LABORATORY EVALUATION OF STONE MATRIX ASPHALT (SMA) MIXES WITH PARTIAL REPLACEMENT OF NATURAL AGGREGATES BY RECLAIMED ASPHALT PAVEMENT (RAP) ALONG WITH REJUVENATOR

Thesis

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

RAGHURAM K CHINNABHANDAR

DEPARTMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,

SURATHKAL, MANGALORE-575025

JUNE – 2023

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JUNE - 2023

DECLARATION

by the Ph.D Research Scholar

I hereby declare that the Thesis entitled "**Laboratory Evaluation of Stone Matrix Asphalt (SMA) Mixes with Partial Replacement of Natural Aggregates by Reclaimed Asphalt Pavement (RAP) Along with Rejuvenator"** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfilment 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 Thesis has not been submitted to any University or Institution for the award of any degree.

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CERTIFICATE

This is to certify that the Thesis entitled "**Laboratory Evaluation of Stone Matrix Asphalt (SMA) Mixes with Partial Replacement of Natural Aggregates by Reclaimed Asphalt Pavement (RAP) Along with Rejuvenator**" submitted by **RAGHURAM K CHINNABHANDAR (197071CV013)** as the record of research work carried out by him, *is accepted as Thesis submission* in partial fulfilment of the requirements for the award of degree of **Doctor of Philosophy**.

(A. U. Ravi Shankar)
Research Guide

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NITK Surathkal RAGHURAM K CHINNABHANDAR

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ABSTRACT

Stone Matrix Asphalt (SMA) is a type of Hot Mix Asphalt developed in Germany in the 1960s to overcome the effect of studded tyres. SMA has mainly two parts - a coarse aggregate skeleton and a high binder content mortar. The coarse aggregate skeleton provides the mixture with stone-to-stone contact, giving it strength, while the high binder content mortar adds durability. A typical SMA composition comprises 70−80% coarse aggregate, 8−12% filler, 6.0−7.0% binder, and 0.3% fibre. SMA uses a gap-graded aggregate gradation because of which the binder mortar drains down from the mixture during production in the hot mix plant and transportation and placement in the field. The fibre acts as a stabilising additive to hold the bituminous binder in the mixture during the high production and placement temperatures.

In the present study, SMA mixtures were as per prepared IRC SP 79 2008 using an aggregate gradation of 13 mm Nominal Maximum Aggregate Size (NMAS). A polymer-modified bitumen PMB 40 and conventional viscosity grade bitumen VG 30 were used to prepare the mixes. Three stabilising additives were used: areca fibre, coconut fibre and pelletized cellulose fibre when mixtures were prepared using VG 30 bitumen. Based on the results of the drain down tests, the Optimum Fibre Content (OFC) was determined to be 0.3% by weight of the mixture, and it was observed that the drain down decreased with an increase in the fibre content. Cylindrical specimens were cast at OFC to determine Optimum Bitumen Content (OBC) using the Marshall method of mix design and Superpave Gyratory Compactor (SGC). The OBC values obtained for the mixes with natural fibres were higher, possibly due to the higher surface area of the fibres and the possible absorption of bitumen by the fibres. The mixture with PMB 40 and coconut coir fibre exhibited the highest and lowest results with respect to Marshall Stability, indirect Tensile Strength, rutting, fatigue and moisture susceptibility, respectively. Further, the performance of the mixture with cellulose fibres in the form of pellets was comparable to that of the mixture prepared with polymer-modified bitumen. The results of the mixtures with natural fibres were comparable, and the performance of SMA with areca fibre was better than that of SMA with coconut fibre. The tests conducted on compacted specimens revealed that all the mixtures (SMA-PMB, SMA-PF, SMA-AF, SMA-CF) satisfied the

requirements of SMA as per IRC SP 79 2008. Since areca fibres are abundantly available in South India and disposed of in empty spaces due to the lack of any applications, areca fibres can be used as stabilising additive in SMA mixes.

Due to the increased construction activities, much demand is being exerted on natural resources such as aggregates and bitumen. Hence, to reduce the environmental impact and conserve natural resources, RAP materials are used as an alternative source of aggregates for the production of fresh bituminous mixtures. Since the RAP aggregates contain aged binder, the bitumen required for producing a fresh bituminous mixture is also lesser. When RAP is used, a rejuvenator is required, which helps rejuvenate the aged binder in the RAP material due to oxidation. Hence, an abundantly available and cost-effective liquid, a by-product of the Cahsewnut processing industry, called Cashewnut Shell Liquid (CNSL), is used as the rejuvenator. In the present study, SMA mixtures were prepared using a 13 mm Nominal Maximum Aggregate Size (NMAS) aggregate gradation. A conventional viscosity-graded VG 30 bitumen was used to prepare the mixtures. The natural aggregates were replaced by RAP in the mixture in percentages of 10%, 20%, 30% and 40% by weight by RAP. The mixtures containing RAP were prepared in accordance with the SMA wearing course specification as per IRC SP 79 2008. For each RAP content, CNSL was added at 0%, 3%, 6% and 9% by weight of the bitumen. The drain-down test conducted on all the mixtures showed that they were within the allowable limit of 0.3% by weight of the mixture. The ratio of VCA_{mix} and VCA_{DRC} was found to be less than 1 for all the mixtures, confirming the presence of an aggregate skeleton. The OBC of the mixtures decreased with an increase in the RAP content. The mechanical properties of the mixtures such as Marshall Stability (MS), Indirect Tensile Strength (IDT), Fatigue, rutting and workability were determined. The moisture susceptibility of the mixtures such as Retained Marshall Strength (RMS), Tensile Strength Ratio (TSR) and stripping test on aggregates was evaluated. Though the results of the tests indicated that a mixture with a maximum RAP content of 40% and 3% CNSL provided the highest results, the mixture with a RAP content of 30% and 6% CNSL yielded the optimal results.

Keywords: Stone Matrix Asphalt, Drain-down, Areca fibre, RAP, CNSL, Workability

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

AASHTO	American Association of State Highway and Transportation Officials
AF	Areca Fibre
ASTM	American Society for Testing and Materials
CDI	Construction Densification Index
CF	Coconut Fibre
CNSL	Cashewnut Shell Liquid
CRMB	Crumb Rubber Modified Bitumen
DS	Dynamic Stability
FHWA	Federal Highway Administration
FL	Fatigue Life
G_{mb}	Bulk Specific Gravity of compacted specimen
G_{mm}	Maximum Theoretical Specific Gravity
G_{sb}	Bulk Specific Gravity of Aggregates
IDT	Indirect Tensile Strength
IRC	Indian Roads Congress
IS	Indian Standards
M_a	Mass of Specimen in Air
MORTH	Ministry of Road Transport and Highways
MS	Marshall Stability
M_{ssd}	Mass of Specimen in Saturated Surface Dry condition
M_w	Mass of Specimen in Water
NMAS	Nominal Maximum Aggregate Size
OBC	Optimum Bitumen Content
OFC	Optimum Fibre Content

PF	Pelletised Cellulose Fibre
PMB	Polymer Modified Bitumen
RAP	Reclaimed Asphalt Pavement
RMS	Retained Marshall Stability
SEM	Scanning Electron Microscope
SMA	Stone Matrix Asphalt
TDI	Traffic Densification Index
TGA	Thermogravimetric Analysis
TSR	Tensile Strength Ratio
V_a	Air Voids
VCA_{DRC}	Voids in Coarse Aggregates in the Dry Rodded Condition
VCA_{mix}	Voids in Coarse Aggregates in the mix
VFB	Voids Filled with Bitumen
VG	Viscosity Grade
VMA	Voids in Mineral Aggregates
WEO	Waste Engine Oil
WG	Waste Grease
WVO	Waste Vegetable Oil

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Indian economy is improving very fast and hence, a lot of infrastructure projects like roads, buildings etc. are coming up. All the villages, towns and cities are well connected by all-weather roads. Due to the increase in traffic volume and loading of vehicles on highways, it becomes essential that the pavements meet the requirements of durability and strength, thereby imparting comfort and safety to road users (Colares et al. 2014). As the intensity of traffic increases, the wear and tear of the pavement increases and gives rise to various distresses such as potholes, cracking, ravelling, and especially rutting. Rutting can be defined as the depression in the longitudinal direction along the wheel path in flexible pavements. Rutting can be attributed to excessive consolidation due to accumulated permanent deformation caused by repeated application of heavy loads, or lateral movement of the material, caused by the shear failure of the bituminous concrete layer, or by a combination of both mechanisms (Khan et al. 2013). Therefore, in the 1960s, to reduce the rutting caused by studded tyres, Stone Matrix Asphalt (SMA) was developed in Germany. The use of SMA continued even after the studded tyres were banned since they were found to resistant to rutting (Nejad et al. 2010; Sarang et al. 2016a; Sheng et al. 2017; Shiva Kumar et al. 2019). After SMA's success in Europe, it was successfully adopted in the USA in the 1990s (Sheng et al. 2017). SMA is a gap-graded mixture in which 70% of the coarse aggregates are at least of size 2.36 mm, and the filler material consists of 10% of material retained on the 75µ sieve (Brown 1992). SMA also consists of a high binder content of 6 to 7%. Some of the advantages of SMA are good rutting resistance, excellent low-temperature performance, improved macrotexture, long service life, low tyre noise, less spray of water from tyres, and low light reflection characteristics on rainy nights (Cooley and Brown 2001).

1.2 STONE MATRIX ASPHALT

Stone Matrix Asphalt (SMA) is a type of Hot Mix Asphalt (HMA) which uses a gap-graded aggregate gradation. The difference in the aggregate gradation between SMA and conventional bituminous mixture is depicted in Figure 1.1. SMA mainly consists of a coarse aggregate skeleton which provides the mixture with strength and a high binder content mortar that adds durability (Asi 2006; Brown and Manglorkar 1993; Kumar et al. 2007). To achieve the aggregate skeleton, the aggregates are arranged in such a way that there exists a stone-to-stone contact, which imparts strength to the mixture. The transfer of load of the vehicles through the SMA layer takes place due to the contact between the coarse aggregate particles. The binder mortar consists of fine aggregates, bitumen, and a stabilising additive (Mahdi et al. 2010). The binder mortar tends to drain through the void spaces in the mineral aggregates of an SMA mixture during production, transportation and laying of the mixture in the field. Hence, to reduce the draindown of the binder mortar, a stabilising additive is used (Brown 1992; Brown and Manglorkar 1993; Tashman and Pearson 2012).

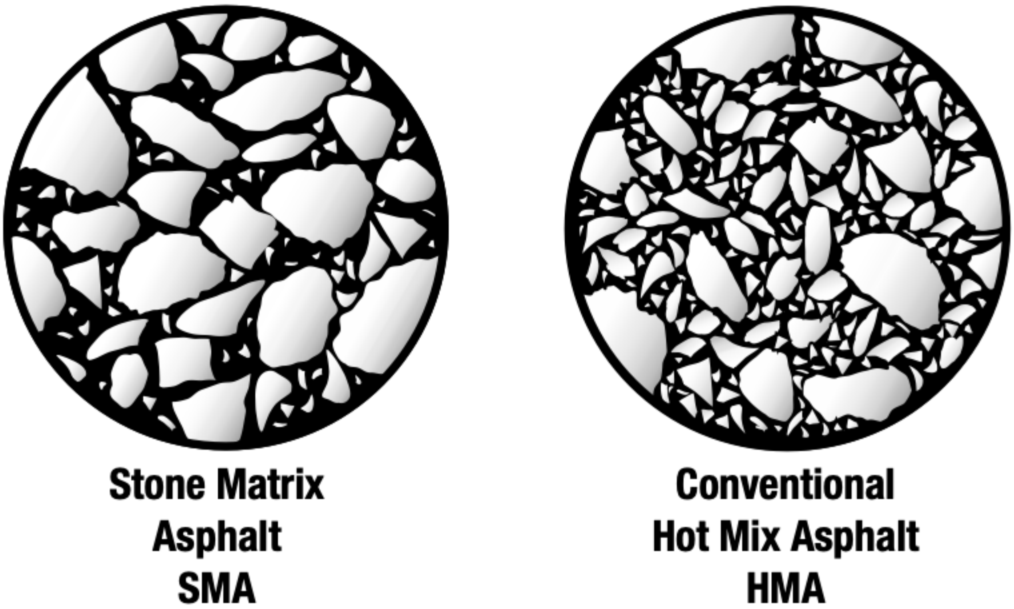

Fig. 1.1 SMA and Conventional HMA (NAPA 2002)

1.3 MECHANISM OF STONE MATRIX ASPHALT

SMA was developed as a rut-resistant mixture and to resist the wear and tear caused by the studded tyres in the 1960s. Hence, in 1971, Zichner developed a bituminous mixture with a high coarse aggregate content which formed an aggregate skeleton providing good resistance to the wear of wheel studs. Zichner believed that the points of contact between the coarse aggregate particles provided strength to the mixture; hence, the coarse aggregates formed the principal constituent of SMA and the rich binder mastic provided durability to the mixture. Hence, coarse aggregates form the major constituent of SMA and form an aggregate skeleton due to the interlock between them. Based on their functions, the aggregates in the mixture can be divided into two parts. The load-carrying coarse aggregate particles forming the skeleton are called active aggregates and the smaller aggregate particles filling the voids spaces between the coarse aggregate particles are called passive aggregates (Błazejowski 2016). The maximum possible compressive strength can be obtained due to the contact between the aggregate particles when the assumed spherical aggregate particles are compacted in a cubical container as depicted in Figure 1.2. In the same way, the load is transferred through the points of contact between coarse aggregates in an aggregate skeleton in the surface layer of pavement as shown in Figure 1.3.

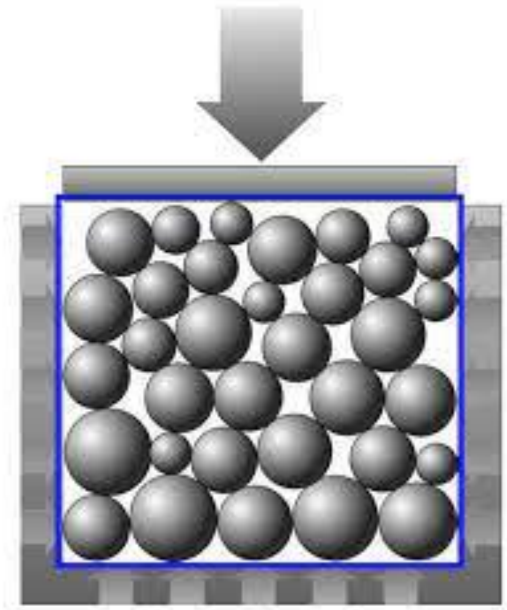

Fig. 1.2 Vertically Loaded grains with side support (Błazejowski 2016)

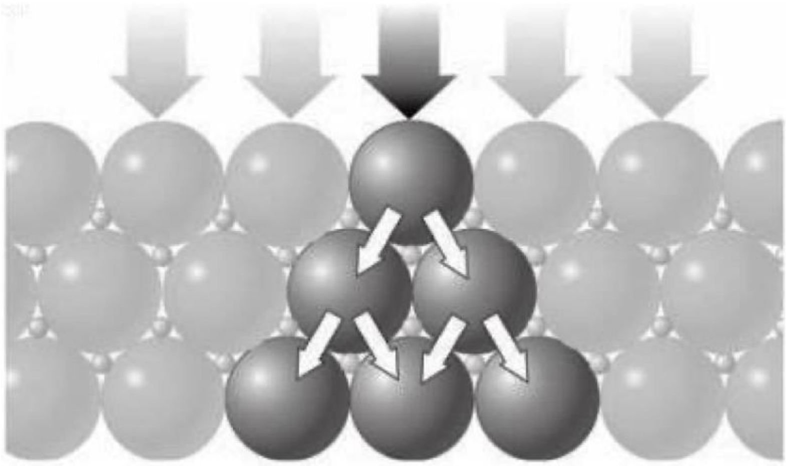

Fig. 1.3 Load Distribution among Aggregates During Uniform Load Distribution

(Błazejowski 2016)

1.4 HISTORY OF SMA

During the 1960s, Gussasphalt (mastic asphalt) and asphalt concrete containing low aggregate content were being used in Germany. Since studded tyres were being used at the time, the surface layers were wearing out quickly, necessitating expensive and frequent maintenance and rehabilitation. Hence, a new mixture called Splittmastixasphalt or SMA was developed by Zichner, a German Engineer at the Central Laboratory for Road Construction at Strabag Bau AG, to resist the wear and tear of the studded tyres (Błazejowski 2016). In the Fall of 1990, the European Asphalt Study Tour showed that SMA had performed well as a surface mixture for the previous two decades and paved the way for the formation of a Technical Working Group (TWG) by the Federal Highway Administration (FHWA) to develop guidelines for materials and construction of SMA in the US (NAPA 2002). In 1991, the first SMA was placed in Missouri, Georgia and Michigan.

In India, the first SMA trial section was constructed in October 2006 between Khajuri Chowk and Brij Puri Chowk on Road no. 59 in Delhi by Central Road Research Institute (CRRI). While producing the mixture in the hot mix plant, it was concluded that a drum mix plant with computerised control or a batch mix plant should be used in order to have proper control on the grading of aggregates. The trial stretch was monitored for two years at an interval of 6 months to evaluate the mixture performance during pre-monsoon and post-monsoon periods (Highway Research Record 2006). Later, a draft specification on SMA was prepared by Prithvi Singh Khandal in 2007, which was later approved by the Highways Specifications and Standards Committee in May 2007 (IRC : SP 79 2008).

1.5 STABILISING ADDITIVE

Since SMA is a gap-graded mixture, the bituminous mortar tends to get separated from the mixture during mixing, transportation and placing of the mixture in the field. To reduce the drain-down in SMA mixtures, the IRC recommends using cellulose fibres in pelletized form (IRC : SP 79 2008). Since cellulose fibres are expensive, they increase the cost of production of SMA mixes. When fibres are added to SMA mixtures, the draindown reduces because of the formation of a fibre network in the mixture which holds the bituminous mortar in place (Sarang et al. 2015). As an alternative to pelletised cellulose fibres, various fibres obtained from waste products such as Fibres Extracted from Refrigerator Doors (FERD), waste nylon wires, waste Polyethylene Terephthalate (PET) and Shredded Waste Plastic, waste tyre and carpet fibres among others have been used as stabilising additives in SMA (Ahmadinia et al. 2011; Putman and Amirkhanian 2004; Ranadive et al. 2018; Sarang et al. 2016b; Yin and Wu 2018). Similarly, naturally occurring fibres such as Banana fibres, coconut coir fibres, Jute fibres, Bamboo fibres and Sisal fibres have been employed in SMA as drainage inhibitors due to their abundant availability and low cost of procurement (Kar et al. 2019; Kumar et al. 2011; Panda et al. 2013a; Sheng et al. 2019; Shiva Kumar et al. 2019). The use of wasted synthetic or natural fibres is also known to improve the mechanical properties apart from reducing the drain-down susceptibility of SMA mixtures (Nejad et al. 2010; Oda et al. 2012).

1.6 RECLAIMED ASPHALT PAVEMENT

With over 62 lakh kilometres, India’s road network is the second largest in the world. About 90% of India’s road network constitutes flexible pavements (MORTH 2021). For the construction of flexible pavements, bituminous materials are commonly used. The production of bituminous materials requires large quantities of natural aggregates and bitumen. Hence, the quest to produce pavements which are sustainable has led to the identification of alternative materials. Once a flexible pavement has served its life, the pavement is excavated to construct a new pavement. The process of recycling hot mix asphalt material results in the generation of a material that can be re-used which consists of a mixture of aggregates and bitumen known as Reclaimed Asphalt Pavement (RAP) (Al-Qadi et al. 2007). In recent times, the use of RAP is gaining momentum due to the continuous exploitation of natural aggregates leading to a decrease in the good quality aggregates and the high costs of bitumen. Some of the advantages of using RAP are reduced energy consumption, decreased transportation costs incurred due to procurement of natural aggregates, conserves natural resources, reduces landfills and decreases depletion of natural aggregates and bitumen which are non-renewable (Copeland 2011). The use of RAP also results in reduced cost of fresh bituminous mixes. The savings in the cost of a mixture with 100% RAP content is up to 50-70% when compared to a conventional mixture and the savings in cost is largely dependent on the price of bitumen which is the costliest material used in bituminous mixes (Behnood and Gharehveran 2019; Zaumanis et al. 2014a). When RAP is used in bituminous mixes, an increase in the rutting resistance and decrease in the moisture susceptibility of HMA mixes is observed (Ghabchi et al. 2016). However, the use of RAP in fresh bituminous mixes poses challenges due to the stiffness imparted to the mixture by the aged binder which affects the low temperature cracking and fatigue behaviour of mixtures. This might lead to premature failure of pavements which in turn will increase the cost of maintenance, consumption of energy and emissions (Daniel et al. 2010; Moghaddam and Baaj 2016).

1.7 REJUVENATOR

When the bituminous binder is heated during the production of a bituminous mixture, bitumen undergoes short-term ageing and owing to the continuous exposure of bitumen to atmospheric conditions during the service life of a flexible pavement, the bitumen undergoes long-term ageing. A typical bituminous binder consists of an oily and a non-oily phase. The oily phase is made of maltenes while the non-oily phase consists of asphaltenes. The viscoelastic behaviour of bitumen is dependent on the asphaltenes to maltenes ratio. Due to long exposure to atmospheric conditions, the polar aromatics are converted to asphaltenes. In addition to this, the naphthalene aromatics get converted to polar aromatics and eventually turn into asphaltenes due to ageing. As a result of this, the ratio of asphaltene to maltene increases. These types of bitumen with high asphaltene contents are called gel-type bitumen which exhibits low ductile properties and a high rate of age-hardening (Behnood and Gharehveran 2019). Hence, a change in the microstructure of bitumen is observed because of an increase in the asphaltene content due to the ageing process (Behnood and Olek 2017a; b). Hence, to decrease the content of asphaltenes and restore the ratio of asphaltenes and maltenes, a suitable rejuvenator is added to the aged binder (Chen et al. 2014a; Gong et al. 2016; Zhu et al. 2017). The role of a rejuvenator is to reverse the effect of ageing on the rheological and engineering properties, thereby restoring the microstructure of bitumen and not reversing the ageing itself. Many researchers have used different materials such as rapeseed, Oleic imidazolines, bio-oil obtained from sawdust, waste edible vegetable oil, waste cooking oil, waste vegetable grease, organic oil, distilled tall oil, aromatic extract etc. (Chen et al. 2014a; Majidifard et al. 2019; Wróbel et al. 2021a; Zaumanis et al. 2014c; Zhang et al. 2019) as rejuvenators. However, the results of the use of rejuvenators are varied. Generally, organic rejuvenators have performed better in reducing the stiffness of aged binders when compared to petroleum-based rejuvenators (Ji et al. 2017; Zhou et al. 2018). The rejuvenator chosen should provide good short-term and long-term performance of the binder in the fresh bituminous mix. The rejuvenator should allow the incorporation of RAP in fresh bituminous mixes, allowing the aggregates to be coated uniformly and providing adequate workability. In the long term, the rejuvenator should restore the physical and chemical properties of bitumen (Zaumanis et al. 2014a).

1.8 OBJECTIVES AND SCOPE

The present study aims to investigate various mechanical properties of SMA mixes in the laboratory using different stabilising additives. The study also tries to evaluate the feasibility of using Reclaimed Asphalt Pavement (RAP) in SMA mixtures using a rejuvenator. The main objectives of the present study are:

- To evaluate the feasibility of using Areca fibres as a stabilising additive in SMA mixtures.

- To determine the optimum RAP content in SMA mixes using Cashewnut Shell Liquid (CNSL) as a rejuvenator.

The scope of the study includes the preparation of SMA mixes using the aggregate gradation for wearing course with 13.2 Nominal Maximum Aggregate Size (NMAS) as per IRC SP 79. The bituminous binders used were conventional viscosity grade (VG 30) bitumen and a Polymer Modified Bitumen (PMB 40). The mixture prepared with PMB 40 was considered the control mixture. The mixtures were prepared using Coconut Coir fibre (CF), Areca fibre (AF) and pelletized Cellulose fibre (PF) as stabilising additives. The Optimum Fibre Content (OFC) for the mixtures with CF and AF as stabilising additive was determined based on the draindown of the mixes except for the mixture with PF, which was added at 0.3% by weight of the mixture as per IRC SP 79. Then, the mixtures were prepared at OFC with varying bitumen contents to determine the Optimum Binder Content (OBC). The various mechanical properties such as Marshall stability, indirect tensile strength, rutting, fatigue, workability and moisture susceptibility were evaluated for the mixtures prepared at OFC and OBC.

Due to the increase in construction activities, natural resources are depleting rapidly. Hence, there is a need to identify alternate materials and conserve the natural resources. RAP is one such material which can be used to replace aggregates, which otherwise would end up in landfills occupying valuable space and causing an environmental hazard. In the present study, natural aggregates have been replaced by RAP in percentages of 10, 20, 30 and 40% by mass of the aggregates. Since RAP consists of an aged binder, a material called rejuvenator is required to restore the properties of the aged binder. In the present study, a waste liquid obtained from the production of Cashewnut known as Cashewnut Shell Liquid (CNSL) is used as the rejuvenator. the draindown of all the mixtures were determined at 7% bitumen content. The OBC of all the RAP incorporated mixtures was determined at 4% air voids. To determine the optimum dosage of RAP and rejuvenator, the specimens prepared at varying contents of RAP and rejuvenator were subjected to various tests to determine the mechanical properties and moisture susceptibility of the mixtures.

