the necessary oils needed to give pavement its full life once again. It is because of this rejuvenating effect, the performance of asphalt binder is enhanced to satisfactorily serve the intended purpose. The reduction in viscosity ensures lesser cracks, less erosion, less brittleness and less dryness in asphalt.

1.5 STONE MASTIC ASPHALT

Stone Mastic Asphalt (SMA) also called Stone Matrix Asphalt was developed in Germany in the 1960's. These mixes provide deformation resistant and durable surfacing suitable for high volume roads. SMA has found its use in Europe, Australia, the United States, and Canada as a durable surfacing option for residential streets and highways. SMA has high coarse aggregate content that interlocks to form a stone skeleton to resist permanent deformation. The stones are filled with mastic of bitumen and filler to which fibers are added to provide adequate stability of bitumen and to prevent drainage of binder during transportation and placement of mixture. A Typical SMA composition consists of 70 to 80% coarse aggregates, 8 to 12% filler, 6 to 7% bituminous binder and 0.3% fiber. The deformation resistance capacity of SMA stands from the coarse skeleton, providing more stone on stone contact when compared to conventional dense graded asphalt. High bitumen content also improves the flexibility of mix. The addition of a small quantity of cellulose or mineral fiber prevents drainage of bitumen during transportation and placement of material.

The essential features of SMA Mix viz., coarse aggregate skeleton, mastic composition, consequent surface texture, and mixture stability are largely determined by the selection of aggregate gradation along with the type and proportions of filler and binder material. SMA is mixed and placed in the same plants that are used with a conventional hot mix. In batch plants, the fiber additive is added directly into the pug mill using individually wrapped bags or by dispensing equipment. Mixing duration may be extended to ensure that the fiber is homogenously distributed throughout the mix and temperature is controlled to avoid over heating or damage to the fiber. In drum plants, particular care must be taken so that both the filler content and fiber content are incorporated in the mixture without excessive loss from the dust extraction system. Filler systems that add filler directly into the drum rather than an aggregate feeder is usually preferred. Palletized fibers may be added through systems designed for the addition of recycled material. The use of a polymer-modified binder in SMA may reduce the mixture workability and may require increased effort to accomplish the standards of compacted density. Achieving specified compaction density with low air voids has been recognized as a vital factor in the performance of SMA mixtures. The layer thickness and nominal maximum aggregate particle size of SMA mixes are generally 2.5 to 3 times thicker. Higher layer thickness will help in achieving the required standards of compacted density.

1.6 NEED AND SIGNIFICANCE OF PRESENT INVESTIGATION

One of the toughest challenges in development of any road network is to execute highway projects with the concept of sustainability. The road industry is, therefore, looking forward to the use of alternative materials and construction technology, which are environmental friendly, energy-efficient and cost-effective all at the same time for construction and maintenance of roads. Most of the current road construction practices are primarily dependent on naturally available aggregates that are obtained from quarries. The extraction of these aggregates from their natural sources results in the loss of forest cover and increases pollution in a large scale leading to environmental degradation. This, in turn, has raised a few environmental concerns in many parts of the world. In order to preserve natural resources, sufficient reserves have to be ensured to meet the demands of aggregates at present and in the future, as these resources are depleting at a faster rate.

On the other hand, price of asphalt binder is also fluctuating and research is needed to reduce the consumption of virgin asphalt binder in rehabilitation strategies through alternate technologies and thereby reduce the cost of construction and maintenance. To cope up with the demand for aggregates, to preserve and maintain the road infrastructure assets, the Ministry of road transport and Highways (MoRT&H) have strongly recommended the use of Reclaimed Asphalt Pavement (RAP) material as an alternative (MoRT&H 2014), and considering their use for Hot Mix Asphalt (HMA). Recycling of asphalt pavement materials has proven to be a valuable approach in terms of economy and environment protection.

Uses of RAP in asphalt concrete mixtures have been in practice over the decades, but the amount of RAP used was limited from 25 to 30% by weight of overall asphalt mixtures. Although the use of higher percentages of RAP reported an improved rutting property of the mix, there was a notable reduction in the fatigue life of these mixtures. This property of reduction in cracking resistance of higher content RAP based asphalt concrete mixes restricted its content to almost 30%. Hence a well-designed bituminous pavement utilizing higher contents on RAP has the potential to overcome the problems of environmental degradation.

The present experimental study focuses on the possible utilization of higher fractions of RAP material in SMA mixtures by adding the rejuvenators into the mix so as to regain the lost properties of aged binder that leads to a better performance of the mix prepared with RAP materials when compared with the conventional mixtures. The aim of this study is not just to protect the natural raw materials, but to recycle the disposal wastes generated from the distressed pavement. Presently in India, there is no standard guideline available for application of RAP materials in construction of highway pavements, which may mainly be due to the limited research outputs, non-acceptability of a new technique by the contractors, lack of expertise and confidence by the site engineers. This scenario can be changed by conducting proper research and communicating the performance of the recycled mixes.

1.7 OBJECTIVES OF THE PRESENT RESEARCH WORK

It has been observed from the literature review that several attempts have already been made by researchers across the globe to understand the mechanisms of using RAP in hot mix asphalt mixes. However, there is limited research reported on the use of rejuvenators to produce effective hot mix asphalt mixes suiting the practical field conditions. The aim of the proposed study is to carry out detailed laboratory investigations to address the suitability and performance of rejuvenated RAP based Stone Matrix Asphalt (SMA) mixtures.

The main objectives of the present research work were identified as follows:

1. To evaluate the viscoelastic behaviour of rejuvenated aged asphalt binders with waste cooking oil (WCO) and waste engine oil (WEO) as rejuvenators.
2. To evaluate the mechanical properties of rejuvenated RAP based SMA mixes.
3. To evaluate the performance behaviour of rejuvenated RAP based SMA mixes.

1.8 SCOPE OF WORK

The MoRT&H recommends use of alternate/ marginal materials and to adopt recycling technology in road construction to save the natural aggregates. Hence, the RAP materials obtained from a distressed pavement stretch was checked for its utility in new construction. Scope of the present study included determining the optimum dosage of rejuvenators to be added in aged binder so as to regain its original properties Tests were carried out to determine the viscoelastic behavior of neat bitumen, aged bitumen and rejuvenated bitumen. Further studies were carried out to determine the effect of rejuvenated RAP material in SMA mixes with varying percentages of RAP viz., 30 %, 50%, and 70%. Engineering properties such as moisture susceptibility, indirect tensile strength, temperature susceptibility, permanent deformation and fatigue characteristics were evaluated to check whether rejuvenated RAP based SMA mixes could meet the required design standards and compare the same with control mixes.

Permanent deformation characteristics of the conventional and rejuvenated RAP mixes with varying contents of RAP was evaluated. Fatigue performance of the conventional and rejuvenated RAP mixtures with varying contents of RAP at varying test temperatures is determined by applying repeated loads on circular specimens using repeated load testing equipment. The fatigue life data obtained are represented and analyzed using S-N curves to establish fatigue equations.

1.9 ORGANIZATION OF THESIS

This thesis is organized into six chapters followed by the list of references and Appendixes.

CHAPTER 1

The background on the road network and the need for adopting recycling techniques in road construction in brief note Reclaimed Asphalt Pavement Materials and rejuvenators; need and significance, objectives and scope of the research are presented in this chapter.

CHAPTER 2

A comprehensive literature review has been carried out to collect adequate information use of RAP, rejuvenators and other materials in bituminous mixtures. Information regarding the research works carried out so far on mechanical, durability and performance properties of RAP and Rejuvenated RAP based asphalt mixtures is also presented.

CHAPTER 3

The details of various materials used, basic properties of virgin and reclaimed materials i.e., aggregates, bituminous binders and rejuvenators etc., The method adopted to arrive at the optimum dosage of rejuvenator, material characterization and performance aspects of rejuvenated RAP based SMA mixes are discussed in this chapter.

CHAPTER 4

This chapter presents a detailed discussion of the results and observations of the rheological, volumetric, and mechanical and performance properties of RAP based SMA mixes.

CHAPTER 5

This chapter presents a detailed discussion of the results and observations of the rheological, volumetric, and mechanical and performance properties of rejuvenated RAP based SMA mixes.

CHAPTER 6

Observations and conclusions are drawn based on the results obtained from the laboratory investigations and scope for future study is presented in this Chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

As always any new innovations in the engineering stream may be sometimes economical and eco-friendly. In some aspects of practicality, this kind of conservative approach is quite common and acceptable considering the complexity in understanding and its implementation process. This is a common phenomenon, especially in civil engineering and construction field which involves large scale infrastructure projects like highway construction. But, in the present conditions of economic and environmental challenges faced by the engineers and highway contracting agencies, use of alternative materials and techniques in road construction is found to be of greater necessity and a viable option. If not, the next generation may have to face serious repercussions related to environmental degradation due to large scale urbanization and developments. Therefore, reduce, restore, reuse and recycle commonly termed as 4R‟s has gained a lot of importance in the current situation. Any kinds of 4R‟s activity are certainly beneficial in cost and environmental protection.

In highway construction domain recycling and reuse of any material has gained importance and has become order of the day due to various reasons. Recycling of pavement material has proven to be a very strong and powerful concept. Although asphalt recycling is about half a century old technique in the west, it is relatively a new-age technique especially in India with respect to its implementation.

These materials are rich in valuable resources like asphalt binders and aggregates. Although the asphalt binder would have lost its volatile properties it would add significant value for the mixes after rejuvenation. On the other hand, aggregates present in the RAP material possesses neutral charge that works well with the binders.

Generally, there are four primary types of asphalt recycling (Basic Asphalt Recycling Manual, ARRA, 1996) depending on the need and availability of resources in terms of men, machinery, and materials. Hot recycling is the most widely used type. The procedure remains same as conventional practice except for the addition of Reclaimed materials in the mix at various proportions. Warm Mix recycling is another type that has gained a lot of importance in recent times in the light of increased carbon footprint due to construction activities. Cold recycling is a technique has been in the later stages of research before it is regularly practiced on a large scale. The predominant factor in all these techniques is the temperature at which the asphalt mixtures are mixed, placed and compacted. All these techniques have applications in various aspects of road construction. The materials in this type of recycling technique can be prepared in the site or in plant and brought to the site for construction

2.2 HISTORICAL DEVELOPMENT OF ASPHALT RECYCLING

Recycling is probably as old as road construction. But the recycling in the early days was an informal method where there were no set guidelines for its usage. As long as the material was strong enough to bear the load, the material was recycled. Instead of the materials that are to be discarded and thrown away after the removal from the distressed pavement, it was used in new applications such as parking areas. Slowly and steadily, this material caught the eyes of entrepreneurs and was made available to them. Such informal applications are still followed and practiced even to this date.

In the early 1860's, in Germany, the reclaimed construction material was first used with OPC for concrete products manufacturing. This led to a systematic study to be done on finding the relative possibilities of utilizing the construction wastes as aggregates in concrete till the mid-19th century. There was little knowledge of how the waste or reclaimed products would perform after processing the same and using it to produce new asphalt mixes.

Until 1900"s use of RAP material in asphalt mixtures were not known significantly. The first use of RAP dated back to 1915. A major emphasis was laid on RAP usage in late 1973 when the members of Arab petroleum Companies proclaimed an oil Embargo. This affected the use of petroleum in countries like the United States, Netherlands, Japan, and several countries. By the end of this embargo, the cost of oil prices, particularly in the US. This was called as first oil shock; later the 1979 oil crisis was termed as second oil shock. The six months of the oil embargo remade the international economy. The long-term effect of the oil embargo was the changes made in the policy of energy consumption, exploration of alternative resources for various activities especially the infrastructure sector.

Since the mid-19th century the construction activities across the globe saw an increasing trend where all the natural resources were made use of for these purposes. Year after year there was a drastic reduction in the forest cover and an increase in the urban area. At present almost up to 40% of the land use in many of the developing countries is of urban-type and this is to gradually lead to 60 % in the next two decades. The availability of landfill site has also depleted due to increase in population density (Shell Bitumen 2003). But, it was in the early 1990s the effect of exponential infrastructure growth was felt in the form of severe global warming with the degradation in the environment. In the year 2008 US National Research Council stated that the human-induced warming of the global climate would be significant in the 21st century and will continue beyond.

Later, in the year 1997, the Kyoto protocol was signed by the 192 nations across the globe and came into effect from February 1998. This leads to a drastic change in the construction industry and enforced them to look into recycling techniques to reduce the effect of development on climate and environmental change.

Currently, most of the roads in western countries have adopted the concept of recycling of asphalt roads. However, very limited roads stretch across India has adopted the recycling technique. Hence, some of the RAP materials are reaching the dump yard or landfill site. In recent years, more emphasis is laid on the use of recycled materials in road construction by government agencies (MoRT&H 2014). This has resulted in increased scope for the highway contractors/ industry regarding the recycling aspects of road technology.

2.2.1 Characteristics of RAP Binder

Typically the composition of RAP obtained from milling operation will have a 5% binder and 95% aggregates (McDaniel et al. 2013). The basic characteristics of RAP material that would greatly influence the properties and performance of the recycled mixtures are the increased stiffness of its binder. The recovered RAP binder has high viscosity and low penetration values than virgin binders due to the effect of the ageing process (Al-Qadi et al. 2007). The physical effects of ageing are caused by chemical changes within the binder. The changes in these rheological properties of the binder are attributed to the loss of volatile oils present in it. This may be due to volatization process when exposed to hot and humid temperature during various stages of construction and service. Asphalt binder exhibits aging in two stages, namely, short term aging and long term aging (Al-Qadi et al. 2009; Kandhal and Mallick 1997).

The aged binder properties are dependent on the service life of the pavement, category of road, air voids content and the extent of damage on the original pavement. Higher the severity of these conditions, changes in the property of asphalt binder increases (Hassan 2010). RAP binders are also prone to accelerated aging in stockpile as it is exposed to air, resulting in oxidation (McMillan, C. and Palsat 1985). If the aged binder is too stiff the RAP incorporated HMA mixtures may not perform better (Kennedy et al. 1998).

2.3 USAGE OF RAP AGGREGATES IN BASE AND SUB BASE LAYERS

Stabilization of any layer in the highway structure is an age-old technique. Stabilization is a process of improving the quality of anything that is intended to serve its purpose. Due to the non-availability of quality raw materials, economic consideration and to make use of locally available materials stabilization has been appreciated the time and again. Many materials as a byproduct of industrial manufacturing have been utilized to replace a significant amount of material by weight of the overall mixture. The use of RAP in the low and intermediate layers of highway pavement has been practiced for many decades. Due to the lack or no availability of proper design standards for usage in a binder and wearing courses, this very valuable material that contains aggregates and bituminous binder was dumped in lower layers of pavements at the as a part of unbound granular layers. However, the usage of RAP in these layers was carried out for a curtained period of time as it reduced the problems of the landfill and other associated environmental issues (Copeland 2010).

Several investigations conducted on the use of RAP in intermediate layers of the pavement yielded favorable results for its usage. The RAP material may be used directly into the base layer. Otherwise, the material can be treated with other additives to achieve better performance. The use of 100% RAP for the construction of base layers is also not very effective due to its significant rate dependency and high creep and deformation (Dong and Huang 2014). But several studies have indicated a better performance in base layers can be achieved by treating the RAP with chemical-based additives such as lime, cement (Hoyos et al. 2011; Taha et al. 2002), fly ash (Hui et al. 2007; Taha et al. 2002) etc., and virgin aggregates. The layers can be further strengthened by providing confinement to the layers using geomembranes (Han et al. 2011; Suku, Lekshmi, Prabhu, Sudheer S and Sivakumar Babu 2017; Thakur et al. 2012). Various properties such as modulus of resilience (MR), California Bearing Ratio (CBR) and unconfined compressive strength (UCS), permanent deformation and creep deformation of the base layer with the stabilized RAP material were investigated. The results provided indicated a better performance in all these parameters of evaluation.

However, considering the valuable bituminous binder material in RAP, the use of the same cannot be justified for its optimum utility by incorporating it in lower and intermediate layers of pavement. Thus, the scope for its use as a part of the surface course was tried and evaluated for its performance over time and for different field conditions.

2.4 BEHAVIORAL PROPERTIES OF RAP IN HMA MIXTURES

2.4.1 Blending of Reclaimed Asphalt Pavement Material

While several research studies have reported the use of RAP and its performance in new asphalt mixtures, none have emphasized the study on how much old asphalt is actually blended with new mixtures during the mixing process (Huang et al. 2005a; McDaniel et al. 2000). The studies conducted on a blended mixture consisting of 20% RAP revealed that only a portion of the aged asphalt participated in the remixing process while the other portions formed a stiff coating around the RAP aggregates and RAP behaved as a composite black rock (Carpenter 1980). (Carpenter 1980) Studies carried out revealed that the materials actually took some time before the actual blending process. It was determined that the blending was somewhere between full blending and no blending.

Researchers at NCHRP carried out various investigations to study the blending interaction between the aged and virgin asphalt binders in various blends. The content of RAP material was also varied from 10 to 40 %. Test results revealed blends with lower RAP content i.e., 10% there was no significant blending that took place in all the blends. However, the authors also suggested that as the RAP percentage was higher i.e., 40% there was an acceptable amount of blending but a complete blending was not observed.

(Stephens et al. 2001) carried out studies on RAP incorporated HMA mixes to evaluate the amount of blending in the mixtures. The RAP materials were heated before adding to the HMA mix. The results indicated that blending took place between the virgin and aged materials. This was justified through the load sustained by the samples prepared using RAP material that was higher compared to that of the sample prepared without using RAP. However, it also suggested that as the preheating time of the sample increases the strength of the mix greatly increases. This indicates that with optimum preheating time proper bonding takes place, resulting in better strength and endurance of pavement. (Oliver 2001) investigated the blending process in HMA mixes with RAP materials in it. The compacted specimens were tested for various properties and found that the mixture with RAP exhibited better strength than that of virgin mixes without RAP.

The blending of the aged asphalt binder with the virgin asphalt binder was studied by conducting laboratory investigations by (Huang et al. 2005a). The study carried out tends to focus on the behavior of asphalt mixture blending due to the pure mechanical mixing process. The RAP materials were mixed with virgin materials and found a reduction in binder content. The diffusion of fresh binder in the aged binder allows rejuvenating of aged binder (Kandhal and Mallick 1997). This, in turn, would effectively contribute to the coating of RAP based

HMA mixtures. However, the results obtained by the mechanical blending of RAP and virgin aggregates ensures about 40% blending at the outer layers of the aggregates.

Despite the similarities between producing virgin asphalt mixtures and RAP asphalt mixtures, there are challenges for maximizing RAP usage. Generally the guidelines are based on the assumption that complete blending occurs between virgin and new mixtures, but later it was understood that the amount of blending that occurs was somewhere between complete blending and no blending; however, there is no actual method available to accurately determine the amount of blending that occurs (Watson et al. 2008). The process of blending of RAP is shown in figure 2.1

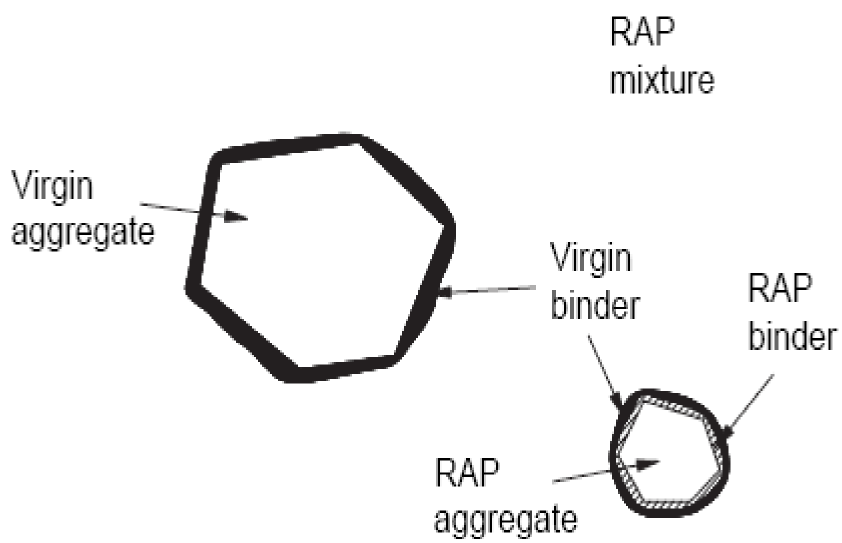


Figure 2.1 Blending process of RAP in HMA

2.5 DESIGN OF RAP MIXTURES

Generally, the asphalt mixtures prepared with RAP aggregates should meet the specified requirements of the mixtures prepared with virgin/ conventional Hot Mix Asphalt materials. The process of mix design incorporating RAP materials involves proper selection of aggregate materials, selecting required gradation, type of binder and its content, mixing procedure with consideration to the temperature and duration of conditioning; and finally the compaction method similar to the conventional mix design. Once the characterization of RAP has arrived, it can be blended with fresh aggregates to meet the gradation requirements. Since there are no specified readily available guidelines in India due to the lack of convincing research data, the judicious use of RAP is a way of sustainable approaches in highway construction practices.

The amount of RAP materials to be used in the HMA mixtures varied depending on the source of RAP material, Source of Virgin materials and the amount of blending that took place between these two mixtures. However, the design guidelines were developed and recommended by the super pave TM expert's task group (Brown et al. 1997).

This states the design of RAP based HMA mixtures in a three-tier system. For usage of RAP in HMA mixtures, up to 15 % did not require any changes to be made in the virgin binder grade. If the usage exceeds 15 % and is within 25 %, a virgin binder grade can be reduced by one grade to account for the stiffness of aged asphalt. If the amount of RAP material usage exceeded 25% use of blending charts is recommended (Brown et al. 1997).

Since the RAP materials consist of 95% of aggregates, gradation is the most important factor that should be considered in the mixture design. To satisfy the gradation, the selected blend of aggregates should comply with the control points for the type of mix considered. The final gradation of asphalt mixtures with varying percentages of RAP should meet the volumetric requirements such as VMA, air voids, etc., The amount of virgin asphalt binder to be added in the RAP based HMA mixture is carefully determined by adopting any of the standard mix design procedures such as Marshall Mix design and more reliable Superpave mix Design before arriving the optimum binder content.

The properties of RAP aggregates are on par with that of the conventionally used aggregates with respect to strength parameters like crushing, abrasion, water absorption or specific gravity. The materials that have not undergone damage due to heavily trafficked loads are as good as new material because all the road aggregates are the fractionated units of rocks of usually igneous origin. Since the life of the aggregates does not have any expiry date, it remains a very good road building material unless damaged by an external source. As mentioned before, the amount of RAP usage in the new asphalt mixtures varies depending on the various volumetric and performance parameters. Various researchers have incorporated RAP as low as 10% (Al-Qadi et al. 2007; Carpenter 1980; Huang et al. 2005a; McDaniel et al. 2000) to as high as 100% (Zaumanis et al. 2014). Most of the reasons for not utilizing higher content of RAP were due to the development of stiffness in the asphalt mixes. This was found to be because of the higher content of stiff binders present in the RAP material (Watson et al. 2008). The highway contractors in India are not ready to use this technology due to lack of confidence and guidance.

RAP materials have found to comply with respect to the mix design in all types of asphalt mixtures that have been in regular construction practices. The important aspect of mix design is to meet the volumetric requirements.

2.6 PERFORMANCE OF RAP MIXTURES

Various researchers have carried out laboratory investigations and field performance studies to arrive at the optimum utilization of RAP and its associated performances. The result reported all over the globe are widely different and no clear outcomes are drawn from the research projects. Few researchers claim to have observed better performance (Aravind and Das 2007; Copeland 2010; Huang et al. 2010; Kandhal and Mallick 1997b; McDaniel et al. 2000; Wiser 2011). Contrary to this some researchers have reported performance inferior to the conventional mixtures (Huang et al. 2005, 2007; Sargious and Mushule 1991).

Aged binders obtained from RAP materials are found to exhibit higher viscosity with low penetration values compared to that of the virgin binders (Carpenter 2007). This may have happened due to the short term and long-term ageing process that occurs throughout the life of the pavement. So more focus should be on how further ageing during the production of the RAP mix can affect the overall performance. Several studies have investigated the use of RAP of up to 50%. Usually, bituminous mixes with 25% RAP are considered to be high RAP mixtures (Copeland 2011).

2.6.1 Moisture Susceptibility of RAP mixtures

The presence of water on the surface of the asphalt mixtures is found to be a major reason for the failure of pavement performance as it leads to stripping of binder from the aggregate surface. This may be due to the loss of adhesion between aggregate and asphalt binder. This loss of adhesion can be studied by several methods such as static immersion test, boiling test, and Indirect Tensile Strength Test (Punith 2004).

Many researchers have carried out indirect tensile strength tests to evaluate the moisture susceptibility of bituminous mixtures. Usually, the test is conducted on a cylindrical sample of a marshal stability test set up. The assessment of the moisture susceptibility of mixtures is very important as it gives a direct indication of the durability of the finished bituminous product. The viscosity of the bituminous binder plays a very important role in provoking the aggregate to strip away. Usually, the binder with higher viscosity tends to hold the aggregate together than compared to the bituminous mixtures prepared with a binder of low viscosity (Khosla et al. 1992). This is because of the binder with high viscosity resists dislocation of aggregates due to higher shear strength by exhibiting better retention in bituminous mixtures (Xiao et al. 2007). On the other hand, the aggregates should not be porous so that it does not absorb water, but the aggregates should be good enough to absorb and hold bitumen when it is formed into a bituminous mixture. Therefore, the bonding in the bituminous mixtures is greatly influenced by the kind of materials used.

The loss in adhesion of material in the mix can lead to premature failure of pavements. Hence this criterion is of great importance as a part of the performance test in bituminous mixtures. As discussed earlier, every year the production of RAP as a part of road repairs and maintenance is increasing annually. This contains highly resourceful and valuable material such as bitumen and high-quality aggregates. Previous performance has indicated a reduced requirement of binder content and increased strength and stiffness in the overall mixture.

Initial studies revealed that the use of RAP in Hot Mix Asphalt mixtures can be more susceptible to moisture-induced damage as the virgin binder does not completely blend with the aged asphalt binder (McDaniel et al. 2000). If the blending is minimum, the chances of layered coating of the virgin binder with RAP aggregate are higher. Therefore the presence of water on such sections prevents bonding between binder and aggregate leading to moisture damage (Huang et al. 2005).

Irrespective of the type of asphalt mixtures viz., Dense graded, gap graded mixtures or the open-graded mixtures, utilization of high percentage RAP with neat bitumen reduced the effectiveness of the mix to prevent moisture-induced damage (Brown et al. 2009). On the other hand, the resistance of the modified bituminous mixes with lower content of RAP materials (10% - 20%) also does not provide satisfactory results regarding the resistance to moisture damage. However, improved resistance to moisture damage was observed when modified binders were used to prepare the asphalt mixtures containing higher percentages of RAP materials (Xiao and Amirkhanian 2010). The addition of rubber to the bituminous binder up to 15% in the mixture containing a higher content of RAP will significantly improve the mixtures‟ ability to resist moisture damage. This was attributed to the better adhesion between the particles of aggregate, rubber and binder.

The application of using rejuvenators in asphalt mixtures containing RAP material has enhanced the property of the recycled mix to perform better and achieve the utilization of higher RAP contents in the mix. This has proved to improve the property of the mixture to resist moisture damage and perform satisfactorily for the design life (Zaumanis et al. 2014). Several studies have indicated utilization of 100% RAP in asphalt mixtures and have claimed that these mixes are on par or better in terms of performance when compared to mixtures prepared with conventional materials of aggregates and a binder (Yu et al. 2014). To add upon the advantages of using RAP without much affecting the moisture damage property many additives such as sylvaroad, etc., are available.

2.6.2 Rutting Properties of RAP Mixtures

The continuous movement of wheel loads on the wheel path leads to an accumulation of the very small amount of unrecoverable strain resulting in permanent deformation over a period of time. Factors such as aggregate gradation, binder type, surface temperature, and additives used influence the rutting resistance of the bituminous mixtures. Some of the standard test methods carried out to determine the rutting resistance of asphalt mixtures includes static creep test, dynamic creep, immersion wheel tracking test, simple shear, and wheel track tests.