1.9 ORGANISATION OF THESIS

The thesis is divided into **six chapters**. The **first chapter** provides a brief introduction to SMA, the role and types of stabilising additives in SMA, RAP and the need for a rejuvenator in RAP-incorporated mixtures. At the end of the chapter, the objective and scope of the present study are discussed.

The **second chapter** provides a review of the literature on SMA, its merits and de-merits, and the types of stabilising additives used in SMA. Different types of fibres such as mineral, synthetic and natural fibres are used in SMA mixes. Since a part of the present study is focused on using a naturally occurring fibre in SMA mixes, a literature review of the use of natural fibres used in SMA is given more importance. The second part of the literature review discusses RAP and its effects on the mechanical properties of bituminous mixtures along with the types of rejuvenators used.

Chapter three discusses in detail the materials used in the study along with their sources, followed by the methodology adopted to achieve the set objectives. A detailed procedure of all the tests conducted in the study is provided.

Chapter four deals with SMA mixes prepared using different fibres. The chapter provides details of the various fibres used in SMA mixes in the present study followed by the results of various tests conducted on SMA mixes.

The details of SMA mixes prepared with different percentages of RAP and rejuvenator are provided in **Chapter five**. A brief discussion on the rejuvenator used in the mixtures prepared with RAP and the results obtained on various mechanical properties are provided.

Chapter six provides discussions and conclusions on the results obtained in chapters four and five.

CHAPTER 2

LITERATURE REVIEW

2.1 STONE MATRIX ASPHALT MIXTURES

Stone Matrix Asphalt (SMA), developed in the 1960s in Germany is a a type of Hot Mix Asphalt (HMA). SMA has been widely used in Europe to resist the wear and tear caused by studded tyres and provide better rutting resistance. But, during the 1970s, the use of studded tyres was banned in Germany. The use of SMA also reduced owing to higher material and construction costs and there no longer appeared a need for SMA mixtures. But SMA began to be re-used in the 1980s because of rutting of conventional HMA mixes due to increased tyre pressures, wheel loads and traffic volumes. Based on the findings of a study group from the USA that visited Europe in 1990, SMA was adopted in the USA in 1991 (Brown 1992).

SMA consists of two parts - a coarse aggregate skeleton which imparts strength to the mixture because of stone-to-stone contact and a high binder content mortar which helps improve the durability of the mixture (Vale et al. 2014). The dense-graded mixtures also have aggregate stone-to-stone contact, but it occurs within the fine aggregates which do not have the same shear resistance as the coarse aggregates. The mortar in SMA mixes consists of fine aggregate, bituminous binder, mineral filler and stabilising additive (Ai-Hadidy and Tan 2011; Asi 2006; Mahdi et al. 2010). A typical SMA mixture consists of 70−80% coarse aggregate, 8−12% filler, 6.0−7.0% binder, and 0.3 per cent fibre by weight of the mixture (Ferreira Da Costa et al. 2020). The role of the fibre is to act as a stabilising additive which helps retain the bituminous binder in the mixture during the high temperatures of production and placement (Brown and Haddock 1997).

2.2 ADVANTAGES OF STONE MATRIX ASPHALT MIXES

Some of the advantages of SMA are:

a. They have good resistance to rutting (Brown et al. 1997; Richardson 1999)
b. They have high durability compared to conventional HMA (Xue et al. 2009)
c. They exhibit better resistance to reflective cracking
d. The tyre noise is low, lesser water spray and low light reflection characteristics generated from SMA layers is low (Cooley and Brown 2001)

2.3 DISADVANTAGES OF STONE MATRIX ASPHALT MIXES

Some of the limitations of SMA are:

a. Since SMA consists of high binder content, the mix is susceptible to binder draindown (Nejad et al. 2010).
b. The initial cost is high compared to conventional mixes since SMA contains high binder content and a stabilising additive to control the draindown (Nejad et al. 2010).

2.4 NEED FOR ADDITIVES IN SMA

Due to the presence of high bitumen content, a stabilising additive is required to retain the bitumen and hence control the draindown of the bitumen mastic in the mixture (Ferreira Da Costa et al. 2020; Kumar et al. 2007). IRC: SP 79-2008 recommends the use of cellulose fibres as stabilising additives to control the draindown of SMA mixtures. Alternatively, SMA mixtures can also be produced using modified binders such as Crumb Rubber Modified Bitumen (CRMB) and Polymer Modified Bitumen (PMB) without a stabilising additive. Such modified binders are known to improve the properties of the mixture. The use of cellulose fibres are not only expensive but also lead to felling of trees since cellulose fibres are plant-based (Kumar et al. 2007). Alternatively, waste synthetic fibres, natural fibres resulting from various agricultural processes and mineral fibres have been used to control drain down in SMA mixes. The advantages of using these fibres are they are abundantly available since they are waste materials and cost-effective. The use of a stabilising additive not only helps reduce the drain down of the bitumen mastic but also improves the various service properties of the mixture by forming a micromesh and hence increases the stability and durability of the mix (Kumar et al. 2011; Panda et al. 2013a; Ramalingam et al. 2017; Vale et al. 2014).

2.5 STONE MATRIX ASPHALT MIXES PREPARED USING STABILISING ADDITIVES

Studies conducted on the incorporation of different fibres in HMA improve fatigue performance, permanent deformation and stiffness (Oda et al. 2012; Shiva Kumar et al. 2019; Slebi-Acevedo et al. 2019). The fibres are effective in reducing the draindown susceptibility of HMA mixtures like Open Graded Friction Courses (OGFC) and SMA (Hassan et al. 2005; Peltonen 1991; Serfass and Samanos 1996). The improved resistance to drain down of SMA mixtures when fibres are added is due to a change in the viscoelastic behaviour of mixtures (Huang and White 1996). Another reason for adding fibres in SMA mixtures is to provide additional tensile strength which helps reduce the formation and propagation of cracks in the resulting mixture. Since SMA and bituminous mixes, in general, are good in compression and weak in tension, the addition of fibres imparts tensile strength to the mixture (Al-Qadi et al. 2003; Bushing et al. 1970). Shiva Kumar and Ravi Shankar (2020) have indicated that the addition of a stabilising additive such as cellulose fibre, mineral fibre or polymers reduces the drain down and also has the potential of reinforcing the mix, thereby increasing the tensile strength of SMA mixes. Fibres derived from various sources such as mineral, synthetic and natural fibres have been used in SMA mixes.

The use of a mineral additive such as Asbuton, obtained in Buton island of Indonesia acted as a drainage inhibitor as well as filler material in SMA mixes (Suaryana 2016). Similarly, the use of Nano Al_2O_3 as a stabilising additive has resulted in better rut-resistant SMA mixture (Chelovian and Shafabakhsh 2017). Sheng et al. (2017) also reported better volumetric characteristics in SMA mixes when a mineral filler was used as a stabilising additive.

Some types of fibres which are synthetic in nature have been evaluated as stabilising additives such as those derived from waste tyres and carpets have improved the toughness property of SMA mixes compared to cellulose fibres (Putman and Amirkhanian 2004). Though comparable results of SMA mixes with an optimum shredded waste plastic content of 8% were observed compared to SMA with PMB, the mixture with shredded waste plastic required higher mixing time (Sarang et al.

2016a). Similar improvements in stability and indirect tensile strength of SMA mixes were observed at a higher waste plastic content of 10% (Bindu and Beena 2010). Fibre Extracted from Refrigerator Door (FERD) also showed an improvement in the stability and indirect tensile strength properties of SMA mixes (Ranadive et al. 2018). Though an improvement in the rutting resistance of SMA mixes was noted when Ground Tyre Rubber obtained from vehicle tyres was used as a stabilising additive, the moisture susceptibility remained the same as conventional SMA mixes (Chiu and Lu 2007). However, textile fibres obtained from processing the end-of-life tyres of vehicles did not show much improvement in terms of stability and stiffness but showed a significant improvement in the fatigue resistance of bituminous mixes (Bocci and Prosperi 2020). Due to the reinforcing mechanism of waste nylon fibres obtained from tooth, hair and paint brushes, the crack propagation of SMA mixes was delayed leading to an improvement in the tensile strength of the mixes (Yin and Wu 2018). But the addition of fibreglass in SMA mixes resulted in a decrease in the stability due to increased air voids in the mixture (Mahrez and Karim 2010).

Various natural fibres obtained from plants have been used as stabilising additives in SMA mixes. Most plant-based fibres are waste fibres obtained from various agricultural processes which are either discarded or burnt causing air pollution due to the lack of application.

Numerous studies have shown that the incorporation of fibres in hot-mix asphalt mixtures improves fatigue performance, permanent deformation and stiffness (Oda et al. 2012; Shiva Kumar et al. 2019; Slebi-Acevedo et al. 2019).

2.5.1 Bituminous mixes prepared using coconut fibres

The coconut fibres are comprised of lignocellulose materials obtained from the mesocarp (the thick fibrous layer). The shred process for obtaining the mesocarp of the coconut fibre can be done by soaking in water or by mechanical means. Coconut fibres are characterised by a lower cellulose content of 36%-43%. But compared to other vegetal fibres such as Sisal and Jute, coconut fibres have twice the amount of lignin at 41%-45% (Vale et al. 2014).

Prasad and Venkatesh (2018) used coconut fibres as stabilising additives in SMA mixes and observed a decrease in the drain down susceptibility of the mixes and an increase in the bulk-specific gravity and stability due to reduced air voids. Panda et al. (2013a) also made the same observations that the addition of coconut fibres to SMA mixes decreased the air voids. Though coconut fibres were effective in reducing the drain down of SMA mixes, the workability of the mix was poor due to the higher lengths of fibres (Vale et al. 2014). Since coconut fibres have good tensile properties, an improvement in the cracking resistance and indirect tensile strength of the mixtures were observed (Khasawneh and Alyaseen 2020). The improvement in the Tensile Strength Ratio (TSR), a measure of moisture susceptibility could also be attributed to the higher tensile strength of coconut fibres (Vale et al. 2014).

2.5.2 Bituminous mixes prepared using Banana fibres

Banana fibres are pseudostem fibres which are obtained from used banana plants. They have a lot of applications their performance is comparable to that of synthetic fibres (Jayaprabha et al. 2011). However, the results on the evaluation of banana fibres in SMA mixes in the very few literature available are varied. The use of Banana fibres as a stabilising additive in SMA mixes reduced the moisture susceptibility and increased the resistance to fatigue and rutting (Shiva Kumar et al. 2019). However, a reduction in the stability of the SMA mixes due to an increase in the air voids was observed when banana fibres were used as stabilising additives (Prasad and Venkatesh 2018). Since most of the literature is available on the use of fibres of a particular added as a percentage of the mixture, very few literature is available on the effect of variation of fibre length on the properties of SMA mixes. Ferreira Da Costa et al. (2020) evaluated the effect of banana fibre length on SMA mixes and observed that though the shorter fibres (5 mm and 10 mm) were more effective in reducing the drain down, the longer fibres (15 mm and 20 mm) showed better fatigue and rutting resistance. The shorter fibres formed a network due to their higher number, which helped reduce the drain down susceptibility of the mix.

2.5.3 Stone Matrix Asphalt and conventional bituminous mixes prepared using Sisal fibres

Sisal fibre is extracted from the leaves of sisal plants which can be grown in wastelands and also require less maintenance. The sisal fibres only have traditional applications such as making ropes and twines. Due to the superior engineering properties of sisal fibre such as tensile strength, higher modulus and elongation, it is also used in the textile industry and as reinforcement in the composite materials (Ramalingam et al. 2017). Sisal fibres are utilised as alternatives to asbestos and fibreglass (Srinivasakumar et al. 2013). Sisal fibres are twice as strong when compared to jute fibres mainly owing to approximately twice the amount of lignin (Esmeraldo 2006). Due to this, high Marshall strength was obtained when they were used in SMA mixes (Kar et al. 2019). Also, the addition of sisal fibres increased the flow values of SMA mixes and increased the air voids (Naveen Kumar and Sunitha 2016). The tensile strength and resilient modulus of SMA mixes with sisal fibres were also comparable to those of SMA mixes with cellulose fibres because of the high tensile strength properties of sisal fibres (Oda et al. 2012). Similarly, the improved fatigue resistance of SMA mixes could be attributed to the higher tensile strength properties of sisal fibres. The higher tensile strength of sisal fibres also reflected in better moisture sensitivity of SMA in terms of Tensile Strength Ratio (TSR) (Ramalingam et al. 2017). However, the workability properties of SMA mixes with sisal fibres were poor with a higher number of gyrations required to achieve 92% of theoretical maximum specific gravity ($G_{mm)}$, higher Construction Densification Index (CDI) and lower resistance to degradation by traffic indicated by low Traffic Densification Index (TDI) (Shiva Kumar and Ravi Shankar 2020).

2.5.4 Bituminous mixes prepared using Jute fibres

Jute fibre, a naturally occurring fibre grown in most tropical conditions is characterised by high strength and biodegradability. Since Jute is a natural fibre, it is also environmental friendly. Since they are economical and abundantly available, they are extensively used for manufacturing geotextiles, which are used to improve drainage properties and act as reinforcements in cracked bituminous pavements. Very little work is reported on the use of jute fibres in SMA mixes. SMA mixes prepared with jute fibres as stabilising additives showed similar performance in terms of most mechanical properties. But the resistance to ageing determined by dynamic modulus at 25°C was better than the mixture with cellulose fibres (Kumar et al. 2011). Ismael et al. (2022) studied the effect of jute fibre length on the performance of SMA mixes and concluded that an optimal length of 7.5 mm and a dosage of 0.5% by weight of the mixture performed similarly to an SMA mixture with cellulose fibres.

2.6 RECLAIMED ASPHALT PAVEMENT (RAP) AND REJUVENATORS

When a flexible pavement has served its life, the surface layer deteriorates requiring renewal of the layer. Before a new layer is placed, the existing surface layer is excavated. The resulting excavated material is called Reclaimed Asphalt Pavement (RAP) which is basically aggregates coated with bitumen. The RAP material is excavated by the process of milling using a milling machine. RAP is a recyclable material which has technical, economic and environmental benefits (Kennedy et al. 1998). The use of RAP also reduces the need for new aggregates. Due to the increased construction activities in recent times and the scarcity of quality aggregates, RAP is used as an alternative source of aggregate. Using RAP in the production of fresh bituminous mixes also reduces the problem of its disposal and also does not deplete nonrenewable natural resources such as aggregates and bitumen (Copeland 2011). The main advantage of using RAP is it contains coated bitumen which reduces the amount of bitumen to be added to a fresh mixture. Since bitumen is the costliest material in flexible pavements, the contribution of bitumen by RAP reduces the total cost of pavement construction by 14% to 34% when the RAP content in the fresh bituminous mix is between 20% to 50% (Kandhal and Mallick 1997). The first documented use of RAP is in 1915 in the United States of America (Taylor 1978). Since the potential of RAP usage was still not fully understood, they were used for applications such as controlling dust on a dirt road, filling shoulders on an embankment and as base layer material in pavements. Hence, the use of RAP was not popular until the 1970s when there was a rise in inflation levels on construction materials and during the Arab oil embargo which increased the prices of bitumen. The first recorded effort to reclaim and re-use bituminous materials was in 1974 in Nevada and Texas (Epps 1978). Recognising that though the asphalt materials in a pavement may still have some value after its service life, the use of existing bituminous materials increased the use of RAP in flexible pavements. Since the 1970s, RAP is extensively used in the preparation of fresh bituminous mixes owing to the scarcity of good quality aggregates (Sullivan 1996). At the same time, long-term field studies conducted in the US to determine the feasibility of using RAP was found to be successful. However, the percentage of RAP used in Hot Mix Asphalt (HMA) was limited to low levels. This was due to the emissions of hydrocarbons or commonly called blue smoke from RAP material which were directly fed in the path of hot gases. The emission of blue smoke is due to the volatilization of RAP binder. In 1997, with the signing of the Kyoto Protocol and its subsequent implementation in 2005, the use of RAP received much attention. Also, due to the improvements and advancements in hot mix plants, the emission of blue smoke is no longer a cause for concern allowing higher RAP contents in fresh bituminous mixes. Since RAP consists of bitumen, it is most commonly used in the surface and intermediate layers of pavements where the less expensive RAP bitumen can replace a small portion of the more expensive fresh bitumen (Copeland 2011).

2.7 METHODS OF RAP RECYCLING

The recycling can be broadly classified into in-place and plant-based recycling methods. Accordingly, the various methods of recycling of RAP can be classified into the following methods:

a. Hot recycling in asphalt plant
b. Hot in-place recycling
c. Cold in-place recycling
d. Full depth reclamation

2.7.1 Hot Recycling in Asphalt Plant

The RAP material obtained after milling or crushing operation is mixed with new aggregates in a batch or drum mix plant resulting in the production of fresh HMA.

The main advantage of using this method is its performance is similar to HMA without RAP.

2.7.2 Hot in-place Recycling (HIR)

In this method, the existing pavement surface is softened by heating and the material is milled. During this process, new material or RAP can be added to the obtained RAP material with the help of a rejuvenator, if required. In a single pass recycling process, the milled material is combined with new material. Whereas in a multiple-pass operation, the obtained RAP material is re-compacted followed by a wearing course consisting of new material. This method is suitable only for surface layers and the depth of recycling varies between 20 mm to 50 mm. According to the Asphalt Recycling and Reclaiming Association (ARRA), there are three different methods of HIR. They are:

a. Surface Recycling

This is the type of recycling where the existing pavement surface is milled to the required depth after it is heated and softened. The milled RAP material is then compacted after mixing with new aggregates.

b. Repaving

This method is a combination of surface recycling and the laying of a new bituminous overlay where both the milled RAP material and new HMA are compacted at the same time.

c. Remixing

In this method, the scarified RAP material is mixed with virgin HMA and a single mixture is prepared which is then compacted.

2.7.3 Cold in-place Recycling (CIR)

In this method, the existing pavement material is recycled without the application of heat. Asphalt emulsion is used as a binder which is proportioned as a percentage of RAP material. The process involves milling the existing pavement surface, screening of RAP based on size, application of bituminous emulsion, lay down of the mix and compaction. The advantages of CIR are that it can recycle up to a depth of 75 to 100 mm and reduce air pollution caused during HIR since no heating is involved.

2.7.4 Full Depth Reclamation (FDR)

It is a method in which the entire asphalt layer along with a pre-decided depth of the material in the underlying base layer is mixed to produce a stabilized base. FDR mainly employs emulsions and chemical agents and it is basically a cold mix recycling method. This process can be divided into four steps viz. pulverization, introducing the additives, compaction and laying a new course. This method is helpful when the depth of recycling is between 100 to 300 mm.

2.8 USE OF RAP IN DIFFERENT COUNTRIES

In the year 2013 itself, Japan had a very efficient system of pavement recycling. The quantity of RAP re-used was about 99% in 2015. On average, 47% of the RAP generated in the country was re-used with the majority used in fresh bituminous mixes and a small quantity in base layers. The reason for the efficient system of pavement recycling is the limited availability of raw materials and since Japan is a small country, the land available for disposal of RAP is also less.

In the USA, more than 99% of the total RAP generated was re-used, making it the most recycled material in the US. In the year 2018, 12,000 tons of RAP were re-used, 97% of which was put back into the production of HMA and WMA mixtures while the remaining 3% was used in other civil engineering applications. Also, regulations have been put in place to use at least 15% RAP in a majority of states in the US (Williams et al. 2019).

A survey conducted by the European Asphalt Pavement Association (EAPA) on the use of RAP in European countries revealed that about 20% of RAP was re-used as aggregates in unbound layers of pavements and about 8.4% of the recycled material was dumped in landfills (EAPA 2018).

In South Africa, since 2009, an average RAP content of 40% has been used in fresh bituminous mixtures and by 2019, in-plant recycling of 40% RAP has become a common practice. In 2014, South Africa produced 3.5 million tons of RAP and only 10% of RAP was re-used in producing new asphalt mixtures (SABITA 2019).

Certain states in Australia such as New South Wales, Tasmania and Victoria mandate the use of at least 15% RAP in bituminous mixtures. However, the use of RAP in other states such as Queensland, Western Australia and South Australia, the use of RAP is not allowed (Lee et al. 2015).

2.9 REJUVENATORS USED IN MIXTURES CONTAINING RAP

When RAP is obtained from the milling process, it contains a stiff aged binder due to short-term ageing while preparation of the mix and long-term ageing due to continuous exposure of bituminous mixes to atmospheric conditions. The process by which bitumen loses aromatics due to short and long-term ageing is called oxidation. The process of oxidation also reduces the properties of bitumen. Such bitumen which is stiff and has also lost some of its properties cannot be directly used in the preparation of a fresh bituminous mix. Hence, rejuvenators are used to introduce the components in bitumen that were lost during oxidation. Various rejuvenators have been used to rejuvenate aged binder in RAP such as waste vegetable oil, waste engine oil, waste grease, distilled tall oil, bio-oil extracted from sawdust, Oleic imidazoline, rapeseed imidazoline etc (Dokandari et al. 2017; Liu et al. 2018a; Wróbel et al. 2021b; Zaumanis et al. 2014a; Zhang et al. 2019).

An oil-based rejuvenator employed not only improved the properties of the binder but also increased the amount of RAP that could be added to the mixture (Shen et al. 2007). Zargar et al. (2012) noted that by using waste cooking oil as a rejuvenator, the properties of the binder could be restored to that of the virgin binder in terms of softening point and penetration. Similar results were obtained when microstructural analyses were conducted using advanced techniques such as digital imaging when waste cooking oil was used to rejuvenate an aged binder. The results revealed that the microstructure of waste cooking oil rejuvenated binder was similar to that of a bitumen modified with a commercially available rejuvenator (Osmari et al. 2017). But, the use of waste cooking oil as rejuvenator at an optimum content of 6% improved the rutting, fatigue and moisture susceptibility characteristics of SMA mixes irrespective of the age of the RAP source (Durga Prashanth et al. 2019). The optimum rejuvenator content depends on the RAP source as well as the type of rejuvenator used. Based on a study on the use of six rejuvenators, it was concluded that organic rejuvenators require a lesser dosage than petroleum-based rejuvenators (Zaumanis et al. 2014b). The use of rejuvenators obtained from the automobile industry viz. Waste Engine Oil (WEO) and Waste Grease (WG) allowed the incorporation of up to 40% RAP compromising on the volumetric properties, stone-stone contact and moisture resistance of SMA mixes. However, the performance of the mixture with WEO was better than the mixture with WG (Devulapalli et al. 2020). But, WEO, when used as a rejuvenator reduced the temperature of mixing and rutting characteristics but improved the fatigue characteristics (Liu et al. 2018b).

The ageing behaviour of three different rejuvenators were When freshly mixed, rejuvenator R3 decreased the stiffness of the mixture but the first two rejuvenators did not have the same effect on the mixture. After ageing, the stiffness of the mixtures rejuvenated with R1 and R2 increased further, reducing the fatigue behaviour of the SMA mixes (Walther et al. 2021).

2.9.1 Moisture susceptibility of RAP mixtures

The use of Waste Vegetable Oil in SMA mixes improved the moisture resistance of SMA mixes in terms of stripping behaviour and Retained Marshall Stability. But, an improvement in moisture resistance in terms of Tensile Strength Ratio was noted which may be due to the presence of stiff aged binder in RAP material (Devulapalli et al. 2019).

Mogawer et al. (2012) noted an increase in the moisture resistance of bituminous mixes with an increase in the RAP content from 0% to 40%. Tests to determine the moisture susceptibility and volumetric properties were carried out on SMA mixtures blended with different percentages of RAP using warm mix technology. The results indicated that at a high percentage of RAP of 40%, there was no noticeable change in the mixture and compacting temperatures. The volumetric properties such as VMA and Voids Filled with Bitumen (VFB) and the moisture susceptibility met the required standards with the addition of RAP (Xiao et al. 2016). Doyle and Howard (2013) studied the moisture susceptibility and rutting potential of warm mix asphalts containing high RAP contents of 25% and more. A new device called PURwheel was employed to evaluate the two parameters together and the results showed that the moisture susceptibility was comparable with that of low RAP warm asphalt mixes. Mogawer et al. (2013) determined the moisture susceptibility of HMA containing 40% RAP produced using warm mix technology. The mixes passed the moisture damage tests and concluded that the addition of either RAP or warm mix additives did not have a significant impact on the moisture susceptibility of the mixtures. Jiao et al. (2020) noted that there was an improvement in the moisture damage resistance of Fine Aggregate Mixes (FAM) containing high levels of RAP and rejuvenating agents.

2.9.2 Rutting resistance of RAP mixtures

Elkashef and Williams (2017) conducted various tests to evaluate the possibility of incorporating 100% RAP material in bituminous mixes using a performance grade bitumen PG 58-28 after modifying it with a soybean-derived rejuvenator. The bitumen modified by the soybean-derived rejuvenator also showed good durability with ageing. Waste vegetable oil, waste vegetable grease, waste engine oil, organic oil, distilled tall oil and aromatic extracts were used as rejuvenators to improve the properties of aged binder derived from RAP material. The results showed that on 12% dosage of all the rejuvenators, the grade of bitumen reduce from PG 94-12 to PG 64-22 while waste engine oil required a higher dose of 18%. The rejuvenated binders, when incorporated in the asphalt mixture, showed good resistance to rutting and fatigue (Zaumanis et al. 2014c). However, the mixtures with rejuvenated binders required more compaction energy compared to virgin materials. Espinoza-luque et al. (2018) conducted studies to determine the effect of an aromatic oil used as a rejuvenator in RAP material. They concluded that up to 15% RAP content could be incorporated into a bituminous mix. Though the cracking susceptibility reduced upon adding the RAP material, the rutting potential increased. Barazi et al. (2019) used the Dynamic Creep test to evaluate the influence of changes in the percentage of RAP material on rutting resistance. The portion of RAP material used varied from 0% to 50% with a warm mix additive of Sasobit and Zycotherm. They concluded that about 20-30% RAP could be added to hot SMA mixtures while RAP content could be increased to 30% when a warm mix additive like Sasobit is added to the mixture. Mogawer et al. (2013) conducted tests to determine the rutting resistance of HMA containing up to 40% RAP with and without a warm mix additive. The results showed the rutting was not affected on addition of either the RAP material or warm mix additives.

2.9.3 Fatigue resistance of RAP mixtures

The research conducted to develop HMA mixes with RAP contents up to 50% indicated that there was decrease in the fatigue properties of the mixture (Norouzi et al. 2014). However, the fatigue behaviour of HMA mixes with 40% and 60% RAP with two aggregate gradations with NMAS of 12 and 20 mm, respectively (Valdés et al. 2011). Pasetto and Baldo (2012) noted results which indicated that the fatigue performance of HMA with RAP and electric arc steel slag was better compared to the mix with conventional aggregates. The four-point flexural beam fatigue test, HMA (hot-mix asphalt) fracture mechanics model, simplified viscoelastic continuum damage model, and the semi-circular bending test was used to evaluate the effect of ageing on the fatigue characteristics of high RAP mixtures modified with rejuvenators. The results indicated that the long-term ageing used in this study did not have a significant effect on the fatigue characteristics of the high RAP mixture with and without rejuvenators (Mogawer et al. 2015). The effect of gradation of RAP mixes on the fatigue performance was evaluated. Two dense-graded and three gap-graded mixtures were used along with Viscosity Grade – 30 (VG-30) bitumen. The observations made were that the fatigue lives of gap-graded RAP mixes were higher than that of dense-graded RAP mixes. Also, there was a good correlation between the fatigue performance of RAP mixes with that of virgin mixes (Bharath et al. 2019). Mangiafico et al. (2017) investigated the fatigue performance of HMA mixes with varying RAP contents. The results showed good fatigue performance for mixes with RAP contents up to 40%. Jiao et al. (2020) determined the fatigue performance of fine aggregate mixes containing high RAP contents and rejuvenating agents. The addition of RAP increased the stiffness of the mix and the rejuvenating agent did not reduce the stiffness of the mix appreciably. The incorporation of rejuvenators improved the fatigue life of the fine aggregate mixes.

2.10 SUMMARY OF LITERATURE

One of the problems associated with SMA mixtures is the drain down of bitumen and bituminous mastic while transporting, handling and compaction. Hence, a stabilising additive is required to control the drain down to permissible limits. Since SMA requires a high binder content, the initial cost of construction of pavements with SMA is higher than conventional bituminous mixes such as dense-graded mixtures. In addition to the higher costs of SMA because of higher bitumen content, the cost is further increased due to the usage of synthetic fibres explicitly produced to reduce the drain down. Hence, unconventional fibres such as naturally occurring plant fibres, waste and mineral fibres have been successfully used as stabilising additives in SMA. These unconventional fibres are abundantly and locally available which reduces the need for patented fibres. There are lots of unexplored fibres which are usually either dumped, creating more landfills or burnt, which emit harmful gases into the atmosphere and pollute the air. Previous research also shows that the addition of fibres improves the stability, tensile strength ratio, rutting resistance and fatigue resistance of SMA mixtures. Hence, it is required to find an unconventional fibre that can be used as a stabilising additive which also does not have any other applications and is abundantly available.

A vast majority of roads in India is flexible pavements. The flexible pavements deteriorate faster than rigid pavements and consequently, they need more repairs in terms of maintenance and rehabilitation. After a flexible pavement has served its design life, it is excavated, and the bituminous materials are recovered. These bituminous materials are called Reclaimed Asphalt Pavements (RAP) and they can be reused in the production of fresh hot mix asphalt. The reuse of RAP not only reduces the problem of RAP disposal but also reduces the usage of natural aggregates which are fast depleting due to the rapid construction activities in India in recent times. Since RAP also consists of a coated layer of bituminous binder, the requirement of bitumen to produce fresh bituminous mixes is also lesser. But, the RAP binder is aged due to the process of ageing. The short-term ageing at the time of producing the bituminous mixes and long-term ageing due to the exposure of bitumen to atmospheric conditions make the bitumen stiff. Also, the process of ageing alters the chemical composition of bitumen and some of the properties of bitumen are reduced. Hence, the RAP binder cannot be directly used to produce a fresh bituminous mix. The properties of the RAP binder need to be improved by adding a rejuvenator which not only reduces the viscosity of the aged RAP binder but also provides the bitumen with the components lost during the process of ageing. Though rejuvenators are commercially available, they are usually expensive. Earlier research has shown that byproducts of different processes and waste materials which do not have any major applications can be used as rejuvenators. These include aromatic extracts, distilled tall oil, Pongamia oil, castor oil residue, waste cooking oil, waste grease, waste engine oil, waste vegetable oil, etc. Hence, there is a need to identify a byproduct or waste material which does not have any major applications that can be used as a rejuvenator.

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1 MATERIALS

The type and properties of materials used in any bituminous mixture play an important role. In this investigation, different materials such as aggregates, bituminous binders, mineral filler, and stabilizing additives are used to prepare SMA mixtures. Similarly, Reclaimed Asphalt Pavement (RAP) and Rejuvenator are used to prepare SMA mixtures. These materials have been tested per standards and compared with relevant specifications to assess their suitability for preparing SMA mixtures. The following sections provide details of the materials and test results with provisions in the code along with their sources.

3.1.1 Aggregates

In any bituminous mixture, aggregates form a major part. It is estimated that about 70-80% of a bituminous mixture consists of aggregates. Hence, it is important to have good quality aggregates. The aggregates should be strong, durable and free from excessive dust. In the present study, aggregates were procured from a quarry consisting of granite rock near Karkala, Udupi district of Karnataka, have been used after ensuring their suitability in SMA mixtures based on IRC guidelines. Similarly, the RAP material was procured from a stockpile in Surathkal, Mangaluru, Dakshina Kannada district, Karnataka. The physical properties of fresh aggregates and RAP aggregates obtained after extraction of bitumen using a Centrifuge Extractor were tested as per the procedures prescribed in IS 2383. The results obtained were compared with the requirements of SMA mixes as per IRC: SP-79 2008. Tables 3.1 and 3.2 show the properties of fresh and RAP aggregates used in the present study.

Table 3.1 Coarse Aggregates Properties

Property	Test	Method	Results	IRC Specifications
Cleanliness	Sieve Analysis	IS:2386 (P-1)	0.51%	< 2% passing 75μ sieve
Particle shape	Combined Index	IS:2386 (P-1)	11.51%	30% max.
Strength	Impact Value	IS:2386 (P-4)	13.40%	24% max.
	Los Angeles Abrasion Value	IS:2386 (P-4)	17.40%	25% max.
Water Absorption	Water Absorption	IS:2386 (P-3)	0.21%	2% max.

Table 3.2 RAP Aggregates Properties

Property	Test	Method	Results	IRC Specifications
Particle shape	Combined Index	IS:2386 (P-1)	12.70%	30% max.
Strength	Impact Value	IS:2386 (P-4)	15.23%	18% max.
	Los-Angeles Abrasion Value	IS:2386 (P-4)	18.99%	25% max.
Water Absorption	Water Absorption	IS:2386 (P-3)	0.15%	2% max.

3.1.2 Bituminous Binder

In the present study, two bituminous binders are used for preparing SMA mixes. A conventional viscosity grade bitumen VG 30 used for most paving applications in India and a polymer-modified bitumen of grade 40 (PMB 40) is used as the modified binder. VG 30 bituminous binder was procured from M/s. Mangalore Refineries and Petrochemicals Limited (MRPL) and PMB 40 was obtained from M/s. Hindustan Colas Ltd., (HINCOL), Mangalore, Karnataka. The tests to determine the basic properties of both the bitumen were conducted as per IS 73 (2013) and IS:15462 (2019) specifications for conventional and modified bituminous binders respectively. Tables 3.3 and 3.4 show the test results of conventional and modified bitumen, respectively.

Table 3.3 Properties of Viscosity Grade (30) Bitumen

Property Tested	Test Method	Results Obtained	Requirements IS 73-2013
Penetration	IS:1203	52	45 Min.
Softening point	IS:1205	49	47 Min.
Ductility	IS:1208	98	-
Specific Gravity	IS:1202	1.01	-
Flash point	IS:1448 [P : 69]	242	220 Min.
Absolute Viscosity	IS:1206 Part 2	2750	2400 – 3600
Kinematic Viscosity	IS:1206 Part 3	380	350 Min.
Test on residue from rolling thin film oven test:			
Viscosity ratio	IS:1206 Part 2	3.2	4.0 Min.
Ductility after thin film oven test at 25°C, cm	IS:1208	48	40 Min.

3.1.3 Mineral Filler

Typically, bituminous mixtures use finely divided aggregate dust as a mineral filler. Granite stone dust and hydrated lime are used as filler materials in the current investigation. Quarry stone dust and hydrated lime satisfying the requirements of mineral filler whose properties are tabulated in Table 3.5 were used as mineral filler. Studies conducted on bituminous mixtures by replacing 2% of quarry dust by hydrated lime have improved the dynamic modulus by 25% (Bari and Witczak 2005). Hence, hydrated lime content was limited to only 2% by weight of the aggregates in the mixture. By making the mastic more rigid, strong, and tough, hydrated lime improves the susceptibility of mixes to moisture damage. It also works well as an anti-stripping agent by strengthening the bond between the aggregate surface and bituminous binder (Kim et al. 2008). At higher temperatures, when hydrated lime is used as a mineral filler, it is known to improve the permanent deformation characteristics and fatigue performance of bituminous mixtures (Mohammad et al. 2000).

Table 3.4 Properties of PMB-40

Property Tested	**Test Method**	**Results Obtained**	**Requirements IS:15462-2019**
Softening point, °C	IS:1205	66	60 Min.
Elastic recovery of half thread	Annex A of IS:15462-2019	78	70 Min.
Specific Gravity	IS:1202	1.01	-
Flash point, °C	IS:1209	246	230 Min.
Viscosity at 150°C, Pa.s	ASTM D 4402	0.9	1.2 Max.
Separation, difference in softening point, °C	Annex C of IS:15462-2019	1.8	3 Max.
Investigation of rolling thin film oven residue			
Mass loss	IS 9382	0.52	1 Max.

Table 3.5 Gradation requirements of quarry dust and hydrated lime

Sieve size (μ)	**Cumulative % by weight of total aggregate passing**		
	Quarry Dust	**Hydrated Lime**	**IRC Specifications**
600	100	100	100
300	96	97	95-100
75	88	92	85-100

3.1.4 Stabilising Additives

Since SMA is a gap-graded aggregate mixture, bitumen or bitumen mastic drains down through the void spaces in the mixture. Hence, to control the drain down within permissible limits a suitable stabilising additive is required. The stabilising additives are usually fibres such as cellulose, polymer and mineral fibres. The Indian Roads Congress (IRC : SP 79 2008) recommends the use of cellulose fibre in its pelletised form.

3.1.4.1 Fibres used in the present study

In the present study, a non-conventional, natural and locally available fibre known as Areca fibre (AF) is evaluated as a stabilising additive in SMA mixes. To compare the results of SMA mixes with Areca Fibres, SMA mixes were prepared with a naturally occurring Coconut fibre, a synthetic Cellulose fibre as per the recommendations of IRC SP 79 and a mixture using a modified bitumen (PMB 40) without a stabilising additive.

Areca, popularly known as beetel nut is a kind of palm that belongs to the palm family, Arecaceae. It is grown in approximately 12 Asian nations, with an estimated 1.2 million tonnes being produced each year. The husks are not used for any industrial or commercial use after the kernels are extracted. Instead, they are burnt as firewood or discarded in the backyards of processing plants (Deshmukh et al. 2019). In India, 853,000 tonnes of areca fruit were produced in total in 2019-20 on an area of 518,000 hectares (National Horticulture Board 2018). About 40% of the fruit is made up of husk. Hence, approximately 341,000 tonnes of husk biomass were produced in India alone. The husk's lingo-cellulosic composition prevents it from decomposing quickly. (Deshmukh et al. 2019). As a result, because there are not enough industrial and commercial uses for husk biomass, vast piles of areca husk cause environmental issues (Swamy et al. 2004). Hence, these fibres can be tried as stabilising additives in SMA. Areca fibre was procured from an Areca field in Tirtahalli Taluk, Shivamogga District, Karnataka. To ensure adequate mixing with the aggregates and binder, the fibres manually cut into smaller pieces of approximately 25 mm length.

Cellulose Fibres were obtained from M/s. Fibre Zone, Vadodara, Gujarat. The husk of coconut fruit was manually peeled to obtain coconut fibres. The physical charcteristics of Areca, Coconut Coir and Cellulose fibres are depicted in Tables 3.6 - 3.8, respectively. Table 3.9 shows the chemical properties of Areca Fibres. Figures 3.1a, b and c show Areca, Coconut coir and Cellulose fibres, respectively.

(a) **Areca Fibre** | **(b)** **Coconut Fibre** | **(c)** **Cellulose Fibre**

Fig. 3.1 Stabilising additives used in SMA

Table 3.6 Physical properties of Areca fibre (Yusriah et al. 2014)

Properties of Fibre	**Areca Fibre**
Diameter, mm	0.45 – 0.55
Length, mm	55-70
Density, g/cm^3	0.70-0.80
Tensile strength, N/mm^2	147-322
Young’s modulus, N/mm^2	1124-3155
Elongation at break, %	10.23-13.15

Table 3.7 Physical properties of Coconut coir fibre (Satyanarayana et al. 1990)

Properties of Fibre	**Coconut Coir Fibre**
Diameter, mm	0.10 - 0.46
Length, mm	20 -150
Density, g/cm^3	1.15-1.46
Tensile strength, N/mm^2	95-230
Young’s modulus, N/mm^2	2800-6000
Elongation at break, %	15-51.4

Table 3.8 Properties of Cellulose fibre (M/s. Fibre zone Pvt. Ltd.)

Properties of Fibre	Cellulose Fibre
Colour and Shape	Grey, cylindrical pellets
Pellet length, mm	2 – 10
Thickness, mm	3.5 ± 1
Bulk density, gm/l	490 – 570
(Length/Dia) ratio	0.80 – 2.22

Table 3.9 Chemical properties of Areca fibre (Satyanarayana et al. 1990; Swamy et al. 2004)

Fibre Type	Cellulose, %	Hemi-cellulose, %	Lignin, %	Ash content, %
Areca fibre	---	35-64.8	13-24.8	4.4
Coconut fibre	32-43	0.15-0.25	40-45	---

3.1.5 Cashewnut Shell Liquid (CNSL)

Cashewnut shell liquid is a by-product of the cashew industry. The nut has a shell of about $(1/8)^{th}$ inch thickness inside, which is a soft honeycomb structure containing a pericarp fluid of the cashewnut, as shown in Figure 3.2. CNSL is a material which has insecticidal, fungicidal, anti-termite and medicinal applications. Resins derived from CNSL are employed widely in the fields of friction materials, automobiles, surface coatings, adhesives, laminates, rubber compounding and have several miscellaneous applications. But, very little work is reported on the use of CNSL as a rejuvenator in the pavement industry.

3.1.5.1 Thermogravimetric Analysis (TGA) of CNSL

To determine the thermal behaviour of CNSL at elevated temperatures, thermogravimetric analysis (TGA) was carried out. Using TGA, the Derivative of Thermogravimetry (DTG) was also evaluated to determine the rate of mass loss with respect to temperature. A nitrogen atmosphere with a purging rate of 20 ml/min was used. The range of heating the sample was between 25°C to 500°C. The rate of heating adopted was 10°C/min. The results of the TGA of CNSL are shown in Figure 3.3. Initially, the mass loss was higher at temperatures of up to 40°C, which may be due to the presence of moisture and other volatile matter in CNSL. Though the degradation of

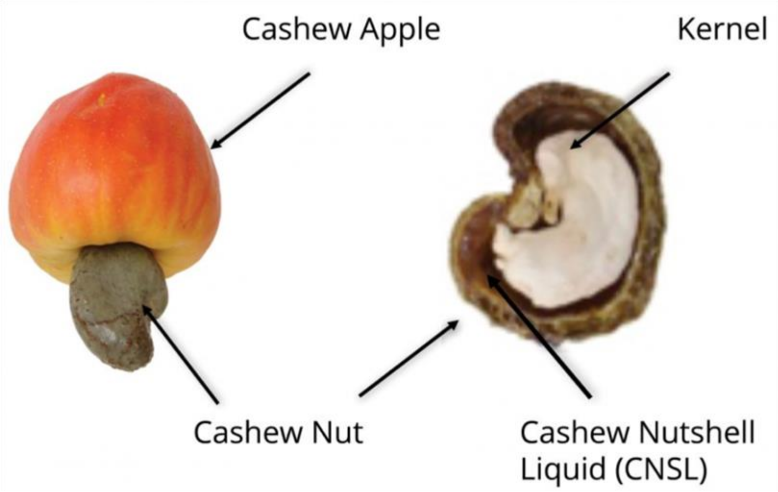

Figure 3.2 Cashew Apple, Nut, Kernel and CNSL

the material starts immediately after the material is heated, the mass loss increases suddenly from a temperature of 200°C and the same trend is continued till a temperature of about 315°C. Since, the sudden increase in the mass loss starts at a temperature beyond the maximum working temperature of 175°C for HMA mixes, CNSL can be evaluated as a rejuvenator. Also, the rate of mass loss increases at a temperature of about 200°C and reaches a peak at a temperature of about 300°C.

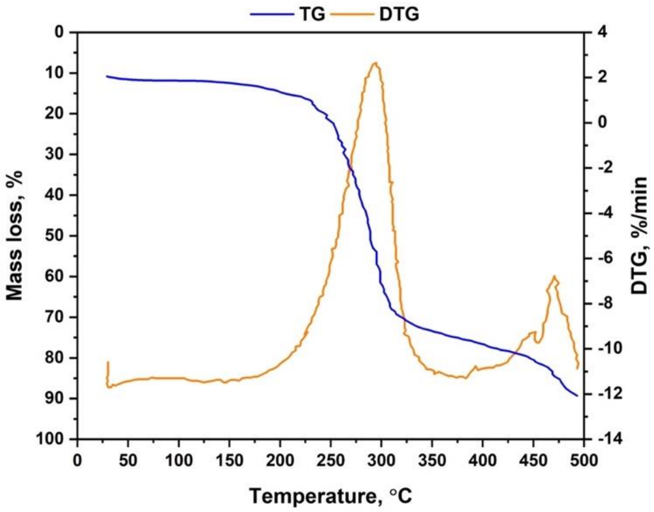

Fig. 3.3 Thermogravimetric analysis of CNSL

3.2 MORPHOLOGY OF FIBRES

The morphology of all the fibres was studied in Scanning Electron Microscope (SEM) and Figures 3.4 – 3.6 show the images taken from SEM. The SEM images reveal the presence of pits and tyloses in Areca fibres. The surface area of coconut fibres is more than that of areca fibres due to the smaller diameter of coconut fibres, which requires a higher bitumen content to coat their surface. Since cellulose fibres contain are coated with bitumen as shown in Figure 3.6, the optimum bitumen content required is lower than the mixture with either areca or coconut fibre.

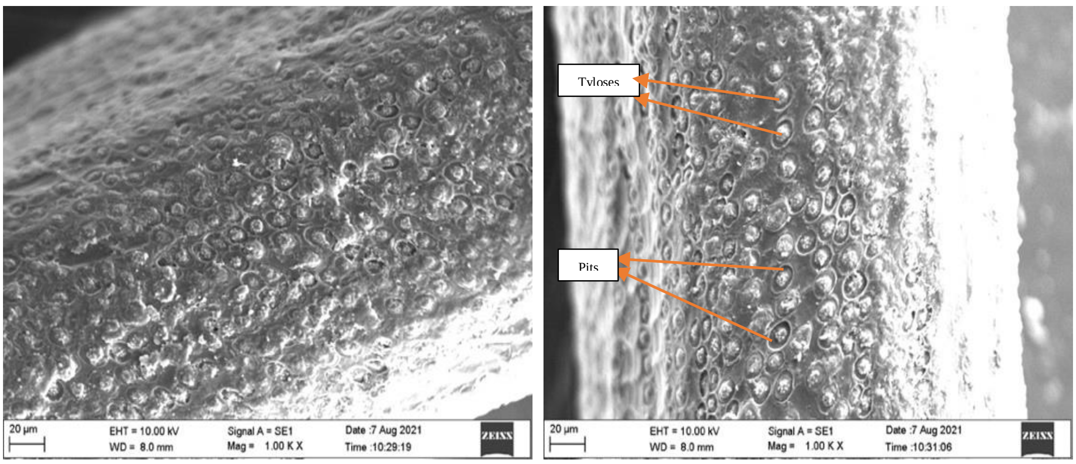

Fig. 3.4 SEM images of Areca fibre

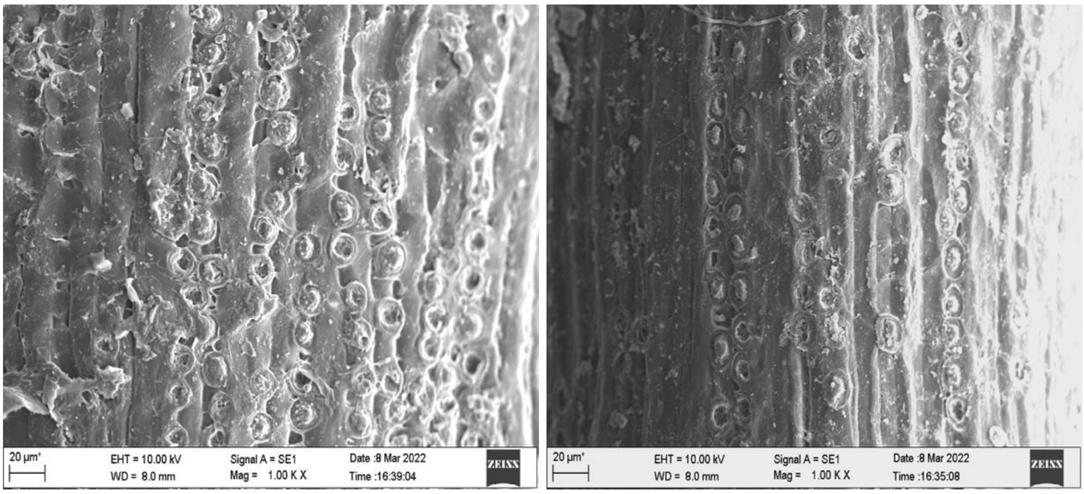

Fig. 3.5 SEM images of Coconut fibre

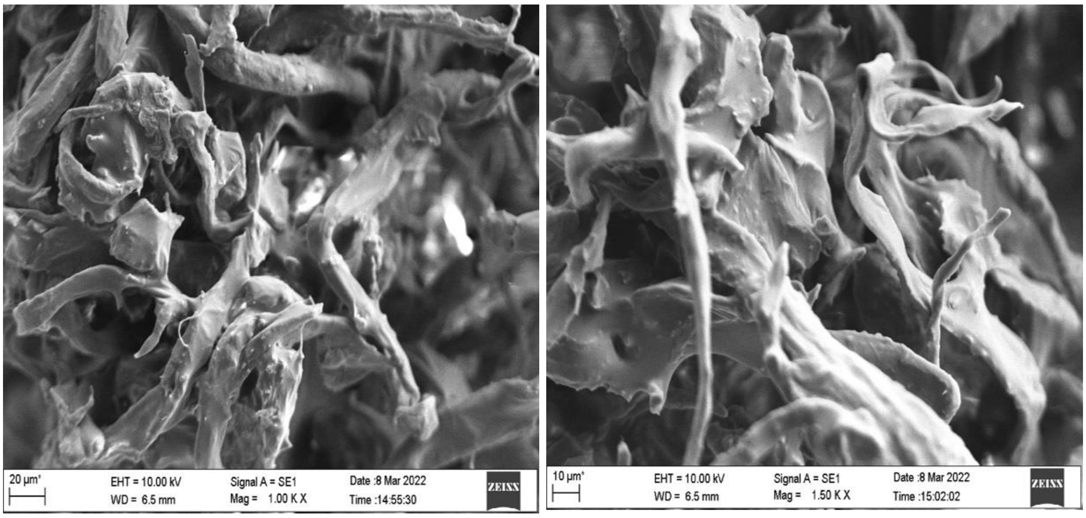

Fig. 3.6 SEM images of Cellulose fibre

3.2.1 Thermogravimetric analysis of Areca Fibre

To determine the thermal behaviour of areca fibre at elevated temperatures, thermogravimetric analysis (TGA) and differential thermogravimetry (DTG) were carried out. The atmosphere used for TGA was Nitrogen with a purging rate of 50 ml/min. The rate of heating adopted was 10°C/min. The areca fibres were heated to temperatures between 20°C to 800°C.