Generally, mixes with higher coarser fraction of aggregates exhibits better rutting performance compared to the mixtures with a lesser coarse fraction of aggregates with the mix being densely packed. This is because of the fact that coarser aggregate can resist more load than the finer particles. When the mix is of coarser fraction it forms an aggregate skeleton so that there forms a stone on stone structure. These Rutting properties of RAP mixtures with reference to control Hot Mix Asphalt mixes with conventional virgin aggregates and asphalt binder was evaluated by various authors and by far the resistance increased with the increase of RAP content in the mix. Rut depths of 50% RAP mixtures measured in the laboratory were within acceptable limits at less than

5mm. (Brown, E Ray, Doyle et al. 2011). Several tests reported no signs of any kind of distress during the initial one year and a rut depth of about 4mm(Brown et al. 2009).

Dense graded asphalt mixes and gap graded asphalt mixes with varying percentages of RAP materials were subjected to rutting by various researchers. It was observed that the gap graded asphalt mixes exhibited higher rutting resistance than the dense-graded mixtures. Further, the addition of RAP increased the resistance of the mixture to rutting (Watson et al. 2008).

The Rejuvenated RAP based HMA mixes were tested for its resistance to permanent deformation in both the dense and Gap graded asphalt mixes. Although their resistances were found to be lower than the RAP mixes, the results were much superior to conventional control HMA mixtures.

2.6.3 Fatigue Properties of RAP Mixtures

The Fatigue life of the asphalt mix is its ability to withstand the repeated load application without cracking. It can be determined through the number of cycles resisted by the mix before failure at various stress and strain level. This test may be performed on the asphalt mixes by applying repeated load on the cylindrical specimen on the diametrical axis or by flexural fatigue. The possibility of using RAP in HMA mixtures were initially not accepted stating that the resultant mix may not result in full blending (Al-Qadi et al. 2007; Huang et al. 2005) resulting the material stiffer with low workability and would lead to performance failure like rutting and fatigue damage (Mallick et al. 2010). However, in spite of this, reluctance in accepting the use of high percentage RAP in HMA mixtures, the unavailability of quality aggregates, degradation of the environment due to quarrying, increased cost of bituminous binder has forced the research and development in many industries to prioritize the recycling techniques to save the available natural resources (Copeland 2010; MoRT&H 2014). Resistance to fatigue of RAP based HMA mixes based on a number of cycles to failure were evaluated by various researchers and mixed conclusions was drawn. In the present study RAP incorporated HMA mixes with varying content is reported. Usually, many of the authors reported the fatigue life of the asphalt mixtures using repeated load indirect tensile tests on cylindrical specimens.

Most of the HMA mix with a high percentage of RAP reported a reduction in fatigue life with respect to the number of cycles to failure. This was quite low compared to the resistance exhibited by the control mix (Watson et al. 2008). Most of the authors have concluded that the reduction in fatigue life may be due to the stiffness developed in the aged binder mix.

To counter this problem of reduced fatigue life in RAP based HMA mixes researchers across the globe have developed various chemical additives that enhance the fatigue performance of asphalt mixes. Test results revealed an improvement in the fatigue life of asphalt mixes with the incorporation of various additives. This behavior was the same irrespective of dense or gap graded mixes.

2.7 FATIGUE CHARACTERISTICS

Fatigue failure is one of the major modes of failure in flexible pavement layers as it is subjected to repeated application of loads in the form of moving vehicles. Repeated loading progressively reduces the tensile strength of the mixtures. Fatigue resistance increases as the binder content increases. This repeated application of load is not large enough to cause failure due to a single application. The characteristics of fatigue performance are usually expressed as the relationship between the maximum stress and the number of load repetitions to failure. The failure due to fatigue occurs as a result of the development of internal cracks and progressive growth of cracks under the action of cyclic loadings, which leads to failure of the pavements at stresses smaller than the modulus of rupture of the material sample (Hui et al. 2007; Lee and Barr 2004).

The fatigue failure is influenced by several parameters such as composition, type, and quality of the materials, traffic load intensity and frequency, minimum stress used in load cycle, stress levels, rest period, the waveform of cyclic load, etc. (Naik et al. 1993). Fatigue loading can be classified as a low cycle and high cycle loading. Low cycle loading involves the application of few load cycles at higher stress levels; while high cycle loading involves the application of a large number of load cycles at lower stress levels. Generally, pavements in highways are classified as high cycle loading. Hence, fatigue strength is one of the important parameters to be considered while designing bituminous concrete mixtures for roads. Over the years, fatigue behavior of neat and modified bituminous mixtures has been studied. However, there has been limited research carried out on the fatigue performance of rejuvenated RAP based SMA mixtures.

2.7.1 S-N Curves and Probabilistic Approach

The fatigue behavior of bituminous mixes is most commonly characterized by two important terms; firstly, the Stress Ratio (SR), i.e. the ratio of stress applied to the modulus of rupture of bituminous mixtures and secondly the Fatigue Life (N), i.e. the number of cycles to failure. Most of the studies on the fatigue behavior of bituminous mixture are intended to arrive at a relationship between the stress ratio and fatigue life. This relationship is commonly plotted on the so-called S-N curve (or Wohler curve). The S–N curve in which S‟ denotes stress level and N‟ denotes the fatigue life; represents a plot between with linear S versus a log N scale and is the most commonly used in engineering terms. The use of S–N curves for representation of the fatigue data gives a clear idea of the distribution of the fatigue life under different stress ratios. It is also generally accepted that the non-dimensional zed S-N curve is independent of the shape of the specimen, mechanical properties of the mix, conditioning of samples, etc., A typical S-N curve is presented in Fig.2.4

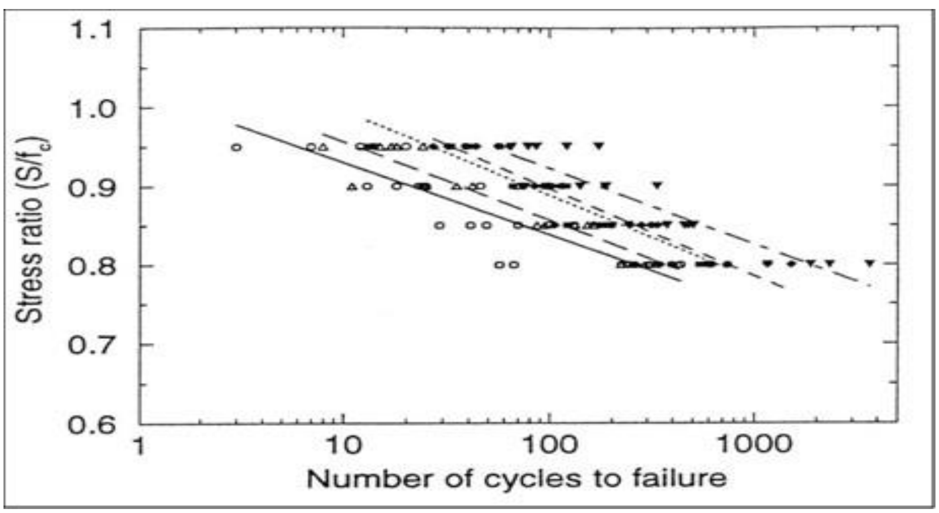


Fig.2.2 Typical S-N curve

(Source:http://www.columbia.edu/cu/civileng/meyer/research/fati1.html)

2.8 UTILIZATION OF RAP IN SMA MIXTURES

Stone Matrix Asphalt (SMA) is a gap graded bituminous mixtures that offer better strength and performance compared to other bituminous mixtures used in the construction of highways. Several studies have reported a minimal rutting across the stretches constructed using SMA mixtures. Since SMA is a gap graded mix, it has certain specifications as per IRC SP 79: 2008 to be fulfilled before it has to be used in the field. (Brown et al. 1997) Proposed methods to determine voids present in coarse aggregates (VCA) in SMA Mix. Five different methods were adopted to determine the VCA and check which method performed best and that can be practically adopted. The results indicated that (SGC) Superpave gyratory compactor and dry rodded methods produced better results and were recommended.

The functional and structural characteristics of the SMA mixes can be examined by constructing the surface course and through conducting various tests (Brown et al. 1997). The data obtained from the study indicated SMA mixes performed well in structural and functional assessment by meeting the requirements. They also exhibited durability and resistance to rutting resulting in the long-lasting pavement.

Stone Matrix Asphalt (SMA) mix design developed for the NCHRP 9-8 project, with Nominal Maximum Aggregate Size other than 19 mm and properties of SMA mixes were compared by considering Marshall Properties, wheel tracking tests, and permeability (Lynn et al. 1999). The test data indicated the NCHRP 9-8 mix design for SMA mixes exhibited more resistance to deformation and found to be less permeable compared to conventional SMA with NMAS 19 mm.

Since certain sizes of materials are missing in the SMA mixes, there is a very high possibility of the mastic material draining down from the mass of the mixture during high working temperatures. In order to control these several precautions needs to be taken into consideration such as the use of any additives. Research conducted on the gap graded mix reported that drain down can be controlled in SMA mixes by using shredded waste plastics (Sarang et al. 2014), the SMA mixes were prepared by varying bitumen content from 5.0 to 7.0% and shredded waste plastics were added at various proportions viz, 0,4,8,12 and 16% weight of the binder. Variations in the Marshall properties, drain down, tensile strength and moisture damage were evaluated and it was found that the optimum dosage of shredded WP was 8%, which resulted in increase in the indirect tensile strength of 37% and also less drain down compared to conventional SMA mixes, therefore shredded WP is efficient in preventing the drain down in SMA mixes which proves to be cost savings rather than using other additives.

Apart from waste plastics, researchers have made an attempt to evaluate the use of natural fibers (Colares Do Vale et al. 2014), fibers extracted from refrigerator doors (FERD) and waste plastic in SMA mixes (Ranadive et al. 2018). Experimental work included the Marshall stability test, drain down, tensile strength ratio by varying the plastic content (0, 4,6, 8,10 and 12% by weight of binder) and fiber lengths (2, 4, 6 and 8mm) For both SMA mixes and Bituminous concrete mixes. Results showed that drain down reduces with increased length of fiber and an increase in indirect tensile strength due to the addition of waste plastics and fibers.

As the road construction industry is growing in manifolds, requirement for new materials in road construction is increasing day by day. Researchers have proved and recommended the use of alternative materials obtained as by-products from various industries. Laboratory performance characteristics of SMA mixes by utilizing electric arc furnace (EAF), steel slag and copper mine tailings (CMT) were reported (Oluwasola et al. 2016). Various tests like Resilient modulus, dynamic creep test, and the rutting test was performed on conventional and recycled SMA mixes The results indicated moisture susceptibility of mixes were within permissible limits.

Apart from industrial wastes, several kinds of marginal material are produced after the service life of the manufactured material. One such material that has been tried and tested in asphalt mixtures is the use of waste tire rubber. The feasibility of using waste tire and carpet fibers in SMA mixes was studied(Putman and Amirkhanian 2004).

Considering the performance tests, results indicated that no significant changes in the performance characteristics of the mixes containing waste tire and carpet fibers, an increase in the toughness were observed in the mixes containing waste tire and carpet fibers than cellulose fibers.

The effects of gradation, binder content and additives have been investigated by using various techniques. One such study was carried out on SMA mixes to evaluate the effect of gradation, binder content, WMA additives such as Zycosoil and Sasobit. Moisture damage was determined by using Response Surface Methodology (RSM) (Khedmati et al. 2017). The results indicated an increase in tensile strength ratio due to the influence of Sasobit and gradation.

As there is a regular production of RAP material during the maintenance and repair work in roads, these materials are stockpiled at a landfill site and used further in many ways as discussed before. Few researchers have investigated the use of RAP materials in SMA mixtures and reported mixed responses regarding the performance of the same. Few scholars evaluated the effect of RAP materials on the performance of SMA mixes, for the study four aggregate sources with four varying RAP content. Viz. 0, 10, 20, and 30% were used for the evaluation of tensile strength, moisture susceptibility, rutting resistance, fatigue resistance and cracking potential of recycled mixes. Results showed as the RAP content increased the tensile strength also increased and up to 20% RAP content there was no significant effect on the fatigue life (Watson et al. 2008). Since the SMA mixtures are known to exhibit better resistance to rutting, fatigue and cracking, the effect of the same with varying contents of RAP is investigated by conducting time flow test and semi-circular bending test (Singh et al. 2018). The test results showed that the mixes containing RAP had better performance resulting in higher values of Indirect Tensile Strength and fracture resistance when compared to mixes without RAP. Whereas tests result from (Shu et al. 2008) by incorporating 0 to 30 % RAP in SMA mixes indicated a higher indirect tensile strength value, but a decreasing trend was observed with respect to the crack resistance of the mixes with increase in RAP content.

The suitability of using Reclaimed Geomembrane Modified Binder (RGMB) for use in bituminous mixtures was also reported. The test evaluated the impact of using RGMB as binder in SMA mixes (García-Travé et al. 2018). Experimental work was carried out by adopting various tests such as moisture susceptibility, rutting and drain down tests and results indicated an increased resistance and less drain down of the SMA mixes by using the RGMB.

The performance of SMA mixes prepared with and without RAP along with the recycling agents provides a better understanding on the effectiveness of recycling agents. Determination of Marshall Properties, rheological parameters of the mixes, indirect tensile strength, rutting and resilient modulus of the mix will assist in evaluating the performance.

2.9 SUMMARY

From the detailed literature review, it is observed that the use of RAP material as a replacement to conventional materials in road construction is gaining importance. Thereby, indicating a need for more sustainable approaches in road construction with respect to economy and ecology. This is mainly because of various benefits provided by the use of RAP material in terms of strength and performance. If RAP based asphalt mixtures are designed properly, greater strength and better durability can be attained compared to conventional mixtures. These tests and performance evaluations were carried out on various types of bituminous mixtures and yielded mixed responses. However, limited investigations have been carried out to evaluate the performance of higher percentage RAP in SMA mixes. Very few studies have been carried out on the effectiveness of rejuvenator in RAP based SMA mixes with reference to strength, durability and fatigue performance. The present research is focused to investigate the properties of RAP based and rejuvenated RAP based SMA mixes under laboratory conditions with an aim of contribution to sustainability aspects.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 INTRODUCTION

The selection of materials for production of SMA mixes is one of the important steps in material characterization. This chapter provides a detailed description of various steps involved in arriving at the use of materials, mix design process for control and rejuvenated RAP based SMA mixes with different dosages of rejuvenators and at varying percentages of RAP materials. The materials used, preliminary mix design, preparation of specimens and procedures adopted for evaluation of SMA mixes in terms of volumetric properties, mechanical properties, resistance to moisture susceptibility, resistance to fatigue and rutting are detailed in this chapter. Sequence of the work carried out is presented in figure 3.1

3.2 INGREDIENT MATERIALS

The materials used for the production of the bituminous concrete mix should satisfy the basic requirements as per the standard codes of practice. A better understanding of the ingredients‟ basic properties is a vital aspect of the mix design procedure, strength behavior, durability and performance of the bituminous concrete mix. The basic properties of various materials used for the preparation of control and rejuvenated RAP based SMA mixes are discussed in the subsequent sections.

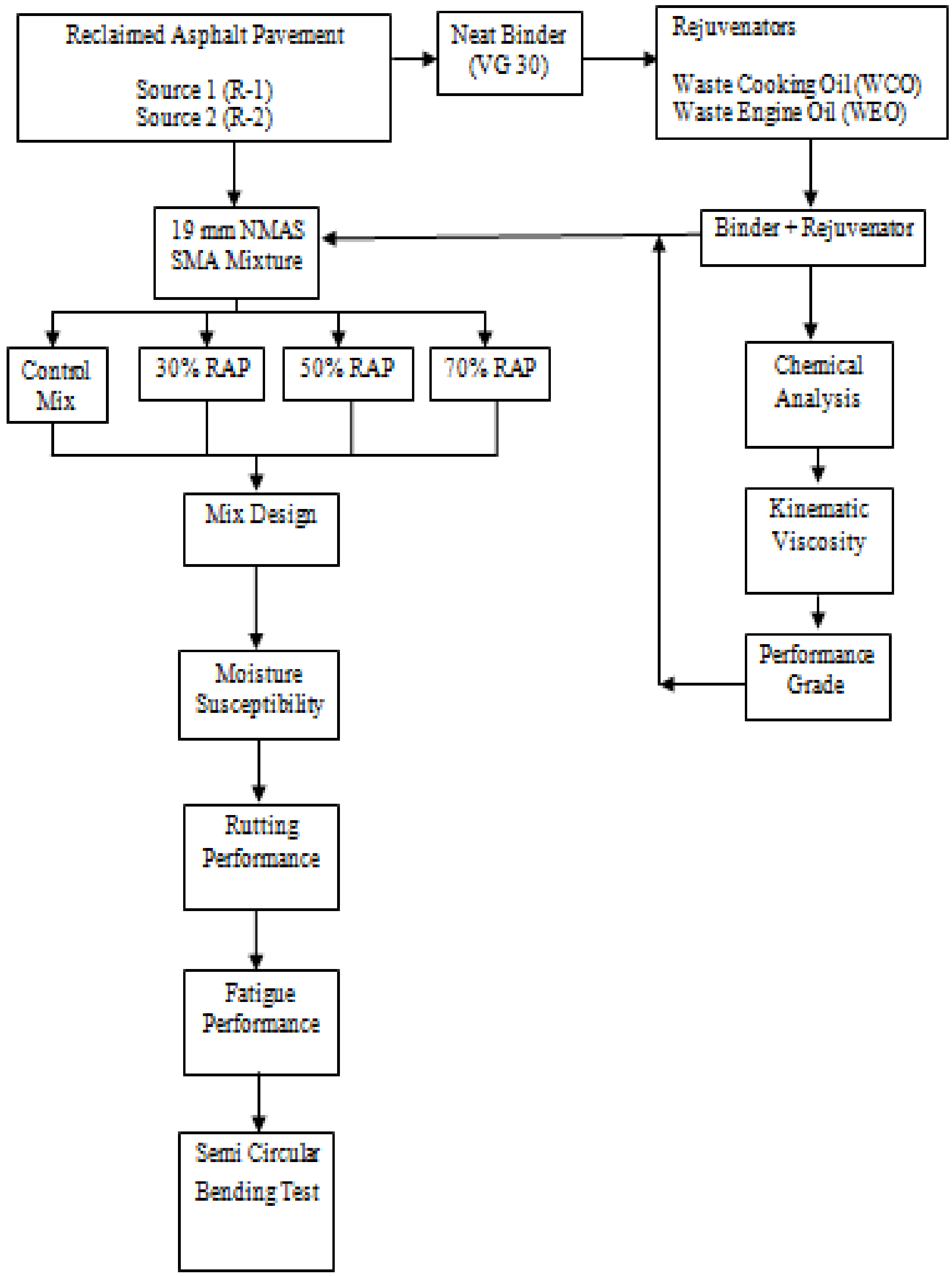


Figure 3.1 Experimental Investigation

3.2.1 Aggregates

Aggregates are used in the components of pavement layers such as base, sub-base and surface courses. Aggregates normally represent combination of distinct particles i.e., gravel, crushed stone, etc., gathered into an aggregate mass. Since the kind of material used is not cohesive in nature. These are individual particles brought together to form a mass. Typically in asphalt pavements aggregates constitute 94% by weight of the paving mix indicating its importance. In SMA mixes, the quality of aggregates plays a vital role to achieve strength and durability. Hence the aggregates used should be durable, exhibit fair resistance to the action of abrasion and impact caused by moving vehicular loads. Aggregates should be clean, properly graded with low porosity, rough-textured and should be hydrophobic.

In the present study, RAP material was obtained from two different sources (R-1 and R-2) that were milled from in-service pavements in and around the city of Bengaluru, India. The virgin material for the current study was procured from a quarry near Bidadi, Bangalore city, Karnataka. The physical properties of these aggregates were found to satisfactorily comply with the recommended values as per IRC guidelines for SMA mixes and are tabulated in table 3.1. The tests were conducted in accordance with IS 2383. The size of RAP aggregates obtained from a local distressed Bituminous Concrete pavement in Bangalore city may not fully suit the gradation of SMA. Therefore it was partly replaced based on the availability of aggregates. The physical properties of R-1(Source 1) and R-2 (Source 2) aggregates are determined and presented in table 3.1. The gradation adopted for the control mix was of 19mm Nominal Maximum Aggregate Size.

Table 3.1Physical properties of Conventional and RAP Mineral aggregates

Sl. No	Properties	Virgin Aggregates	R-1 Aggregates	R-2 Aggregates	Requirements as per IRC: SP 79-2008 specifications
1	Impact value, AIV (%)	17.10	13.40	22.5	Max 18
2	Aggregate Crushing Value (%)	24.3	17.3	20.5	Max 30
2	Los Angeles Abrasion value, LAV (%)	18.5	15.2	21.5	Max 25
3	Water Absorption Value(%)	0.48	0.12	0.43	Max 2
4	Specific Gravity test	2.58	2.68	2.66	-
		2.65	2.63	2.63	-
5	Combined Index, CI (%)	21.89	20.87		Max 30

Table 3.2: Gradation of aggregates for Stone Mastic Asphalt mix as per IRC: SP 79-2008

IS Sieve size (mm)	Passing (%)
26.5	100
19	90-100
13.2	45-70
9.5	25-60
4.75	20-28
2.36	16-24
1.18	13-21
0.60	12-18
0.30	10-20
0.075	8-12

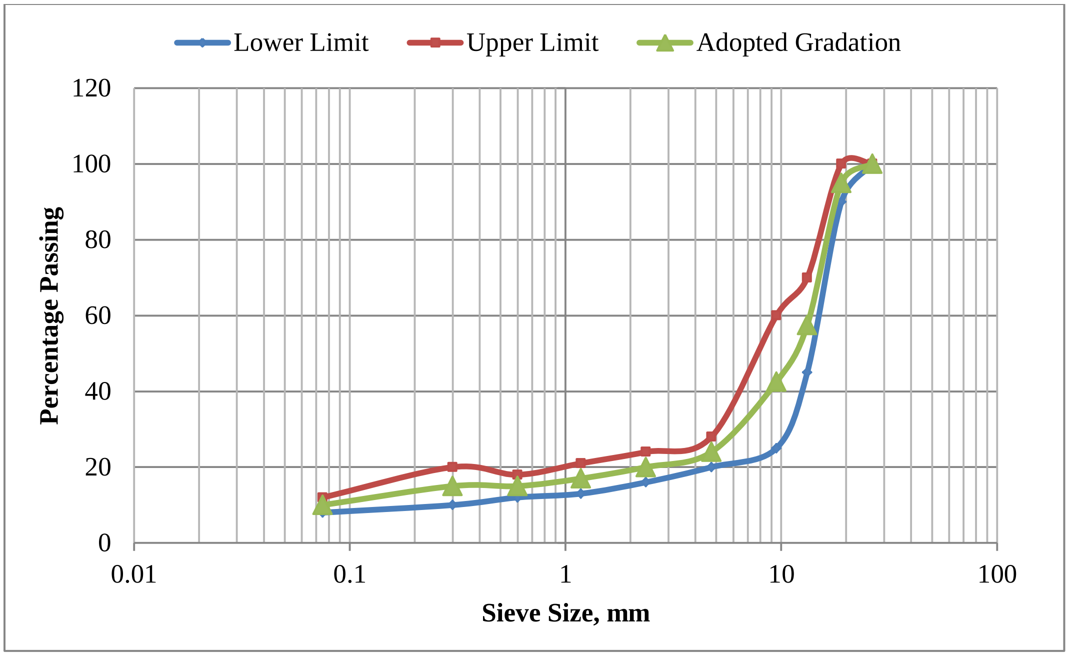


Figure 3.2 Gradation curve of the SMA binder course as per IRC SP: 79-2008

3.2.2 Bituminous Binder

A bituminous mix is made of two materials where bitumen forms to be one part and aggregate the other. Bitumen acts like a glue that binds and holds the aggregate mass. The proportioning of aggregates and bitumen is very important to arrive at a bituminous mix so that the highways paved with these mixes should satisfactorily serve throughout the design life. In this study, the aged bitumen obtained from two different sources of RAP and a conventional neat bituminous binder of VG 30 grade is used. The bitumen used in the study was procured from Hincol, Mangalore, and Karnataka. Bitumen was tested for different properties as per IS codes and found to be satisfying IS 73 (2013) specifications. The properties of tested virgin and aged bitumen from R-1 and R-2 materials are tabulated in Tables 3.3.

Table 3.3 Properties of Virgin Bitumen (VG 30) and RAP Bitumen

Property Tested	Test Method	Results Obtained			IS 73 (2013) Requirements for VG-30 Bitumen
		VG 30	R-1 Binder	R- 2 Binder	
Penetration at 25°C, 0.1 mm, 100g, 5s	IS 1203	60	49	43	45 Minimum
Softening point, (R&B), °C	IS 1205	58.1	60.2	70.5	47 Minimum
Flash Point, °C	IS 1209	280	--	--	>220
Ductility at 25°C (5 cm /minute pull), cm	IS 1208	85	65	61	75 Minimum
Specific Gravity	IS 1202	1.01	1.07	1.09	0.99 Minimum
Kinematic Viscosity at 135°C, cSt	IS 1206 Part 3	541.2	625	825	350 Minimum

3.2.3 Fillers

The mineral filler used in the present study was crushed stone dust from the same aggregate source and the gradation is tabulated in table 3.4 as per IRC: SP:79-2008.

Table 3.4 Gradation Requirement for Mineral Filler

IS Sieve (µ)	Cumulative % by weight of total aggregate passing
600	100
300	95-100
75	85-100

3.2.4 Stabilizing Additives

Due to the problem of the drain down associated with SMA mixtures, a suitable stabilizing additive is generally used. Cellulose, mineral, and polymer fibers are typically suggested in this regard by different countries and institutions. IRC recommends using cellulose fiber in pelletized form. In the present study, cellulose fibers of 0.3% by weight of the mix were added in SMA mixes confirming to recommendations as per IRC: SP: 79-2008.

3.2.5 Rejuvenators

Rejuvenators are the external additives added to the mixture which tends to restore original properties like flexibility, cohesion, ductility and bonding characteristics of aged (oxidized) asphalt binders. This is simply achieved by the ability of rejuvenators to restore the original asphaltenes to the maltenes ratio. The rejuvenating materials usually possess a larger proportion of low viscosity maltenes to help in restoring the balance between asphaltenes and maltenes in RAP binder that will be altered during the process of aging throughout its service life. The rejuvenators should rapidly diffuse into RAP binder and soften it to produce a workable mix so that it can be easily paved and compacted to the required density. The major part of diffusion should take place even before the vehicles are allowed to move over the finished surface to avoid reduction in friction and increased susceptibility to rutting.

In long term, rejuvenators should reconstitute the chemical and physical properties of aged asphalt binder and should aid in maintaining stability for another service period. The binder rheology has to be altered to reduce fatigue and low-temperature cracking without over softening the binder leading to rutting issues. The two types of rejuvenators used in the present study are discussed further.

3.2.5a Waste Cooking Oil (WCO)

Waste cooking oil is derived from edible oils used for frying any foodstuffs. This used oil gets spoiled or rancid after using a couple of times and it should not be used for cooking or frying any more as it may lead to many health issues. But it still has a lot of energy that can be recycled for various purposes. Millions of liters of cooking oils are generated every day. Usually, the cooking oil such as sunflower, palm or soya oil can be recycled. The product used for this study was used Sunflower cooking oil from a local source and the sample of the same is shown in figure 3.3a.

(a)

(b)

Figure 3.3 Rejuvenators samples used in the present study
(a) Waste Cooking Oil (b) Waste Engine Oil

3.2.5 b Waste Engine Oil (WEO)

Waste Engine Oil is synthetic based or petroleum-based used oil. This oil upon usage gets contaminated physically or chemically and renders the material inappropriate for further intended usage. Through several studies, these used engine oils have found to act as rejuvenators for aged bituminous binders while using higher percentages of RAP materials. Waste engine oil was procured from a local source in Bangalore city which is petroleum-based oil. The sample of the same is shown in figure 3.3 b.

3.3 TESTS CONDUCTED

3.3.1 Extraction and recovery of binder

The RAP material consists of different sizes of aggregates coated with binder that has aged according to the rate of oxidation process and exposure to usage through moving vehicular traffic. The RAP binder cannot be directly used to produce new bituminous mixtures. Thus, properties of RAP material should be evaluated to assess the potential of aggregates and binders in developing new mixtures. Hence, the material such as aggregates and binders should be separated and tested for its quality. This separation of bitumen from the RAP aggregates is achieved by adopting any standard recommended technique; in the present study centrifuge extractor as shown in figure 3.4, was used to extract bituminous binder as per ASTM D 2172. Benzene was used as a solvent in centrifuge extraction process. The extracted material contains bitumen and benzene. The bitumen is further separated by Abson recovery apparatus. The amount of bitumen in R-1 and R-2 was found to be 3.7 % and 4.0 % respectively.

Figure 3.4 Binder recovery through Centrifuge Extractor.

3.3.2 Viscosity test on binder

Viscosity test was carried out on virgin binder, RTFO aged binder, RAP and rejuvenated binder as per ASTM D4402 using the Brookfield Rotational Viscometer apparatus shown in figure 3.5. This test was conducted to determine the high-temperature rheological properties related to workability of asphalt mixtures at 135^0C. A known quantity of binder sample is heated to a temperature of 75 to 100^0C and allowed to settle at room temperature. After the sample settles, it is transferred to a thermos container of a known volume and allowed to settle. As the sample attains the test temperature, the spindle is immersed in the thermostat container to test the resistance offered by bitumen sample to rotation. This also provides an insight into the measure of consistency asphalt binders.

Figure 3.5 Brookfield Rotational Viscometer

The test temperature of 135^0C (kinematic viscosity) was maintained throughout the experiment. The spindle rotates at the required RPM, torque is generated and viscosity is measured. This test is conducted on samples of neat binder, short term Rolling Thin Film aged binder and aged RAP binder from two different sources R-1 and R-2. Further viscosities of RAP binders with two different types of rejuvenators namely Waste Cooking Oil (WCO) and Waste Engine Oil (WEO) with varying dosages were tested.

3.3.3 Rheology of Aged and Virgin Binder

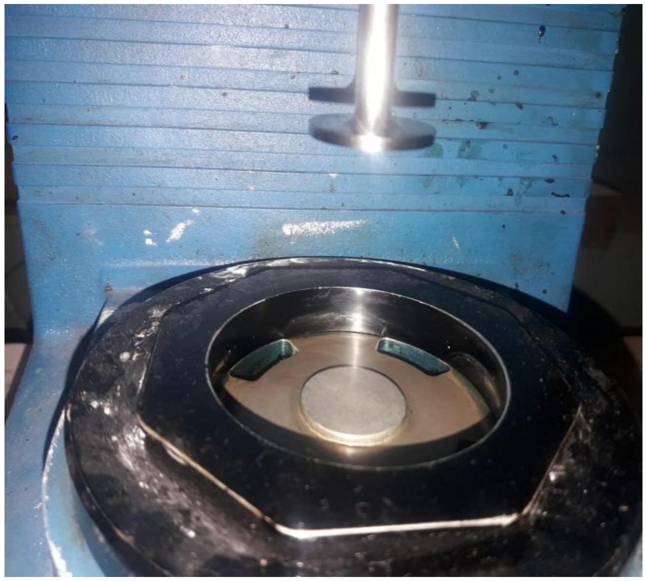
Dynamic Shear Rheometer (DSR) apparatus as shown in Figure 3.6 was used for determining the high temperature and intermediate temperature properties using 25 and 8 mm plates with 1 and 2 mm gap between plates respectively.

The DSR test provides information regarding the applied stress and the resulting strain developed within the material at various temperatures. The relationship between the applied stress and the resulting strain is used to compare complex modulus (G*). The time lag between the applied stresses to the resulting strain is the phase angle (δ). The rutting (G*/sin δ) and fatigue (G* sin δ) parameter are determined considering complex modulus and phase angle. The complex modulus and phase angle parameters can be used to relate the rheological performance of the binder in terms of rutting and fatigue resistance.

The test is conducted according to AASHTO M T315. A computer is connected to the DSR test apparatus and two separate diameter plates of 8 and 25 mm are used for short term aged binder and long term aged binder, respectively. The temperature is set as per the standards considering the rheometer plates. Initially, the temperature has to be controlled to the required test temperature, including all distinctions to be provided. After the constant temperature has attained, the sample is placed in the specified plate and sandwiched and allowed for 10 minutes to initiate the test. The stress, plate gap, oscillation parameters, and the temperature are set. Software intruded to the rheometer to control the stress level and temperature automatically.

The test temperature for fresh and aged binder was varied from 40-82^{O}C and 10-40^{O}C respectively, and for every 6^{O} C interval the phase angle (δ), complex modulus (G*), elastic modulus, viscous modulus, complex viscosity is measured which is system integrated. With the test results obtained, the rutting (G*/sin δ) and fatigue (G* sin δ) parameters are evaluated. The data system automatically reduces the data acquired and evaluation of rheological parameters is easier.

(a)



(b)

Figure 3.6 Dynamic Shear Rheometer (a) DSR Set up (b) Close up view of Shear Surface.

3.3.4 Fourier Transform Infrared Spectroscopy (FTIR) Analysis

The FTIR spectroscopy is used to identify and quantify functional groups in bitumen responsible for aging characteristics. FTIR helps to analyze the chemical composition of the material, which provides an important insight into the nature of the material used as rejuvenator. FTIR represents absorption peaks corresponding to the vibration frequencies between the atomic bonds of compounds in binder. In this study, spectra were collected in the range of 4000 cm-1 to 400 cm -1 and peak values are integrated into their functional groups.

Figure 3.7 Fourier Transform Infrared Spectroscopy set up

3.3.5 Binder Drain Down

Any gap graded mixes which has high mastic content tends to drain down while transporting and placing of mix in the field. Hence, to prevent these problems, design codes recommend use of fibers in the mixture so as to hold the mastic. To check whether drainage of the binder is within acceptable limits, drain down test was conducted as per ASTM D 6390. The test was conducted at OBC on loose mixtures. 1 kg of SMA Mix was allowed to remain in wire basket that was suspended in a thermostatically controlled oven maintained at a temperature of 160°C with a catch plate kept at bottom of the basket. This set up is maintained for an hour before checking the drain down property. The ratio of the mass of aggregate after and before the testing of mixes results in the amount of material drain down in percentage. The results obtained were found to be within the acceptable limits of 0.3 % by weight of total mixture.

3.4 MIX DESIGN METHOD

Marshall Method of mix design as per the specification prescribed by the Asphalt Institute (AI) in Manual Series – 2 (MS – 2) was adopted. This mix design method was developed by Mr. Bruce Marshall of the Mississippi Highway Department in 1939. Later the corps of Engineers conducted studies in 1943 and developed it further as they required a portable apparatus to design and control asphalt mixes for airfield pavements during World War II. This was done mainly to develop a laboratory compaction effort to simulate field density after the construction and two-year traffic densification. In India, the flexible pavements with bituminous surfacing is widely used and designed as per the Marshall specifications (Chandra and Choudhary 2013) (Prakash Giri et al. 2018)(Ranadive et al. 2018). In order to suit the requirements of IRC:SP;70-2008, SMA mixture was compacted with 50 blows on each side using the Marshall rammer.

The Marshall method of mix design as per ASTM D6927-15 was followed to understand the volumetric, flow and strength properties to arrive at the optimum binder content (OBC). The SMA mixture requirement specified by IRC is presented in Table 3.5. Cylindrical specimens of SMA mixes were prepared to evaluate the volumetric properties, Marshall Characteristics, Indirect Tensile (IDT) strength, fatigue behaviour and moisture susceptibility characteristics of SMA mixtures. In order to study the rutting behavior, rectangular slab specimens were prepared.

Table 3.5 SMA Mixture Requirements as per IRC: SP: 79-2008

Mix design parameters	**Requirement**
Air void content, %	4.0
Bitumen content, %	5.8 min.
Cellulose fibers	0.3% min. by weight of total mix
Voids in Mineral Aggregate (VMA), %	17 min.
VCA_{MIX}, %	Less than dry rodded VCA (VCA_{DRC})
Asphalt drain down, % (AASHTO T 305)	0.3 max
Tensile Strength Ratio (%) AASHTO T 283	85 min.

Fig. 3.8 Marshall Test Setup

3.4.1 Marshall Characteristics

Marshall Test is generally conducted as a part of the Marshall Mixture design to evaluate the resistance of bituminous mixtures to plastic flow. The prepared specimens were kept immersed in a thermostatically controlled water bath at 60±1 ºC for 30 to 40 minutes. The specimens were taken out, placed in the Marshall Test head (Figure 3.8) to determine the Marshall Stability (MS) value which is a measure of strength of the mixture. It is the maximum resistance which the mixture develops at a test temperature of 60ºC when load is applied under specified test conditions. Flow value is the total deformation that the Marshall test specimen undergoes at the maximum load, expressed in mm units. The flow value indicates the extent of deformation a specimen undergoes due to loading.

3.4.2 Optimum Bitumen Content (OBC)

Any asphalt mixture should have necessary binder content to coat the aggregates completely and fill a desired portion of VMA, but its quantity should not be high to result in problems like instability, bleeding, etc. Different agencies have suggested different procedures to decide the optimum binder content of the design mix using the results of the Marshall method of mix design. The OBC for SMA mixtures is usually selected to produce 4.0% air voids. Marshall Stability and flow values are generally measured for information, but not used for acceptance. The binder content (5.0, 5.5, 6.0, 6.5 and 7 %) was plotted against air voids and the binder content corresponding to the specified range of air voids (4%) was found from the plots. In the present study, the binder content at 4% of air voids was taken as OBC for SMA mixtures. All the properties obtained at OBC were compared with the specification values to ensure that they are in the required limits.

3.4.3 Indirect Tensile Strength

The Indirect tensile strength test in one of the most commonly used tests in the characterization of asphalt mixture to assess the durability of bituminous mixes. SMA mixes is not practically strong in tension as it is in compression. Hence more emphasis is laid to evaluate the tensile strength of SMA mixes. Tensile properties of SMA mixes are determined by conducting the indirect tensile strength test. Higher the tensile strength of mix indicates stronger resistance to moisture damage and cracking. The IDT strength of SMA mixtures was conducted as per ASTM D 6931. The specimens were prepared at OBC and immersed in the water bath for about one hour at 25^0C. The conditioned specimen was taken out of water bath and surface dried.

Figure 3.9 Indirect Tensile Strength Test set up

The sample was placed over the bottom loading strip and then the upper portion of mould was lowered to ensure adequate contact between specimens along the diametric plane. The entire set up was placed in Marshall Head as shown in figure 3.9. A vertical compressive load is applied, by maintaining a constant deformation rate of 50mm/minutes till the specimen was no longer capable to take up the further load.

Procedure for determining the indirect tensile strength of bituminous mix:

1. The specimens are compacted by preparing the moulds at optimum binder content obtained from the Marshall Stability test.
2. To determine the moisture damage i.e. the Tensile strength ratio (TSR) the specimens are prepared for two cases i.e. one for conditioning and other for un-conditioning.
3. Three specimens for each case are to be prepared to determine the TSR. And the diameter and the thickness of the individual samples are noted.
4. In the case of the un-conditioned samples, the test is conducted by immersing the specimens in a thermostatically controlled water bath at 25°C for duration of two hours.
5. The specimen is placed in marshal fixture and loading is applied, the rate of loading is 50mm/min and the load at which the sample fails is noted.
6. Indirect tensile of the specimen is determined and a similar procedure is adapted for other proportion of RAP.

$$ITS = \frac{2*P}{\pi*D*T}$$

Where,

P= Maximum load at which the specimen fails (N)

T= Height of the specimen (mm)

D= Diameter of the specimen (mm)

ITS= Indirect Tensile Strength in MPa

3.5 PERFORMANCE TESTS

After ensuring a proper mix design characteristics, the designed mixture should be able to perform without any signs of distress for the service life. Therefore, the designed mixture should be tested for its performance characteristics in the field simulated laboratory conditions. Performance tests such as the resistance of mixture to permanent deformation, repeated loading and to satisfactorily resist moisture-induced damage. The details of the test carried out to measure the above mentioned properties of SMA mixes are discussed in the further sections.

3.5.1 Rutting Resistance

The designed bituminous mixture should be good enough to resist permanent deformations along the wheel path. This occurs due to the accumulation of unrecoverable strains due to heavily trafficked loads over the pavement surface. This accumulation of smaller magnitudes of unrecoverable strains is tested for the designed SMA mixture samples at 7% air voids by subjecting it to undergo a rutting test on Wheel Tracking Device, shown in Figure 3.10. The wheel load of 100 kg was applied directly to the sample through a steel tyre which corresponds to the contact pressure of 620 kPa, which was maintained constant for all the test samples. A compacted slab specimen of a design SMA mixture with dimensions of 600mm in length, 200mm in width and with 50 mm depth is prepared for the test. The device consists of a rubberized wheel of 200 mm diameter and a thickness of 50 mm, a cantilevered loading arm to provide a load on to the wheel and a mould with lateral confinement to hold the prepared specimen rigidly A motor and a reciprocating device give back and forth travel to the platform with the specimen for a distance of 600mm, with the loaded wheel kept in a static position above the specimen surface. The depth of deformation caused by the movement of the wheel is measured by a means of two LVDT"s (Linear Variable Deflection Transducers) fixed on either side of the wheel where the readings are displayed.

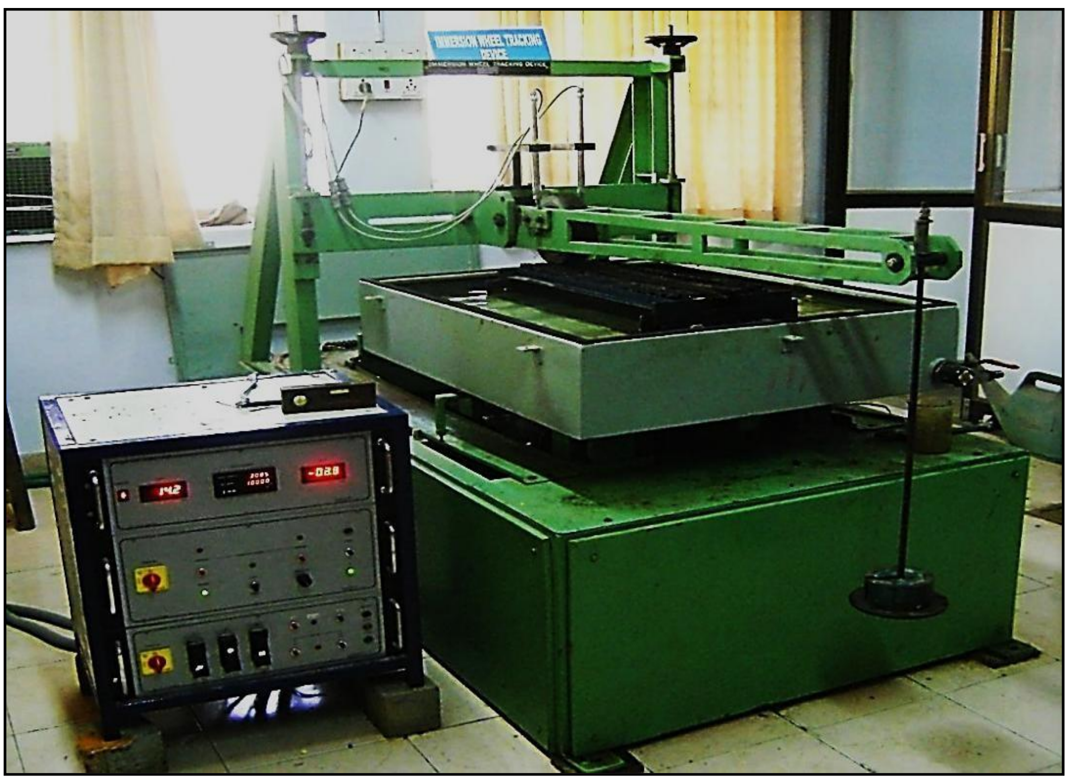


Figure 3.10 Wheel Tracking Device

The procedure carried out rutting deformation test is discussed below:

1) The aggregates are heated and mixed uniformly as per the design requirements. Then the required quantity of heated bitumen was added with the hot aggregate.
2) This loose mixture of SMA is compressed in a sturdy steel mould (600 × 200 × 50 mm) using a static compression machine to the required density and thickness
3) The compacted specimen is shown in Figure 3.16. After 24 hours of casting, the slab will be placed in the machine and all the sides will be encased with confining plates.
4) The static wheel is brought into contact with the slab surface. Depending upon the stress level to be maintained, the weight pads on the cantilever were adjusted.
5) LVDTs are fixed on both sides and connected to the control unit. The speed of the specimen platform is adjusted to the required level.
6) The slab was subjected to reciprocating load repetitions for 10000 passes and the depression on the slab surface is recorded. Water is applied externally to the specimen.

(a)

(b)

(c)

(d)

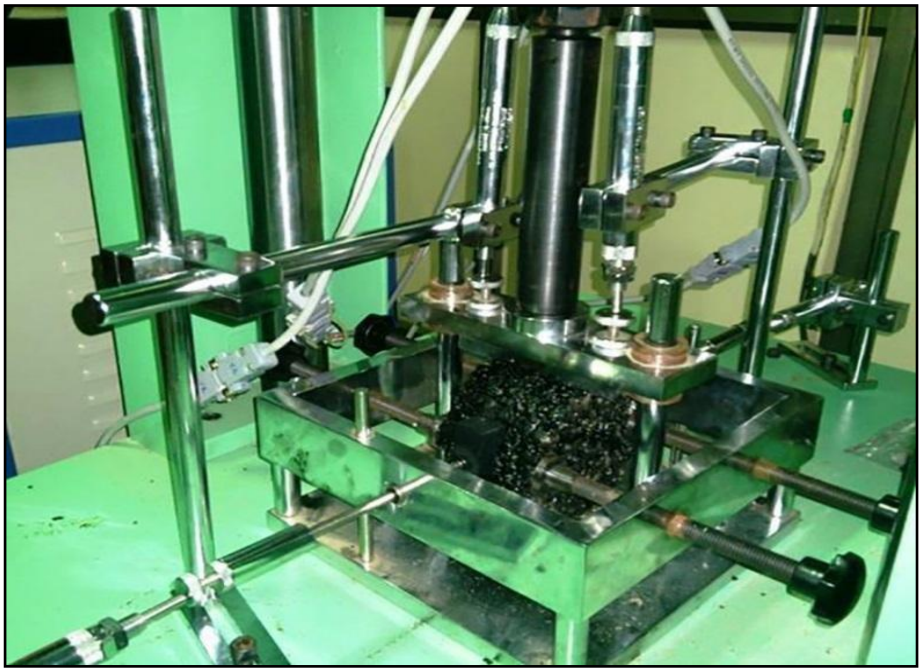
Figure 3.11 Samples at different stages of Rutting performance testing (a) Mixing of aggregates (b) Heating of SMA aggregate mix (c) Preparation of slab for testing (d) Prepared slab sample for rut test.

3.5.2 Fatigue test

Fatigue cracking due to repeated loading has been an everlasting issue in the design and performance of bituminous pavements. The repeated application of damage- inducing stress (and strain), results in the initiation of micro cracks, which, if not healed, cause to form macro cracks, ultimately leading to pavement failure (Tarefder et al. 2013). The Fatigue behaviour of SMA mixtures was assessed using the Repeated Load Testing Machine shown in Figure 3.12 a (Ravi Shankar, A.U., Koushik, K. and Sarang 2013). The device is a modified version of similar equipment reported by (Palit, S. K., Sudhakar Reddy, K., and Pandey 2001). This is a dynamic diametrical tensile test and the load is applied to the cylindrical specimen in a positive sinusoidal pattern. The dynamic loading is applied using the hydraulic loading system present in the machine and is transferred to the specimen through a movable shaft. A cooling system is attached to the control temperature of the machine and the pressure can be adjusted to maintain a balance between input and output loads. The specimen arrangement is shown in Figure 3.12 b.

The specimen is fixed in between two steel strips present at the top and bottom of the test setup. The position of the specimen is adjusted in such a way that, it is exactly below the loading shaft and to apply the load along its diametrical plane. Two vertical and two horizontal LVDTs, with 0.01mm sensitivity, are connected with the specimen to measure the deflections. The machine is capable of applying load with frequency from 1 to 10 Hz and the rest period 0 to 0.9 seconds. The machine is attached to a PC and can be controlled using a software „fatigue 4.0", which is also used to provide various input values.

(a)



(b)

Fig. 3.12Fatigue testing process (a) Repeated load testing machine set up (b) Specimen Arrangement in Repeated Load Testing Machine

In this study, SMA specimens at OBC were tested with loadings approximately 10%, 20%, 30% and 40% of the corresponding IDT strength failure loads. The specimens were subjected to the 1Hz frequency and 0.9 s rest period, and the number of cycles required for failure was considered as Fatigue Life (FL).

Other than the mixture characteristics, the applied load is also a significant factor affecting the Fatigue life of the mix, along with the dimensions of the tested specimen, and hence FL value alone cannot be used to represent the fatigue behaviour of a mixture. Since the applied load is a fraction of IDT strength, the FL may be higher for a weak mixture with lesser IDT strength and lesser applied load, and to the contrary, a lower FL value may be obtained from a strong mixture. In order to obtain a more accurate picture of the fatigue behaviour of SMA mixtures, the FL values were related to the corresponding tensile stress, which includes load applied to the specimen and its dimensions.

3.5.3 Moisture Induced Damage Test

Moisture susceptibility of bituminous mixtures is one of the main reasons for distresses in flexible pavements, which leads to loss of strength, stripping, raveling, fatigue damage, and permanent deformation. The detrimental effects of water in bituminous mixtures and the pavement distresses was recognized from the 1930s itself. The moisture damage can be defined as the degradation of the mechanical properties of the material due to the presence of moisture in the microstructure (Caro et al. 2008; Kakar et al. 2015). The moisture susceptibility of SMA mixtures was assessed using three parameters, Retained Stability (RS), Tensile Strength Ratio (TSR) and stripping.

i) Retained Stability

The retained stability test is a way of assessing moisture susceptibility of SMA mixes based on Marshall Stability values. In this test, Marshall Stability values for two sets of SMA specimens were considered, unconditional and conditional sets. The values determined as per ASTM D 6927 were taken as the unconditioned Marshall stability, whereas the other set of specimens were conditioned by keeping the specimens in a water bath at 60°C for 24 hours. These specimens were tested for stability after conditioning and the ratio of conditioned stability for unconditioned stability is termed as Retained Stability.

ii) Tensile Strength Ratio

The Tensile Strength Ratio (TSR) of bituminous mixtures is an indicator of their resistance to moisture susceptibility. The test was carried out according to AASHTO T283 specifications, by loading a Marshall specimen with the compressive load acting parallel to and along the vertical diametric-loading plane. This method covers the preparation of compacted bituminous mixtures and the measurement of the change of diametric tensile strength resulting from the effects of water saturation and laboratory accelerated stripping phenomenon to the freeze-thaw cycle. The result may be used to predict long-term stripping susceptibility of bituminous mixtures and evaluate liquid anti- stripping additives that are added to the bitumen or pulverized mineral materials such as hydrated lime, which are added to the mineral aggregate.

The test is similar to the Indirect Tensile Strength Test. But in this test, the specimens are prepared with 7±0.5 % air void content to maximize the effect of moisture action. The compacted specimens were prepared at OBC and required air void content. Test procedure for determination of Tensile Strength Ratio is as follows:

1) Specimens for each SMA mixture at varying content of RAP for both the types of rejuvenated mixtures were prepared using Marshall Compactor.
2) Two sets of specimens are prepared for testing, i.e. one to be tested dry and the other to be tested after partial saturation and moisture conditioning with a freeze-thaw cycle.
3) One set of specimens is brought to temperature of 25±1°C, by keeping them in water bath maintained at test temperature for 2 hours. These specimens are called as unconditioned specimens.
4) Another set of specimens are placed in the vacuum container filled

with water at room temperature for 30 minutes. The vacuum is removed and specimens were submerged in water for 5 to 10 minutes.

5) Then specimens are placed in plastic bags containing 10 ±0.5 ml of water and sealed and kept in freezer at a temperature of -18 ±3°C for a minimum period of 16 hours.
6) The specimens are then kept in a water bath for 24 ±1 hours maintaining 60 ±1°C temperatures. This complete process in steps (3), (4), (5) and (6) is called a freeze and thaw cycle.
7) The specimens are then kept in another water bath for 2 hours maintaining temperature of 25 ±1°C. These specimens are called conditioned specimens for ITS test.
8) The conditioned and unconditioned specimens are tested for ITS using the same mould and method adopted for IDT strength mentioned in section 3.2.5, and ITS is calculated.
9) The ratio of the ITS value of the conditioned subset to that of the unconditioned subset is termed as Tensile Strength Ratio (TSR)

iii) Stripping

The development of good adhesion between aggregate and binder is one of the paramount functions of bituminous material The effectiveness of the bituminous coating on the stone aggregate lies in its strong and durable adhesion to the aggregate surface under varying climatic and traffic conditions, and this plays a very significant role in the satisfactory performance and durability of the roads. The boiling test as per ASTM D 3625 was conducted to assess the stripping potential of SMA mixtures. About 250g of loose SMA mixture was prepared at OBC and was allowed to cool to a temperature of 85 – 100 °C. A clean container, half-filled with distilled water, was kept for boiling. The mixture was placed in the boiling water and the container was boiled for 10 minutes ± 15 seconds (Figure 3.13). Then the container was removed and skimmed off the free bitumen from the water surface to prevent recoating. After cooling, the water was decanted and the mixture was placed on a white paper towel and the surface was observed. The stripping area and the percent of stripping were determined based on visual observation.

Figure 3.13 Sample of SMA mix for Boiling Test

3.5.4 Cracking Resistance by Semi-Circular Bending (SCB) Test

The method aims in the determination of horizontal tensile stresses at the bottom of the bituminous layer by performing Semi-Circular Bending test as per ASTM D 8044, the cracking (fracture) resistance of the bituminous mixes is determined, which includes various steps such as sample preparation, testing, analysis and measurement of cracking by Semi-Circular Bending (SCB) test.

The SCB test samples are a half-disk with a notch, the notch is cut parallel to the loading and vertical axis. Notch depths for testing the cracking resistance of bituminous mixes are of varying depth, i.e. 25mm, 32mm and 38 mm. The test method describes the determination of strain energy from the load-displacement curve. These parameters are used to determine the cracking (fracture) resistance of asphalt mixes.

Figure 3.14 Semi Circular Bending test on sample

To determine the cracking (fracture) resistance of the RAP based SMA mixes, the Modified Marshall Mix design is adapted for the preparation of the samples for the SCB test. The adopted gradation is followed for the proportioning of materials for conventional and RAP materials.

The preparation of the test sample is similar to that of preparing the specimens for the Marshall Stability test; here the Marshall samples are prepared at OBC by compacting the SMA mix with varying percentages of RAP and specified number of blows on either face of the specimens by using the modified Marshall rammer.

Laboratory-compacted asphalt mixture samples

- The dimensions of the specimens prepared shall be 150 mm in diameter by 100 mm thick.
- Prepare a minimum of three modified marshal specimens at the optimum binder content obtained from the Marshall Stability test, density and void analysis.
- The Semi-Circular half disk shaped samples are prepared by cutting a 150 mm diameter by 100 mm thick specimen into (two) equal circular test samples 50 mm thick. These samples are cut about its central axis into two equal semi-circular samples. The height (radius) of the two samples shall be within 1 mm of each other.
- A straight vertical notch is cut along the symmetrical axis of each Semi-Circular half disk samples. The location of the notch shall be in the centre of the specimen within 0.3 mm. The three nominal notch depths as per ASTM D 8044 are 25 mm, 32 mm, and 38 mm. Tolerance for the notch depth is ± 1.0 mm. Notch width of the sample shall be less than 3.5 mm.

Testing Procedure

- Inspect the fixture to ensure all contact surfaces are clean and free from any undulations. Place the sample between the testing fixture.
- Load the sample placed in the fixture, by ensuring the sample is in uniform contact (level) on roller supports.

- Set the conditioning chamber temperature and allow it to stabilize to the test temperature 35°C. A dummy sample with temperature sensor mounted to its centre can be monitored to determine when the sample reaches the test temperature 35°C. In the absence of dummy sample, the samples are placed in the conditioning chamber set at the test temperature for a minimum of 2 ± 0.5 h to reach the required temperature for the test.
- After the test temperature is reached, a seating load of 45 ± 10 N is applied for a maximum duration of 30s to sample to ensure the sample is seated properly. After ensuring the sample is levelled, release the load.
- Begin to apply load to the sample, displacement is controlled at a rate of 0.5 mm/min ensuring that (time, load, and displacement)‟s are measured and recorded. The test may be terminated when the applied load decreases to 25 % of the peak load means when the samples have yielded.
- Calculation of the critical strain energy or critical value of the J-integral (Jc) is determined using the following relation;

Calculation of Strain energy, U in (kJ)

$$U = \Sigma_{i=1}^{n}(u_{i+1} - u_i) \times P_i + \frac{1}{2} \times (u_{i+1} - u_i) \times (P_{i+1} - P_i)$$

Where:

P_i = applied load (kN) at the I load application.