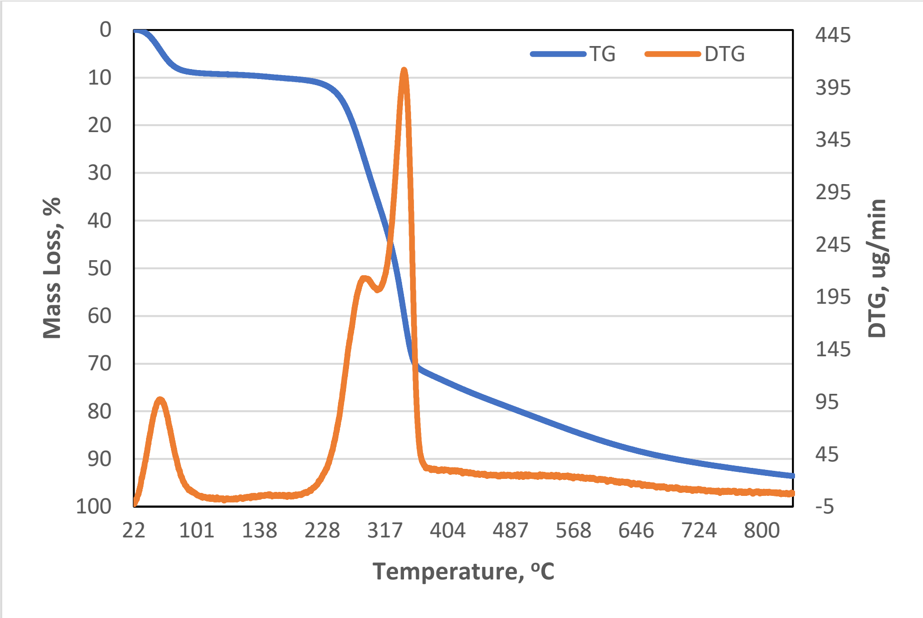

Fig. 3.7 Thermogravimetric analysis of Areca Fibre

The results of the TGA are shown in Figure 3.7. Areca fibres began to degrade thermally at around 200°C and quickly increased to about 350°C. The early peak in the DTG curve could be explained by the fibres losing moisture. Since the disintegration of areca fibres begins above the operating temperatures of either aggregates or mixes, Areca fibres can therefore be evaluated as a stabilising additive in SMA.

3.3 AGGREGATE GRADATION

The aggregate gradation with an Nominal Maximum Aggregate Size (NMAS) of 13.2 mm specified for the wearing course in IRC:SP 79-2008 was used in the study to prepare SMA mixes. Table 3.10 lists the SMA aggregate gradation specified for wearing course and the gradation achieved using only natural aggregates, which is used for the preparation of the mixes with areca fibres, coconut fibres, cellulose fibres and PMB 40 bitumen. Figure 3.8 shows the limits of specified and achieved aggregate gradation using natural aggregates. The gradation of RAP aggregates used in the present study is shown in Table 3.11. The achieved gradation with 10%, 20%, 30% and 40% RAP are shown in Figures 3.9 – 3.12.

Table 3.10 SMA wearing coarse aggregate gradation as per IRC SP 79-2008 and achieved gradation

IS Sieve Size (mm)	Percentage Passing	Achieved gradation
19.0	100	100
13.2	90-100	96.88
9.50	50-75	66.41
4.75	20-28	25.16
2.36	16-24	19.14
1.18	13-21	15.12
0.60	12-18	12.91
0.30	10-20	12.49
0.075	8-12	8.93

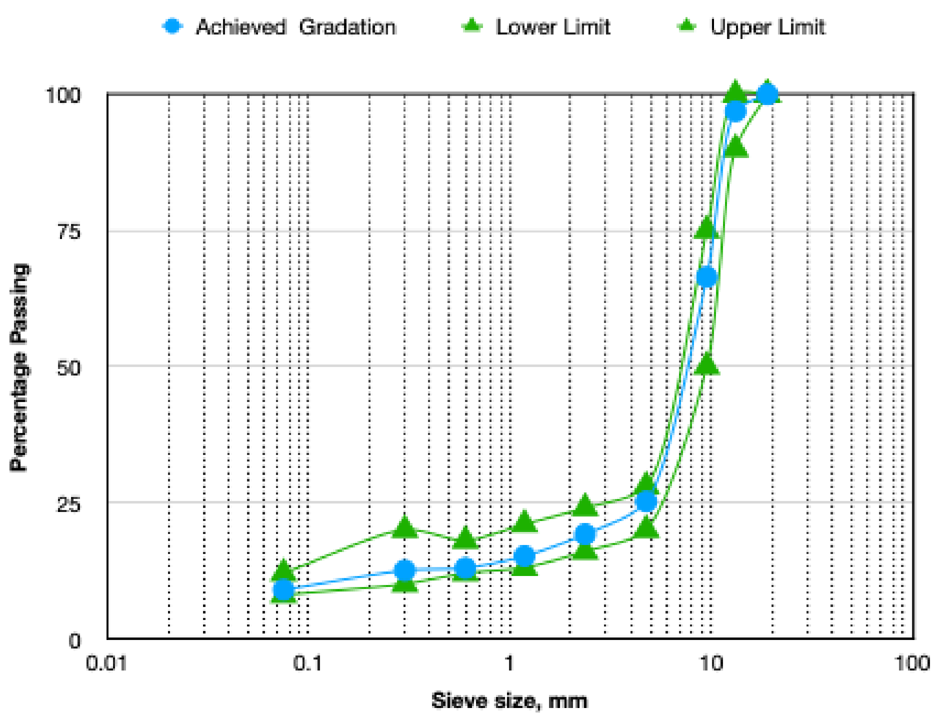

Fig. 3.8 Specified and achieved aggregate gradation with natural aggregates

Table 3.11 SMA wearing coarse aggregate gradation as per IRC SP 79-2008 and achieved gradation using RAP

IS Sieve Size (mm)	Percentage Passing	Achieved gradation			
		10% RAP	20% RAP	30% RAP	40% RAP
19.0	100	100	100	100	100
13.2	90-100	96.40	96.28	96.10	95.62
9.50	50-75	66.50	67.00	67.50	67.59
4.75	20-28	24.69	24.78	24.94	24.47
2.36	16-24	18.56	18.62	18.70	18.12
1.18	13-21	14.79	15.17	15.49	15.16
0.60	12-18	12.85	12.91	12.99	12.93
0.30	10-20	12.51	12.58	12.66	12.69
0.075	8-12	8.91	9.03	9.14	9.13

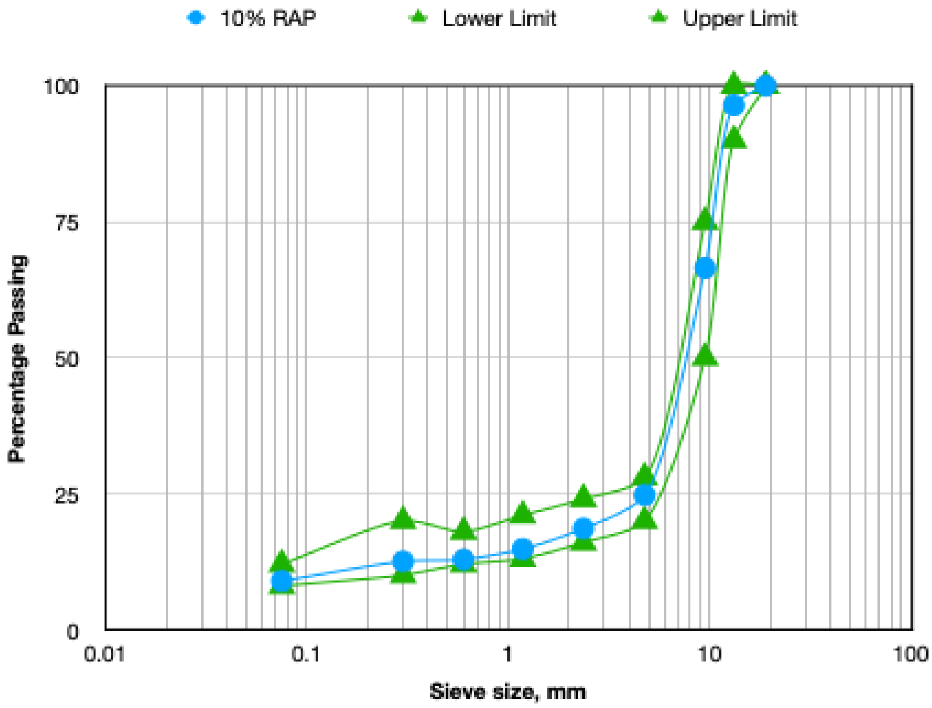

Fig. 3.9 Specified and achieved aggregate gradation with 10% RAP aggregates

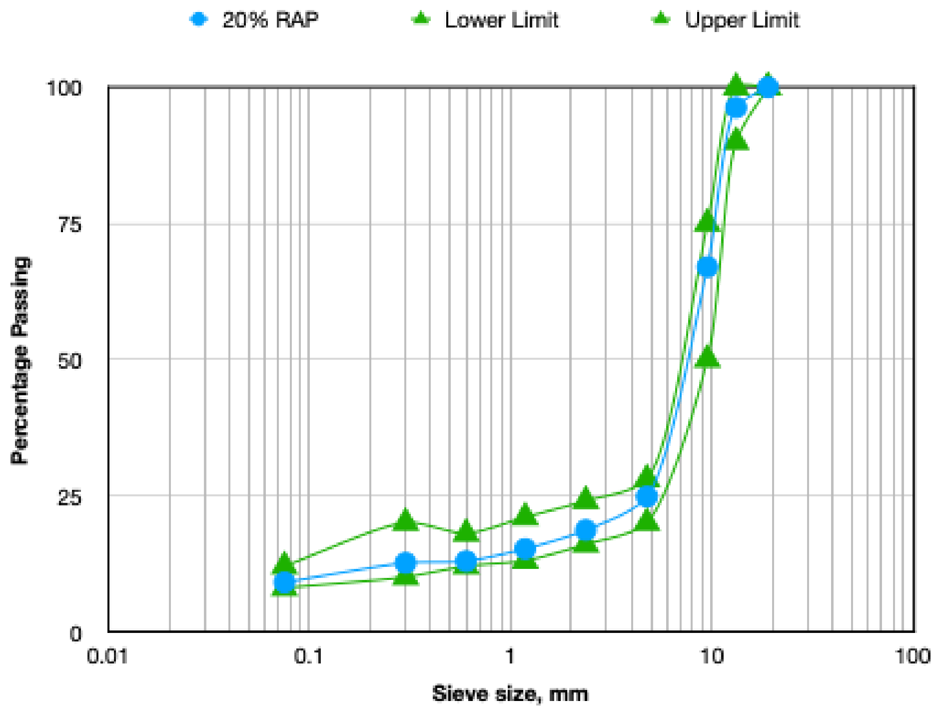

Fig. 3.10 Specified and achieved aggregate gradation with 20% RAP aggregates

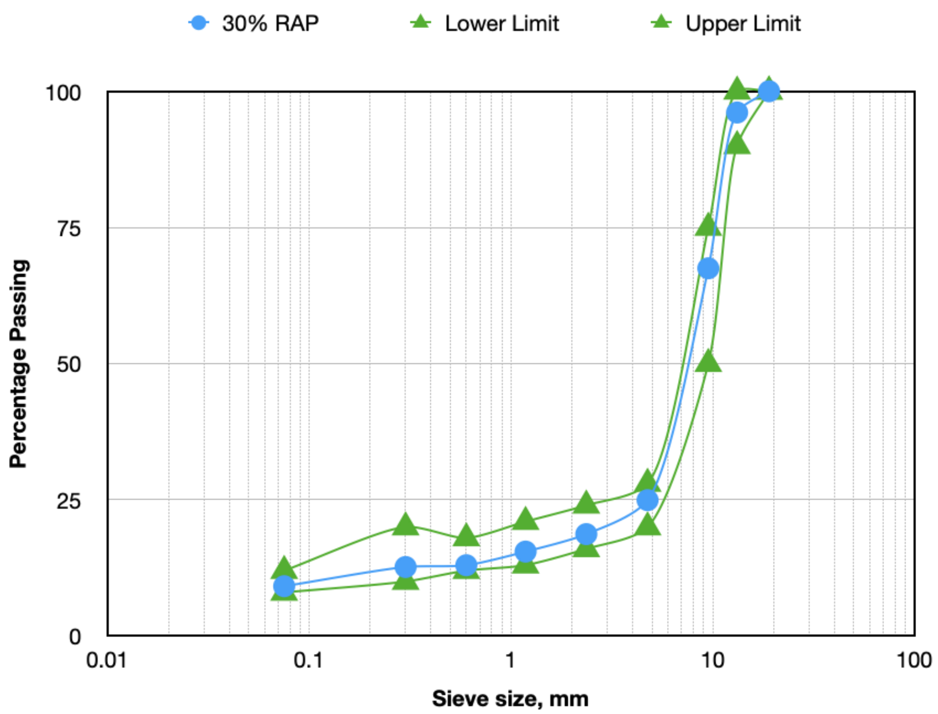

Fig. 3.11 Specified and achieved aggregate gradation with 30% RAP aggregates

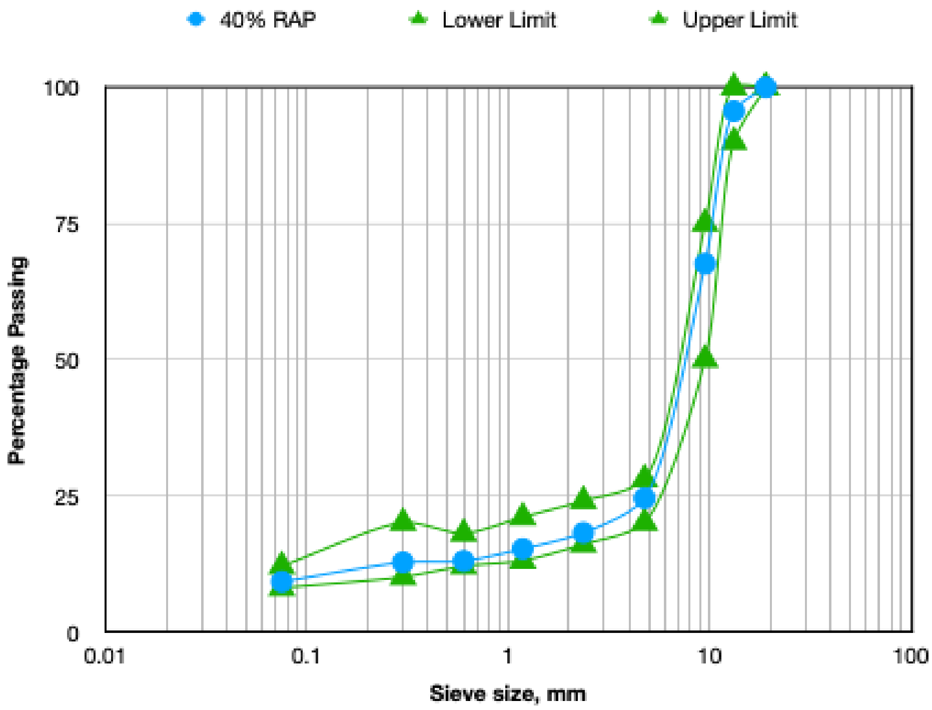

Fig. 3.12 Specified and achieved aggregate gradation with 40% RAP aggregates

3.4 METHODOLOGY

According to the requirements of the Asphalt Institute (AI) in Manual Series-2, the Marshall method of mix design was used in the current study (Asphalt Institute 2001). Table 3.12 displays the IRC-specified SMA mixture requirements.

Table 3.12 Requirements of SMA Mixture

Mix design parameters	Requirement (IRC: SP 79 2008)
Air voids, %	4.0
Bitumen content, %	5.8 min.
Cellulose fibres, %	0.3 by weight of total mix, min.
Voids in Mineral Aggregate (VMA), %	17 min.
VCA_{MIX}, %	Less than dry rodded VCA (VCA_{DRC})
Draindown, % (AASHTO T 305)	0.3 max
Moisture susceptibility (TSR), % AASHTO T 283	85 min.

To determine the maximum theoretical specific gravity (G_{mm}) using the asphalt mixture density tester and draindown susceptibility of the mixes, loose mixes were prepared. The cylindrical specimens of 100 mm diameter were cast in the Superpave Gyratory Compactor (SGC) shown in Figure 3.13 by providing 100 gyrations to each mixture at bitumen contents of 5.5, 6.0, 6.5 and 7.0 per cent by weight of the aggregates to determine the Optimum Bitumen Content (OBC). The OBC was determined based on the requirement of 4% air voids in SMA mixes. To evaluate the mechanical properties of the mixes, cylindrical samples were prepared and subjected to various tests to determine the Marshall Stability (MS), Indirect Tensile Strength (IDT), fatigue behaviour and moisture susceptibility in terms of Retained Marshall Stability (RMS), Tensile Strength Ratio (TSR) and stripping. The cylindrical specimens with a diameter of 100 mm were gyrated 225 times in the SGC to evaluate the workability properties of the mixes.

The rutting behaviour of the mixes was evaluated using a slab of dimensions 300x300x50 mm.

Fig. 3.13 Superpave Gyratory Compactor

For the preparation and compaction of mixes, the following steps were used:

Preparation of Loose Mixtures

For mixtures with fibres

- The fresh aggregates were weighed as per the achieved gradation, mixed and heated to a temperature between 150 – 170°C.
- The fibres were then added in different percentages in the required quantity to the heated aggregates and are thoroughly mixed. For the mixes with cellulose fibres, fibres were added at 0.3% by weight of the mixture as per the specifications in IRC SP 79 2008. However, no fibres were added to the mixture prepared with PMB-40 since it consists of an elastomer-based polymer Styrene-Butadiene-styrene (SBS) which acts as a stabilising additive.

For mixtures with RAP

- For the mixtures containing RAP, the obtained gradation for RAP incorporated mixtures is adopted as shown in Figure 3.9 – 3.12. The mixture of fresh and RAP aggregates was heated to a temperature of 100 to 125°C, and the required quantity of rejuvenator was added.
- For all the RAP mixes, pelletised cellulose fibres were added at 0.3% by weight of the mixture as per the specifications in IRC SP 79 2008 and thoroughly mixed.
- After being heated to 150 to 160°C, the bitumen is added to the hot mixture of aggregates and RAP in the required proportions (5.5 – 7.0 per cent in increments of 0.5% by weight of aggregates) and mixed thoroughly by maintaining a temperature of 150 – 165 °C.
- For the mixtures prepared with modified bitumen, the temperature of the bitumen was raised by 10 – 20 °C.

Compaction in SGC:

- The SGC mould of 100 mm diameter with the puck as shown in Figure 3.14 is heated in an oven. The prepared mixture is then placed in the mould carefully.

Fig. 3.14 SGC mould of 100 mm diameter

- After levelling the top surface, the mould containing the mixture is kept inside the SGC, and the glass door is closed.
- In the menu status, the pressure is set to 600 kPa, angle of gyration to 1.25°, rate of gyration to 30 rpm, number of gyrations to 100 and the number of dwell gyrations to 10.
- When the 'Start' button is pressed, the ram moves down to apply the pre-set pressure of 600 kPa to the mix. The mould then tilts to 1.25° while the upper and lower pucks remain parallel to each other and perpendicular to the original axis of the cylinder. While maintaining the pressure and preventing the mould from rotating, the mould is gyrated at 1.25° about the original central axis at 30 rpm.
- While the specimen is being compacted, the data of height of the specimen versus number of gyrations is automatically recorded in the computer connected to the SGC.
- The angle is removed and the ram is automatically raised once 100 gyrations and 10 dwell gyrations have been completed.
- Then the mould along with the specimen is taken out and the specimen is removed using a sample extractor.

- The masses of the cylindrical specimens were then measure in air, water and saturated surface dry (SSD) condition.

3.4.1 Draindown Test

As per ASTM standards, draindown is defined as that part of the material that gets separated from the prepared loose mixture and is deposited in the catch plate placed below the wire basket during the test. The material that gets separated may be either bitumen or a combination of bitumen, fine aggregates and additives.

As illustrated in Figure 3.15, the draindown test is carried out in accordance with ASTM D6390 in a wire mesh basket consisting of 6.3 mm standard sieve cloth. In order to confirm that the drainage of the bituminous mortar is within allowable limits, the test is performed on loose mixtures at 7% bitumen content and Optimum Bitumen Content (OBC). A catch plate is placed beneath the wire basket to catch the drained material after about 1000g of SMA mixture is prepared and placed in the basket. The wire basket is then suspended in a temperature-controlled oven that is kept at the anticipated plant production temperature of 160°C. The test is conducted for a period of one hour. After the test period of an hour, the ratio of the weight of material separated from the mixture to the weight of the mixture taken for the test, expressed in percentage is the drain-down. To account for the variation in the plant production temperature, the test is also conducted at a temperature of 170°C. The drain down test provides an evaluation of the drain down potential of SMA mixtures during production, transportation and placement in the field.

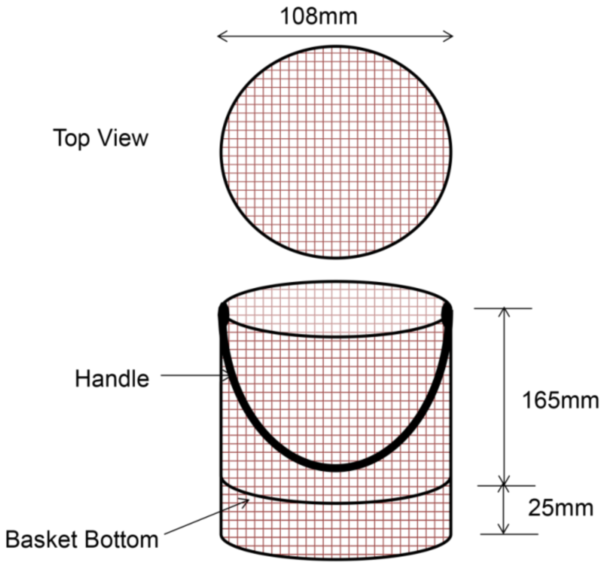

Fig. 3.15 Drain down Test Assembly

3.4.2 Volumetric Properties

Maximum Theoretical Specific Gravity

The determination of the theoretical maximum specific gravity (G_{mm}) of the prepared mixture provides a measure of absorption of bitumen by the aggregates. The asphalt mixture density tester is used to calculate the G_{mm} in accordance with the guidelines provided in ASTM D 2041, as illustrated in Figure 3.16. A brief procedure to determine G_{mm} is as follows:

1. Oven-dry aggregates are used to prepare the SMA mixtures and the aggregate particles of the mixture are manually separated without fracturing them, so that the fine particles of the aggregates are not larger than 6 mm. After that, the mixture is allowed to cool to ambient temperature.
2. The mixture is weighed when it is still in the cylindrical container of the asphalt mixture density tester. The net mass of the mixture is referred to as A.
3. After adding adequate water to completely cover the mixture at a temperature of about 25°C, the container is closed with a lid.
4. The container containing the mixture and water is then placed inside the asphalt mixture density tester. Agitation is then immediately started, and the vacuum

pressure is gradually increased (using a vacuum pump connected to it) until the residual pressure manometer records 3.7±0.3 kPa, releasing any trapped air in the mixture. Within two minutes, the necessary vacuum is attained, and it is kept there for 15±2 minutes while the specimen is being stirred.

5. The vacuum pressure is gradually released using the bleeder valve. The mass of the container, mixture, water and lid is determined and designated as E.
6. The bleeder valve is used to gently release the vacuum pressure. The container is weighed with the lid (D).

Equation 3.1 is used to compute the theoretical maximum specific gravity of the mixture.

$$G_{mm} = \frac{A}{[A + D - E]} \tag{3.1}$$

Where,

G_{mm} = Maximum theoretical specific gravity of the mixture,

A = Mass of the dry sample in air, g

D = Mass of the volumetric cylinder and lid completely filled with water, g

E = Mass of the volumetric cylinder, lid, sample and water filled completely, g.