P_{i+1} = applied load (kN) at the i+1 load

U_i= crosshead displacement (m) at the I step

U_{i+1} = crosshead displacement (m) at the i+1 step

Calculation of cracking resistance using the critical strain energy, J_c in (KJ/m²)

$$Jc = \frac{-1}{b}\{dU|da\}$$

Where;

J_c - Critical strain energy release rate (kJ/m²)
B- Thickness of the sample (m)
A- Notch depth (m)
U- Strain energy to failure (kJ)
dU/da - Change of strain energy with notch depth (kJ/m)

3.6 SUMMARY

For any bituminous mix to perform better in the field, it should satisfy certain requirements as per the specifications for the samples tested in the laboratory. From this chapter the various materials used are tested as per the specifications were discussed. The various tests that need to be conducted to evaluate the property of the conventional and RAP based SMA mixes are also discussed. The performance of SMA Mix with untreated RAP is discussed in the following chapter 4.

CHAPTER 4

PERFORMANCE OF RAP BASED SMA MIXES

4.1 General

This chapter deals with the volumetric and performance characteristics of control SMA mixes and SMA mixes with varying content of RAP. The basic properties of original and reclaimed aggregates and binders are discussed in the previous chapter in section 3.1.1 and 3.1.2. It is observed that the properties of aggregates obtained from RAP are superior to that of the conventional aggregates. This indicates that the properties of the aggregates will not be lost unless they are damaged. It also indicates the usage of better-quality aggregates during construction. With respect to the basic properties of the binder, the properties of the fresh VG 30 binder confirmed to the specific requirements as per IS 73: 2013. Whereas, the reclaimed binder from RAP was found to satisfy the majority of the paving binder requirements even after ageing effect on the binder. In view of the major benefits to be obtained by the use of RAP material in new bituminous mixtures, minor qualities were compromised.

4.2 MIX DESIGN PROPERTIES

As mentioned in previous chapter, the Marshall method of mix design was adopted to study the volumetric and strength properties of bituminous mixtures. For mixes with RAP, the required quantity of RAP was first heated to 150^0C prior to mixing the natural aggregates. The required quantity of fresh aggregates preheated at 175^0C was added to the

RAP and mixed thoroughly, then the VG 30 binder was heated and to 145^0C and added to the aggregates and mixed thoroughly by heating the entire mix at 160^0C before compaction. Prior to mixing the amount of bitumen in RAP aggregate was found to be 4%. So while doing the mix design, the amount of natural bitumen required to be added was found out by usual procedure. Marshall cylindrical specimens were cast and prepared for conventional and varying contents of RAP material. The resultant volumetric strength and flow properties were determined. The variation of these mix design parameters for different RAP contents are presented in the table 4.1

Table 4.1 Properties of SMA Mixtures with Different percentages of RAP

Mixture properties	**Control Mix**	**R-1**		**R-2**	
		30%	**50%**	**30%**	**50%**
OBC (%)	6.04	5.55	4.39	5.7	4.43
G_{mm} (g/cc)	2.44	2.39	2.41	2.36	2.4
G_{mb} (g/cc)	2.32	2.31	2.32	2.3	2.32
V_v (%)	4.2	3.7	3.9	3.5	4.0
VMA (%)	18.3	17.3	16.76	18.1	17.42
VCA_{MIX} (%)	38.45	30.65	26.94	28.56	26.68
MS (kN)	13.4	15.1	17.3	14.9	16.8
Flow Value (mm)	3.9	4.1	4.0	4.1	4.0

From table 4.1, it clearly indicates that the volumetric properties of the bituminous mix satisfy the requirements as per IRC SP: 79-2008 specifications. The increase in RAP has provided better results compared to that of the reference control mix. This indicates that the addition of higher percentages of RAP has not degraded the quality of the mix. This may be attributed to the stiffness gained in the total mixture due to the addition of RAP in higher quantities in the overall mix. However, improvement in stiffness of the mix does not indicate the overall mixture performance. The stiffer mix may not always perform better under every condition and bituminous mixture with a little lower stiffness may perform better in many conditions. Hence, further analysis of the performance characteristics such as moisture resistance, resistance to plastic deformation and also resistance to deformation under a repeated number of load application of the mixture needs to be investigated before concluding the mix to perform better. In addition, poor workability was also experienced in the bituminous mixes with an increase in RAP content due to higher RAP binder stiffness.

4.3 INDIRECT TENSILE STRENGTH

The indirect tensile strength test was conducted on the unconditioned and conditioned bituminous mix samples prepared with target air voids of 4%. The specimens were mounted on the Marshall Test head and the load was applied until the specimens could no longer take any load. The test results are tabulated in Table 4.2. It can be observed that ITS values increased as there was an increase in RAP content irrespective of the type/source of RAP. The ITS test results have found to follow the stability trend seen in the mix design process. This may be again due to the hardness/ stiffness provided by the inclusion of aged RAP in the mix. However, the trend needs to be verified for moisture susceptibility to ensure the performance of RAP mixtures.

Table 4.2 ITS of optimum Mixture for Control and RAP mixes

Mix Type	ITS (Mpa)
Control Mix	0.78
30% R-1	0.89
50% R-1	0.97
30% R-2	0.81
50% R-2	0.91

4.4 MOISTURE SUSCEPTIBILITY

The susceptibility of any asphalt mixtures to the presence of moisture is one of the main reasons for failures in flexible pavements such as stripping, pothole, cracking, raveling, fatigue break up and permanent deformation. Hence moisture damage is defined as the degradation of strength in bituminous mixture due to the presence of water. To assess this property of the mixes with and without RAP material in terms of the Tensile Strength Ratio (TSR) ITS test was conducted on SMA specimens prepared with 7% air voids for both unconditioned and conditioned samples. The results are presented in table 4.3 as obtained. As observed in the case of the ITS test, the tensile strength ratios of asphalt mixture with the inclusion of RAP materials tend to decrease. This may be attributed to the fact that the aged material in RAP does not have enough adhesion to hold the mix. This indicates that the addition of rejuvenated RAP in the mixtures does not reduce the moisture resistance property of the mix.

Table 4.3 Tensile Strength Ratio of Control and RAP Samples

Mix Type	TSR (%)
Control Mix	87.29
30% R-1	76.21
50% R-1	73.83
30% R-2	77.80
50% R-2	75.46

4.5 RUTTING PROPERTIES

Laboratory rutting test on SMA mixes with varying content of RAP was conducted using the immersion wheel tracking machine. The wheel load of 100 kg applied directly placed on the sample through a steel tyre, which corresponds to the contact pressure of 620 kPa, was kept constant for all the tests. Tests were conducted and rutting in the mixes was measured using a data acquisition system acquired through linear Vertical Displacement Transducer (LVDT) after 10,000 load cycles. One load cycle means to and fro movement of the loaded wheel on the test sample. Table 4.4 summarizes the rutting test results of SMA mixes without RAP, 30% RAP, and 50% RAP content. From the figure, it can be seen that the mixes with higher RAP content indicate lower deformation values. It can be seen that the rut depth of all the samples is below 5mm indicates a better stone to stone contact established between the aggregates in the mix. Further, the addition of RAP in the mix has reduced the rut depth approximately by 1mm. This may be due to the increased stiffness in the mix up on the RAP. The variation of the rut depth for control mix and RAP based mix is presented in figure 4.1.

Table 4.4 Rutting Values of RAP based SMA Mix

Number of Passes	Deformation (mm)						
	Control Mix	R-1			R-2		
		30%	50%	70%	30%	50%	70%
0	0	0	0	0	0	0	0
1000	1.1	0.8	0.7	0.6	0.6	0.6	0.5
2000	1.3	1.0	0.8	0.8	0.9	0.8	0.7
3000	1.5	1.2	1.0	1.0	1.1	1.0	1.0
4000	1.7	1.5	1.3	1.3	1.5	1.2	1.2
5000	1.9	1.7	1.5	1.5	1.7	1.5	1.4
6000	2.2	1.9	1.7	1.6	2.0	1.7	1.5
7000	2.3	2.0	1.9	1.8	2.1	1.8	1.7
8000	2.5	2.2	2.2	2.0	2.2	2.0	1.8
9000	2.6	2.3	2.3	2.2	2.3	2.2	2.0
10000	2.8	2.5	2.5	2.3	2.5	2.3	2.1

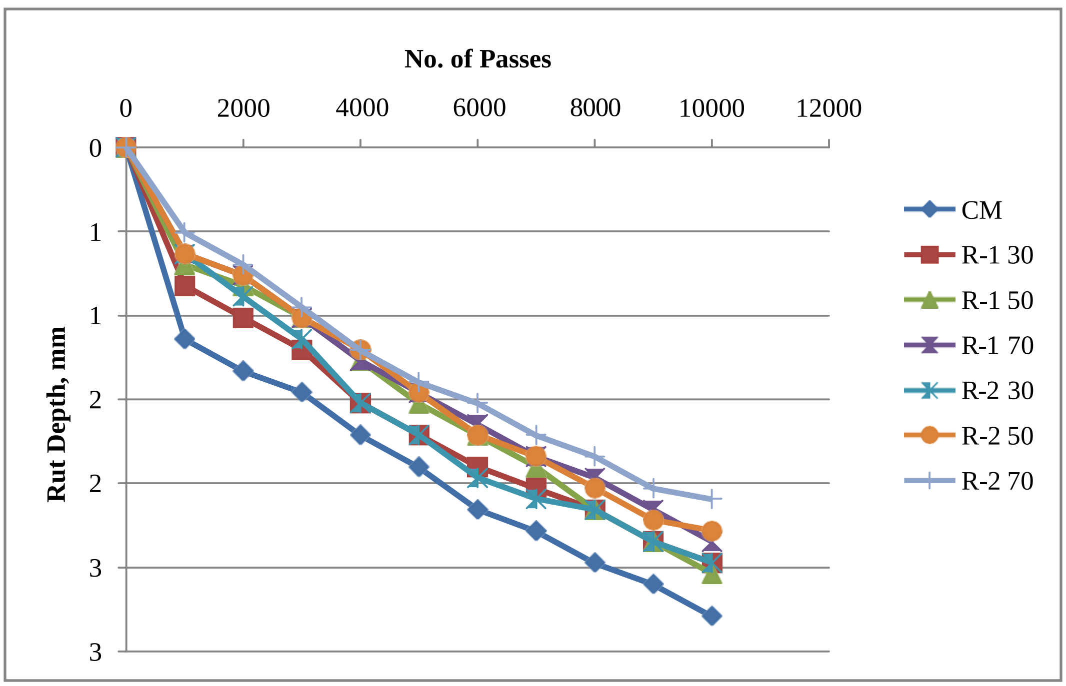


Figure 4.1 Rutting Deformation of Control and RAP based SMA mix

4.6 FATIGUE PROPERTIES

To evaluate the fatigue properties of the RAP based SMA mixes repeated load indirect tensile test was carried out. The specimens were prepared to target air voids of 4%. The specimens were tested at the stress levels of 10%, 20%, 30% and 40% of the Indirect Tensile Load. The test was conducted at 25^0C. The number of repetitions taken by the specimen to either deform horizontally or vertically by 5mm at each stress level was recorded. The test results are tabulated in Table 4.5 and presented in figure 4.2.

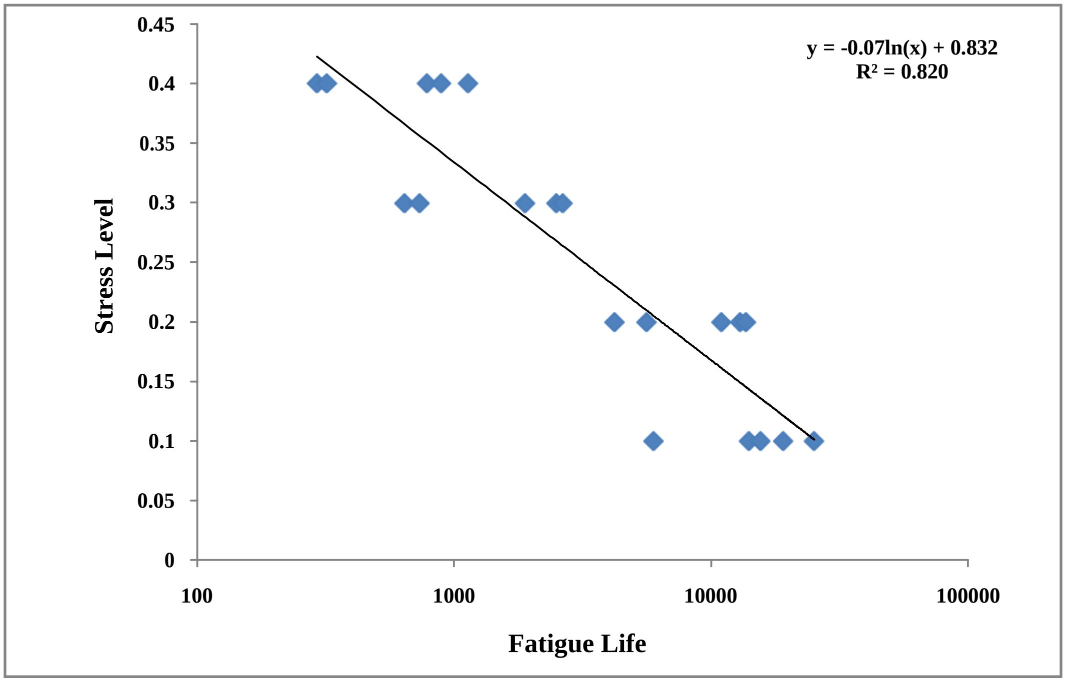
Table 4.5 Fatigue Life of Control and R-1 based SMA Mixtures

Mix ID	Specimen No	Stress Ratio			
		0.4	0.30	0.2	0.1
	No of cycles to failure (Fatigue Life), N				
CM	1	292	643	4212	5990
	2	320	732	5600	14073
	3	784	1890	10962	15546
	4	892	2498	12985	19058
	5	1132	2644	13692	25173
30%	1	182	803	1657	2936
	2	351	834	3327	5762
	3	416	1169	7513	16109
	4	538	1726	8104	17513
	5	940	2271	9790	20714
50%	1	103	333	1678	3334
	2	158	568	2485	4655
	3	185	594	3097	6937

	4	287	1124	4831	9351
	5	424	1368	5804	11425

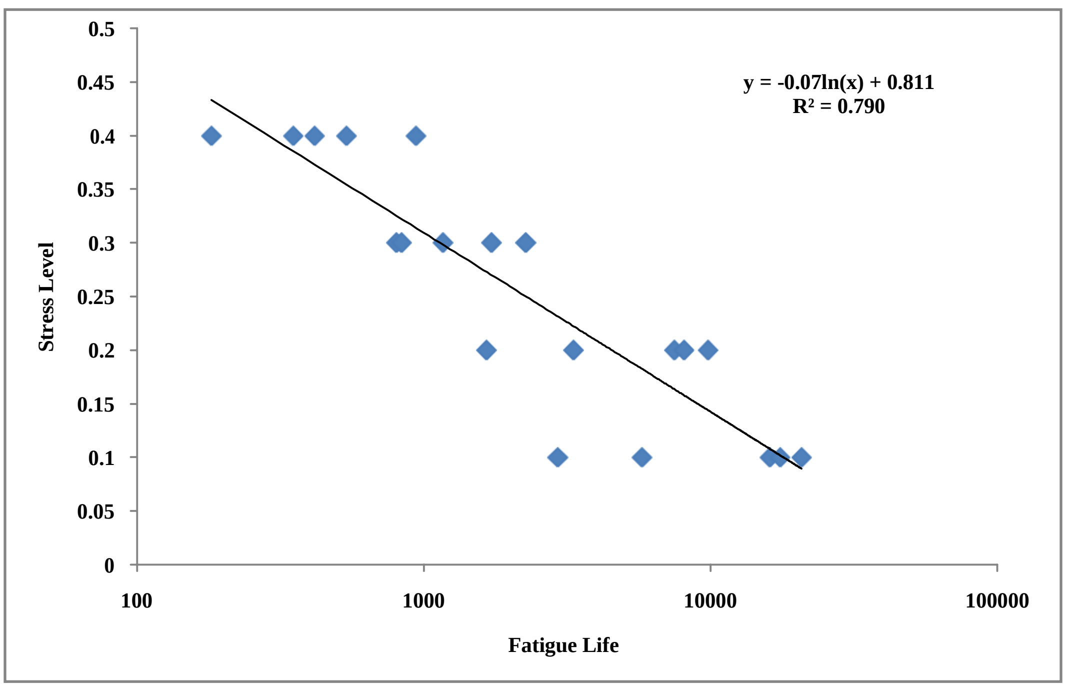
Table 4.6 Fatigue Life of Control and R-2 based SMA Mixtures

Mix ID	Specimen No	Stress Ratio			
		0.4	0.30	0.2	0.1
	No of cycles to failure (Fatigue Life), N				
CM	1	292	643	4212	5990
	2	320	732	5600	14073
	3	784	1890	10962	15546
	4	892	2498	12985	19058
	5	1132	2644	13692	25173
30%	1	151	668	1378	2442
	2	292	694	2767	4792
	3	346	972	6248	13398
	4	447	1435	6740	14565
	5	782	1889	8142	17228
50%	1	123	399	2008	3990
	2	189	680	2974	5572
	3	221	711	3707	8302
	4	343	1345	5782	11191
	5	508	1637	6946	13674



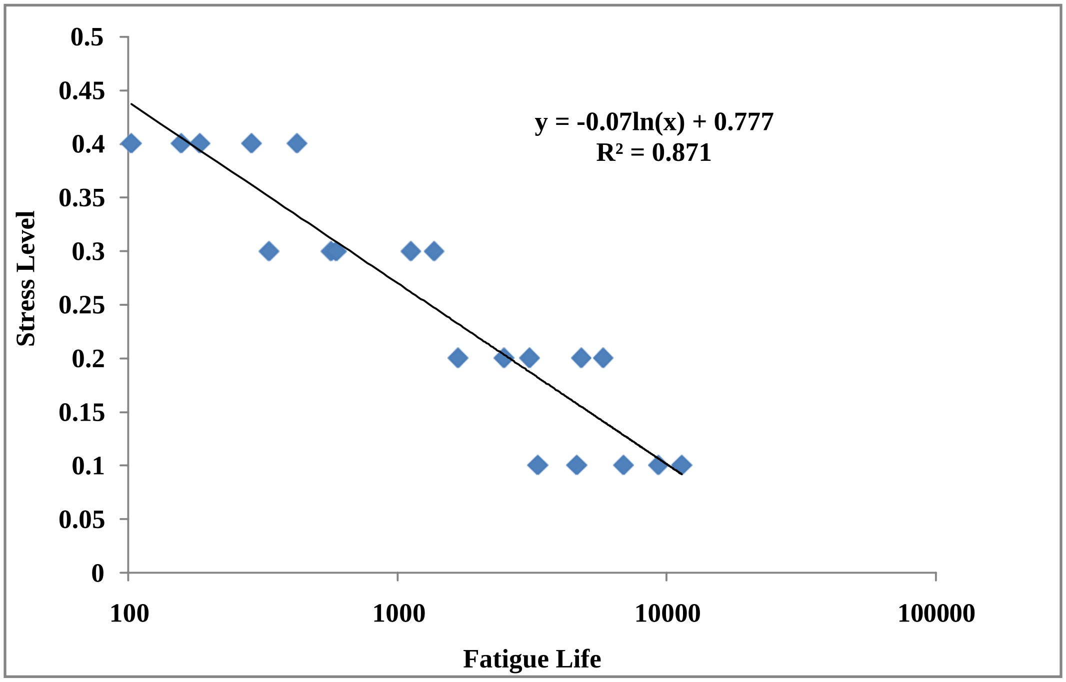
y = -0.07ln(x) + 0.832
R² = 0.820
Stress Level
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
100
1000
10000
100000
Fatigue Life

(a)

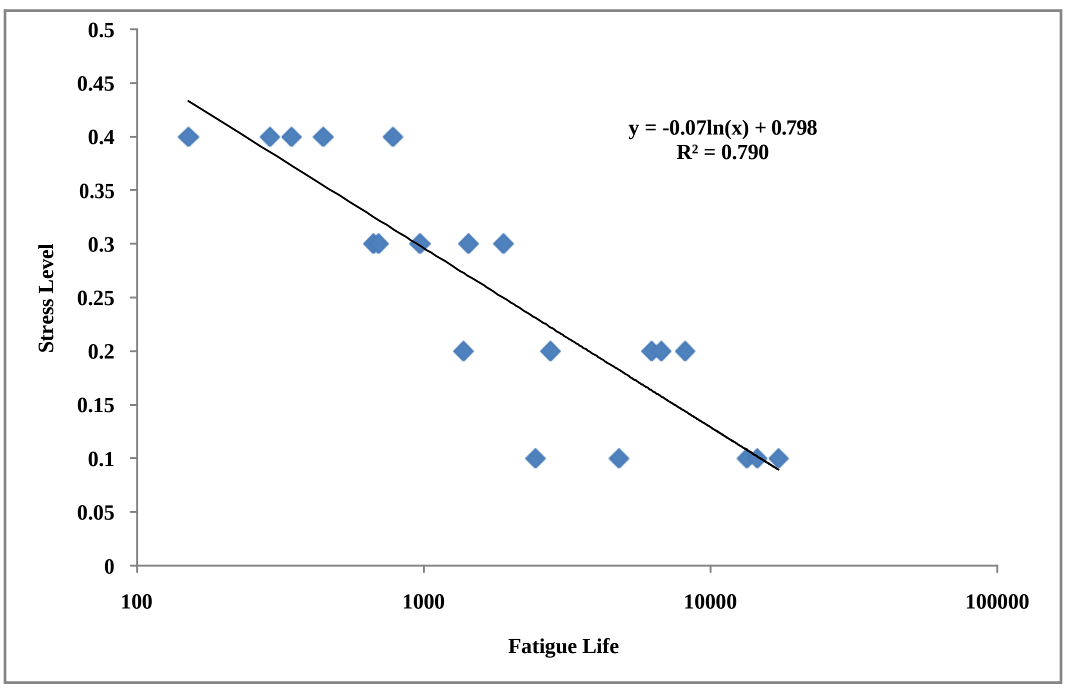


y = -0.07ln(x) + 0.811
R² = 0.790
Stress Level
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
100
1000
10000
100000
Fatigue Life

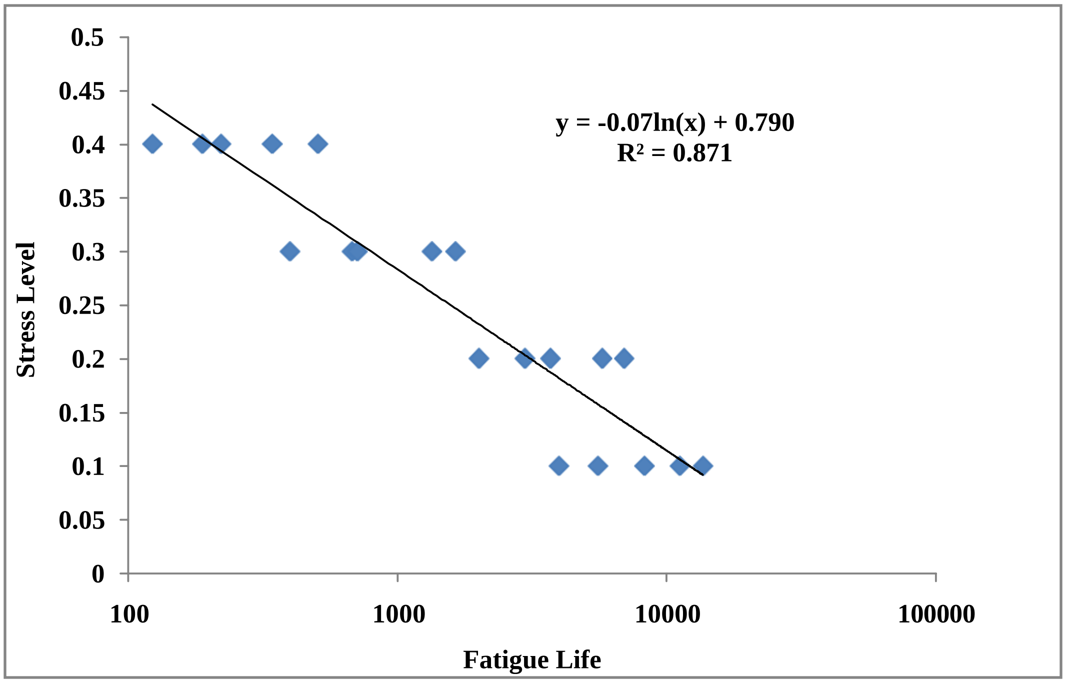
(b)


y = -0.07ln(x) + 0.777
R² = 0.871
Stress Level
Fatigue Life
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
100
1000
10000
100000

(c)


y = -0.07ln(x) + 0.798
R² = 0.790
Stress Level
Fatigue Life
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
100
1000
10000
100000

(d)



(e)

Figure 4.2 Variation in S-N curves for (a) Control Mix (b) 30% R-1 Mix (c) 50% R-1 Mix (d) 30% R-2 Mix (e) 50% R-2 Mix

Table 4.7 Relationship between fatigue cycle (N) and stress level (SR)

Mix ID	Equations	R^2
CM	ln(N)=0.832-SR/0.07	0.820
RAP mixes		
30% R-1	ln(N)=0.811-SR/0.07	0.790
50% R-1	ln(N)=0.777-SR/0.07	0.871
30% R-2	ln(N) = 0.798-SR/0.07	0.790
50% R-2	ln(N) = 0.790-SR/0.07	0.871

From the figure 4.2, table 4.5, it can be noticed that the R-1 based SMA mixes correspond to lower resistance to fatigue failure as compared to that of the control mix irrespective of the applied stress level.

However, RAP material is usually stiff with low strain levels. This may be due to the loss of interfacial bond between the RAP and original materials occurring in RAP mixes as compared to that occurring in control mixes (Watson et al. 2008). The reduction in fatigue life is also affected by the gradation of the RAP material. Higher the fine content in the RAP higher is the amount of aged binder and this leads to higher stiffness in the overall binder. This failure in recoverable strain leads to premature failure of bituminous mix. A similar trend was observed in R-2 mixes thereby indicating insignificance in adding higher content of RAP material.

4.7 SUMMARY

The tests conducted on the SMA mix with the varying RAP content revealed that the performance characteristics such as the moisture susceptibility, and fatigue characteristics reduced with an increase in RAP. This may be mainly due to the stiffness of the mix with higher amount of RAP as the quantity of the aged binder in the mix increases. This resulted in the reduced performance of the mixes. This ability of the mix to perform better even at higher percentages of RAP is very essential. Hence, the needs for performance enhancement by the addition of additives like rejuvenators are necessary. In chapter 5, the performance of the RAP based SMA treated with rejuvenators is discussed.

CHAPTER 5

BEHAVIOUR AND PERFORMANCE OF REJUVENATED RAP BASED SMA MIXES

5.1 GENERAL

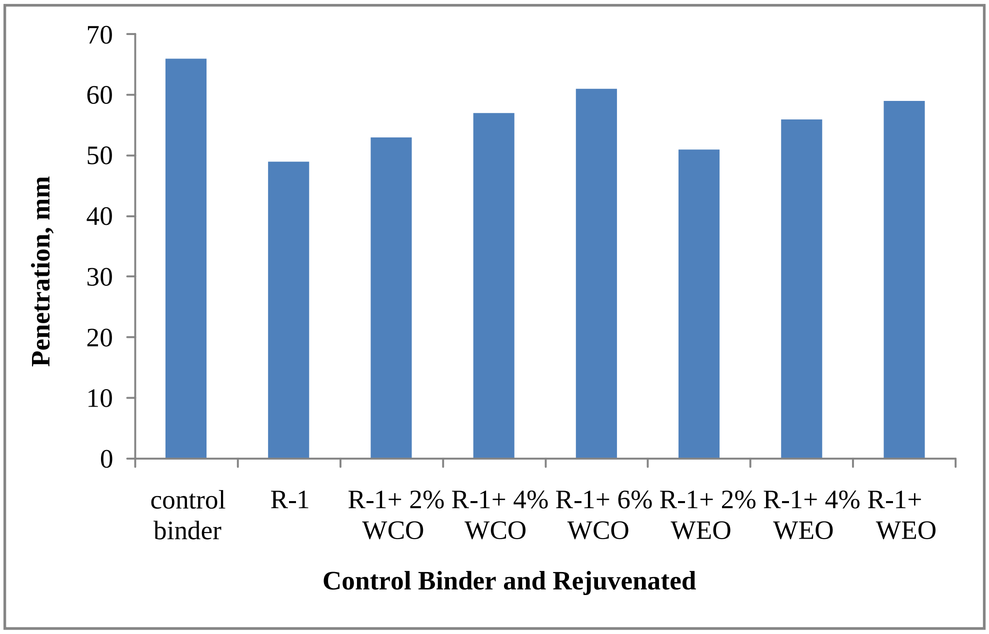
This chapter details the behaviour and performance of rejuvenated RAP based SMA mixes that include rheological parameters of the Virgin binder, aged binder, and rejuvenated RAP binder. Mix design characteristics of SMA mixes with varying RAP content, moisture-induced damage, rutting and fatigue behaviour for control mix and varying contents of rejuvenated RAP based SMA mix.