For each composition, the theoretical maximum specific gravity was calculated at two bitumen contents: one above and below the expected OBC of the mixture. At least two specimens were prepared for determining the G_{mm} for each bitumen content and the average of the two specimens was obtained. Equation 3.2 was used in each case to calculate the specific gravity of aggregates, with the average of two values adopted.

$$G_{se} = \frac{P_s}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \tag{3.2}$$

G_{se} = Effective specific gravity of aggregates

P_s = Percentage of aggregate by total mixture weight

G_{mm} = Maximum theoretical specific gravity for each binder content determined in accordance with ASTM D2041

P_b = Percentage of bitumen by weight of the mixture at which the G_{mm} test was conducted

G_b = Specific Gravity of Bitumen

Then, using Equation 3.3, G_{mm} of mixes with various bitumen contents is determined.

$$G_{mm} = \frac{100}{\frac{P_s}{G_{se}} + \frac{P_b}{G_b}} \tag{3.3}$$

P_s = Aggregate content, as a percentage of the mixture's total weight

Fig. 3.16 Asphalt Mixture Density Tester

Bulk Specific Gravity of Aggregates (G_{sb})

By calculating the specific gravities of quarry dust, hydrated lime, coarse aggregates and fine aggregates, the G_{sb} of aggregates was calculated using Equation 3.4.

$$G_{sb} = \frac{100}{\frac{W_1}{G_1} + \frac{W_2}{G_2} + \frac{W_3}{G_3} + \frac{W_4}{G_4}} \tag{3.4}$$

where,

W_1 = coarse aggregates, expressed as percentage of total aggregate

W_2 = fine aggregates, expressed as percentage of total aggregate

W_3 = filler, expressed as percentage of total aggregate

W_4 = hydrated lime, expressed as percentage of total aggregate

G_1 = coarse aggregate specific gravity

G_2 = fine aggregate specific gravity

G_3 = filler specific gravity

G_4 = hydrated lime specific gravity

Bulk Density of Compacted Sample (G_{mb})

Equation 3.5 was used to determine the G_{mb} of each compacted sample.

$$\mathrm{G_{mb}} = \frac{M_\mathrm{a}}{M_\mathrm{ssd} - M_\mathrm{w}} \tag{3.5}$$

where,

M_a = Mass of the sample in air

M_w = Mass of the sample in water

M_{ssd} = Mass of the sample in Saturated Surface Dry (SSD) condition

Air Voids in Total Mix (V_a)

Small pockets of air between coated aggregate particles in the compacted mix are measured as a proportion of the total volume of the mix and are referred to as "voids in the mix." Equation 3.6 is used to calculate the air voids in the total mix.

$$\mathrm{V_a} = \frac{\mathrm{G_{mm}} - \mathrm{G_{mb}}}{\mathrm{G_{mm}}} \times 100, \% \tag{3.6}$$

where,

G_{mm} = Theoretical maximum specific gravity of the mixture

G_{mb} = G_{mb} of the compacted specimen

Voids in Mineral Aggregates (VMA)

In the compacted mixture, the void spaces between aggregate particles are referred as VMA. VMA includes the air voids and the volume of bitumen not absorbed into the aggregates. The VMA is determined using equation 3.7.

$$\mathrm{VMA} = 100 - \frac{\mathrm{G_{mb}} . \mathrm{P_s}}{\mathrm{G_{sb}}} \tag{3.7}$$

where, G_{sb} = Bulk specific gravity of total aggregates used in the mixture

Voids Filled with Bitumen (VFB)

Equation 3.8 is used to determine VFB, which is the proportion of the volume of air voids that is filled with the bitumen.

$$\mathrm{VFB} = \frac{\mathrm{VMA} - \mathrm{V_a}}{\mathrm{VMA}} \times 100 \tag{3.8}$$

Voids in the Coarse Aggregates (VCA)

The procedure laid out in ASTM C 29 was used to determine the voids in the coarse aggregates. The coarse aggregates are first washed and dried. The dried coarse aggregates are filled in a cylindrical measure of approximately 10-litre volume in three equal layers by tamping 25 times with the rounded end of a tamping rod. Equation 3.9 was used to determine the unit weight of coarse aggregates by the dry rodding method (γ_s), taking into account the weight of the measure with the aggregates.

$$\gamma_s = \frac{\mathrm{A} - \mathrm{B}}{\mathrm{C}} \tag{3.9}$$

γ_S	=	Unit weight of the coarse aggregates in dry rodded condition, kg/m^3
A	=	Mass of the measure plus aggregate, kg
B	=	Mass of the measure, kg
C	=	Volume of the measure, m^3

Equation 3.10 was used to determine the dry rodded VCA of the coarse aggregates.

$$\mathrm{VCA_{DRC}} = \frac{\mathrm{G_{ca}}\gamma_w - \gamma_s}{\mathrm{G_{ca}}\gamma_w} \times 100 \tag{3.10}$$

$\mathrm{VCA_{DRC}}$	=	VCA in the dry rodded condition
G_{ca}	=	Bulk specific gravity of the coarse aggregates
γ_w	=	Unit weight of water (998 kg/m^3)
γ_s	=	Unit weight of coarse aggregate fraction in dry-rodded condition (kg/m^3)

Equation 3.11 was then used to determine the VCA of the mixture ($\mathrm{VCA_{MIX}}$)

$$VCA_{MIX} = 100 - \left(\frac{G_{mb}}{G_{ca}} \times P_{ca}\right) \tag{3.11}$$

G_{ca} = Bulk specific gravity of the coarse aggregate fraction

P_{ca} = Percent coarse aggregate in the total mixture

3.4.3 Marshall Characteristics

As a part of the Marshall mix design process, the Marshall test, which is carried out in accordance with ASTM D 6927, provides a way to assess the resistance that bituminous mixes offer to plastic flow. In this test, the samples are preconditioned for 30-40 minutes in a water bath that is maintained at 60 ± 1ºC. The specimens are then removed from the water bath and placed on the Marshall test head and tested to determine the Marshall Stability (MS), which is a measure of the strength of the mixture. Marshall Stability, which is measured in kilo Newton (kN), is defined as the maximum resistance offered by the mixture until failure when tested at a temperature of 60ºC in a standard Marshall equipment. The maximum deformation from the time of application of load to failure of the specimen is defined as flow, which is measured in millimetres (mm). The MS and flow values are determined for all the bitumen contents while determining the OBC of all mixtures. The values for stability and flow are used to determine the Marshall Quotient (MQ) expressed in kN/mm using Equation 3.12.s

$$MQ = \frac{MS}{Flow} \tag{3.12}$$

3.4.4 Optimum Bitumen Content

It is important that in any bituminous mixture the bitumen content should not be too low so that the aggregates are not fully coated, resulting in lack of bonding between the aggregate particles and not too high that it causes bleeding. As a result, the OBC in SMA mixtures is calculated at 4% air voids in the mixture. Marshall test is carried out on SMA mixes with different bitumen contents and their volumetric properties are determined. A graph is plotted with the bitumen contents on the x-axis, and the air voids on the y-axis.

3.4.5 Indirect Tensile Strength

When measured along the diametrical plane of a cylindrical specimen, indirect tensile strength (IDT) strength gives an indication of the tensile strength of bituminous mixes. The IDT value provides an estimate of the resistance of the mixture to cracking and fatigue. The IDT of compacted specimens are evaluated in accordance with the procedure laid out in ASTM D 6931. The prepared specimens are kept in a water bath maintained at 25°C for about 1 hour. The specimen is placed on the lower strip of the IDT test set-up, and the upper strip is lowered to touch the specimen so that both the strips are placed diametrically opposite to each other. The entire test set-up with the specimen was placed in the Marshall equipment and the maximum load required for specimen failure was noted by applying a vertical compressive load at a deformation rate of 50 mm/min. Equation 3.13 is used for the determination of IDT of compacted specimens.

$$S_t = \frac{2000\ P}{\pi D t} \tag{3.13}$$

S_t	=	Tensile strength, MPa
P	=	Load at failure, kN
D	=	Specimen Diameter, mm
t	=	Specimen Thickness, mm

3.4.6 Rutting Resistance

Due to the continuous movement of vehicles on the wheel paths of flexible pavements, depression in the longitudinal direction takes which leading to permanent deformation or rutting. Nievelt and Thamfald (1988) defined rutting as the build-up of unrecoverable strain of lower magnitudes caused by the heavy stresses applied on pavements by the passage of traffic. In this investigation, the Wheel Rut Tester (WRT) as depicted in Figure 3.17, is used to repeatedly run a typical wheel over a slab specimen in order to evaluate how SMA mixtures behave when subjected to permanent deformation.

For this test, a slab specimen with the dimensions (300x300×50) mm was cast. The WRT consists of a 200 mm diameter and 50 mm thick rubber wheel which applies a standard load of 150 N. Since the specimen is placed in the mould, it is rigidly restrained on all sides and placed on a platform. The platform carrying the mould and the specimen can move back and forth for a distance of 250 mm due to a motor and a reciprocating device with a loaded wheel remaining stationary above the surface of the specimen. A motor and a reciprocating device provide back and forth movement to the platform containing the mould and the specimen for a distance of 250 mm, with the loaded wheel kept in a static position above the surface of the specimen. An LVDT (Linear Variable Deflection Transducer) placed to the side of the wheel measures the depth of deformation due to the movement of the platform, and real-time data and a graph showing the total permanent deformation in relation to the number of passes are shown in the computer connected to the WRT.

A total of 10,000 wheel passes are made over the slab, and the total permanent deformation along the wheel path is recorded. The amount of load repetitions necessary to produce 1-mm rutting during the final 15 minutes of a 1-hour test is used to calculate the Dynamic Stability (DS) of the mixtures. Equation 3.14 is used to calculate DS as follows:

$$\text{Dynamic Stability} = \left(\frac{N_{15}}{d_{60} - d_{45}}\right) \tag{3.14}$$

Where,

N_{15} = 15-min loading cycles,

d_{60} = rut depth at 60 min, mm

d_{45} = rut depth at 45 min, mm

The slabs are prepared at the corresponding OBC and with 7% air voids for each SMA mixture. The required quantity of aggregates was taken based on the density of the mixture and the volume of the mould. The procedure for casting a slab specimen is briefly explained as follows:

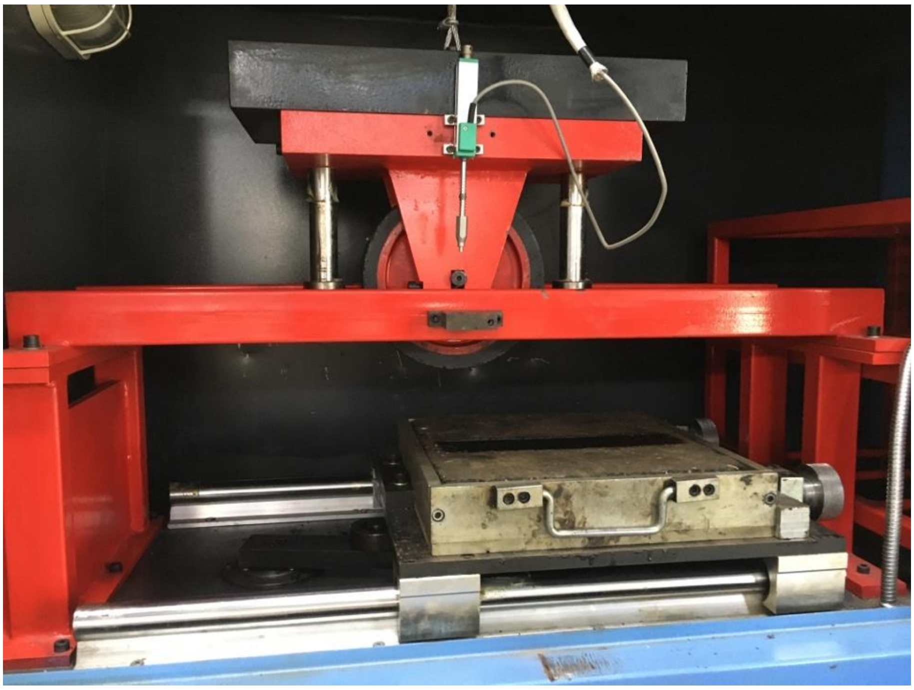

Fig. 3.17 Wheel Rut Tester

1. The heated aggregates are uniformly mixed. The required quantity of heated bitumen is measured and mixed with the hot aggregates. For the mixes with RAP, the fresh aggregates and RAP are heated, and then the rejuvenator is added before adding the heated bitumen.

2. The prepared loose SMA mixture in the mould is then compacted in a Wheel Rut Shaper, as shown in Figure 3.18, by applying 24 repetitions of the pendulum to achieve the required density of the mixture.

3. After 24 hours of casting, the specimen along with the mould is placed in the WRT. The specimen is then conditioned in the chamber of WRT at 60°C for 4 hours before the test is begun.

4. The wheel is lowered along with the LVDT to touch the slab surface, which applies a load of 150 N on the specimen. The test is started after ensuring the chamber temperature is maintained at 60°C.

Fig. 3.18 Wheel Rut Shaper

3.4.7 Fatigue Resistance

During the service life of a pavement, repeated wheel loads cause flexiblem pavements to deteriorate. The application of repeated loads applies stress on the pavements, which results in the formation of micro-cracks which develop into macro-cracks and ultimately lead to the failure of the pavement. Using a Repeated Load Testing (RLT) system as shown in Figure 3.19, the fatigue behaviour of SMA mixtures is assessed in the laboratory.

The load is applied to the cylindrical specimen in a positive sinusoidal pattern during the fatigue test, which is a dynamic diametrical tensile test. A hydraulic loading system and a movable shaft are used to apply the dynamic loading to the specimen.

Fig. 3.19 Repeated Load Testing (RLT) Device

The dynamic loading is applied to the specimen by means of a hydraulic loading system and a movable shaft. The specimen is placed in the fatigue test apparatus in the same way as the IDT test set-up, where the required load is applied on the diametrical plane through the load strips. An oil cooling system is used to control the temperature of the hydraulic system, and a pressure valve is used to set the required pressure. Two vertical and Two horizontal LVDTs accurate to 0.01 mm are connected to the apparatus to measure the deformation of the specimen, whose values are displayed on the software 'Fatigue 4.0' installed in the computer attached to the equipment. The frequency of loading can be adjusted from 1 Hz to 10 Hz. The loading and the rest periods used for the present study is 0.1 second and 0.9 seconds, respectively. The experimental set-up with all the required attachments is shown in Figure 3.20. Fatigue Life (FL) was defined as the total number of load repetitions necessary to cause the specimen to fail. For the fatigue test, the permanent deformation of 5 mm was considered as the failure criterion. In this study, stress values of 15%, 33.3% and 50% of the lowest IDT failure load are investigated on SMA specimens prepared at OBC.

Fig. 3.20 Specimen arrangement in RLT device

The height of the cylindrical specimens has an impact on the FL of the mixtures in addition to the properties of the mixture and the applied stress. As a result, the FL value by itself cannot be utilised to describe the fatigue behaviour of a mixture. Given that applied load is a function of IDT strength, a weak mixture with lower IDT strength and lower applied load may have a greater FL value, whereas a strong mixture may have a lower FL value.

The FL values are related to the tensile stress, which includes the load applied to the specimen and its dimensions, to obtain a more precise picture of the fatigue behaviour of SMA mixes. Equation 3.15 is used to compute the tensile stress.

$$\text{Tensile Stress } = \frac{2000\ \text{P}}{\pi \text{dt}}, \text{MPa} \tag{3.15}$$

where,

P = load applied, kN

d = Specimen Diameter, mm

t = Specimen Thickness, mm

3.4.8 Workability Characteristics

Compactibility, which is defined as the effort necessary to achieve the consolidation of asphalt mixtures, is what determines the workability and is essential for effective long-term performance in the field. Evaluation of the mix design and mechanical characteristics of asphalt mixes is required during the design process. Therefore, it would be helpful to measure the compactibility of mixes.To determine the workability of mixes, based on the SGC curve for densification, two indices – Construction Densification Index (CDI) and Traffic Densification Index (TDI) were developed, which are helpful in determining the compactibility of the mixtures and densification caused due to traffic loading (Fatin and Mahmoud 2004). A typical Superpave Gyratory Compactor (SGC) curve with CDI and TDI is shown in Fig. 3.21.

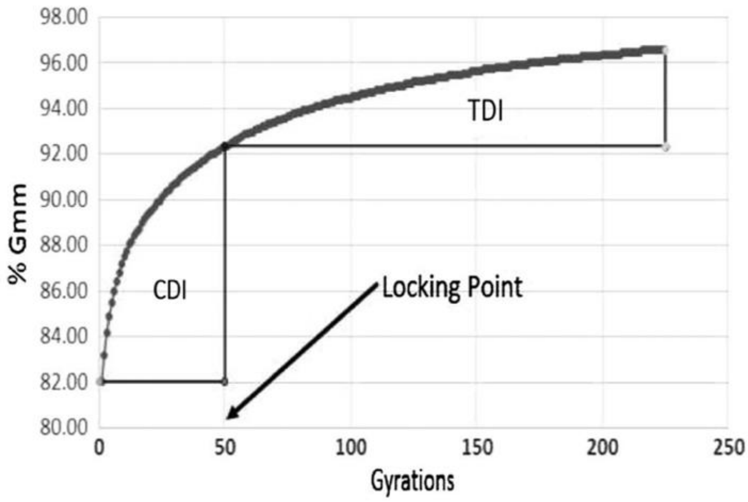

Fig. 3.21 SGC densification curve (Shiva Kumar and Suresha 2017)

Bahia *et al.* (1998) introduced the CDI and TDI concepts based on the SGC curve. CDI is the area in the compaction curve from the 8th gyration to the number of gyrations required to achieve 92% of theoretical maximum density (G_{mm}). TDI is measured as the area in the densification curve from the number of gyrations required to achieve 98% G_{mm} from 92% G_{mm}.

Vavrik *et al.* (1999) devised methods to quantify the compactibility of asphalt mixtures based on compaction curves and introduced the locking point method. The locking point corresponds to the first gyration in the first occurrence of three gyrations of the same height preceded by two sets of two gyrations with the same height measured to an accuracy of 0.1 mm. Using the locking point method, the compaction curve was divided into two areas, CDI and TDI. The CDI determines the area in the densification curve from the first gyration to gyration at locking point. The TDI relates to the densification of the mixture caused by traffic. It is determined as the area in the densification curve to achieve 98% G_{mm} from the number of gyrations at locking point.

3.4.9 Moisture Susceptibility

The susceptibility of bituminous mixtures to moisture damage is one of the primary causes of numerous distresses in flexible pavements. Different distresses including fatigue damage, loss of strength, stripping, ravelling and permanent deformation are caused by moisture susceptibility. Moisture damage is the degradation of the mechanical characteristics of the materials caused by the presence of moisture in the microstructure. The moisture damage can be defined as the degradation of the mechanical properties of the material due to the presence of moisture in its microstructure. In the present study, tests such as Retained Marshall Stability (RMS), Tensile Strength Ratio (TSR) and Stripping test are used to evaluate the moisture susceptibility of SMA mixes.

3.4.9.1 Retained Marshall Stability

The RMS is a test used to evaluate the susceptibility of bituminous mixtures to moisture based on the Marshall stability values determined in accordance with ASTM D6927. In this test, two sets of cylindrical specimens are prepared at OBC. One set, called the 'unconditioned' set, is tested for its Marshall stability after conditioning them in a water bath maintained at 60°C for 30 minutes. The Marshall stability of the second set of specimens called the 'conditioned' set, is also determined after conditioning in a water bath maintained at 60°C for 24 hours. RMS is defined as the ratio of the Marshall stability values of the conditioned and unconditioned set of specimens. The results of this test show how water immersion for 24 hours affects the stability of SMA specimens, which shows the effect of moisture on the mixture.

3.4.9.2 Tensile Strength Ratio (TSR)

This test, conducted according to AASHTO T 283 specifications, provides an assessment of the resistance offered by the bituminous mixes to moisture damage. The test method covers the preparation of the specimens and testing, which is similar to the IDT test setup. The test is designed to evaluate the effect of water saturation and stripping following a freeze-thaw cycle on the tensile strength of the compacted specimens. The outcome of the test may be used to forecast the long-term stripping susceptibility of bituminous mixtures and assess liquid anti-stripping additives added to bitumen or pulverised mineral materials added to mineral aggregates, such as hydrated lime.

The specimens are prepared at 7±0.5% air void content to maximise the influence of moisture. Other than that, the test is very identical to the IDT test. Lesser gyrations are used to prepare the specimens at OBC and 7±0.5% air void content.

The method recommended by AI Superpave series (SP) 2 manual is used to compute the number of gyrations for each mixture. SP-2 provides a relationship between the density of the specimen at the design air voids (G_{mb}) and the density estimated based on the diameter and height of the specimen after the design number of gyrations (in this case, 100) ($E_{st.}\ G_{mb}$), applying a Correction Factor, C as presented in Equation 3.16.

$$\text{Correction Factor} = \frac{\text{Est.}\,G_{mb}}{G_{mb}} \tag{3.16}$$

93% of the theoretical maximum specific gravity provides the required actual density of the specimen at 7% air voids (G_{mb} at 7%). The density of the specimen at 7% air voids can be estimated using the same Correction Factor computed from equation 3.16 based on the specimen's diameter and height ($E_{st.}\ G_{mb}$ at 7%), as indicated in Equation 3.17.

$$\text{Est.}\,G_{mb}\text{ at }7\% = \text{Correction Factor} \times G_{mb}\text{ at }7\% \tag{3.17}$$

This $E_{st.}\ G_{mb}$ at 7% can be used to get the estimated height of specimen for 7% air voids (E_{st}.h at 7%). The number of gyrations necessary to produce a height of E_{st}.h at

7% air voids can be determined using the gyrations versus height data of the specimen at the design air voids, and the same procedure can be used to prepare specimens with a 7% air void content. The following steps provide a brief procedure:

At the corresponding OBC, the specimens for each SMA mixture were prepared by providing the number of gyrations necessary to produce 7% air voids. 2 sets of specimens are prepared, and they are categorised into ‘unconditioned’ and ‘conditioned’ sets. The ‘unconditioned’ set of specimens is conditioned in a water bath maintained at a temperature of 25±1°C for 2 hours. The "conditioned" set of specimens is put into plastic bags with approximately 10 ml of water, sealed, and kept in the freezer for at least 16 hours at a temperature of -18±3°C. This process simulates one freezing cycle. At the end of 16 hours, the specimens are removed from the freezer and transferred to a water bath maintained at 60°C for a period of 24 hours, which simulates the thawing effect in the field. Hence, the specimens are subjected to one freeze-thaw cycle. The specimens are then kept in a water bath maintained at 25±1°C for a period of 2 hours. Then, IDT was determined using Equation 3.18 for both the conditioned and unconditioned specimens using the procedure used for IDT strength described in section 3.4.5.

$$\mathrm{IDT} = \frac{2\,\mathrm{P}}{\pi \mathrm{Dt}} \tag{3.18}$$

where,

IDT = Indirect Tensile Strength, kPa

P = Load at failure, kN

D = Specimen Diameter, mm

t = Specimen Thickness, mm

Tensile Strength Ratio (TSR) is the ratio of the IDT values of the conditioned set of specimens to those of the unconditioned set and is determined using Equation 3.19.

$$\mathrm{TSR} = \frac{S_2}{S_1} \times 100 \tag{3.19}$$

where,

S_1 = IDT of unconditioned set, MPa

S_2 = IDT of conditioned set,, MPa

3.4.9.3 Stripping

It is important that there exists a proper bond between aggregate and bituminous binder in any bituminous mixture. The bituminous binder should have a strong and long-lasting adherence to the aggregate surface in order to ensure good performance and durability of flexible pavements. Hence, the boiling test as per ASTM D 3625 is conducted to assess the stripping potential of SMA mixtures. Figure 3.22 shows the boiling test being conducted and the sample kept for observation after the test. At OBC, around 250 grams of loose SMA mixture is prepared for the test and allowed to cool to a temperature of 85 to 100°C. Distilled water, taken in a clean beaker is boiled on a heating device. The prepared mixture in its loose form is placed in the beaker with boiling water. The boiling is carried out for about 10 minutes. In order to avoid recoating, the container is then removed and the free bitumen on the surface of water is skimmed off. The water and the mixture are allowed to cool to room temperature. After cooling, the water is removed, and the mixture is placed on a white paper towel for visual inspection of stripping of bitumen. Based on visual observation, the amount of stripping and the area stripped, if any, was calculated. This test is a qualitative test and the assessment of stripping is subject to individuals.

(a) Boiling test **(b) sample after boiling test**

Fig. 3.22 Stripping test

3.5 SUMMARY

In this chapter, the various materials used in the present study are discussed along with their sources. The aggregates were procured from a stone quarry in Karkala, Udupi district, Karnataka. The RAP aggregates were procured from NH 67 near Surathkal, Mangaluru, Dakshina Kannada District of Karnataka state. Two types of bitumen are used in the present study viz., Viscosity Grade 30 (VG 30) and Polymer Modified Bitumen (PMB 40). VG 30 was procured from M/s. Mangalore Refineries and Petrochemicals Ltd., and PMB 40 was procured from M/s. HINCOL, Mangaluru. Similarly, Areca fibres were obtained from Tirthahalli Taluk, Shivamogga district. Coconut fibres were obtained from Puttur Taluk, Dakshina Kannada District. Cellulose fibres were purchased from M/s. Fibre Zone Pvt. Ltd, Vadodara, Gujarat. All the materials were tested according to standards and were found to satisfy the requirements specified in the relevant codes. The chapter also outlines the methodology adopted for the study and discusses in detail the procedure adopted to prepare specimens. The testing procedure of the prepared specimens is also discussed in detail.

CHAPTER 4

SMA WITH FIBRE ADDITIVES AND MODIFIED BITUMEN

4.1 GENERAL

To control the drain down of SMA mixes, various fibres have been used as stabilising additives by many agencies when mixtures are prepared with conventional bitumen. The IRC suggests the use of cellulose fibres in the form of pellets when conventional bitumen is used. Various naturally available fibres such as coconut fibres, Sisal fibres, Banana fibres etc., have been successfully used in SMA (Ferreira Da Costa et al. 2020; Kar et al. 2019; Panda et al. 2013b)

4.2 CELLULOSE AND ARECA FIBRES

Cellulose fibres are made from plants and are often collected from a variety of plant parts, such as wood, bark, leaves, etc. The high absorption capacity of cellulose fibres increases the binder content and aggregate retention in bituminous mixtures. Along with these qualities, accessibility of cellulose fibres has made them a typical stabilising additive in SMA to control draindown. For this, tiny pellets consisting of cellulose fibres covered in a low-viscosity bituminous binder are utilised. In contrast to loose fibres, the pelletised fibre is not susceptible to humidity and permits quick dispersion and a more uniform mixture.