5.2 PERFORMANCE OF CONTROL, RAP AND REJUVENATED RAP BINDER

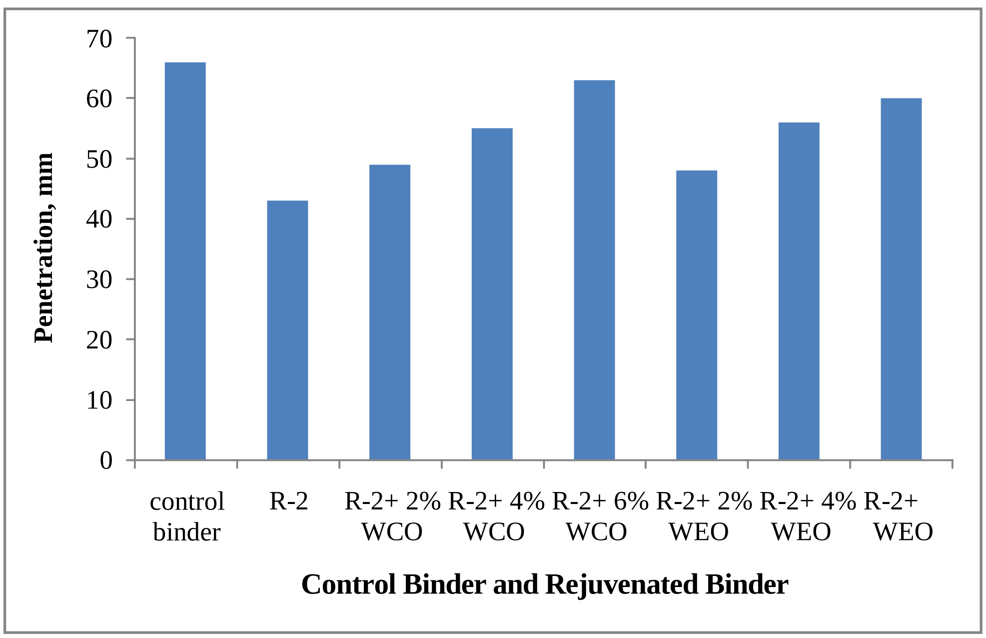
The SMA mixture comprises of aggregates and binder. To achieve better performance of the mixture, both aggregate and binder matrix should exhibit enough resistance to wear and tear due to traffic loads and weathering action. In order to understand the effect of RAP in SMA mixtures, the binder and mixture properties that may affect the performance of the pavement are separately studied. The details of results of the various test conducted separately on the binder and whole SMA mixtures are discussed in subsequent sections.

5.2.1 Penetration and softening behaviour of binder

Figure 5.1 illustrate the effect of Waste Cooking Oil (WCO) and Waste Engine Oil (WEO) as rejuvenators on the penetration values of aged bitumen. Penetration test were carried out as per with IS 1203.



(a)



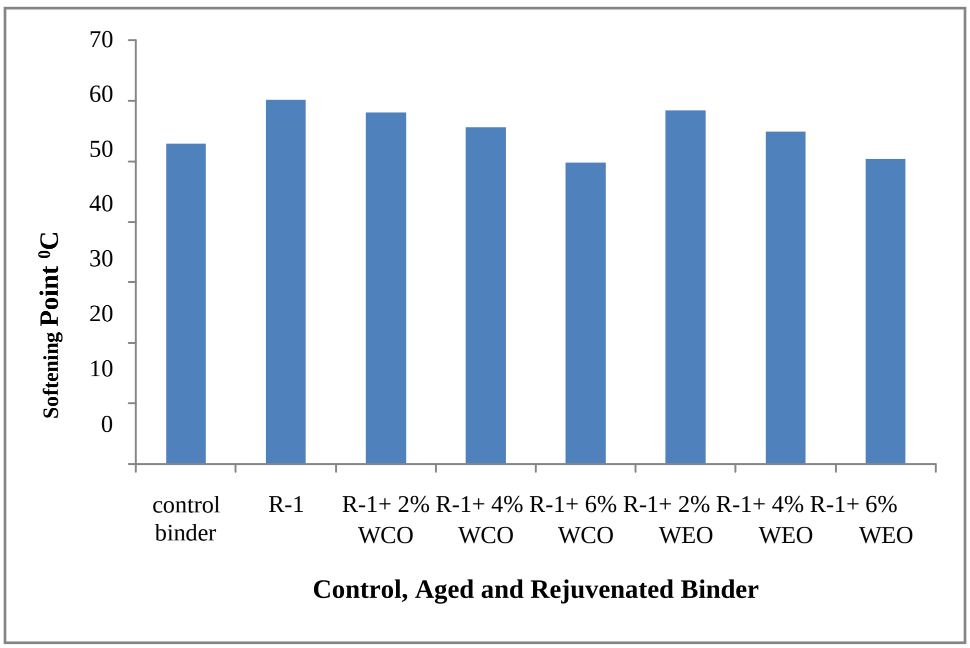
(b)

Figure 5.1 Penetration Behaviour with WCO and WEO

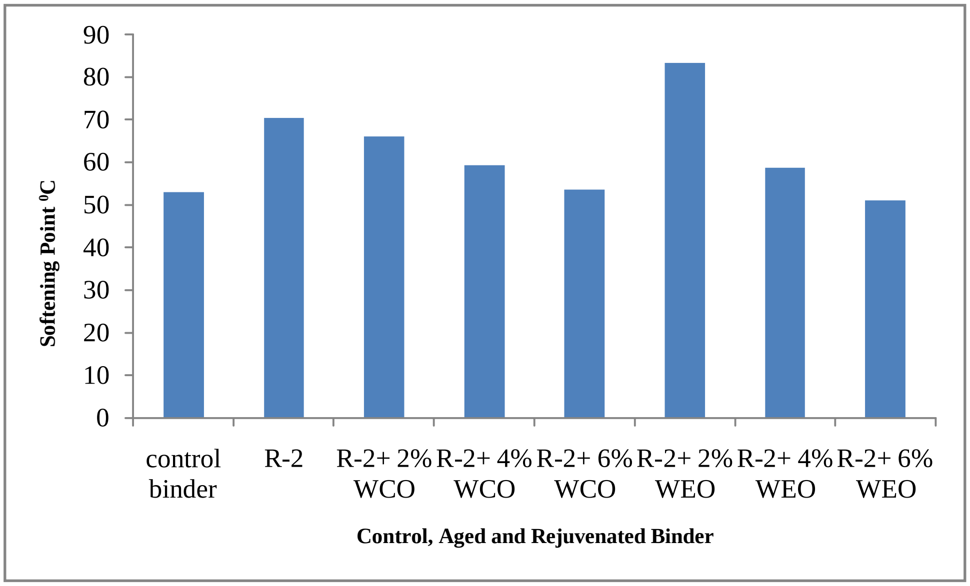
(a) R-1 Rejuvenated Binder (b) R-2 Rejuvenated Binders

A linear variation in increase of penetration values was observed with the increase in dosages of rejuvenators to reach the target penetration grade of 60/70. The increase in penetration values of the binder mixed with rejuvenators may be attributed to the decrease in the ratio of asphaltenes to maltenes. At 6 % addition of WCO and WEO, the values of penetration of rejuvenated binder were found to be similar or somewhere close to that of the control binder.

The softening point test was conducted in accordance with IS; 1205. Figure 5.2 exhibits the softening point temperatures for various binder samples. The softening point temperature of the RAP binder decreased with the addition of varying dosages of rejuvenators. Based on penetration and softening point test results, it is understood the addition of a 6 % rejuvenator affected the RAP binder to behave closely as compared to the control binder.



(a)



(b)

Figure 5.2 Softening point Behaviour with WCO and WEO
(a) R-1 rejuvenated Binder (b) R-2 Rejuvenated Binder

5.2.2 Viscosity behaviour of binder

The viscosity results for fresh VG30 binder, RTFO (Rolling Thin Film Oven) aged binder, R-1 binder and R-2 binder with varying dosages of WCO and WEO as rejuvenators are tabulated in Table 5.1.

Unfortunately, ensuring correspondence to mixture volumetric or binder specifications, be those empirical or super pave requirements has been shown in many studies to be insufficient to claim through RAP rejuvenation. In binder testing, 100% diffusion of rejuvenators into the RAP binder film is artificially assumed, but multiple studies have concluded this is not the likely case in actual field conditions. Rejuvenators or their overdose also can cause a reduction in adhesion and cohesion in asphalt mixture and thus performance testing of the material is highly recommended. Rejuvenator diffusion can significantly affect the performance of asphalt mixes. In mix design assumption of full binder, attrition can lead to a deficiency on the other hand assumption of the Black rock situation, when the RAP binder actually contributes to the performance of the mixture will lead to the overdose of rejuvenator and softens the mixture leading to permanent deformation or rutting.

Table 5.1 Viscosity of aged and rejuvenated binders

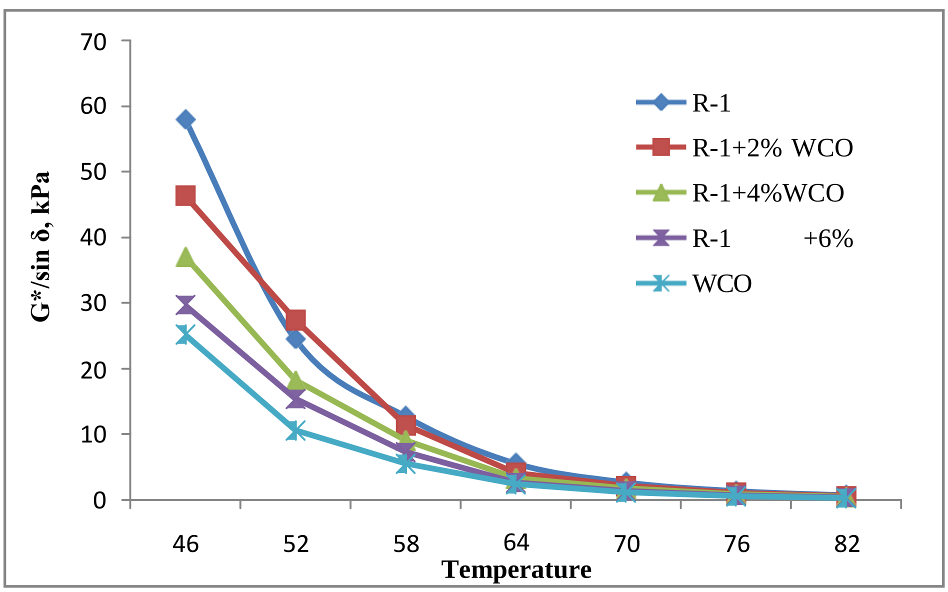
Property	Without rejuvenators	With Rejuvenators					
		WCO			WEO		
Viscosity (Centipoise)	RTFO Aged						
	0%	2%	4%	6%	2%	4%	6%
	2925	1230	825	425	1085	805	410
	R-1 Binder						
	0%	2%	4%	6%	2%	4%	6%
	625	568	515	485	543	492	455
	R-2 Binder						
	0%	2%	4%	6%	2%	4%	6%
	825	795	685	650	765	724	680

Table 5.1 shows the results of investigating R-1 and R-2 binder with varying dosages of WCO and WEO as rejuvenators. It is observed that the viscosity of RTFO aged binder is 2925 centipoise, while the viscosity of R-1 binder is 625 centipoise and for the binder sample from R-2 the viscosity observed is 825 centipoise. With the addition of WCO and WEO as rejuvenating agents at varying dosages (2%, 4%, and 6%), the viscosity is found to decrease in all the types of the binder combinations. Viscosity of binder is governed by the presence of aromatic and saturated hydrocarbons in large proportions. The loss of these aromatic and saturated hydrocarbons due to oxidation makes the binder stiff resulting in increased viscosity. The addition of WCO and

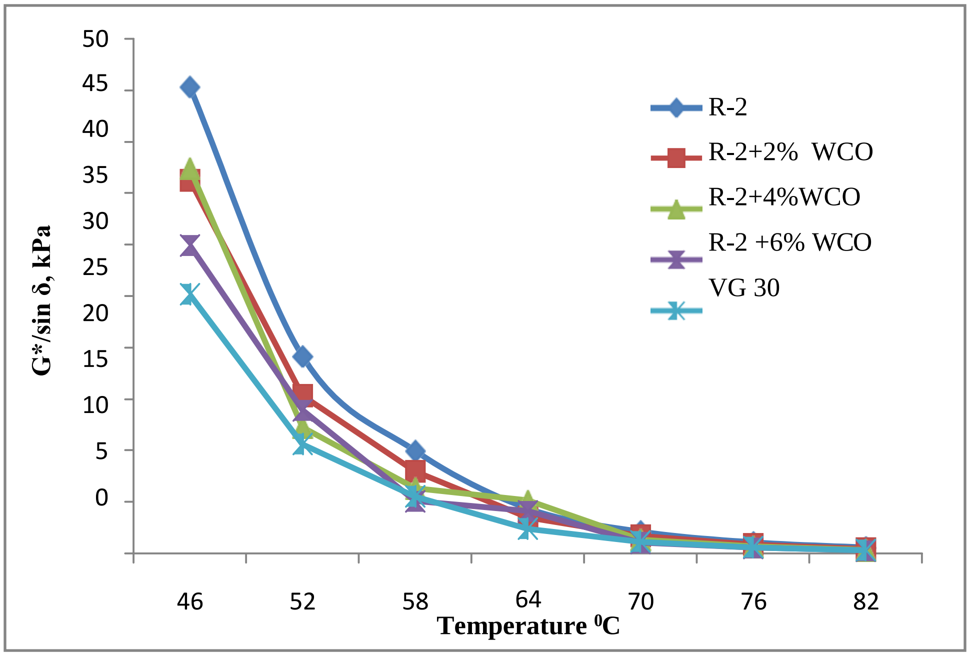
WEO, which contain aromatic and saturated hydrocarbons, reverses the oxidation process and reduces the material's ability of resistance to flow. Asphaltenes, which have higher molecular weight, dissolve in the rejuvenator's oily medium having a low molecular weight and these asphaltenes and maltenes present in binder causes changes in viscous behavior (Ahmadinia et al. 2011). It was observed that all the binders with or without rejuvenators satisfied the minimum kinematic viscosity specification of 325 centipoise.

5.2.3 Rutting and Fatigue parameter

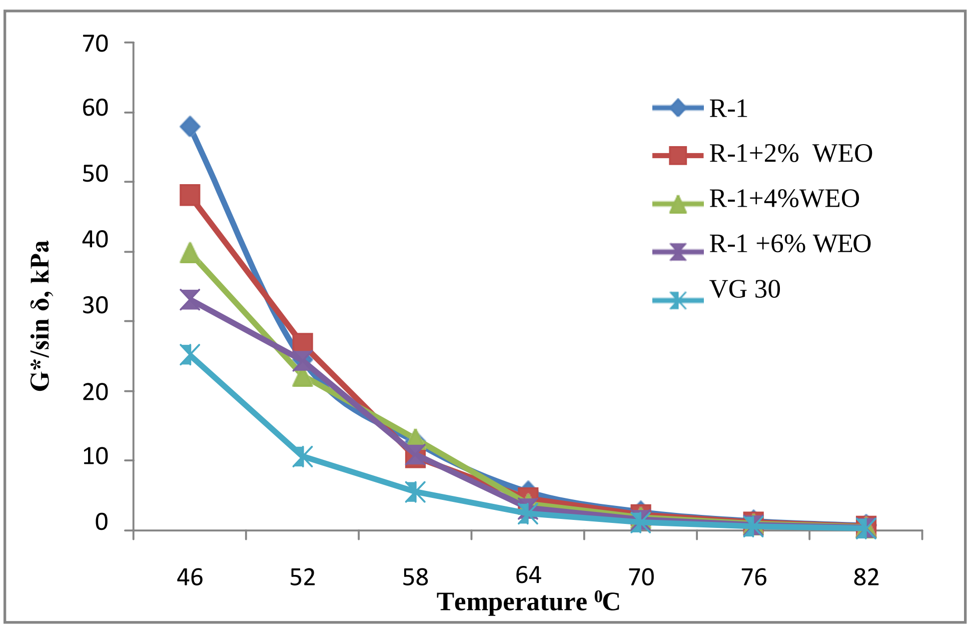
Dynamic Shear Rheometer (DSR) test was conducted as per AASHTO T315 guidelines and the rutting; fatigue resistance parameters of binders are evaluated. The limiting values of the resistance to rutting parameter (G*/ sin δ) should be more than or equal to 2.2 kPa and the resistance to fatigue parameter (G* sin δ) should be equal or less than 5000 kPa . Figure 5.3 Provides the variation of rutting parameter (G*/ sin δ) with temperature for fresh and RTFO aged binder specimen.



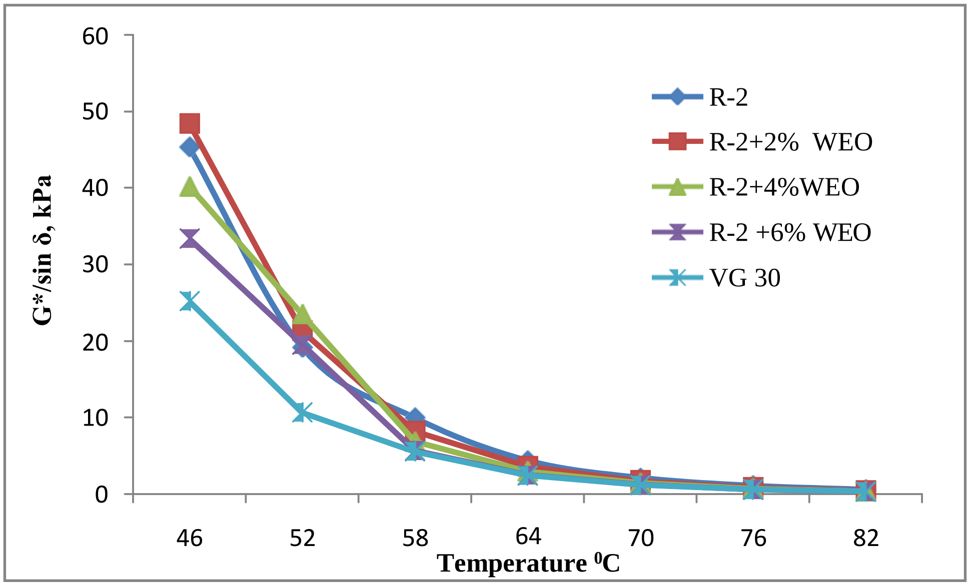
(a)


50
45
40
35
30
25
20
15
10
5
0
G*/sin δ, kPa
46
52
58
64
70
76
82
Temperature ⁰C
R-2
R-2+2% WCO
R-2+4%WCO
R-2 +6% WCO
VG 30

(b)


70
60
50
40
30
20
10
0
G*/sin δ, kPa
46
52
58
64
70
76
82
Temperature ⁰C
R-1
R-1+2% WEO
R-1+4%WEO
R-1 +6% WEO
VG 30

(c)

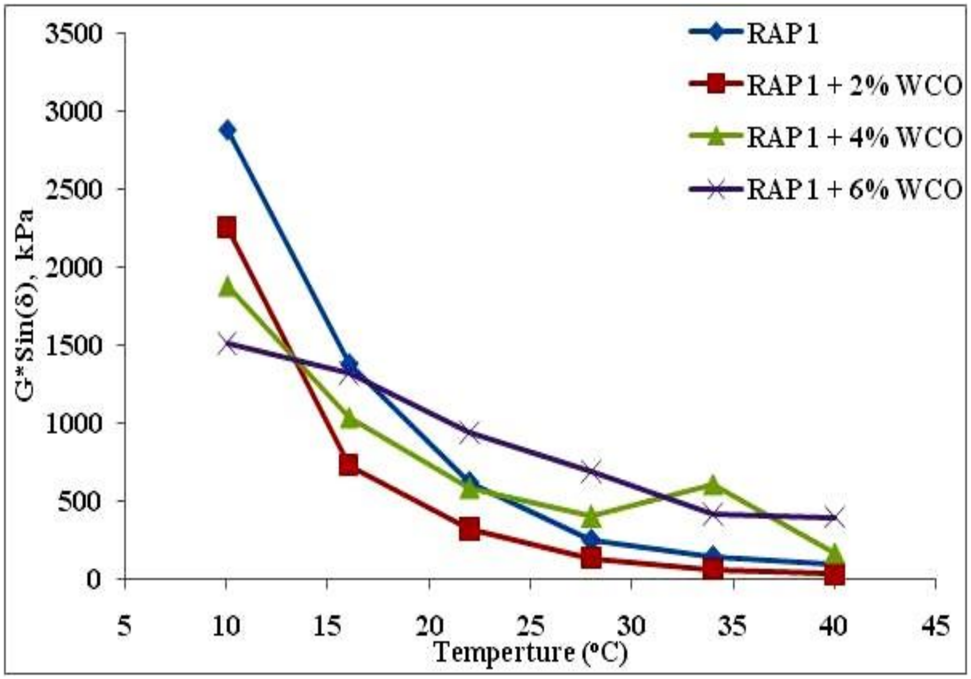


(d)

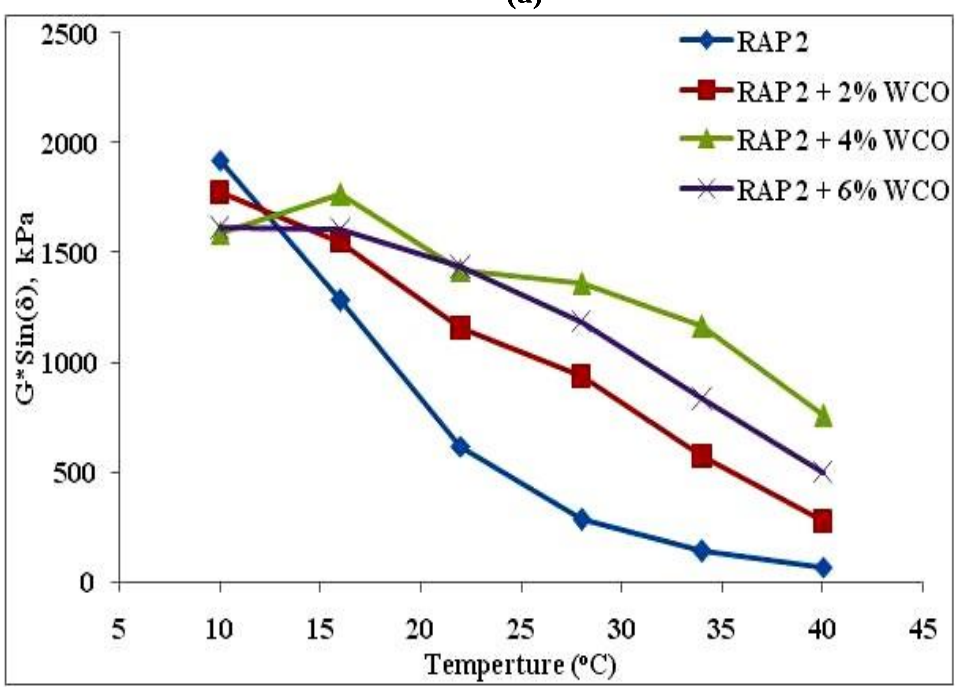
Figure 5.3 Variation of rutting parameter with temperature (a) R-1 with WCO (b) R-2 with WCO (c) R-1 with WEO (d) R-2 with WEO

From Figure 5.3, it may be noted that the virgin binder (VG30) satisfies the rutting parameter of G*/sin δ, recording values greater than 1.0 kPa, even at higher temperatures. However, the RTFO aged binder fails to meet the specified rutting parameter above 68^{0}C indicating that the material loses its stiffness at higher temperatures. The variation of the rutting parameter (G*/sin δ) with the temperature of aged binder and rejuvenated binders for varying percentages of rejuvenators are depicted in figure 5.3.

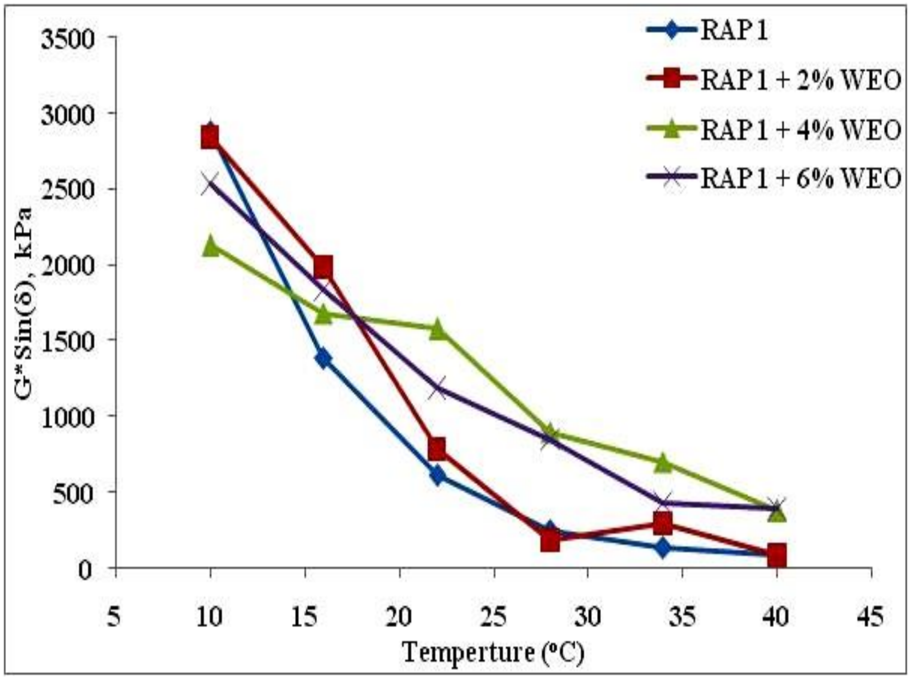
From Figure 5.4, it may be observed that fatigue parameter values (G*sin δ) for the aged binder are quite higher as compared to the virgin and RTFO binder, thus indicating the formation of stiffer and brittle binder with aging. However, the addition of WCO and WEO rejuvenators softens the binder materials, thus improving the binder's resistance to fatigue failure as good as virgin binder. Based on these rutting and fatigue criteria, the optimum rejuvenator content was fixed at 6% for both WCO and WEO.