The Areca fruit consists of about 40% of husk, which means an estimated 341,000 tonnes of husk biomass was generated out of the total areca production of 853,00 tonnes in India in 2019-20. The areca fibres were extracted manually from the areca husk. Figure 4.1 shows the Areca fruit, kernel and husk from which the fibres are removed.

4.3 EXPERIMENTAL PROGRAM

According to irc:sp 79 2008, sma mixtures were prepared with vg 30 bitumen using the gradation for wearing course with 13 mm nmas. The areca fibres were cut into smaller lengths of 25 mm. The required quantity of fibres was added by weight of the aggregates and bitumen. The fibres were added to the aggregate and bitumen mix and thoroughly mixed to ensure uniform distribution of fibres in the mixture. For the present study, the

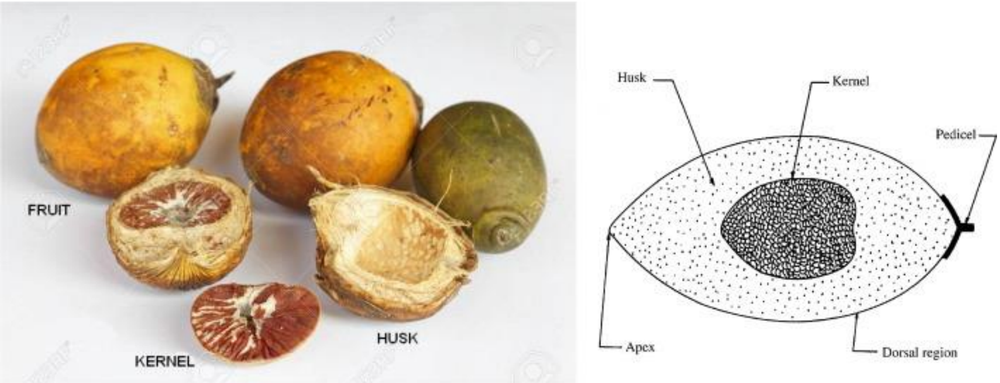

Fig. 4.1 Components of Areca Fruit

fibres were added in percentages of 0.0%, 0.1%, 0.2%, 0.3%, 0.4% and 0.5%. Another naturally available fibre, namely, coconut coir fibre was also used for preparing SMA mixes with VG 30 bitumen. Similarly, SMA mixtures were prepared with cellulose fibres in the form of pellets were added at 0.3% by weight of the aggregate as per the specifications in IRC SP 79 2008. SMA mixture produced using VG 30 bitumen and cellulose fibre (SMA-PF) is taken as the control mixture. The notations used for the various mixtures prepared are tabulated in Table 4.1.

Table 4.1 Notations of SMA mixtures

Aggregate Gradation	**SMA 13 mm NMAS**
Mixture Constituents	**Notations**
VG 30 Bitumen + Areca Fibre	SMA-AF
VG 30 Bitumen + Coconut coir Fibre	SMA-CF
VG 30 Bitumen + Pelletized Cellulose Fibre	SMA-PF
PMB 40 Bitumen (without stabilising Additive)	SMA-PMB

A minimum of three trials of drain down test on all the mixtures were conducted at 160°C and 170°C, respectively. After arriving at the Optimum Fibre Content (OFC) from drain down test results for SMA-AF mixtures, cylindrical specimens were cast in SGC with OFC at different bitumen contents from 5.0 to 7.0 per cent by weight of the aggregates in increments of 0.5 per cent to determine the volumetric and Mechanical properties. At OBC, cylinfrical specimens were prepared for determining various properties such as MS, IDT, RMS, TSR, rutting and fatigue. For determining the rutting properties of SMA mixes, slab specimens were prepared. The procedure mentioned above is repeated for SMA-PF with 0.3% cellulose fibre, SMA-CF and SMA-PMB without any stabilising additive.

4.4 RESULTS AND DISCUSSIONS

4.4.1 Draindown

SMA mixtures prepared with fibres at 7% bitumen content were subjected to draindown tests. The findings are shown in Figure 4.2. The fibre contents were added at 0.0%, 0.1%, 0.2%, 0.3%, 0.4% and 0.5% by weight of the mixture. The maximum permitted draindown value of 0.3% is recommended by IRC.

Based on the results, in all the mixtures the drain-down requirement was satisfied at a fibre content of 0.3%. As a result, the OFC was set at 0.3% for each fibre and subsequent tests were conducted with the same fibre dosage.

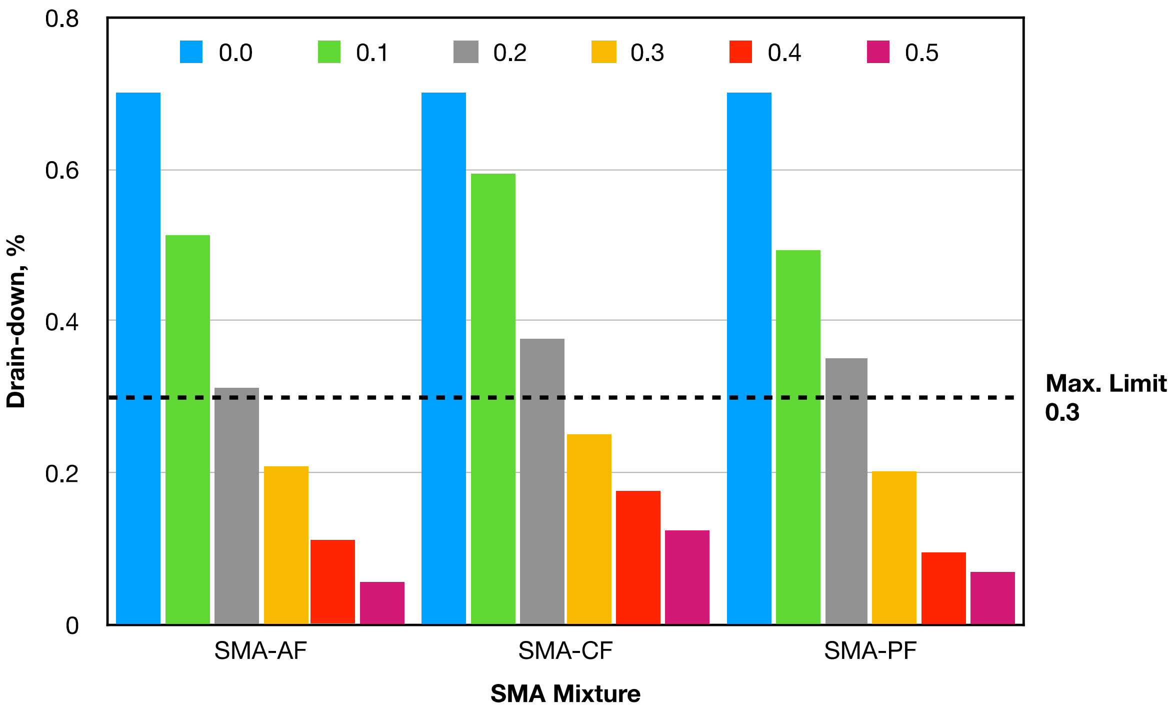

Fig. 4.2 Draindown of SMA mixtures with Fibre additives at 7% Bitumen

4.4.2 Volumetric and Marshall Properties

The volumetric, Marshall characteristics and the OBC of all the SMA mixtures are presented in Tables 4.2 to 4.5. The values of Theoretical Maximum Density, G_{mm} decreased with an increase in bitumen content, whereas Bulk Specific Gravity of the compacted mixture, G_{mb} values first increased as bitumen contents increased, peaked and then began to decline as illustrated in Figure 4.3. For all four mixtures, VMA was more than the minimum requirement of 17% per IRC SP 79 2008 as shown in Figure 4.4. Following the typical trend in bituminous mixtures, it was found that air voids decreased as bitumen concentration increased. The values were in the range 6.55 - 3.05%, 6.82 – 3.22%, 7.27 – 3.50% and 6.59 – 3.39% for SMA-PMB, SMA-AF, SMA-CF and SMA-PF mixtures, respectively. For the gradation used for the present study, the VCA_{DRC} was found to be 41.23% for all the mixtures.

Stone-to-stone contact was observed to exist in all of the mixtures represented in Figure 4.5, because VCA_{MIX} was found to be lesser than the VCA_{DRC} value. Marshall stability values were observed to increase initially and decrease with bitumen content after reaching a maximum value following the same trend as bulk specific gravity as shown in Figure 4.6.

Table 4.2 Properties of SMA Mixture prepared with PMB

Property	Bitumen content by weight of mix				
	5.0%	5.5%	6.0%	6.5%	7.0%
G_{mm} (g/cm^3)	2.509	2.488	2.468	2.444	2.428
G_{mb} (g/cm^3)	2.345	2.357	2.366	2.356	2.354
V_v (%)	6.55	5.28	4.14	3.62	3.05
VMA (%)	66.64	73.89	80.52	83.31	87.55
VFB (%)	17.42	17.37	17.46	18.20	18.63
VCA_{MIX} (%)	38.15	38.12	38.18	38.74	39.07
VCA_{MIX}/VCA_{DRC}	0.93	0.92	0.93	0.94	0.95
Marshall Stability (kN)	14.31	17.21	18.89	17.58	16.56
Flow Value (mm)	3.33	3.79	4.56	4.98	5.32
Marshall Quotient (kN/mm)	4.30	4.54	4.14	3.53	3.11
OBC (%)	6.10				

Table 4.3 Properties of SMA Mixture prepared with Areca fibre and VG 30 (SMA-AF)

Property	Bitumen content by weight of mix				
	5.0%	**5.5%**	**6.0%**	**6.5%**	**7.0%**
G_{mm} (g/cm^3)	2.481	2.461	2.441	2.421	2.402
G_{mb} (g/cm^3)	2.312	2.323	2.337	2.332	2.325
V_v (%)	6.82	5.61	4.25	3.68	3.22
VMA (%)	18.82	18.82	18.69	19.26	19.88
VFB (%)	60.81	67.22	74.27	77.91	81.04
VCA_{MIX} (%)	39.12	39.12	39.02	39.45	39.92
VCA_{MIX}/VCA_{DRC}	0.95	0.95	0.95	0.96	0.97
Marshall Stability (kN)	11.12	12.63	13.58	12.97	12.13
Flow Value (mm)	3.89	4.62	5.19	5.88	6.45
Marshall Quotient (kN/mm)	2.86	2.73	2.62	2.21	1.88
OBC (%)	6.15				

Table 4.4 Properties of SMA Mixture prepared with Coconut fibre and VG 30 (SMA-CF)

Property	Bitumen content by weight of mix				
	5.0%	**5.5%**	**6.0%**	**6.5%**	**7.0%**
G_{mm} (g/cm^3)	2.469	2.450	2.430	2.421	2.392
G_{mb} (g/cm^3)	2.290	2.321	2.330	2.327	2.308
V_v (%)	7.27	5.23	4.11	3.87	3.50
VMA (%)	57.86	67.00	73.08	77.11	78.16
VFB (%)	19.59	18.87	18.94	19.42	20.46
VCA_{MIX} (%)	39.78	39.24	39.30	39.66	40.44
VCA_{MIX}/VCA_{DRC}	0.96	0.95	0.95	0.96	0.98
Marshall Stability (kN)	10.96	11.84	13.19	12.24	11.78
Flow Value (mm)	4.12	4.91	5.48	6.03	6.68
Marshall Quotient (kN/mm)	2.66	2.41	2.41	2.03	1.76
OBC (%)	6.17				

Table 4.5 Properties of SMA Mixture prepared with Cellulose fibre and VG 30 (SMA-PF)

Property	Bitumen content by weight of mix				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cm^3)	2.502	2.481	2.461	2.442	2.421
G_{mb} (g/cm^3)	2.337	2.347	2.360	2.350	2.339
V_v (%)	6.57	5.41	4.11	3.78	3.41
VMA (%)	64.57	71.13	78.29	81.08	83.55
VFB (%)	17.92	17.97	17.91	18.65	19.40
VCA_{MIX} (%)	38.35	38.38	38.34	38.90	39.46
VCA_{MIX}/VCA_{DRC}	0.93	0.93	0.93	0.94	0.96
Marshall Stability (kN)	13.01	15.62	16.88	14.87	13.27
Flow Value (mm)	3.33	3.79	4.56	4.98	5.32
Marshall Quotient (kN/mm)	3.91	4.12	3.70	2.99	2.49
OBC (%)	6.12				

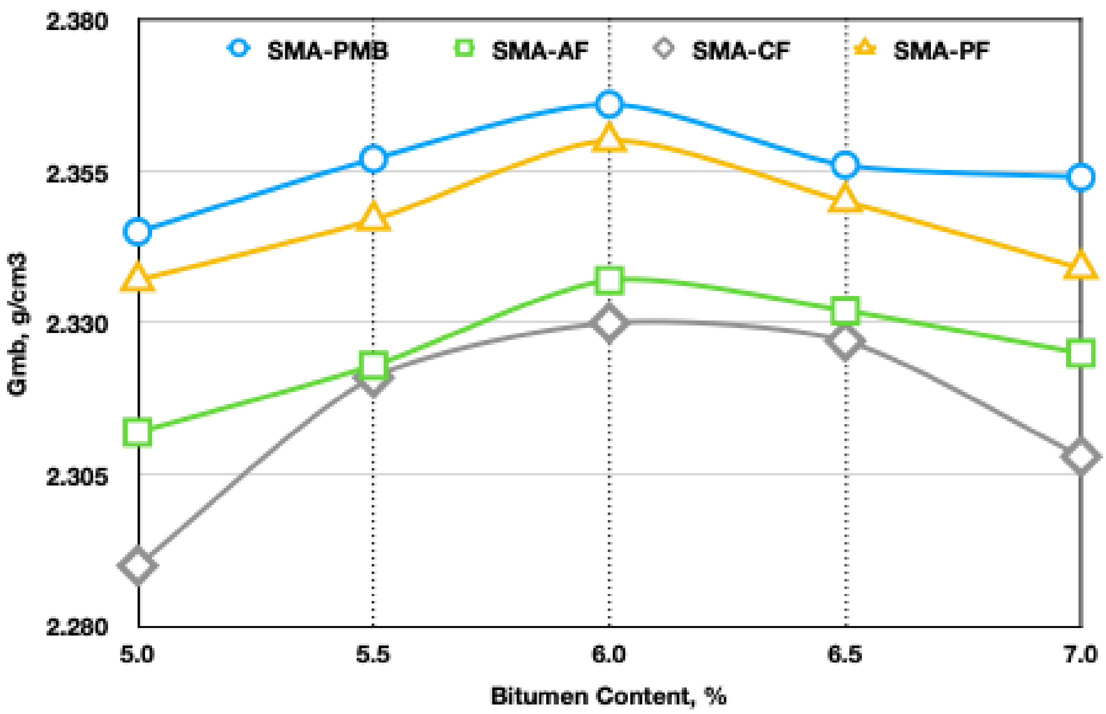

Fig. 4.3 Bulk Density of SMA Mixtures

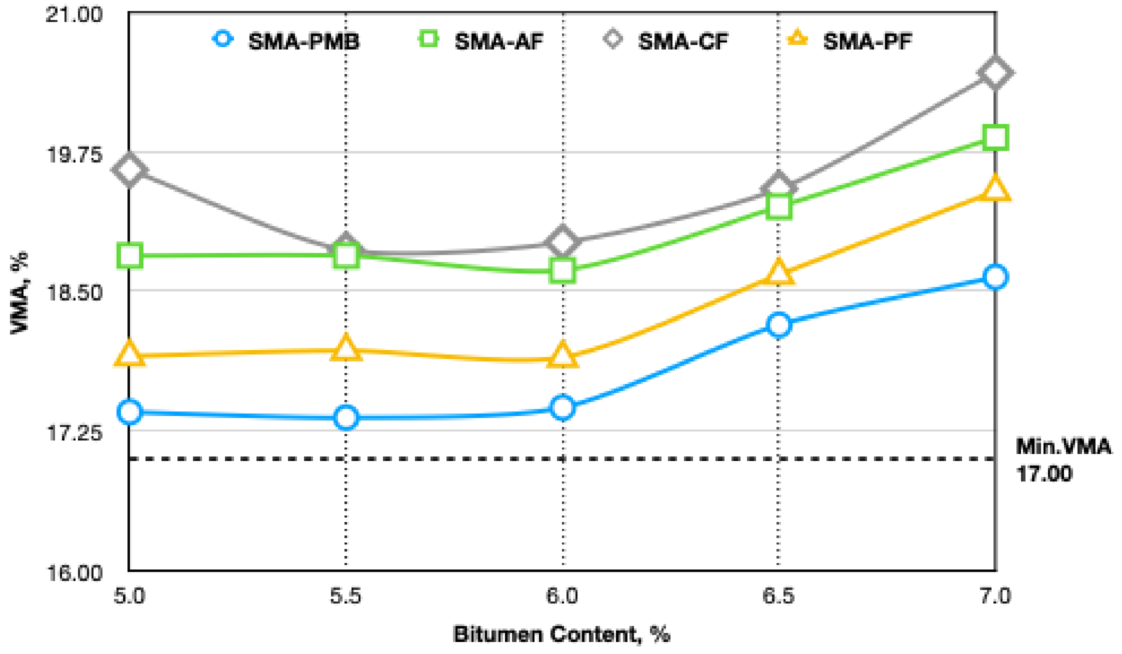

Fig. 4.4 Voids in the Mineral Aggregates of SMA Mixtures

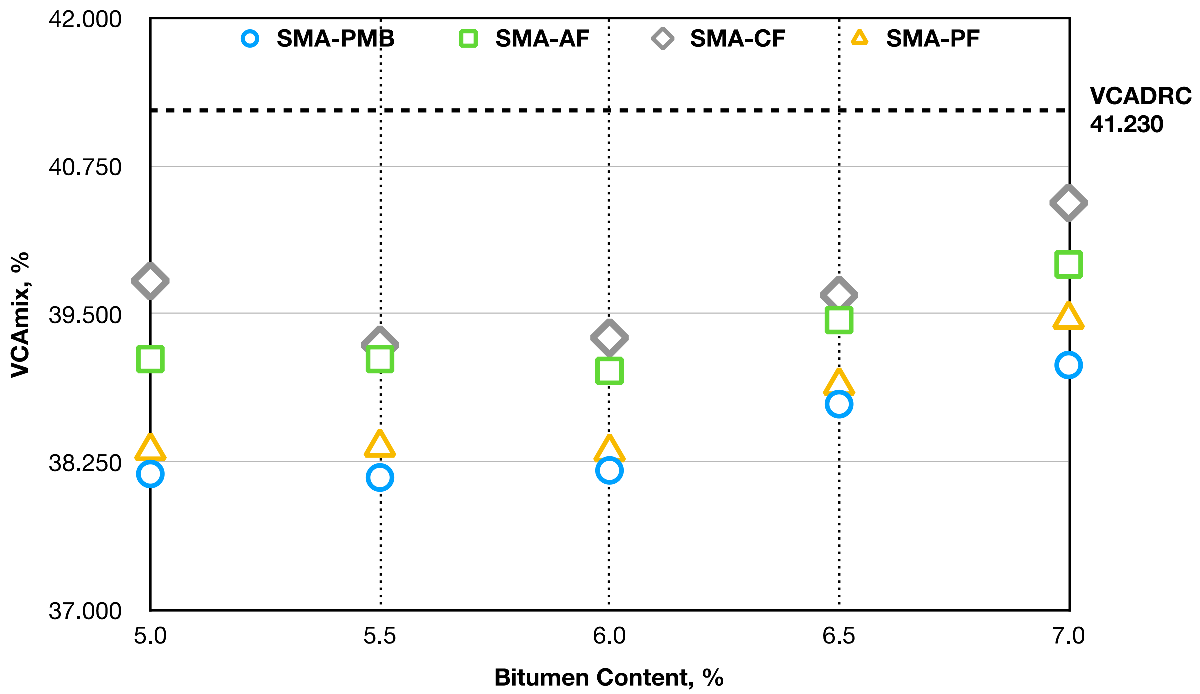

Fig. 4.5 Voids in the Coarse Aggregates of SMA Mixtures

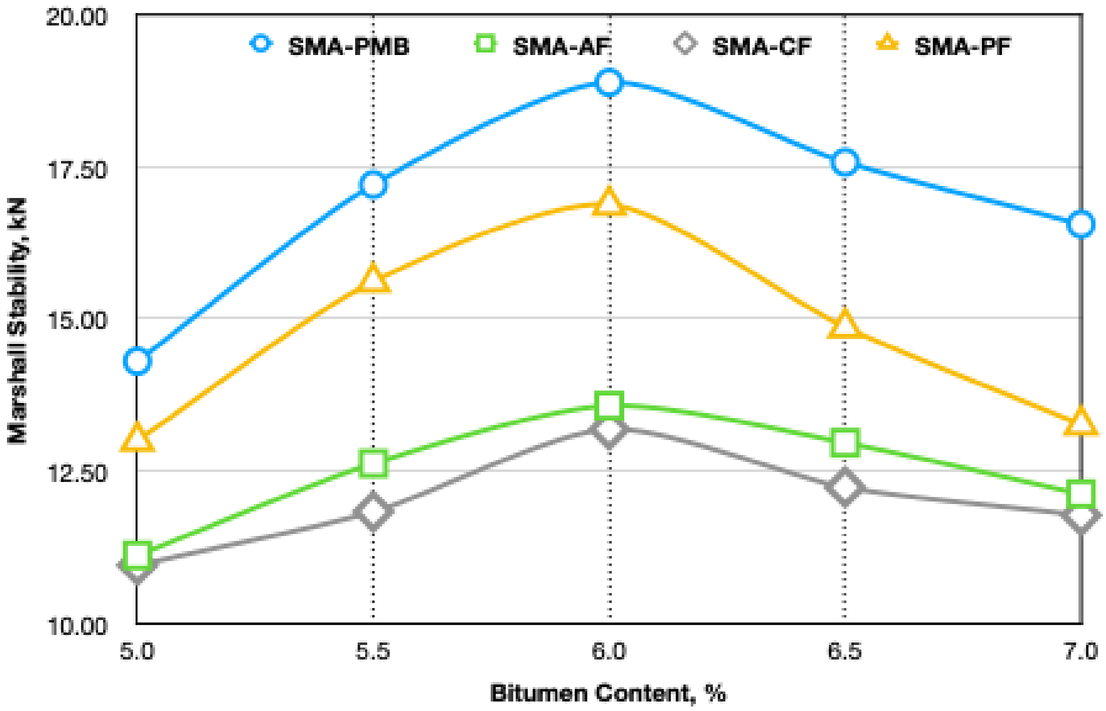

Fig. 4.6 Marshall Stability of SMA Mixtures

The OBC values obtained for SMA-PMB, SMA-AF, SMA-CF and SMA-PF are 6.10%, 6.15%, 6.17% and 6.12%, respectively. Of the different fibres used, coconut coir fibre has the smallest diameter resulting in the highest surface area. Hence, the bitumen content required to coat the surface of the fibres is high which is reflected in the highest OBC for SMA-CF. Among the mixtures with fibres, the SMA mixture with cellulose fibre resulted in low OBC since the pellets already have a coating of bitumen which required only a smaller quantity of bitumen to be added to the mixture. Table 4.6 lists the characteristics of all the mixes produced by OBC. Because SMA-PMB mixtures contain an elastomer-based polymer Styrene-Butadiene-Styrene, which has superior properties above standard bitumen, they have the highest density and stability values.. The properties of SMA-PF mixes were comparable to that of SMA-PMB. Due to the better properties of areca fibre compared to coconut coir fibre, the properties of the SMA-AF mixture were better than SMA-CF mixes, among the mixes with natural fibres. when compared to mixes with coconut coir fibre, the enhanced tensile strength of areca fibre offered improved properties for SMA-AF mixes. When fibres are added to the mixture, the tensile and compressive strength properties of the mixture improve because of the formation of a network of fibres in the mixture.

Table 4.6 Properties of SMA Mixture prepared with Different Fibres at OBC

Mixture	**SMA-PMB**	**SMA-AF**	**SMA-PF**	**SMA-PF**
OBC, %	6.10	6.15	6.17	6.12
G_{mm} (g/cm^3)	2.464	2.435	2.427	2.456
G_{mb} (g/cm^3)	2.362	2.335	2.328	2.356
V_v (%)	4.00	4.00	4.00	4.00
VMA (%)	17.67	18.89	19.15	18.14
VFB (%)	80.73	75.26	74.26	78.51
VCA_{MIX} (%)	38.32	39.14	39.414	38.133
VCA_{MIX}/ VCA_{DRC}	0.93	0.95	0.96	0.92
MS (kN)	18.22	13.28	12.91	15.82
Flow Value (mm)	4.78	5.51	5.74	4.82
Marshall Quotient (kN/mm)	3.81	2.41	2.25	3.28

4.4.3 Drain down at OBC

After determining the OBC values for all the mixtures, the drain down was checked again at OBC values. The drain down was determined at temperatures of 160°C and 170°C, respectively. Figure 4.7 shows the drain down values of all the mixtures prepared at OBC and 0.3% fibre content for mixtures with fibres. At 160°C, the drain down values observed were lesser than the drain down values at 170°C. The drain down was the lowest for SMA-PMB mixes followed by SMA-PF. Among the mixtures with natural fibres, SMA-AF was more resistant to drain down than SMA-CF.

4.4.4 Indirect Tensile Strength

On cylindrical specimens prepared at OBC, IDT tests were performed to determine the tensile strength characteristics of each mixture. Figure 4.8 shows the results of IDT of the mixtures prepared. SMA-PMB had the highest OBC followed by SMA-PF, SMA-AF and SMA-CF. The difference in the IDT values among the mixtures prepared may be attributed to the variation in the properties of fibres used in the mixture. The IDT properties of SMA-PF are comparable to that of SMA-PMB.

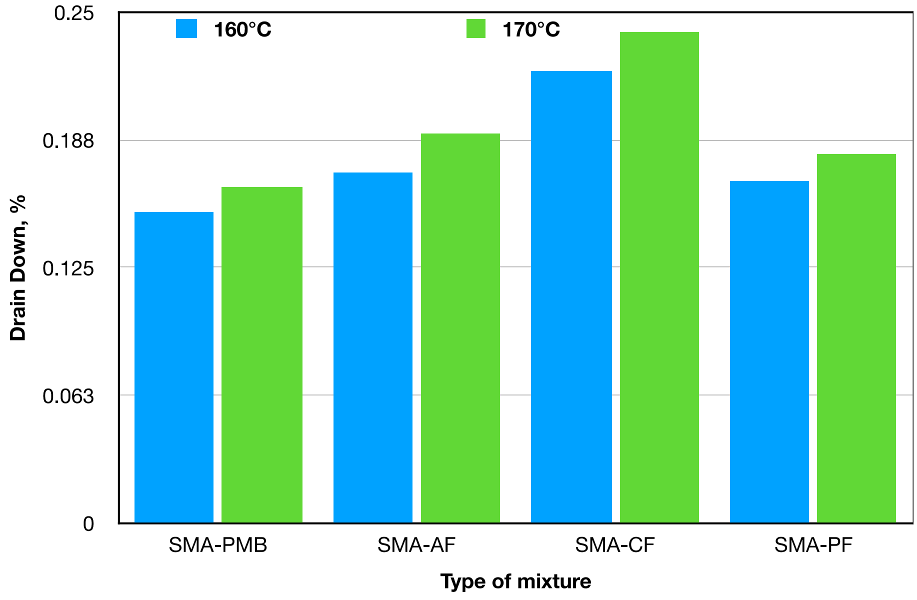

Fig. 4.7 Draindown at OBC

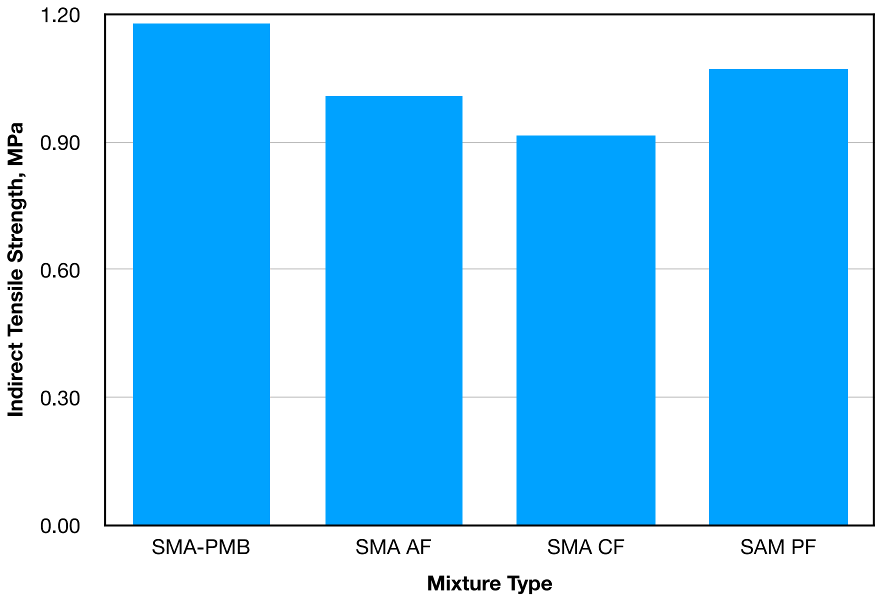

Fig. 4.8 IDT Strength of SMA Mixtures

4.4.5 Rutting Behaviour

The rutting characteristics of the prepared mixtures were determined using the Wheel Rut Tester. The results of permanent deformation versus the number of passes are shown in Figure 4.9. The total deformation at the end of 10000 passes of the standard wheel was reported as the total rut depth of the mixtures. The test was conducted at 60°C after conditioning the samples at the same temperature for 4 hours. The failure criteria for rutting is taken as 6 mm (Kandhal and Cooley 2003). The permanent deformations recorded are 4.41, 4.87, 5.24 and 5.69 mm for SMA-PMB, SMA-PF, SMA-AF and SMA-CF mixtures, respectively.

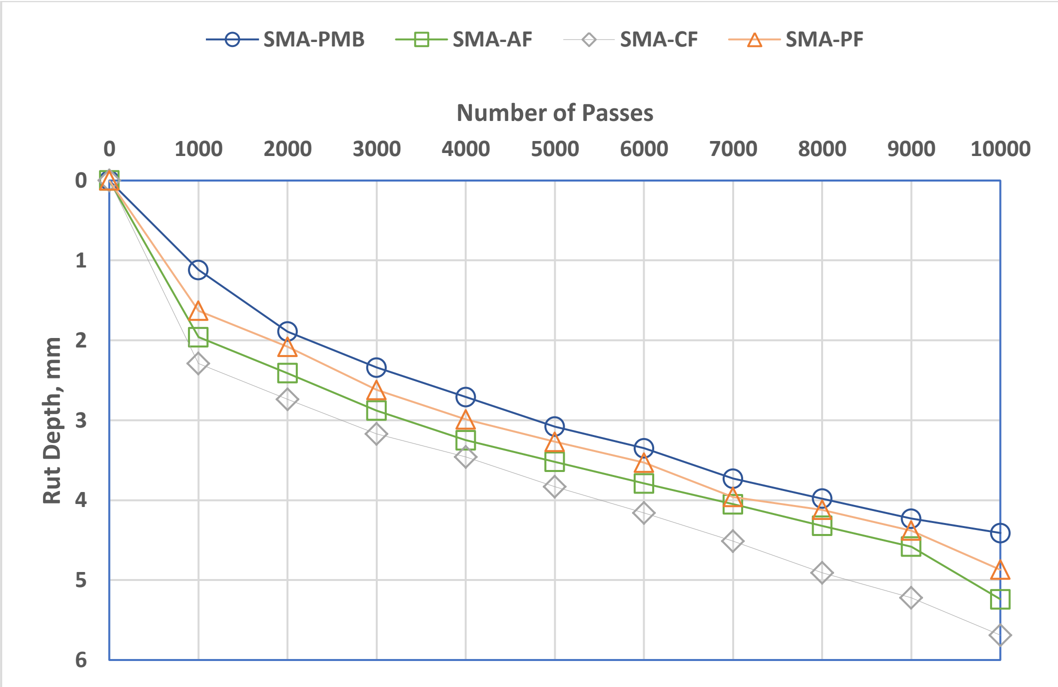

Fig. 4.9 Rutting characteristics of SMA Mixtures

4.4.6 Fatigue Characteristics

The fatigue characteristics of each of the four mixes were evaluated. For the purpose of comparison, the lowest of the failure loads among all the four mixtures was considered. The lowest failure load of 9.78 kN was obtained for the SMA-CF mixture. Then, to determine the fatigue characteristics of the mixtures, 15%, 33% and 50% of the lowest failure load was applied for all the mixtures. The samples were considered to be failed when the total deformation reached 5 mm. The number of load repetitions to failure was recorded in the RLT device.

Tables 4.7 – 4.10 show the fatigue life of all the mixtures with the corresponding loads applied in absolute. terms and percentage. The fatigue life for SMA-PMB was the highest among all the mixtures followed by SMA-PF, SMA-CF and SMA-AF for all the stress levels. The specimen dimensions and the initial load, which have an impact on the initial stress applied on the specimen, determine the fatigue life. Figure 4.9 shows the FL of all the mixtures with the corresponding initial stress applied.

Table 4.7 Fatigue Life of SMA-PMB Mixtures

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
SMA-PMB	978.00	155.50	15.90	11748	12241
		152.89	15.63	12715	
		155.12	15.86	12260	
		325.67	33.30	7356	7148
		331.17	33.86	7166	
		326.89	33.42	6922	
		493.89	50.50	3119	3356
		489.92	50.09	3290	
		490.11	50.11	3659	

Table 4.8 Fatigue Life of SMA-AF Mixtures

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
SMA-AF	978.00	156.48	16.00	7739	7023
		158.33	16.19	6304	
		157.36	16.09	7026	
		334.61	34.21	3754	4066
		332.45	33.99	4132	
		335.18	34.27	4312	
		500.22	51.15	2023	1855
		501.35	51.26	1709	
		500.94	51.22	1833	

Table 4.9 Fatigue Life of SMA-CF Mixtures

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
SMA-CF	978.00	155.59	15.91	8573	9104
		152.17	15.56	9191	
		154.23	15.77	9548	
		329.59	33.70	5201	4992
		333.47	34.10	5047	
		331.26	33.87	4728	
		487.01	49.80	2761	2416
		492.73	50.38	1989	
		490.11	15.91	2498	

Table 4.10 Fatigue Life of SMA-PF Mixtures

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
SMA-PF	978.00	145.72	14.90	11070	11293
		146.35	14.96	11423	
		144.13	14.74	11387	
		320.78	32.80	6179	6048
		324.54	33.18	5730	
		321.72	32.90	6235	
		484.11	49.50	2982	2874
		482.15	49.30	3108	
		485.62	14.74	2532	

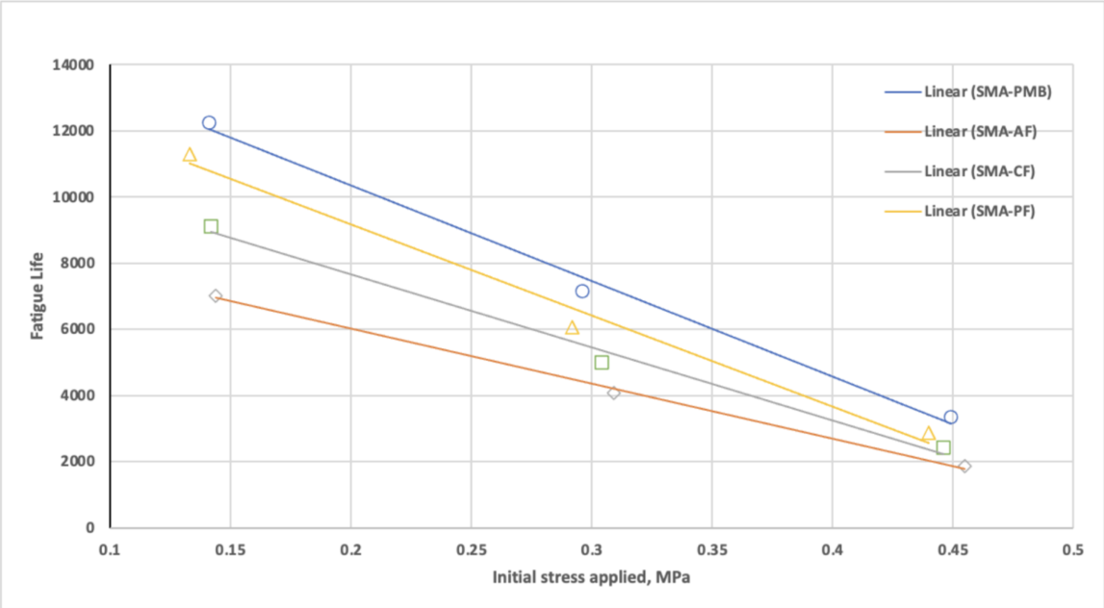

Fig. 4.10 Tensile Stress Variation with FL

4.4.7 Moisture Susceptibility

4.4.7.1 *RMS*

All the mixes prepared at OBC were subjected to RMS tests and the results are displayed in Table 4.11 and Figure 4.11. With SMA-PMB and SMA-CF maintaining the highest and lowest stability values of 92.66% and 89.19%, respectively all the produced mixes showed good resistance to moisture damage. SMA-AF and SMA-PF showed RMS values of 90.82% and 91.21%, respectively. The small difference in the retained stability values may be due to the effect of fibres on the drain-down characteristics of the mixtures.

Table 4.11 Retained Marshall Stability of SMA Mixtures

Mixture Type	SMA-PMB	SMA-AF	SMA-CF	SMA-PF
RMS (%)	92.66	90.82	89.19	91.21

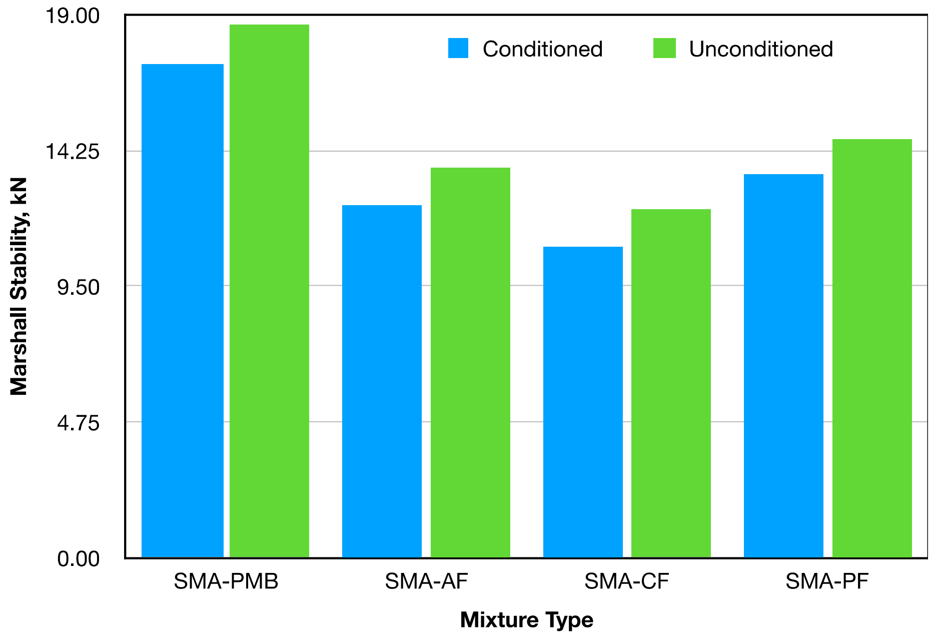

Fig. 4.11 Marshall stability of Unconditioned and conditioned mixtures

4.4.7.2 TSR

To determine the effect of moisture, IDT experiments were performed on cylindrical specimens prepared at 7% air voids for both unconditioned and conditioned specimens. The obtained results are shown in Table 4.12 and Figure 4.12, respectively. The tensile strength ratio (TSR) was determined as a ratio of IDT values of conditioned to unconditioned specimens. The TSR values for both conditioned and unconditioned specimens exhibited the same pattern as IDT at 4% air voids.

The obtained values of TSR were in the range of 87.55% to 92.07% for SMA-CF and SMA-PMB, respectively. All the mixtures satisfied the minimum TSR requirement of 85% as per AASHTO T 283.

Table 4.12 TSR of SMA Mixtures

Mixture Type	**SMA-PMB**	**SMA-AF**	**SMA-CF**	**SMA-PF**
TSR (%)	92.07	89.94	87.55	90.94

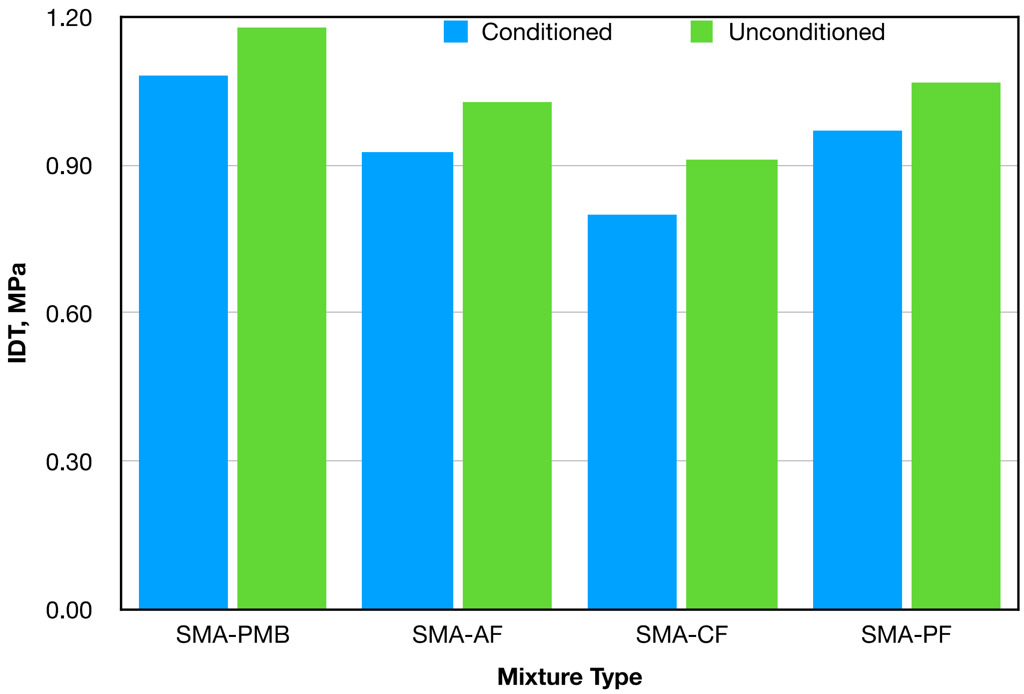

Fig. 4.12 IDT of Unconditioned and Conditioned SMA Mixtures

4.4.7.3 Stripping

In accordance with ASTM D3625, all the mixtures made at the corresponding OBC were subjected to a boiling test in their loose state while being visually checked for the removal bitumen from the surface. All the tested mixes had a stripping area less than 5%.

4.5 SUMMARY

This chapter summarises the preparation and experimental investigation of SMA mixes prepared using Areca fibre, coconut fibre and cellulose fibre were discussed. Also, the method of preparation and experimental investigation of another SMA mixture prepared with PMB was also discussed. Many agencies suggest the use of cellulose fibres for preparing SMA mixes. Hence, the mixture prepared with pelletised cellulose fibre was considered as the control mixture. But, the preparation of cellulose fibres requires cellulose to be extracted from plants and trees leading to environmental degradation. Hence, the experimental investigation was aimed to evaluate the feasibility of using Areca fibres as a stabilising additive in SMA mixes. The draindown tests performed on the mixes that contained fibres revealed a reduction in the susceptibility to draindown as the fibre level increased. The mixture that produced a draindown of 0.3% by weight of the mixture or less was used to calculate the OFC. For the determination of OBC, the specimens were cast in an SGC at OFC. The OBC values obtained were the lowest for SMA-PMB at 6.10% followed by SMA-PF at 6.12%. The mixes with fibres required higher OBC values which may be due to the possible absorption of bitumen by the fibres. For all the mixes, the ratio of VCA_{mix} to VCA_{DRC} was less than one, confirming the presence of aggregate skeleton. The bulk density of the mixtures was the highest for SMA-PMB at 2.362 g/cm^3 and the lowest for SMA-CF at 2.328 g/cm^3. The Marshall stability values also followed the same trend as the bulk density with SMA-PMB sustaining the highest load at 18.22 kN and SMA-CF, the lowest at 12.91 kN. In terms of volumetric properties, SMA-PMB was the best and SMA-CF was poor. The VMA in SMA-PMB and SMA-CF was 17.67% and 19.15%, respectively. The more fibres in the mixture may be the cause of the increased VMA in SMA-CF. The IDT of SMA-PMB was the highest among all the mixtures due to the improved characteristics of PMB. Among the mixes with fibres, due to the low tensile properties of coconut fibres, the indirect tensile strength of SMA-CF was the lowest. The rutting characteristics of the mixes showed that SMA-PMB had the highest resistance to rutting followed by SMA-PF. Among the natural fibres, the rutting observed in SMA-AF was lesser compared to SMA-CF, which was close to failure criterion at 5.69 mm. The fatigue characteristics of the mixtures with PMB and cellulose fibres were comparable. Whereas the fatigue characteristics of the SMA mixes with natural fibres were comparable. Compared to SMA-AF, SMA-CF withstood more cycles until failure, which could be explained by the slightly higher stress levels used to calculate the fatigue life of SMA-AF. All the mixtures satisfied the moisture susceptibility requirement in terms of TSR. The TSR of SMA-PMB was the highest due to the improved properties of polymer modified bitumen. The lowest TSR was found in SMA-CF, which may be due to the low tensile strength of coconut fibre. Since the filler material used is hydrated lime, which also acts as an anti-stripping agent, the stripping of bitumen observed after subjecting the mixes to boiling test was below 5%.

CHAPTER 5

SMA MIXES USING RAP AND REJUVENATOR

5.1 GENERAL

Due to the rapid increase in infrastructure development, there is stress on natural resources used for construction activities, such as aggregates, sand, and bitumen, among others. Hence, to reduce the stress on natural resources, there is a need to identify alternate materials to maintain the pace of construction activities. A large amount of natural aggregates are required to construct flexible pavements, and it is estimated that aggregates form about 80-85% of the total material required for flexible pavement construction. One such material which is being used as a replacement for natural aggregates is RAP, which is a material obtained after milling the wearing and binder courses of flexible pavements after their service life. Previously, RAP was discarded and dumped on vacant lands resulting in massive landfills. The amount of natural aggregates required is decreased when RAP is used to prepare a fresh bituminous mixture. Since, the RAP consists of a bitumen coating, the quantity of fresh bitumen required for the production of a fresh mixture is also lesser. The percentage of natural aggregates that can be replaced by RAP depends on various factors such as the properties of aggregates, bitumen and rejuvenator. A rejuvenator is a substance that is used to restore the properties of the deteriorated bitumen found in RAP. Since the RAP binder is aged due to oxidation, it would have become stiff, which also imparts stiffness to the fresh bituminous mixture. Therefore, a rejuvenator helps to reduce the stiffness of the aged binder by reducing its viscosity, in addition to renewing the aged bitumen. In the present study, a by-product of the cashewnut production process, called ‘Cashewnut Shell Liquid’ (CNSL) is used.

5.2 EXPERIMENTAL INVESTIGATION

The gradation for wearing course with 13 mm NMAS as mentioned in IRC SP 79 2008 was used to prepare SMA mixes using conventional VG 30 bitumen. The natural aggregates were substituted by RAP material at 10%, 20%, 30% and 40% by weight of the aggregates in the mixture to determine the effect of RAP and the optimum RAP content that can be used in SMA mixes (Devulapalli et al. 2019, 2020). A rejuvenator is included to improve the characteristics of aged bitumen since the RAP increases the stiffness of the mixture due to the presence of aged binder. Various rejuvenators have been used in the past to incorporate RAP in bituminous mixtures such as waste edible vegetable oil (Chen et al. 2014b), waste cooking and cotton seed oil (Chen et al. 2014c), waste engine and grease oil (Devulapalli et al. 2020), castor oil residue (Zeng et al. 2018), bio-oil based on waste wood (Zhang et al. 2018) etc. In the present study, a by-product obtained from the process of cashewnut, known as Cashewnut shell liquid (CNSL) is evaluated as the rejuvenator (Lubi and Thachil 2000). In the current investigation, the rejuvenator was added to all RAP incorporated mixes, in percentages of 0, 3, 6 and 9 by weight of the binder. Overall, 17 mixture combinations were produced and Table 5.1 shows the mixtures prepared with the notations used. A control mixture (abbreviated as CM) produced using pelletised cellulose fibre and without the addition of RAP was used to compare all the RAP- incorporated mixtures.

Table 5.1 SMA mixtures with notations

Mixture combination	Notation used	Mixture combination	Notation used
10% RAP + 0% RA	10%-0%	30% RAP + 0% RA	30%-0%
10% RAP + 3% RA	10%-3%	30% RAP + 3% RA	30%-3%
10% RAP + 6% RA	10%-6%	30% RAP + 6% RA	30%-6%
10% RAP + 9% RA	10%-9%	30% RAP + 9% RA	30%-9%
20% RAP + 0% RA	20%-0%	40% RAP + 0% RA	40%-0%
20% RAP + 3% RA	20%-3%	40% RAP + 3% RA	40%-3%
20% RAP + 6% RA	20%-6%	40% RAP + 6% RA	40%-6%
20% RAP + 9% RA	20%-9%	40% RAP + 9% RA	40%-9%

*RA = Rejuvenator

The mixes became too stiff when Areca fibres were added as a stabilising additive while preparing mixes with RAP. Hence, all the RAP-incorporated mixes were prepared with pelletised cellulose fibre as the stabilising additive. To verify for stone-to-stone contact in the mixture, the ratio of VCA_{mix} to VCA_{DRC} for each of the 17 mixture combinations was calculated. The draindown test was then performed a minimum of three times at temperatures of 160°C and 170°C with a bitumen content of 7%. The cylindrical specimens were cast in SGC at various bitumen contents of 5.5, 6.0, 6.5, and 7.0 percent by weight of the aggregates in order to evaluate the OBC of each mixture combination. The OBC was determined at 4% air void content. To check whether the draindown was within acceptable limits, the draindown test was again carried out at OBC. To assess the MS, IDT, fatigue, workability, and moisture susceptibility of the mixtures such RMS and TSR, at least three cylindrical specimens were cast. Three slab specimens were prepared in order to assess the rutting properties of the mixtures.