RAP 1
RAP 1 + 2% WCO
RAP 1 + 4% WCO
RAP 1 + 6% WCO
G*Sin(δ), kPa
Temperture (ºC)
3500
3000
2500
2000
1500
1000
500
0
5
10
15
20
25
30
35
40
45

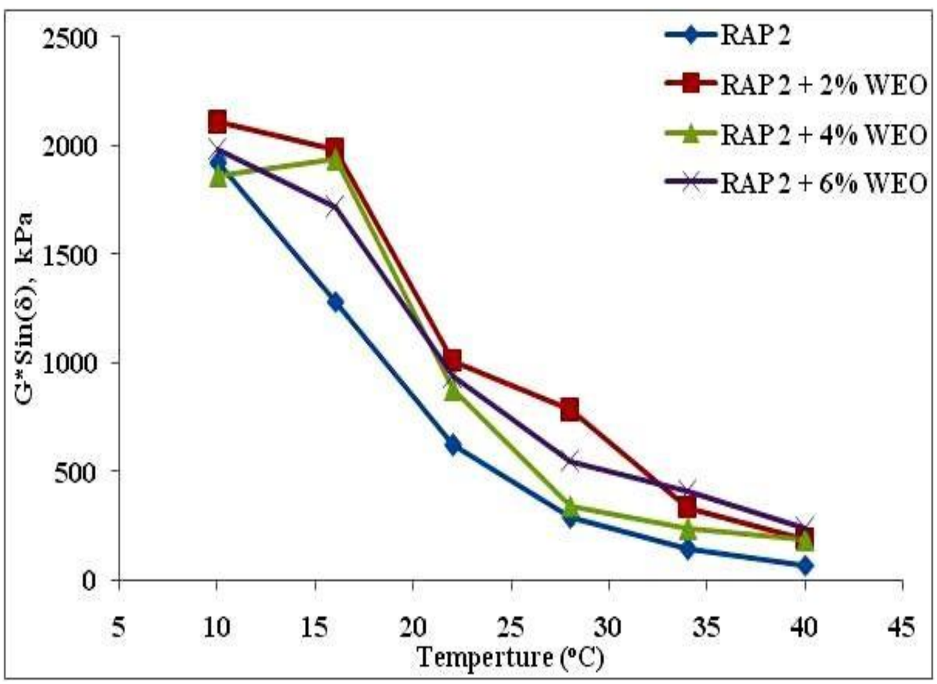
(a)


RAP 2
RAP 2 + 2% WCO
RAP 2 + 4% WCO
RAP 2 + 6% WCO
G*Sin(δ), kPa
Temperture (ºC)
2500
2000
1500
1000
500
0
5
10
15
20
25
30
35
40
45

(b)



(c)

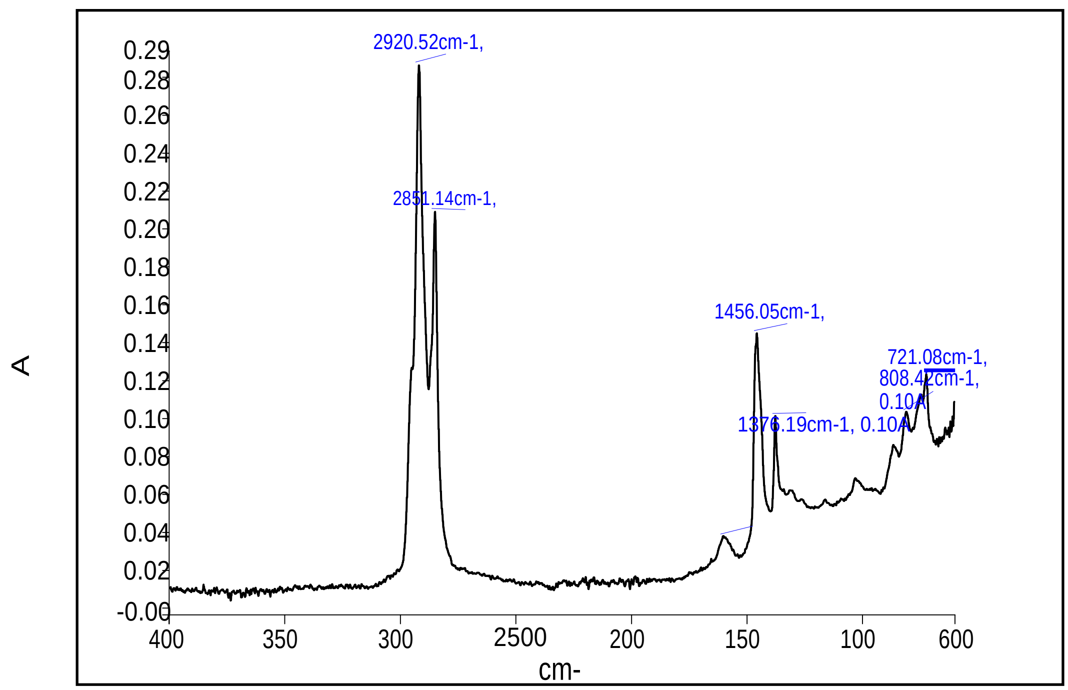


(d)

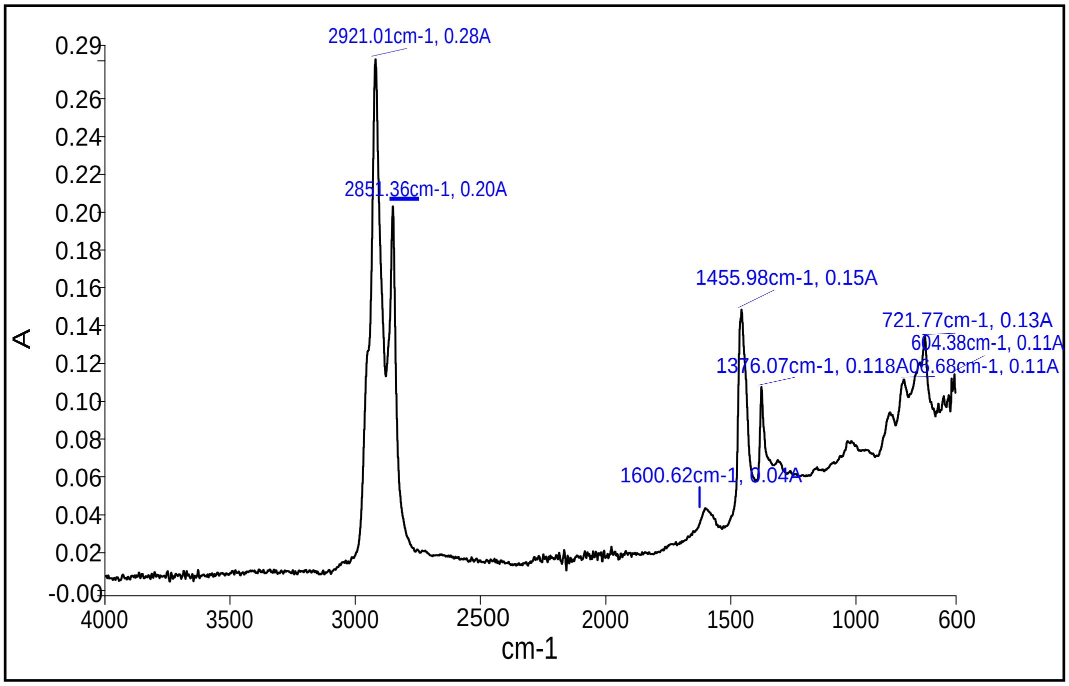
Figure 5.4 Variation of fatigue parameters with temperature for various binders (a) R-1 with WCO (b) R-2 with WCO (c) R-1 with WEO (d) d) R-2 with WEO

5.2.4 Fourier Transform Infra Red spectrum results

The FTIR spectroscopy test was carried out to determine the aging behavior of virgin binder, RTFO aged, RAP binder without rejuvenators and rejuvenated RAP binder (R-1 and R-2) with the addition of 6% WCO and WEO. The test results are depicted in Figures 5.5 a to Figure 5.5 f. The spectrum obtained relates to the absorbance and wave number and the peak height is observed at the wave number 2918 to 2922 cm-1. The wavenumber indicates the different functional groups present in the sample and includes compounds aldehydes, carboxylic acid, ketone, and the wavenumber resolution generally ranges from 400 to 4000 cm-1.

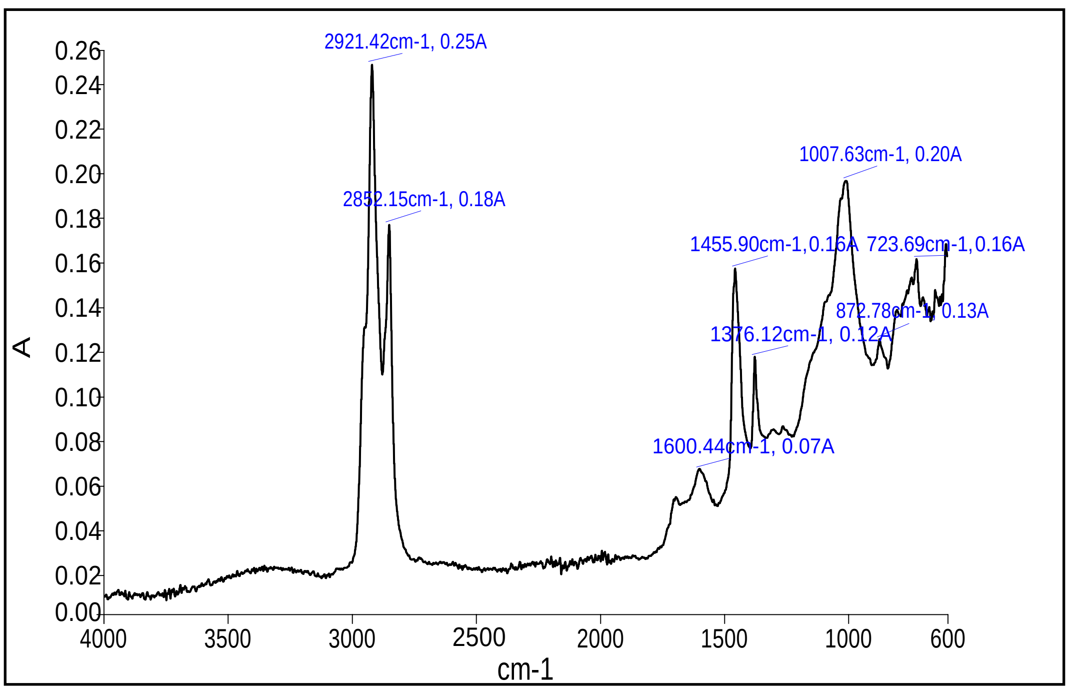


(a)



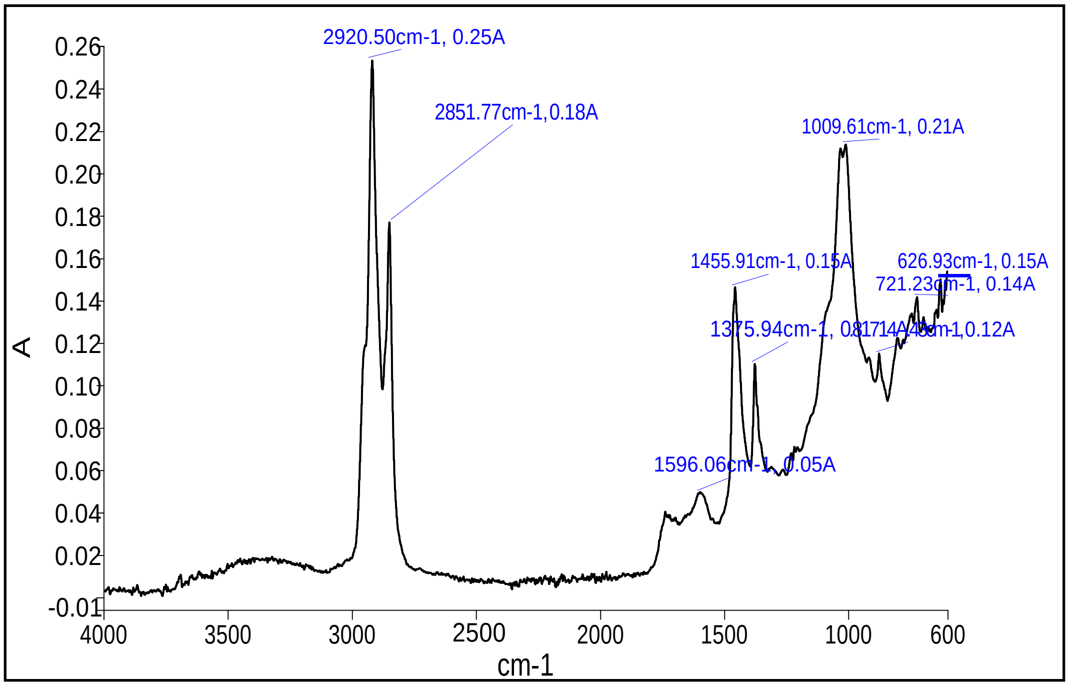
2921.01cm-1, 0.28A
2851.36cm-1, 0.20A
1455.98cm-1, 0.15A
721.77cm-1, 0.13A
604.38cm-1, 0.11A
1376.07cm-1, 0.118A
606.68cm-1, 0.11A
1600.62cm-1, 0.04A
A
cm-1

(b)

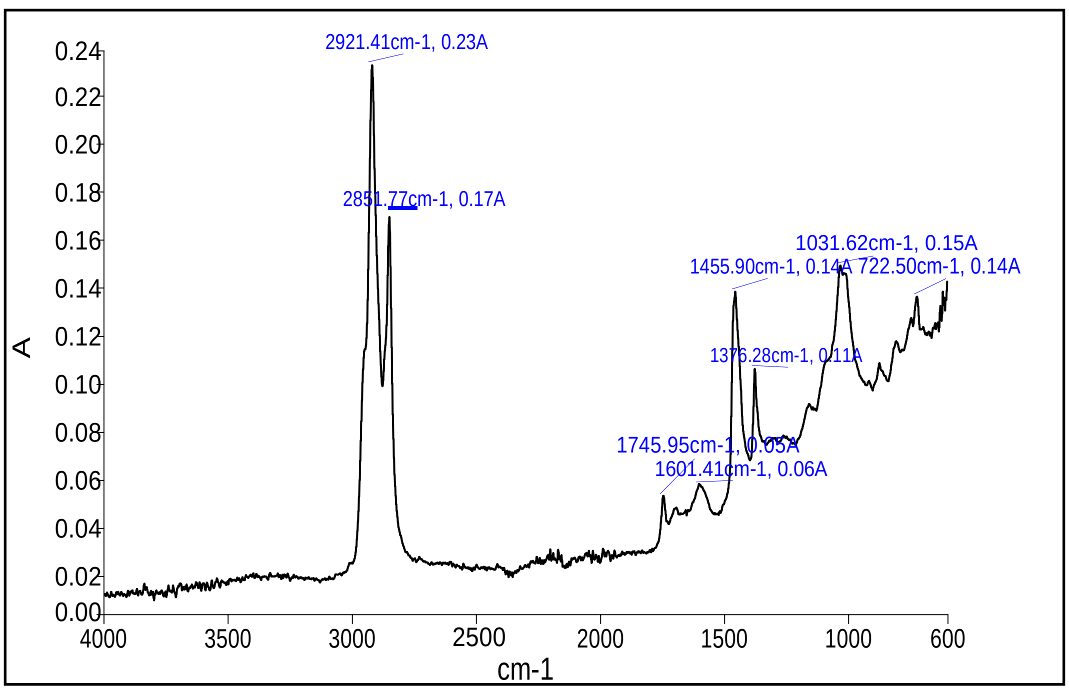


2921.42cm-1, 0.25A
2852.15cm-1, 0.18A
1007.63cm-1, 0.20A
1455.90cm-1, 0.16A
723.69cm-1, 0.16A
872.78cm-1, 0.13A
1376.12cm-1, 0.12A
1600.44cm-1, 0.07A
A
cm-1

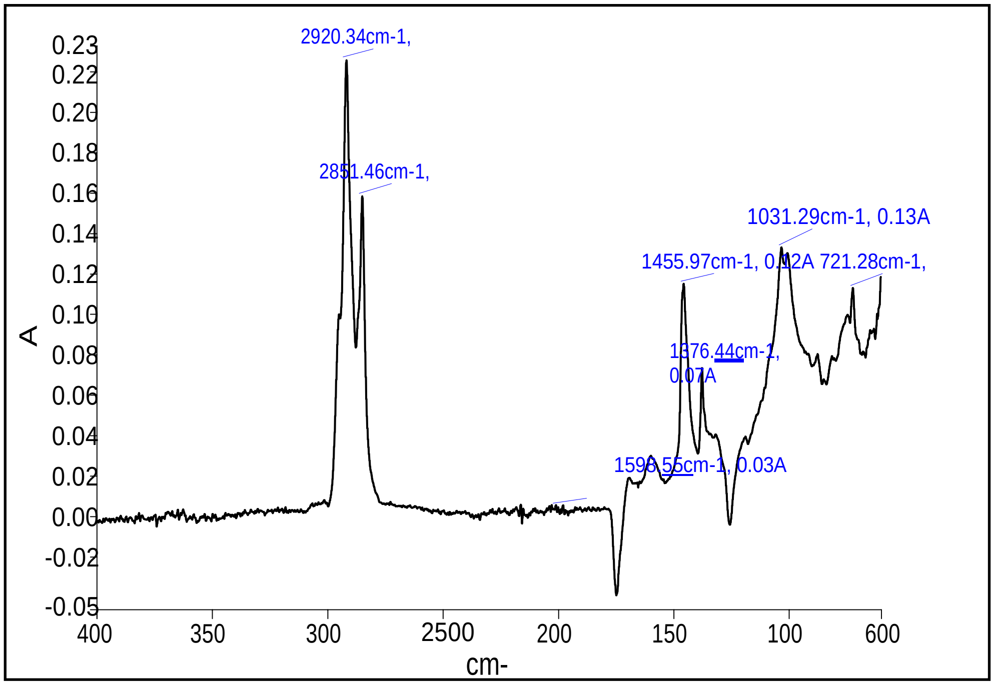
(c)


2920.50cm-1, 0.25A
2851.77cm-1, 0.18A
1009.61cm-1, 0.21A
1455.91cm-1, 0.15A
626.93cm-1, 0.15A
721.23cm-1, 0.14A
1375.94cm-1, 0.11A
1596.06cm-1, 0.05A
A
cm-1

(d)


2921.41cm-1, 0.23A
2851.77cm-1, 0.17A
1031.62cm-1, 0.15A
1455.90cm-1, 0.14A
722.50cm-1, 0.14A
1376.28cm-1, 0.11A
1745.95cm-1, 0.05A
1601.41cm-1, 0.06A
A
cm-1

(e)



(f)

Figure 5.5 FTIR Spectrum of VG 30, RAP and rejuvenated RAP Binder (a) Virgin VG 30 Binder (b) RTFO aged Binder (c) R-1 Binder (d) R-2 Binder (e) WCO rejuvenated Binder (f) WEO rejuvenated Binder

The results from the test had a similar spectrum having valleys and peaks, with major variations with the addition of plastic. The peak value obtained was in the range of 2845 – 2922 cm-1 which indicates the presence of saturated hydrocarbons in large proportion. From Figure 5.5, it is observed that the intensity of wave number around 1000 cm-1 for virgin binder and the RTFO aged binder is a lower indicating negligible quantity of sulfoxide group compounds. However, at the same wavenumber, the intensity is higher in binder reclaimed from R-1 material and R-2 material as seen in Figures 5.5c and 5.5 d. This indicates the presence of considerable amount of sulfoxide to cause oxidation leading to the ageing effect. In Figures 5.5 e and 5.5 f, the intensity has reduced by about 35% by the addition of 6% waste cooking oil and by about 30 % by the addition of 6 % waste engine oil. In addition, the area under this range has also spread over a wider area. This reduction in the sulfoxide compounds in rejuvenated binder mix is due to the presence of aromatic and aliphatic hydrocarbons in waste cooking and waste engine oils that renders softening to the stiff binder. This happens due to the reduction in the ratio of asphaltenes to maltenes, ensuring more maltenes are in the binder.

5.3 PERFORMANCE OF CONTROL, RAP AND REJUVENATED RAP MIXTURES

Different blends of rejuvenated RAP binders were investigated for preliminary investigation as discussed in the previous section. The current section deals with the viability of using rejuvenators in bituminous mixtures. Different ratios of RAP (30, 50 and 70 percent by weight of the total mixture) were blended with conventional/ original aggregates. For RAP mixes with rejuvenators, the required quantity of RAP aggregates was first heated to 150^0C and rejuvenators were added prior to addition of natural aggregates. The required quantity of natural aggregates was added and was further heated to 170^0C.Then the required quantity of VG 30 binder heated to 150^0C was added to the heated aggregate and mixed thoroughly until the surface of aggregates are uniformly and fully coated with the binder. Prior to mixing the amount of bitumen, the RAP aggregate contains was found to be 4%. So while doing mix design, the amount of natural bitumen to be added was found out by usual procedure. These specimens were later tested for determination of mixtures volumetric properties, static indirect tensile strength, moisture susceptibility, resistance to deformation caused due to rutting and fatigue. This section presents the details of SMA mix performance with different content of rejuvenated RAP material.

5.3.1 Volumetric and mechanical properties

Mixtures prepared with control and with different blends of rejuvenated RAP were evaluated for determining the Marshall properties. A total of thirteen mixes was considered for the study. The combinations of the mixes designed are illustrated in table 5.2 and 5.3 along with various volumetric properties of the mixes.

Table 5.2 Properties of SMA Mixtures with Different percentages of RAP rejuvenated with WCO

Mixture properties	Control Mix	R-1			R-2		
		30%	**50%**	**70%**	**30%**	**50%**	**70%**
OBC (%)	6.04	4.93	4.2	4.3	4.99	4.06	4.12
G_{mm} (g/cc)	2.44	2.443	2.437	2.439	2.438	2.434	2.435
G_{mb} (g/cc)	2.32	2.321	2.315	2.317	2.310	2.3	2.29
V_v (%)	4.2	4.4	4.08	4.1	4.3	4.25	4.2
VMA (%)	18.3	18.47	17.42	17.64	17.47	17.89	18.12
VCA_{MIX} (%)	38.45	34.13	32.67	31.64	35.91	33.09	33..08
VCA_{MIX}/ VCA_{DRC}	0.86	0.91	0.91	0.91	0.92	0.93	0.93
MS (kN)	13.4	17.2	18.69	20.1	16.36	18.12	19.20
Flow (mm)	3.9	4.3	4.5	4.7	4.46	4.59	4.67

From table 5.2, it clearly indicates that the volumetric properties of different mixes satisfy the requirements as per IRC: SP; 79-2008 specifications for stone matrix asphalt which was obtained through the Marshall Mix design process. It may be observed; as the RAP content in the mix is increased there is an increase in the binder content. This may be due to the fact that aged RAP materials tend to absorb more bitumen because of the thirst for more binder content. The increase in RAP has provided better results compared to that of the reference control mix. This indicates that the addition of higher percentages of RAP has not degraded the quality of the mix. It may also be observed that the addition of rejuvenator in the mix has also not affected the mix in a negative manner. A similar observation can be made in table 5.3 for the mixtures prepared with waste engine oil as a rejuvenator.

Table 5.3 Properties of SMA Mixtures with Different percentages of RAP rejuvenated with WEO rejuvenator

Mixture properties	Control Mix	R-1			R-2		
		30%	50%	70%	30%	50%	70%
OBC	6.04	4.90	4.23	4.0	4.94	4.28	4.12
G_{mm} (g/cc)	2.44	2.443	2.437	2.439	2.438	2.434	2.435
G_{mb} (g/cc)	2.32	2.321	2.315	2.317	2.310	2.3	2.29
V_v (%)	4.2	4.5	4.1	4.1	4.4	4.2	4.2
VMA (%)	18.6	18.49	18.42	18.64	17.32	17.69	18.03
VCA_{MIX} (%)	38.45	34.13	32.67	31.64	35.91	33.09	33..08
VCA_{MIX}/ VCA_{DRC}	0.86	0.92	0.93	0.93	0.92	0.93	0.93
MS (kN)	13.4	17.6	18.9	20.3	17.47	18.1	18.74
Flow Value (mm)	3.9	4.0	4.47	4.68	4.1	4.50	4.57

5.3.2 Indirect Tensile Strength

This test was conducted on cylindrical specimens compacted to 4% air voids as per ASTM D 6931 through Marshall Compactor. The cylindrical samples were loaded along its diametrical axis until failure at a constant rate of 75mm/min. A test was conducted until there was no further increase in load resisted by the sample. Table 5.4 presents the test results of IDT strength for control and RAP mixtures prepared with two different rejuvenators. It can be seen that as the content of RAP increased, the ability of the mixture to resist vertical deformation also increased. This is because the virgin binder is replaced by stiffer rejuvenated binder as there is an increase in RAP content. There is an approximate increase in ITS values by 14%, 25% and 33% in 30, 50 and 70 percent of RAP replacement. The table also suggests a better performance of the WCO rejuvenated mixture when compared to WEO rejuvenated RAP mixtures.

Table 5.4 Tensile strength values for various rejuvenated RAP mixtures

Mix Type	**ITS (Mpa)**	
Control Mix	0.78	
Rejuvenator	**WCO**	**WEO**
30% R-1	0.89	0.83
50% R-1	0.97	0.90
70% R-1	1.01	0.94
30% R-2	0.81	0.79
50% R-2	0.91	0.84
70% R-2	0.98	0.87

5.3.3 Moisture Susceptibility

a. Retained Stability Test

Retained stability tests were conducted on Control and two Rejuvenated RAP mixtures. The test results of retained stability are presented in the table. It can be seen that the rejuvenated RAP mixtures in general, improves the moisture susceptibility of the mixtures. It is also observed that the retained stability values in the case of mixtures with RAP having higher RAP content are higher than those with lower RAP content.

Table 5.5 Retained stability characteristics of rejuvenated RAP mixtures

Mix Type	Retained Marshall Stability (wet/Dry x 100)	
Control Mix	85.1	
Rejuvenator	**WCO**	**WEO**
30% R-1	87.2	86.9
50% R-1	89.0	88.3
70% R-1	92.9	90.0
30% R-2	86.2	84.3
50% R-2	87.6	86.8
70% R-2	89.1	88.4

b. Tensile Strength Ratio

The mixes should perform satisfactorily under various climatic conditions and changes in temperature throughout the day and also to the change in seasons throughout the year. The mixes were prepared and subjected to alternate freezing and thawing so as to simulate the field conditions. This test indicates the bonding of the mix under the presence of moisture. The unconditioned and conditioned specimens were tested for their strength. The ratio of the two should not be less than 80% so as to satisfy the recommendations laid down by the standards. The results of the tested samples are tabulated in table 5.6. It can be seen that the addition of rejuvenated RAP has not succumbed to the moisture effects. This may be due to the presence of strong aged binder film present over the particles and this bond between aged and fresh binder is assumed to be stronger with that of the fresh binder (Van Loon and Butcher 2003). This behaviour of rejuvenated RAP mix against the moisture damage were found to be consistent with both the RAP material and rejuvenators.

Table 5.6 Tensile Strength Ratio of Samples

Mix Type	TSR (%)	
Control Mix	81.25	
Rejuvenator	**WCO**	**WEO**
30% R-1	83.75	89.38
50% R-1	97.35	92.67
70% R-1	94.59	86.56
30% R-2	86.69	85.18
50% R-2	94.96	87.51
70% R-2	91.5	83.69

c. Boiling Test

The test was conducted as per ASTM D3625. The loose SMA mixtures were added to the boiling distilled water for 10 minutes. The average area of the aggregate surface stripped of the bitumen was visually observed and determined in terms of percentage after the mixture in beaker was cooled to room temperature. The test results are tabulated in table 5.7

Table 5.7 Stripping values of Control and rejuvenated RAP mixes

Mix Type	Average area of Stripping (%)	
Control Mix	10	
Rejuvenator	**WCO**	**WEO**
30% R-1	5	5
50% R-1	0	0
70% R-1	0	0
30% R-2	5	5
50% R-2	0	0
70% R-2	0	0

From table 5.7, it can be seen that there is considerable improvement in stripping characteristics of rejuvenated RAP based SMA mixes. The test results indicate a progressive decrease in stripping value with increase in RAP content. It is also observed that with the addition of RAP above 30% there were no traces of stripping. This may be because; generally RAP materials are already covered and protected with RAP binder (Al-Qadi et al. 2007). Thus, it can be assured that a RAP mixture has better resistance towards moisture damage compared to conventional mixtures.

5.3.4 Rutting Properties

Rutting is one of the major causes of pavement functional failures. It is the accumulation of the plastic deformation resulted from the application of repeated traffic loads. This may be due to the densification of bituminous mixtures or shear deformation. These characteristics are influenced by the gradation and stiffness of the mixture. It is learned that the addition of RAP in asphalt mix increases its ability to resist plastic deformation and hence testing of this property is of utmost importance. Laboratory rutting test on rejuvenated RAP based SMA mixes was studied using the immersion wheel tracking test machine. Tests were conducted and rutting in the mixes was measured using a data acquisition system acquired through linear Vertical Displacement Transducer (LVDT) after 10,000 load cycles. One load cycle means to and fro movement of the loaded wheel on the test sample. Table 5.8 summarizes the rutting test results of SMA mixes without RAP, 30% RAP, 50% RAP and 70% RAP content. From the figure, it can be seen that the mixes with higher RAP indicate lower deformation values. It can be seen that the rut depth of all the samples is below 5mm indicates a better stone to stone contact established between the aggregates in the mix. Further, the addition of RAP in the mix has reduced the rut depth approximately by 1mm. This may be due to the increased stiffness in the mix upon the inclusion of RAP.

Table 5.8 Rutting Values of RAP based SMA mix with WCO Rejuvenator

Number of Passes	Deformation (mm)						
	Control Mix	R-1			R-2		
		30%	50%	70%	30%	50%	70%
0	0	0	0	0	0	0	0
1000	1.8	1.3	1.1	1.0	1.0	1.0	0.8
2000	2.1	1.6	1.3	1.2	1.4	1.2	1.1
3000	2.3	1.9	1.6	1.6	1.8	1.6	1.5
4000	2.7	2.4	2.0	2.0	2.4	1.9	1.9
5000	3.0	2.7	2.4	2.3	2.7	2.3	2.2
6000	3.4	3.0	2.7	2.6	3.1	2.7	2.4
7000	3.6	3.2	3.0	2.9	3.3	2.9	2.7
8000	3.9	3.4	3.4	3.1	3.4	3.2	2.9
9000	4.1	3.7	3.7	3.4	3.7	3.5	3.2
10000	4.4	3.9	4.0	3.7	3.9	3.6	3.3

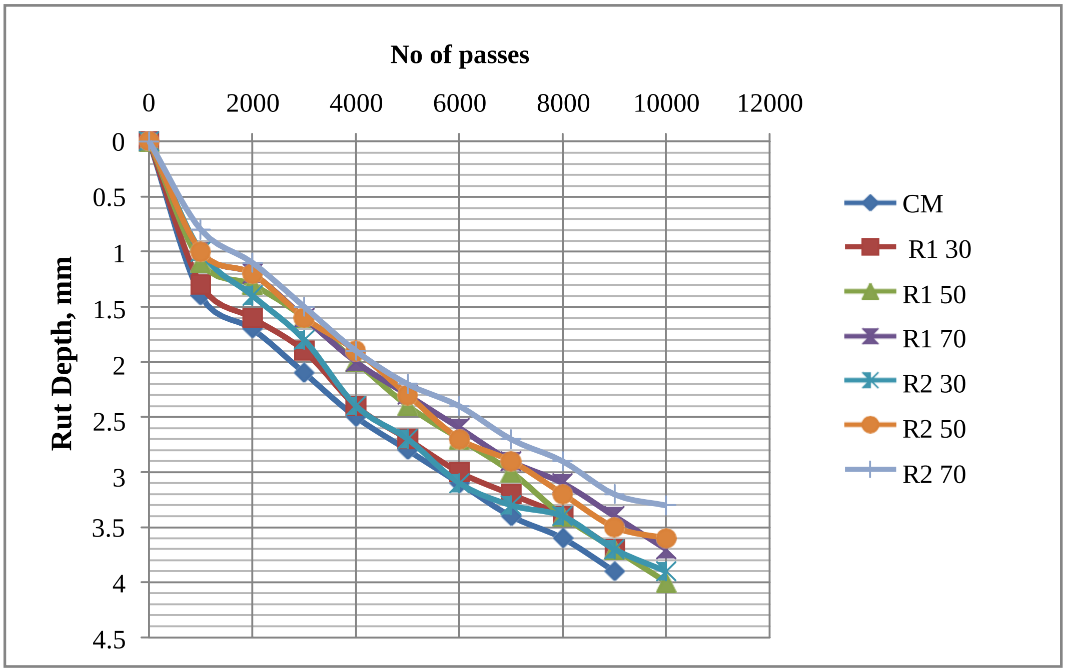


Figure 5.6 Rutting Deformation of RAP based SMA mix with WCO Rejuvenator

Table 5.9 Rutting Values of RAP based SMA mix with WEO Rejuvenator

Number of Passes	Deformation (mm)						
	Control Mix	R-1			R-2		
		30%	50%	70%	30%	50%	70%
0	0	0	0	0	0	0	0
1000	1.8	1.4	1.1	0.9	1.2	1	0.8
2000	2.5	1.6	1.4	1.2	1.3	1.1	1.1
3000	3.6	2	1.6	1.6	1.8	1.3	1.4
4000	4.3	2.5	2.1	2	2.2	1.5	1.6
5000	5.2	2.7	2.4	2.2	2.5	1.8	1.9
6000	5.6	3.1	2.8	2.6	2.8	2.2	2
7000	5.8	3.2	3.1	2.9	3	2.4	2.2
8000	6.6	3.5	3.4	3	3.3	2.7	2.5
9000	7.3	3.8	3.6	3.4	3.5	3	2.7
10000	7.7	4.3	4	3.6	3.8	3.2	3

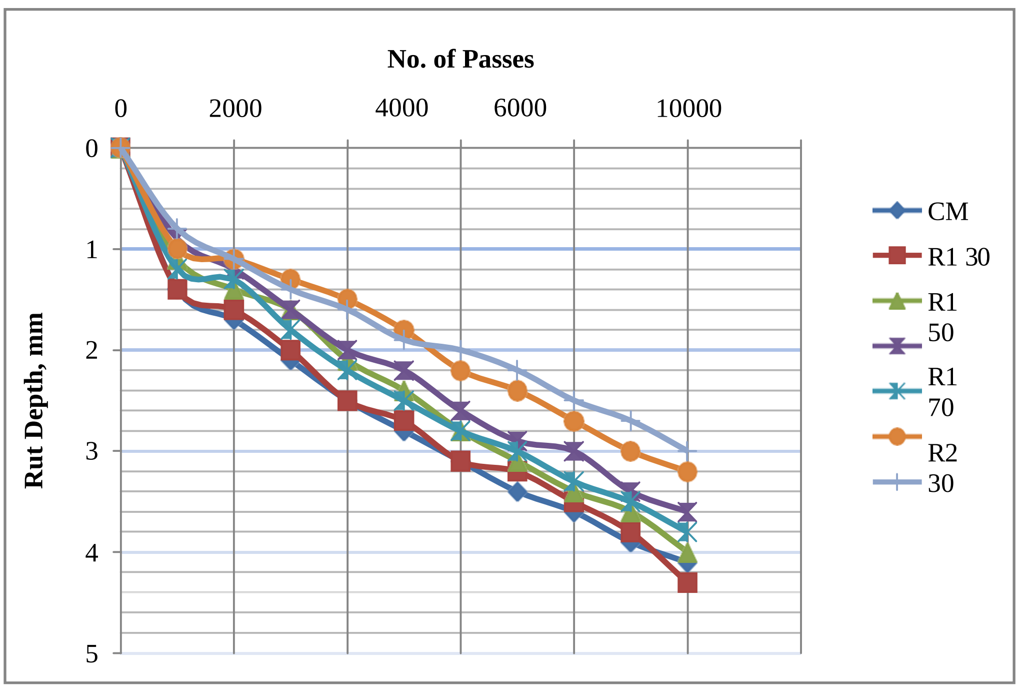


Figure 5.7Rutting Deformation of RAP based SMA mix with WEO Rejuvenator

5.3.5 Fatigue Properties

The nature of highway traffic loading and climatic environment is such that any point within a pavement is subjected to a diverse and almost infinite spectrum of stresses and strains Traditionally the design of flexible pavements have followed the approach wherein the pavement thickness is expressed as the number of repetitions of standard loads to failure under various subgrade support values. Fatigue is the accumulation of damage in bituminous mixes under the effect of repeated loading. The fatigue damage accumulation results in cracking which is one of the main types of distress occurring in flexible pavements. Therefore, thorough information of damage caused by fatigue on the pavement becomes very essential if pavement design principles are to be applied. To evaluate the permanent deformation of the RAP based SMA mixes rejuvenated by Waste Cooking Oil and Waste Engine Oil, repeated load indirect tensile fatigue test in controlled stress mode test was carried out. Failure in controlled stress mode can be defined wherein; the stress is kept constant by increasing the strain on the samples during the test. In this mode, the stress will break the sample at the completion of the test. This makes it easier to define the failure as the fracture of the sample. The specimens were prepared to target air voids of 7%. The specimens were tested at the stress levels of 15%, 30% and 45% of the Indirect Tensile Load. The test was conducted at 25^0C. Determination of failure limit in a repeated load indirect fatigue test in the laboratory has relied completely on the arbitrary selection of the fixed criterion. The number of repetitions taken by the specimen to either deform horizontally or vertically by 5mm at each stress level was recorded. The test results are tabulated in Table 5.10 and presented in figure 5.8.

Table 5.10Fatigue Life of R-1 based SMA Mixtures with WCO Rejuvenator

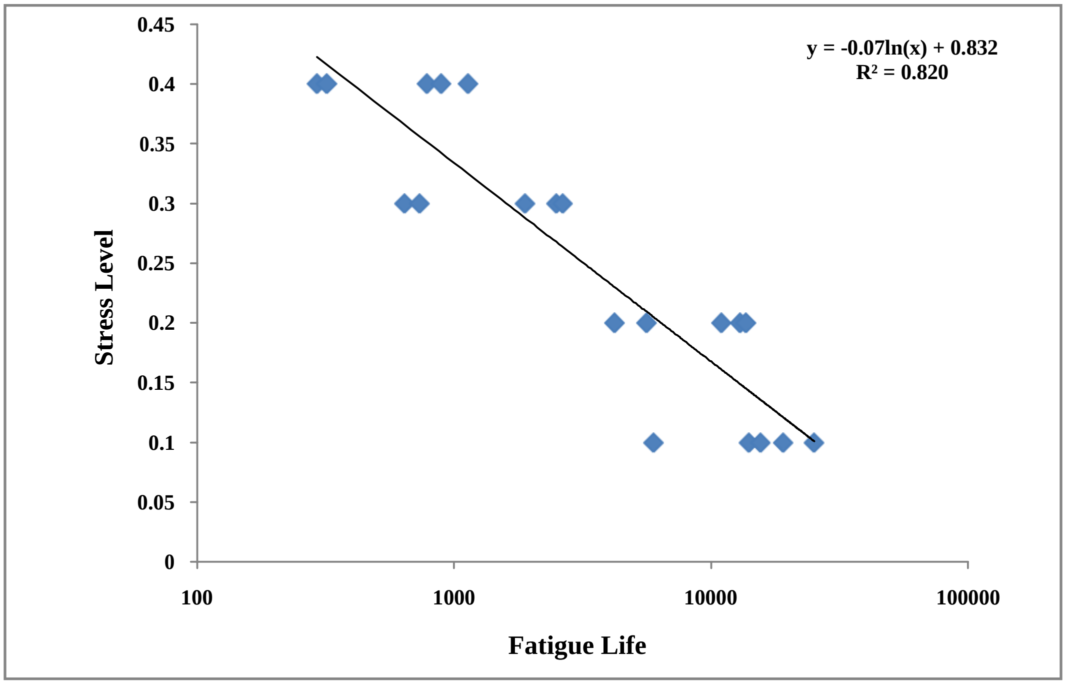
Mix ID	Specimen No	Stress Ratio			
		0.4	0.30	0.2	0.1
	No of cycles to failure (Fatigue Life), N				
CM	1	292	643	4212	5990
	2	320	732	5600	14073
	3	784	1890	10962	15546
	4	892	2498	12985	19058
	5	1132	2644	13692	25173
30% R-1	1	276	1204	2498	4415
	2	528	1290	5030	8675
	3	628	1779	11369	24414
	4	816	2619	12212	26477
	5	1400	3396	14753	32366
50% R-1	1	316	996	5015	9966
	2	472	1576	7427	13917
	3	560	1802	9260	20736
	4	880	3156	14444	27954
	5	1268	3972	17351	34155

70% R-1	1	364	1156	3604	10589
	2	444	1752	9227	16579
	3	652	1940	9803	22215
	4	1304	3684	13902	30649
	5	1456	4248	18364	37655

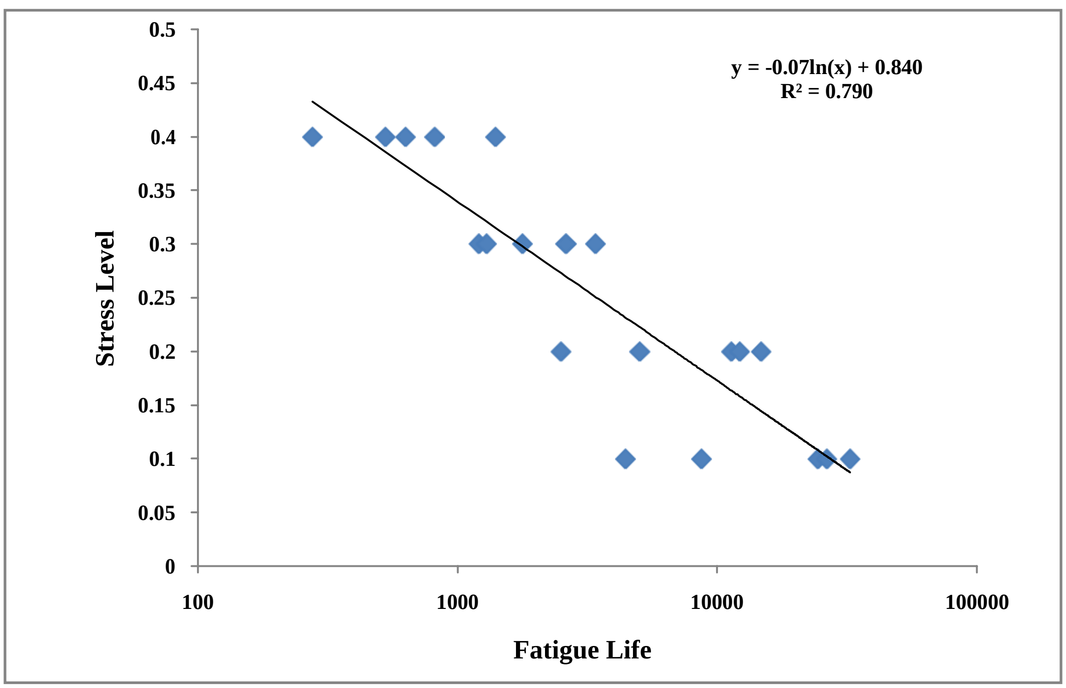
From the table 5.10 and figure 5.8 it can be observed that the number of repetitions for the samples to reach the 5mm failure criteria in the case of RAP rejuvenated mixes is higher than the control mix. However, there is an increasing trend in the load repetitions with an increase in the RAP content. This may be attributed to the fact that the RAP in the mix offers the required strength up to a certain extent and also the rejuvenators soften the binder to ensure that the binder does not lose its flexibility and become stiff at a lower temperature.

Table 5.11 Fatigue Life of R-2 based SMA Mixtures at with WCO Rejuvenator

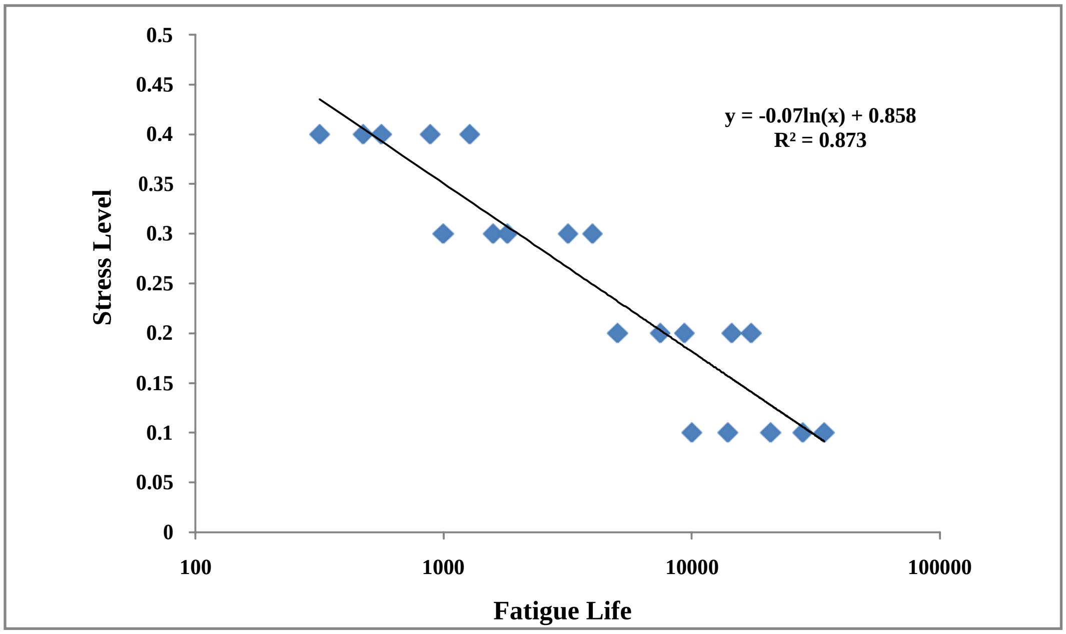
Mix ID	Specimen No	Stress Ratio			
		0.4	0.30	0.2	0.1
	No of cycles to failure (Fatigue Life), N				
CM	1	292	643	4212	5990
	2	320	732	5600	14073
	3	784	1890	10962	15546
	4	892	2498	12985	19058
	5	1132	2644	13692	25173
30% R-2	1	234	896	3631	8591
	2	314	1195	5719	14161
	3	496	1316	10223	16208
	4	643	2195	11343	19262
	5	1117	3246	15113	27014
50% R-2	1	243	872	3517	8115
	2	378	1379	6685	11332
	3	448	1577	8334	16885
	4	704	2762	12999	22762
	5	1014	3476	15615	27812
70% R-2	1	294	1052	3849	7056
	2	544	1297	7110	12453
	3	602	1563	8791	22762
	4	784	2959	13416	27006
	5	1206	4102	17313	29886


y = -0.07ln(x) + 0.832
R² = 0.820
Stress Level
Fatigue Life
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
100
1000
10000
100000

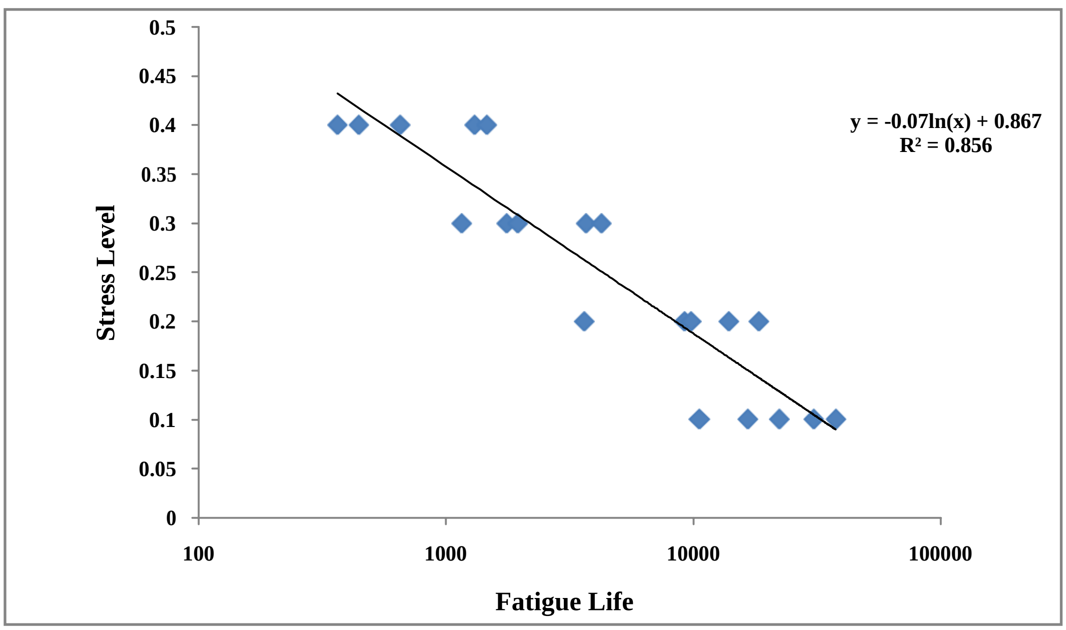
(a)


y = -0.07ln(x) + 0.840
R² = 0.790
Stress Level
Fatigue Life
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
100
1000
10000
100000

(b)



(c)



(d)

Figure 5.8 S-N curve for Control Mix and WCO based R-1 SMA Mixes (a) Control Mix (b) 30% R1 (c) 50% R1 (d) 70% R1

Table 5.12 Fatigue Life of R-2 based SMA Mixtures with WEO Rejuvenator

Mix ID	Specimen No	Stress Ratio			
		0.4	0.30	0.2	0.1
	No of cycles to failure (Fatigue Life), N				
CM	1	292	643	4212	5990
	2	320	732	5600	14073
	3	784	1890	10962	15546
	4	892	2498	12985	19058
	5	1132	2644	13692	25173
30% R-1	1	226	937	1892	10044
	2	307	1845	4900	12365
	3	692	2266	8351	18972
	4	1228	3013	14641	22120
	5	1447	3438	15741	27166
50% R-1	1	281	896	2604	8827
	2	437	1418	7180	12327
	3	518	1622	8951	18367
	4	814	2840	13962	24759
	5	1173	3575	16772	30252
70% R-1	1	351	1364	3658	3747
	2	533	1571	10726	14171
	3	1084	2563	13376	21145
	4	1147	3413	16466	27936
	5	1561	3915	19709	31278

Table 5.13Fatigue Life of R-2 based SMA Mixtures at with WEO Rejuvenator

Mix ID	Specimen No	Stress Ratio			
		0.4	0.30	0.2	0.1
	No of cycles to failure (Fatigue Life), N				
CM	1	292	643	4212	5990
	2	320	732	5600	14073
	3	784	1890	10962	15546
	4	892	2498	12985	19058
	5	1132	2644	13692	25173
30% R-2	1	269	691	2736	5774
	2	358	854	5528	8685
	3	509	1712	8583	13391
	4	554	2592	8788	22761
	5	1027	2758	14837	23500
50% R-2	1	228	847	2780	7973
	2	354	1340	5447	11134
	3	420	1532	6791	16589
	4	660	2683	10592	22363
	5	951	3376	12724	27324
70% R-2	1	256	912	3694	9601
	2	387	1265	5036	11250
	3	454	1789	8980	14473
	4	781	3091	14915	23853
	5	1088	3532	15969	29239

Table 5.14 Relationship between fatigue cycle (N) and the stress level (SR) for control and varying percentages of rejuvenated RAP based SMA mixes.

Mix ID	Equations	R^2
CM	ln(N)=0.832-SR/0.07	0.820
WCO Rejuvenated RAP mixes		
30% R-1	ln(N)=0.957-SR/0.02	0.790
50% R-1	ln(N)=0.954-SR/0.02	0.873
70% R-1	ln(N)=0.948-SR/0.02	0.856
30% R-2	ln(N) = 0.954-SR/0.02	0.871
50% R-2	ln(N) = 0.952-SR/0.02	0.861
70% R-2	ln(N) = 0.944-SR/0.02	0.849
WEO Rejuvenated RAP mixes		
30% R-1	ln(N)=0.955-SR/0.02	0.802
50% R-1	ln(N)=0.951-SR/0.02	0.847
70% R-1	ln(N)=0.950-SR/0.02	0.763
30% R-2	ln(N)=0.956-SR/0.02	0.832
50% R-2	ln(N)=0.953-SR/0.02	0.870
70% R-2	ln(N)=0.949-SR/0.02	0.853

From the table 5.14, it can be noticed that the WCO rejuvenated RAP mixes with 50% RAP display higher resistance to fatigue failure as compared to control mix and mixes with 30% and 70% RAP irrespective of the applied stress level. This may be due to the better interfacial bond between the RAP and original materials occurring in RAP mixes as compared to that occurring in control mixes (Zaumanis et al. 2014). The fatigue life of rejuvenated RAP mixes decreased with the inclusion of 70% RAP but exhibited resistance that was comparatively better to that of a control mix. A similar trend was observed in the WEO rejuvenated RAP mixes. The fatigue behaviour of rejuvenated SMA mixes with a higher content of RAP was better compared to that of the mixes without rejuvenation and also the control mixes, thereby indicating the significance of rejuvenation in aged RAP. These results suggests the possibility of using RAP up to 100% in controlled condition can be done thereby ensuring that these precious material do not go waste into the landfill or dump yards (Zaumanis et al. 2014).

5.3.6 Fracture resistance of SMA mixes

The resistance to fracture of SMA mixtures can be determined using the Semi-Circular Bending (SCB) test based upon the principle of fracture mechanism.

Table 5.15 Cracking resistance of WCO rejuvenated R-1 SMA Mixes

Sl. No	RAP (%)	Displacement (mm)	Maximum load (N)	Strain Energy (N-mm)
25 mm Notch				
1	0	3.04	364.5	910.0000
	30	2.32	718.4	1400.100
	50	2.78	808.00	1425.000
	70	2.29	950.80	1585.000
32 mm Notch				
2	0	3.85	357.00	750.000
	30	2.95	674.80	1085.000
	50	2.59	792.00	1135.00
	70	2.24	926.40	1343.00
38 mm Notch				
3	0	1.82	325.00	645.000
	30	1.70	648.60	960.000
	50	1.60	783.00	995.000
	70	1.40	866.20	1083.000

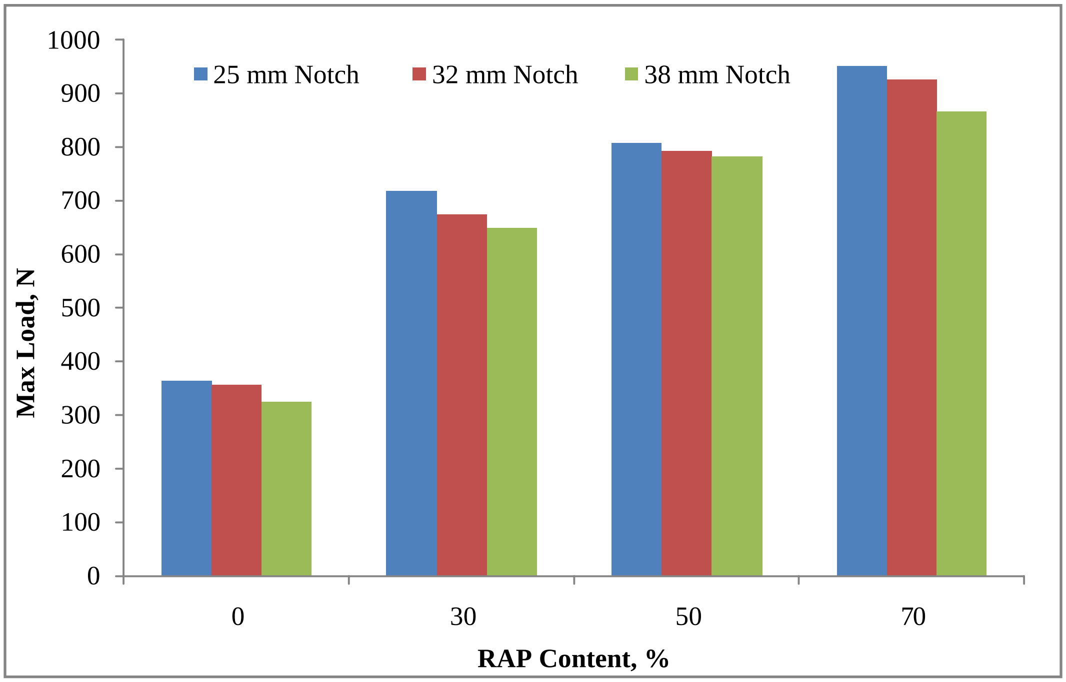


Figure 5.9 Maximum Load sustained by WCO rejuvenated R1 Mixes at different Notch Depth

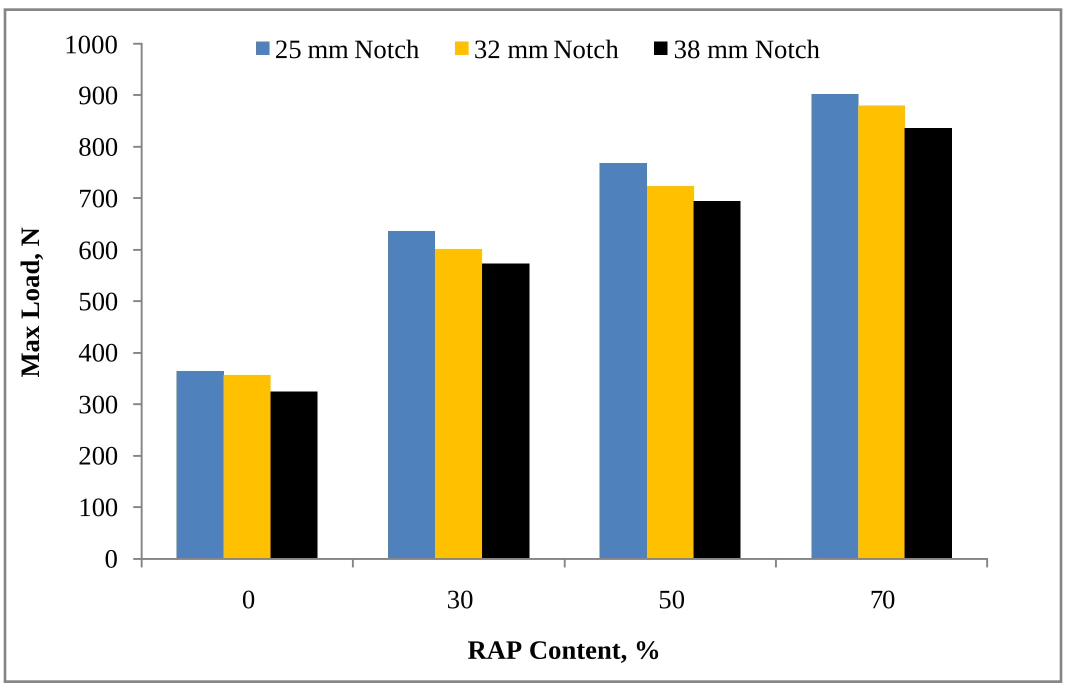


Figure 5.10 Load sustained by WCO rejuvenated R2 Mixes at different Notch Depth

Table 5.16Critical Strain Energy for WCO rejuvenated R-1 SMA mixes

Sl. No.	RAP Content %	Notch Depth, m	Strain Energy, KJ	Slope	Critical Strain Energy, Jc
1	0	0.025	0.000910	-0.034	0.46
		0.032	0.000750		
		0.038	0.000645		
2	30	0.025	0.001400	-0.033	0.52
		0.032	0.001025		
		0.038	0.000960		
3	50	0.025	0.001425	-0.032	0.59
		0.032	0.001135		
		0.038	0.000995		
4	70	0.025	0.001585	-0.038	0.70
		0.032	0.001343		
		0.038	0.001083		

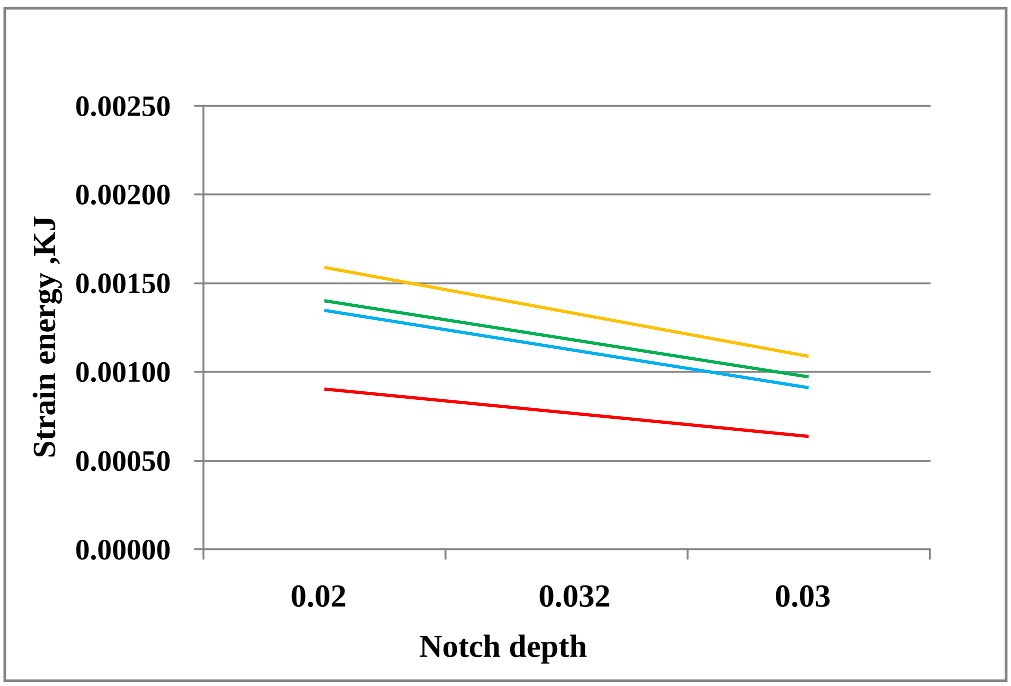


Figure 5.11 Strain Energy of WCO Rejuvenated R-1 SMA mixes

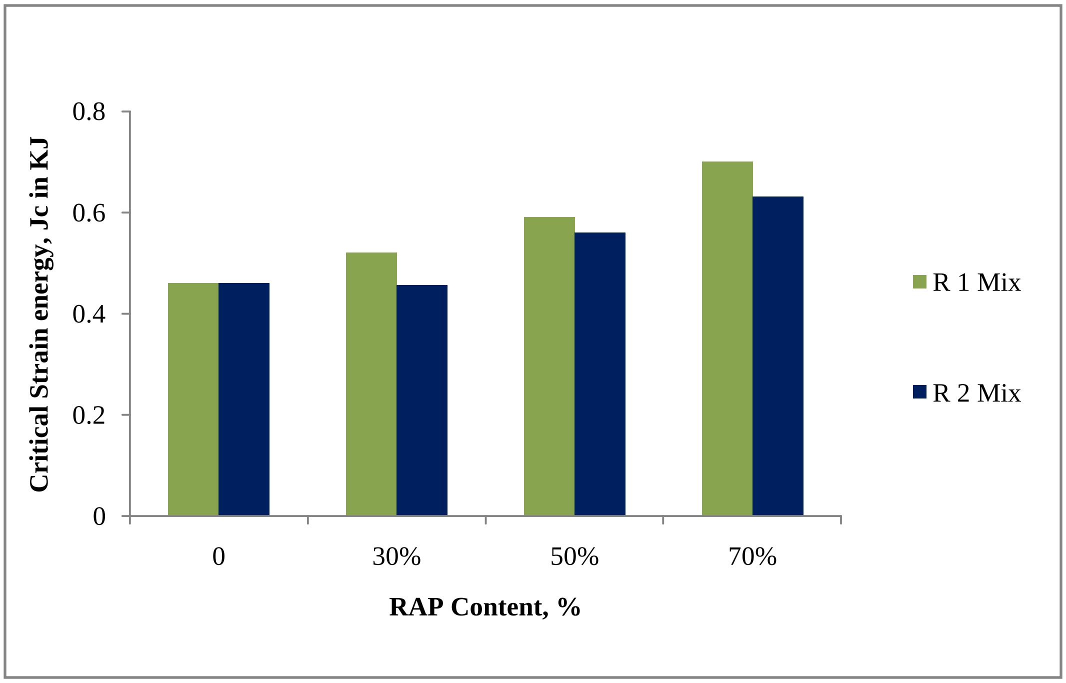


Figure 5.12 Critical Strain Energy for WCO Rejuvenated RAP based SMA mixes.

This test is very useful to predict fracture potential of asphalt mixtures. Higher the value of the J- integral indicates better resistance of the mix to fracture. The rate of critical energy release also called Jc was determined by the SCB test.

The typical results of SCB tests indicates a vertical load applied on the specimen gradually increases and the actuator controlled displacement measured in terms of mm is progressively increased. The specimen resists the applied load up to a fracture point and then starts to fail till the prescribed displacement is reached. The test results predicted the mix with rejuvenated RAP mix will fail at a much higher level of displacement indicating the better elongation capabilities of the mix after the rejuvenation. This was elongation capabilities was not observed with the mix containing untreated RAP indicating more brittleness compared to the control mixes. Also the figure 5.18 depicts a comparison of critical strain energy rate for WCO rejuvenated R-1 SMA mix with the different RAP content evaluated in this study. From the figure, the addition of RAP in the mix engineered with rejuvenating additive outperformed the control/ conventional mixes prepared with fresh binder and aggregates given its high stiffness characteristics (Behnood 2019; Majidifard et al. 2019; Porot et al. 2017) . The increase in critical strain Energy value was found to be about 13%, 28% and 52 % to 30%, 50% and 70% RAP respectively when compared to the value obtained for control mixes. A similar trend was observed in the mixes rejuvenated from WEO irrespective of the source of RAP. The overall observations indicated a significant effect of rejuvenation of RAP mixes to increase the performance aspects with higher replacement levels (Zaumanis et al. 2014). These studies endorse the sustainable pavement construction through 100% utilization of RAP in bituminous mixes (Mallick et al. 2010; Zaumanis et al. 2014)

5.4 SUMMARY

The tests conducted on the rejuvenated RAP based SMA mixes revealed that the properties of the mix were better compared to that of the control mixes in all the tests conducted to check the suitability of higher RAP usage. The hardened aged binder in the RAP tends to soften upon the use of rejuvenators and more or less display the same characteristics exhibited by the conventional VG30 binder. The performance aspects such as rutting, fatigue and moisture susceptibility of the rejuvenated mix were found to be better to conventional mix. Overall results indicate the significance of rejuvenators usage in the utilization of high RAP content in SMA mix. The major conclusions of the research work are drawn in the chapter 6.

CHAPTER 6

CONCLUSIONS

6.1 GENERAL

The development and understanding of recycling of asphalt pavement mixes are of significant interest because these techniques are proven to be cost-effective along with superior mechanical and durability performance, with lower carbon footprints. The current study presents the investigations carried out to evaluate the suitability of Reclaimed Asphalt Pavement (RAP) with rejuvenators to produce bituminous mixes. The main focus of the study was oriented towards the utilization of a higher amount of RAP material without compromising the durability and performance of the outcome bituminous mixture.

The following conclusions are drawn based on the results on the mechanical and performance properties of RAP based SMA mixes with Waste Cooking Oil and Waste Engine Oil as Rejuvenators.

A. Binder Characteristics

1. The binders became stiffer with the increase in RAP binder content. This was quite evident in the reduced value of penetration and an increased mercury level in the softening point of the fresh and RAP binder.
2. The inclusion of Waste Cooking Oil and Waste Engine Oil as a rejuvenator to the RAP binder was found to negate the problem of stiffness in the resulting mix. This was very much reflected in the results of penetration, softening point and G* values. The rejuvenating effect of Waste Engine Oil and Waste Cooking Oil was found to perform better at 6% by weight of the binder.
3. The improvement in rutting and fatigue parameters of the Rejuvenated RAP binder was very clear on the values of $G^*/\sin\delta$ and $G^*\sin\delta$ that resulted in the utilization of higher RAP content.

B. Evaluation of Volumetric and Mechanical properties

4. The mix design properties of RAP based SMA Mix with reference to the Control Mix are better. The OBC required in RAP has increased with the increase in the RAP content. This may be due to that the RAP aggregates coated with bitumen may absorb more binder. However, the quantity of the Virgin binder added to the mix is comparatively low with respect to the conventional mixes. The other properties of Mix design were found to be within the specified limits as per IRC recommendations.

C. Performance Characteristics

5. The rejuvenated RAP based SMA mixes exhibited better resistance to moisture damage in all the tests conducted to evaluate durability i.e., TSR, Boiling test and retained stability indicating that the RAP materials in the mix have not affected its performance. The RAP mixes have exhibited better resistance to moisture damage compared to that of the base mixes indicating better durability. This may be due to the rejuvenating effect with larger binder content.
6. Based on the findings of the performance of rejuvenated RAP mixes, the best performance was found with respect to the rutting resistance of SMA mixes. With the increase in RAP content the mixtures exhibited an enormous amount of resistance to permanent deformation. Higher the RAP content better was the rutting performance. These results were consistently observed in both the binder and bituminous mixture.
7. The fatigue performance of RAP mixtures without any rejuvenation resulted in a deteriorated performance with the increase in RAP content. This may be due to the stiffness in overall mixtures; this reduces the material's ability to recover the accumulated strain due to the repeated application of loads. Thus, leads to premature failure.
8. The inclusion of Waste Cooking Oil and Waste Engine Oil as rejuvenators has clearly indicated the reduction in the stiffness of the age binder at low temperature. This resulted in the overall reduction in stiffness of the mixture and thus enabling the mix to recover the strain level and perform better when compared to the reference mix without RAP.
9. Both the rejuvenators proved to be significantly effective in utilization of Reclaimed Asphalt Pavement material in larger quantities.
10. Higher the percentage of RAP in the mix reduces the need for fresh aggregates which is a big bonus in the light of environment protection and energy usage.

The rejuvenated SMA mixes with higher RAP have shown satisfactory results for their use in highway applications. It can be stated that the utilization of RAP base bituminous mixes leads to the minimized consumption and production of conventional bituminous mixes, which in turn can contribute to lower CO2 emissions. The utilization of RAP in bituminous mix leads to the conservation of natural aggregates and solves the disposal related problem associated with RAP. Efforts should be made by the government to patronage and to popularize the use of these types of recycling activity in the national infrastructure projects.

6.2 SCOPE FOR FUTURE STUDIES

Based on the present study further investigations can be extended to:

- Validation of higher RAP content by test track studies.
- Use of other rejuvenators to study the performance of SMA mixes.
- Other cost-effective techniques to endorse the concept of sustainability to meet the current environment deterioration issues.

APPENDIX A

Example: Calculation of mix design properties of Control SMA Mix.

Consider a mixture with 5% of bitumen content.

- Weight of aggregate = 1200g
- Weight of bitumen= 69g
- Total weight of mixture = 1269g
- Bulk Specific gravity of aggregates Gsb = 2.684g/cc
- Maximum theoretical density of loose mixture, Gmm = 2.488g/cc
- Bulk Density of specimen Gmb =2.32g/cc
- Air Voids V_v = $\frac{Gmm-Gmb}{Gmm}$ x100 = 6.46%.
- Aggregate Content = 100 x [1200/(1200+66)] = 94.78
- Voids in Mineral Aggregates (VMA) =100- $\frac{Gmb*Ps}{Gsb}$ = 18.7%
- Voids filled with Bitumen =$\frac{VMA-Vv}{VMA}$ x 100

APPENDIX B

Example: Calculation of unconditioned and conditioned ITS and TSR values of Control SMA mix with 6.04 % of binder content.

Indirect Tensile Strength = $\frac{2000P}{\pi D t}$

Unconditioned Specimen

P, Load at failure = 7.79 KN

D, Diameter of Specimen= 100 mm

T, Thickness of specimen =63.5 mm

ITS= 780.673kPa

Conditioned Specimen

P, Load at failure = 6.33 KN

D, Diameter of Specimen= 100 mm

T, Thickness of specimen =63.5 mm

ITS= 634.297 kPa

Tensile Strength Ratio = $\frac{\text{Conditioned ITS}}{\text{Unconditioned ITS}}$

TSR= 81.25 %

APPENDIX C

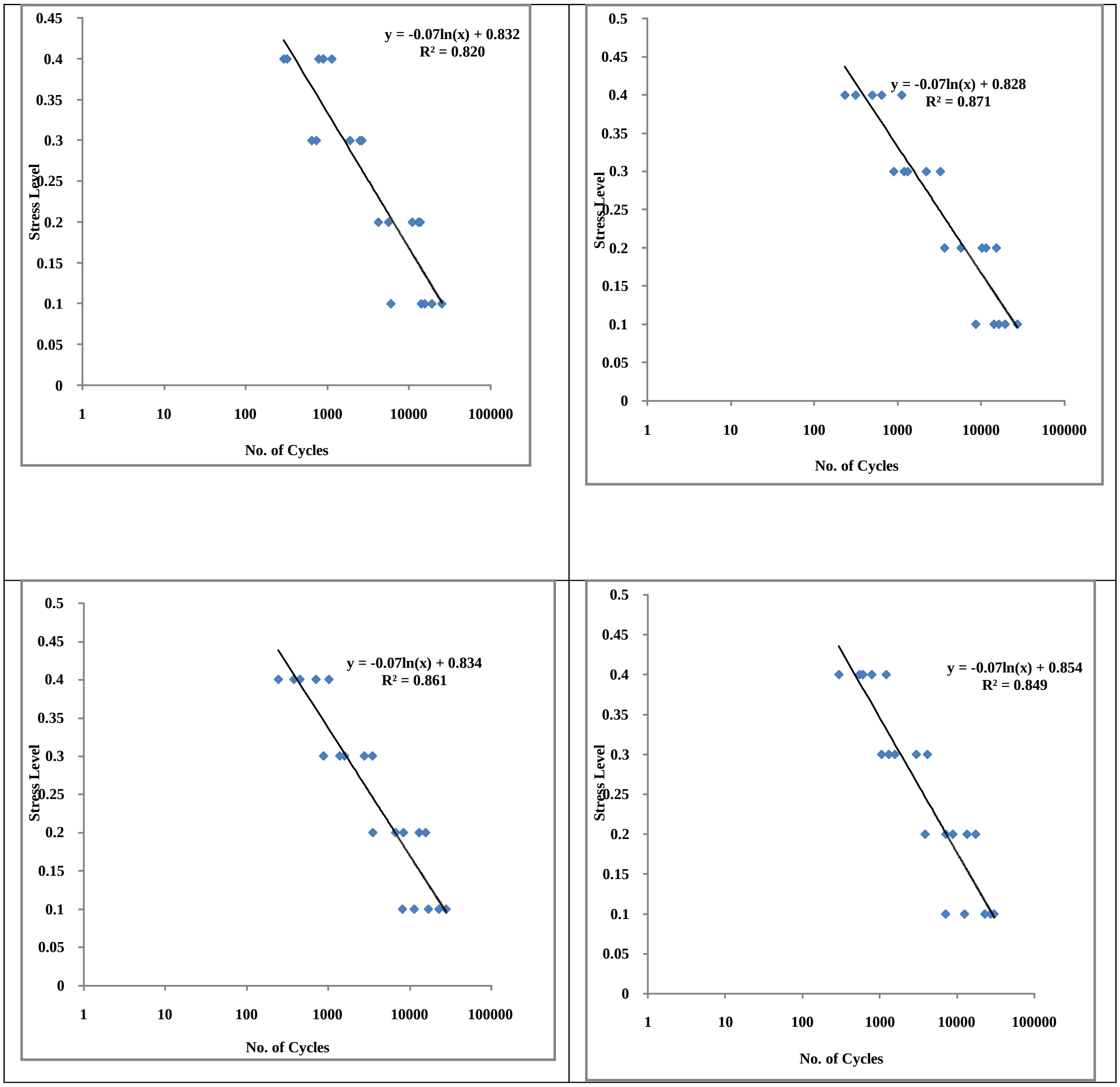


Figure A 5.1 S-N curve for Control Mix and WCO based R-2 SMA Mixes

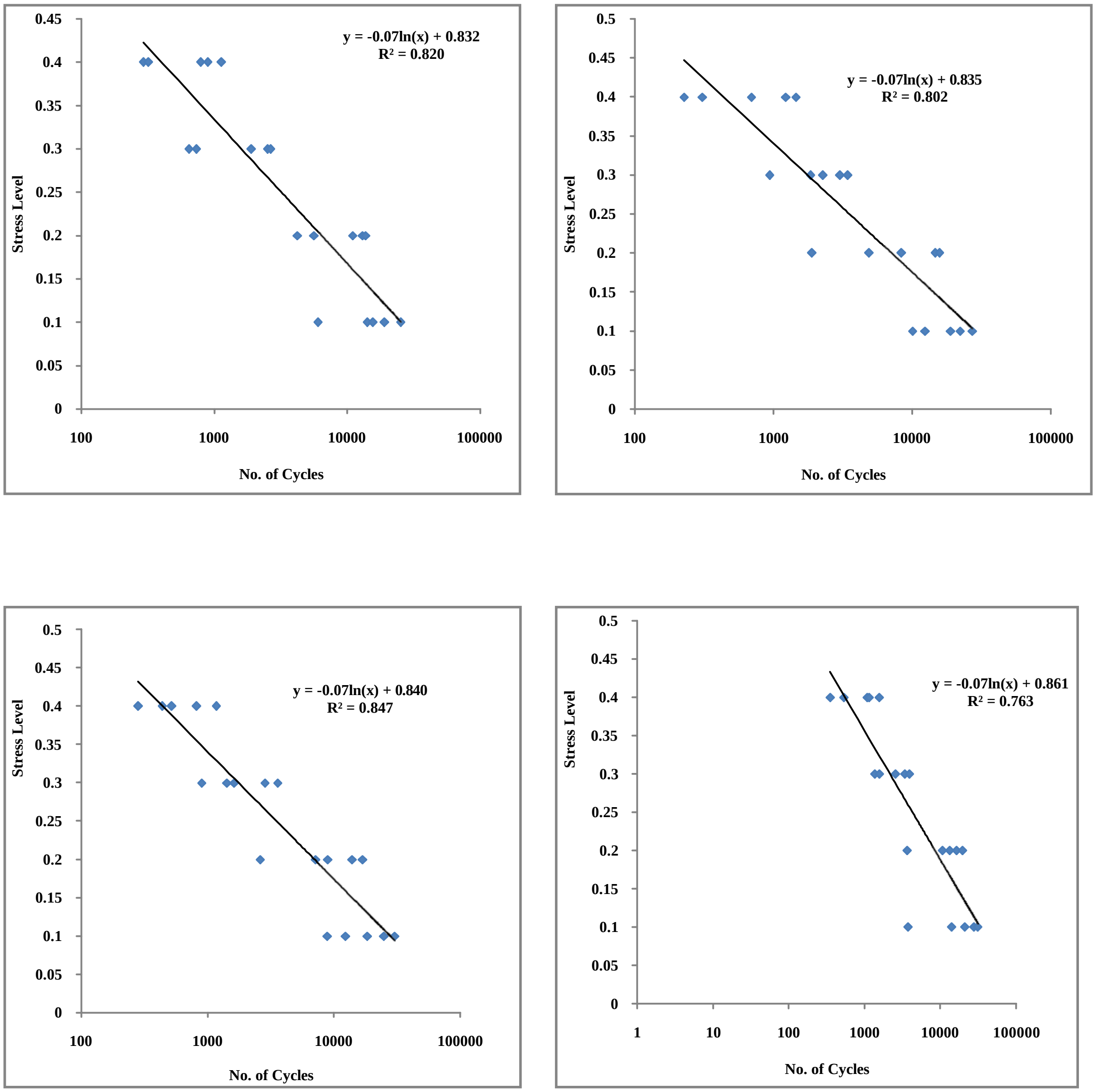


Figure A5.2 S-N curve for Control Mix and WEO based R-1 SMA Mixes

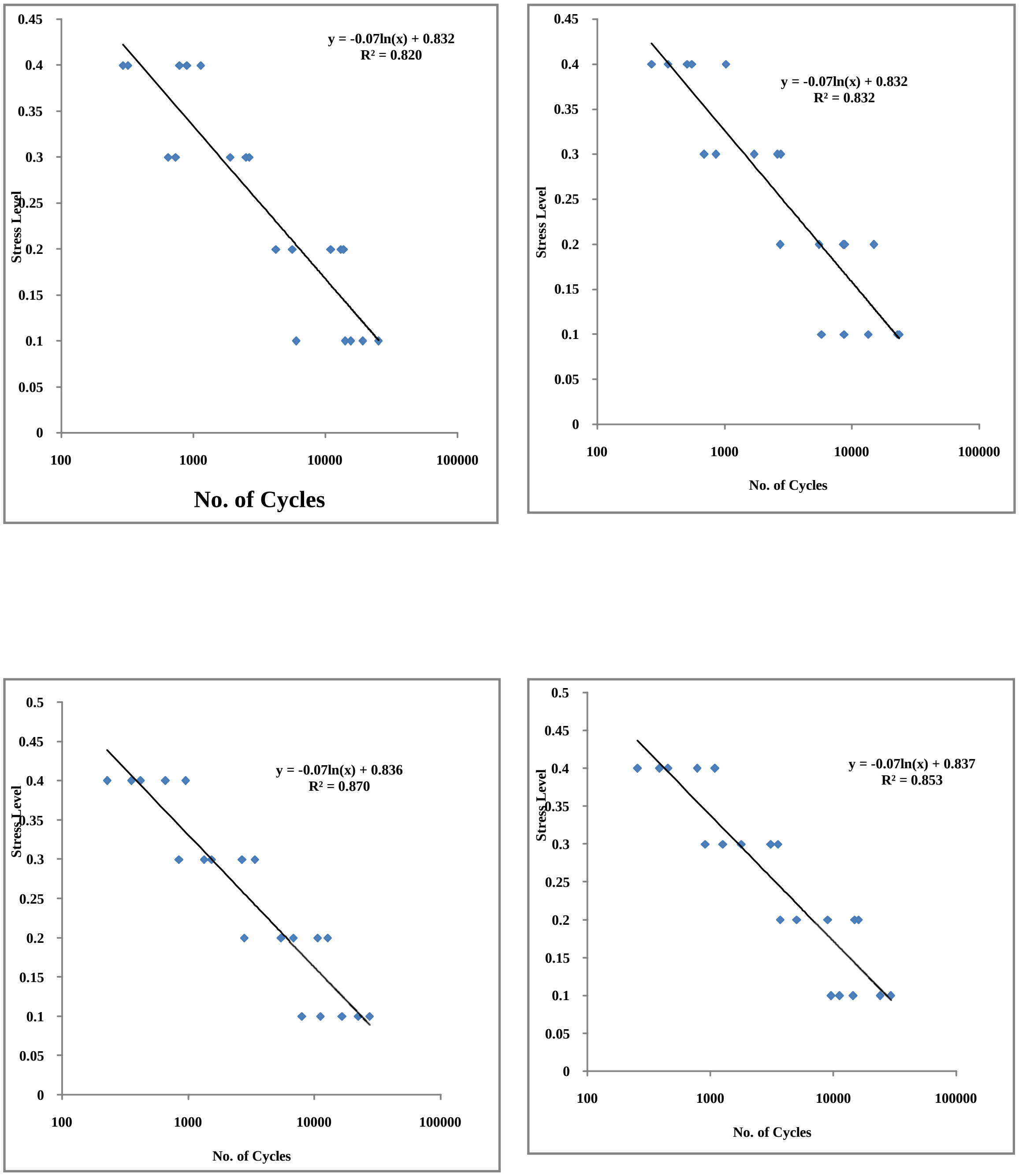


Figure A 5.3 S-N curve for Control Mix and WEO based R-2 SMA Mixes

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PUBLICATIONS BASED ON PRESENT RESEARCH

Articles in Journals

1. L Durga Prashanth, Nitendra Palankar, and A.U. Ravi Shankar, "A study on the effect of rejuvenators in reclaimed asphalt pavement-based stone mastic asphalt mixes.", *International Journal of Pavement Research and Technology, 2019, Springer,* https://doi.org/10.1007/s42947-019-0002-7
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3. L Durga Prashanth, Nitendra Palankar and A U Ravi Shankar "Effects of Waste Engine Oil rejuvenation on rutting and fatigue properties of Reclaimed Asphalt Pavement based stone mastic asphalt mixes" *Resources, Conservation and Recycling, Elsevier* **(Communicated).**

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1. L Durga Prashanth, Trupti konin, A U Ravi Shankar and Harish Gowda Patil "Laboratory evaluation of Stone Mastic Asphalt mixtures containing Reclaimed Asphalt Pavement Materials" *International Conference on Sustainable Civil Infrastructures,* ASCE*, 2014*.
2. Harish Gowda R P, Trupti Konin, L Durga Prashanth and A U Ravi Shankar "Studies on the effect of Reclaimed asphalt pavement materials in Stone Mastic Asphalt Mixes" *International Conference on Recent Advance in Engineering Sciences*, Proceedings Published in *Journal of Civil Engineering Technology and Research*, Vol. 2, Issue 1, 2014, pp 533-540.
3. L Durga Prashanth, Nitendra Palankar and A U Ravi Shankar "Studies on the effect of rejuvenator incorporated capsules on the self-healing properties of stone mastic asphalt mixes" *RILEM International Symposium on Bituminous Materials (ISBM Lyon 2020), which will be held in* ***Lyon (France)*** *on June 8- 10th, 2020* ***(Abstract Accepted).***
4. L Durga Prashanth, Nitendra Palankar and A U Ravi Shankar "Investigations on rejuvenator incorporated capsules on the self-healing characteristics of bituminous concrete mix" ASCE India Conference on "*Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies (CRSIDE 2020)"* Kolkata, March 02-04, 2020.

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List of Publications:

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1. L Durga Prashanth, Nitendra Palankar, and A.U. Ravi Shankar,(2019) "A study on the effect of rejuvenators in reclaimed asphalt pavement-based stone mastic asphalt mixes.", *International Journal of Pavement Research and Technology*, *Springer*, https://doi.org/10.1007/s42947-019-0002-7
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