5.3 RESULTS AND DISCUSSIONS

5.3.1 Draindown Characteristics

All SMA mixtures having a bitumen content of 7% by weight of aggregates and 0.3% cellulose fibre by weight of the bitumen were subjected to the draindown test. Figure 5.1 depicts the outcomes of the draindown test. The maximum permissible drain down as per IRC SP 79 is 0.30%. With an increase in RAP content, the values of draindown reduced. The draindown value observed for the Control Mix was at 7% bitumen content 0.202% by weight of the mix.

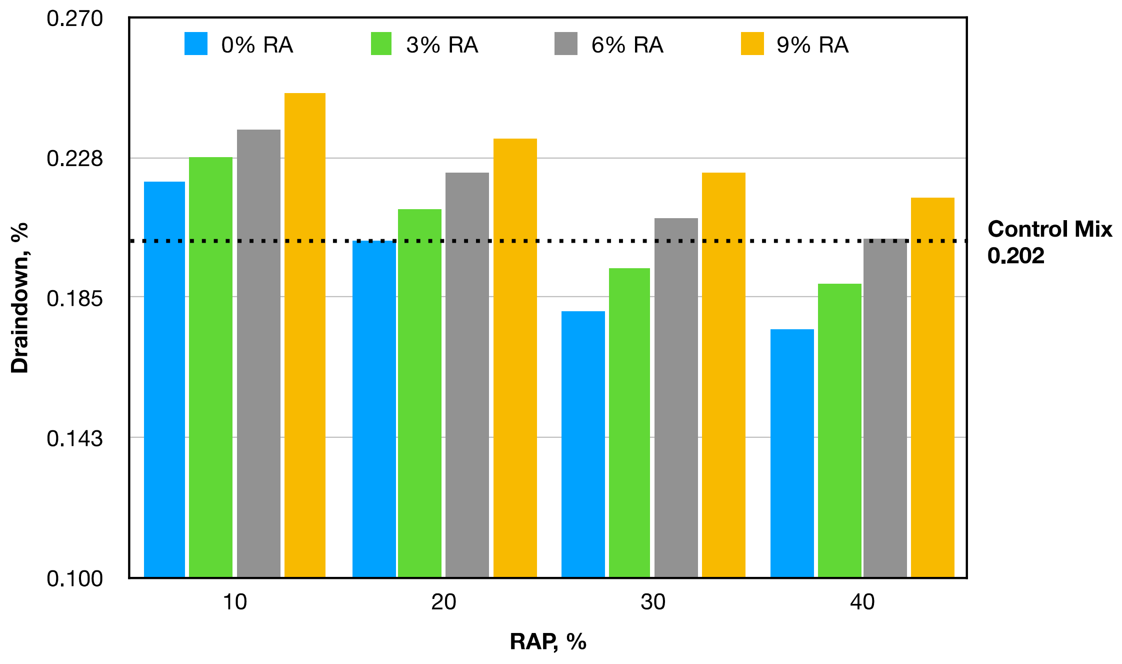

Fig. 5.1 Drain Down of SMA Mixtures at 7% Bitumen Content

5.3.2 Optimum Bitumen Content (OBC)

The OBC values of the SMA mixtures were determined using VG 30 bitumen and 0.3% cellulose fibre by weight of the bitumen. Table 5.2 provides the values of OBC values of all the mixtures. As the rejuvenator content rises, the OBC value of the RAP mixture decreases. With an increase in the RAP content, a similar trend was observed in the OBC values of RAP mixtures. However, the OBC values of 40%-6% and 40%-9% mixtures are 5.74% and 5.69%, respectively, which are less than the minimum bitumen content requirement of 5.80% in accordance with IRC SP 79 2008. The 40%-3% mixture has an OBC content of 5.81%, which barely meets the minimum binder content requirement. The OBC values expressed as a percentage by weight of aggregates of RAP-incorporated and control mixes are represented in Figure 5.2.

Table 5.2 OBC of RAP incorporated SMA mixes

RAP, %	Rejuvenator dosage			
	0% RA	3% RA	6% RA	9% RA
10	6.08	6.04	5.99	5.94
20	6.06	6.00	5.95	5.91
30	6.00	5.93	5.88	5.82
40	5.88	5.81	5.74	5.69

After determining the OBC of the mixes, the drain-down tests were carried out at OBC again to ensure they were within limits. Figures 5.3 and 5.4 show the results of the drain-down at OBC conducted at 160 and 170°C, respectively.

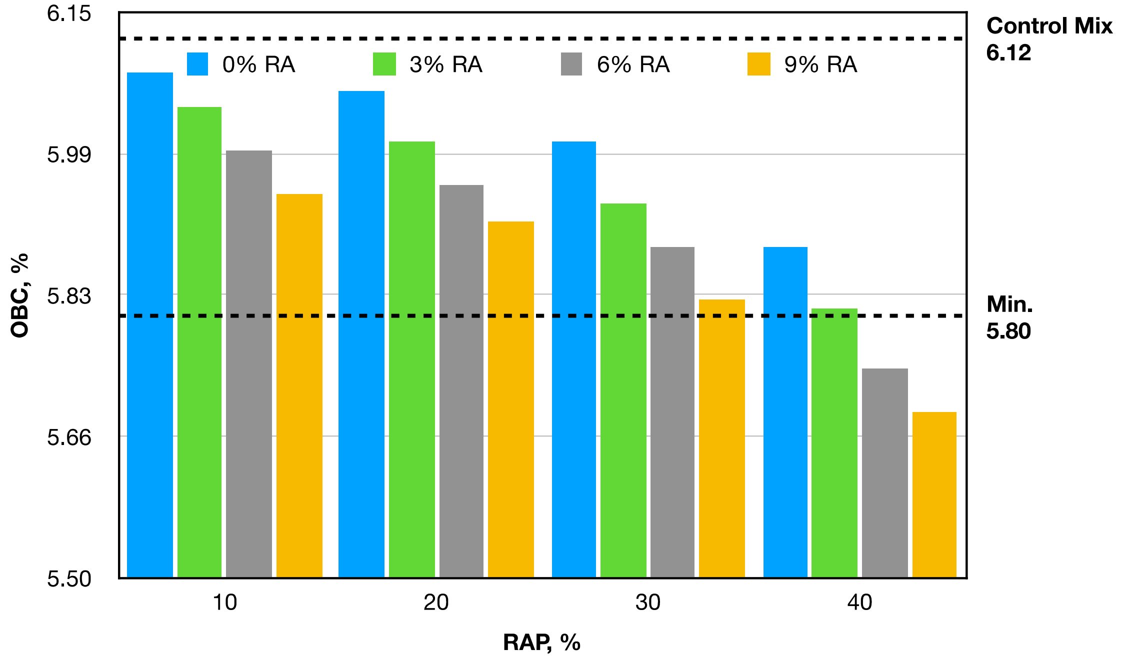

Figure 5.2 OBC of SMA mixtures with RAP

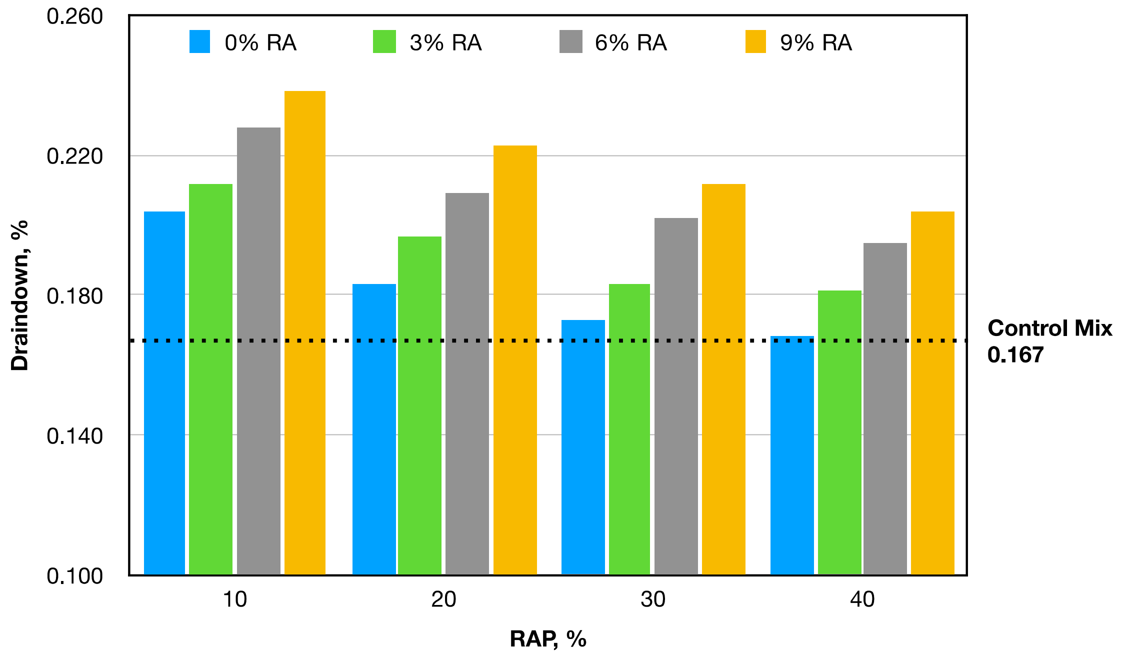

Figure 5.3 Drain-down test results at OBC conducted at 160°C

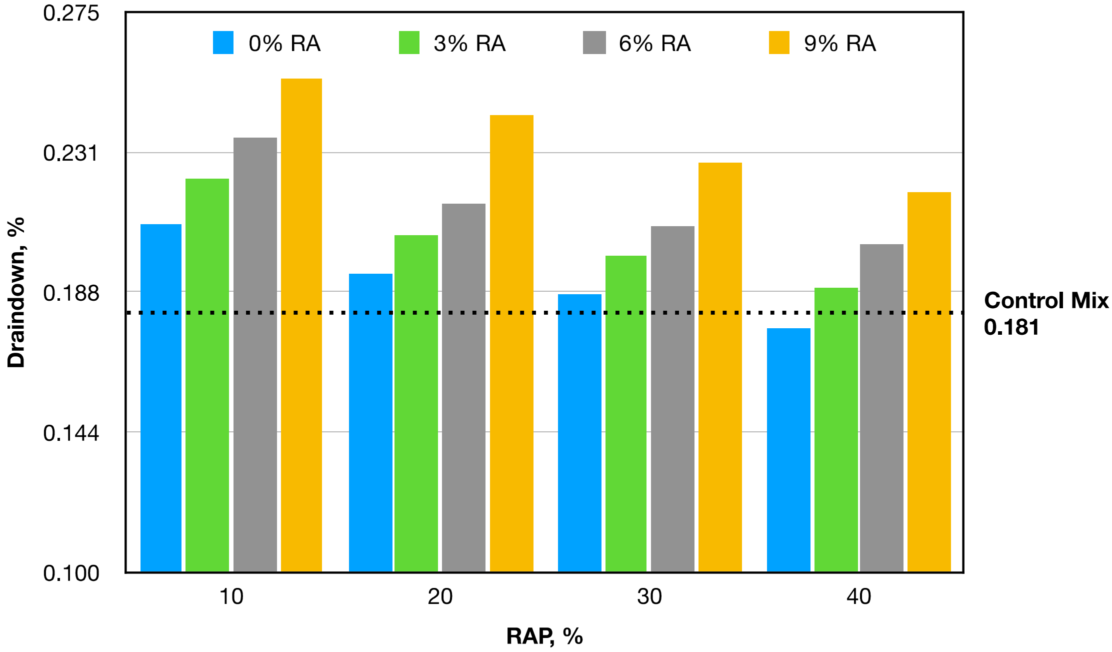

Figure 5.4 Drain-down test results at OBC conducted at 170°C

5.3.3 Voids in Coarse Aggregates and Voids in the Mineral Aggregates of RAP incorporated mixes

Stone-to-stone contact was confirmed in the SMA mixtures by measuring VCA_{DRC} and VCA_{mix} and calculating the ratio of VCA_{mix}/VCA_{DRC}. The values of VCA_{mix} of all the mix combinations are shown in Figure 5.5. The VCA_{DRC} of the control mix was 41.230%, while the VCA_{mix} of all the RAP-incorporated mixes are lower than VCA_{DRC}. The stone-to-stone contact is proven to exist since the ratio of VCA_{mix}/VCA_{DRC} is less than 1. Figure 5.6 shows the ratios of VCA_{mix}/VCA_{DRC} of all the mixtures. For every mixture, VMA was computed. The VMA of the prepared mixtures is tabulated in Table 5.3 shows the VMA of the mixtures produced. The VMA decreased with the addition of higher RAP and rejuvenator content. This decrease could be the result of the rejuvenator activating the binder and the subsequent removal of the binder from the RAP aggregates. This results in the reduction in size of the RAP aggregates. All other mixture combinations meet the minimum criteria of VMA of 17%, with the exception of mixtures 40%-6% and 40%-9%.

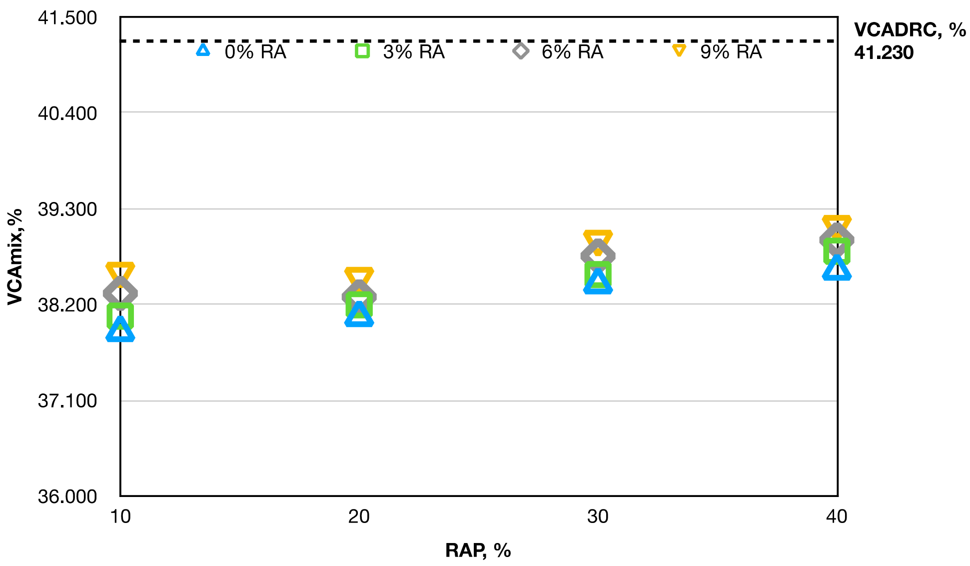

Figure 5.5 Variation of VCA_{mix} with RAP content

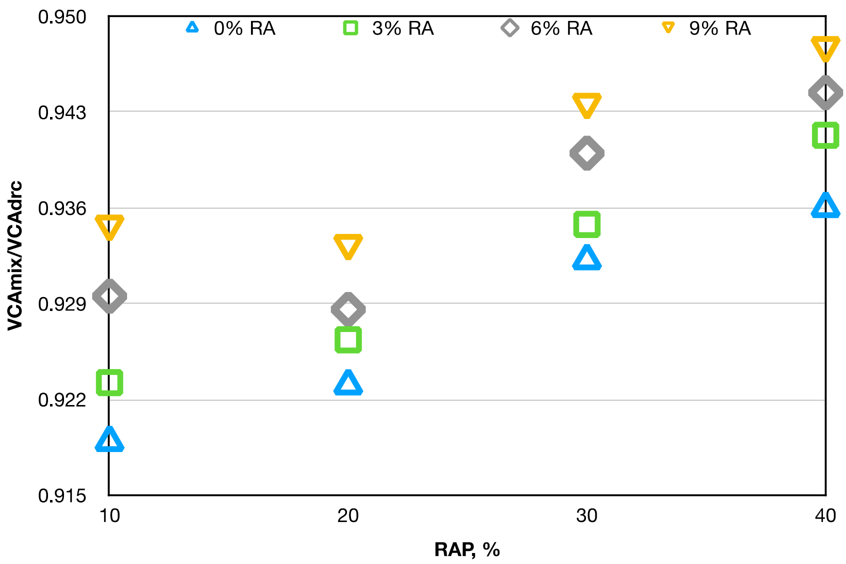

Figure 5.6 Variation of VCA_{mix}/VCA_{DRC} with RAP content

Table 5.3 VMA of RAP-incorporated SMA mixtures

RAP, %	Rejuvenator dosage			
	0% RA	**3% RA**	**6% RA**	**9% RA**
10	17.72	17.61	17.55	17.47
20	17.49	17.41	17.35	17.28
30	17.31	17.23	17.14	17.08
40	17.19	17.09	16.96	16.89

5.3.4 Bulk Specific Gravity and Marshall Stability values

The bulk specific gravity and MS values of compacted cylindrical specimens at OBC are shown in Tables 5.4 and 5.5, respectively. The bulk specific gravity and Marshall stability of the control mixture at OBC are 2.356 g/cm^3 and 15.82 kN, respectively. The bulk specific gravity of all the RAP mixtures was higher than that of the control mixture. The increase in the bulk specific gravity may be due to the decrease in the viscosity of the RAP binder, which reduces its stiffness and hence, provides better lubrication.

Table 5.4 Bulk Specific Gravity (G_{mb}, g/cm^3) of SMA mixtures with RAP

RAP, %	Rejuvenator dosage			
	0% RA	**3% RA**	**6% RA**	**9% RA**
10	2.378	2.391	2.398	2.404
20	2.393	2.397	2.403	2.411
30	2.401	2.406	2.410	2.414
40	2.411	2.409	2.416	2.418

Marshall Stability values of RAP mixes were determined using the Marshall apparatus. Except for 10%-0% and 10%-3% mixtures, the MS values of the RAP mixtures were greater than the CM. the stiffness of the RAP binder may be the reason why the MS value rises as the RAP content increases. The MS values are significantly affected by the RAP and rejuvenator content. The MS value of any particular RAP content increased up to a rejuvenator dosage of 6% and decreased at 9%. Since the aged binder was activated by a rejuvenator content up to 6%, an increased in the MS was noted. The increased fluidity of the mixture may be the cause of the decrease in MS at 9% rejuvenator. The highest MS value was obtained for 30%-6% mixture at 17.47 kN.

5.3.5 IDT strength

When the rejuvenator dosage was increased up to 6%, the IDT values of the mixtures increased, and when it was increased to 9%, the IDT values decreased. However, at 9% rejuvenator dosage, the mixture becomes too flexible and results in the reduction of IDT value. A similar trend was observed in the IDT values when the RAP contents were increased. after reaching a RAP content of 30%, the IDT values started to decline.

Table 5.6 provides the details of the IDT values of all the mixtures. The IDT of the control mixture was 1.080 MPa, and the maximum IDT was obtained for 30%-6% mixture at 1.097 MPa.

Table 5.5 Marshall Stability of RAP-incorporated SMA mixtures

RAP, %	Rejuvenator dosage			
	0% RA	3% RA	6% RA	9% RA
10	13.87	14.26	14.91	14.40
20	14.50	14.85	15.29	15.16
30	15.11	16.69	17.47	16.21
40	14.46	15.38	16.43	16.02

Table 5.6 IDT values RAP-incorporated SMA mixtures

RAP, %	Rejuvenator dosage			
	0% RA	3% RA	6% RA	9% RA
10	1.083	1.088	1.091	1.089
20	1.089	1.091	1.095	1.093
30	1.092	1.094	1.097	1.093
40	1.088	1.091	1.091	1.090

5.3.6 Rutting Characteristics

The rutting characteristics of SMA mixtures with RAP were evaluated in the WRT. Because there was a stiff old binder present, the overall tendency was that the rut depth decreased as the RAP content increased. The rut depths of the mixtures measured in millimeters after 10,000 passes of the standard wheel is shown in Table 5.7. The failure criterion for rutting is 6 mm.

The rut depth of the mixture with 10%-9% was 6.15 mm, while the rut depth of 10%-6% mixture was very close to failure at 5.59 mm. The maximum rut depth of CM after 10,000 passes was 4.87 mm. With an increase in RAP content, the DS values of the mixtures rose. The DS values of all the prepared mixtures are presented in Figure 5.8.

Table 5.7 Rut Depth of SMA mixtures with RAP

RAP, %	Rejuvenator dosage			
	0% RA	3% RA	6% RA	9% RA
10	4.37	4.83	5.59	6.15
20	2.35	2.67	2.84	3.06
30	2.24	2.28	2.79	3.01
40	1.61	2.29	2.51	2.92

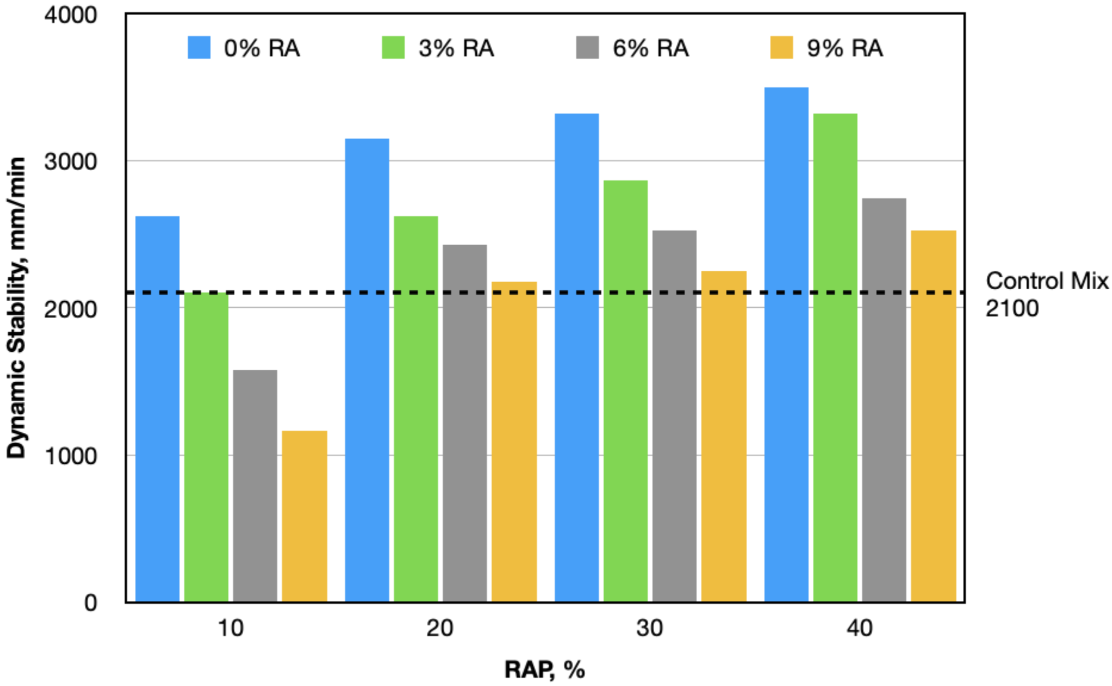

Figure 5.7 Dynamic Stability SMA mixtures

5.3.7 Fatigue Characteristics

The RLT device was used to investigate the fatigue properties of RAP mixtures. The failure criterion for fatigue testing was taken as 5 mm and the number of load repetitions required to reach the permanent deformation of 5 mm was noted. The loads applied for determining the FL were 15, 33 and 50% of the lowest IDT failure load obtained for all the SMA mixtures with different RAP contents and rejuvenator dosages. The lowest failure load observed was 11.17 kN for the control mixture.

Tables 5.8 to 5.11, 5.12 to 5.15, 5.16 to 5.19, 5.20 to 5.23 and Figures 5.8 to 5.11 provide the details of the fraction of load applied, FL and the corresponding initial stress applied. The mixture with 30%-6% combination of RAP and rejuvenator sustained the highest number of load repetitions to failure. The FL of the mixes was influenced by both the rejuvenator dosages and the RAP content. The FL rose with an increase in rejuvenator dosage up to 6% and dropped at 9%, for a specific RAP content. This could be a result of the stiffness of the mixture due to the addition of RAP. However, at 9% rejuvenator dosage, the mixture becomes too flexible because of the action of the rejuvenator. In addition to this, the FL rose up to a 30% rise in the RAP content, and reduced at 40% RAP content, which may be due to improper blending of the mixes.

Table 5.8 Fatigue Life of SMA Mixtures with 10%-0% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
10%-0%	1117.00	163.22	14.61	13159	13594
		166.54	14.91	14028	
		362.59	32.46	7867	7390
		366.88	32.85	6912	
		551.20	49.35	3573	3405
		554.23	49.62	3236	

Table 5.9 Fatigue Life of SMA Mixtures with 10%-3% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
10%-3%	1117.00	164.52	14.73	14753	14481
		169.12	15.14	14209	
		368.56	33.00	7933	7881
		366.71	32.83	7829	
		558.36	49.99	3892	3766
		562.19	50.33	3639	

Table 5.10 Fatigue Life of SMA Mixtures with 10%-6% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
10%-6%	1117.00	166.34	14.89	14565	14753
		171.89	15.39	14940	
		371.11	33.22	8437	8333
		366.46	32.81	8228	
		556.38	49.81	4023	3903
		552.87	49.50	3782	

Table 5.11 Fatigue Life of SMA Mixtures with 10%-9% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
10%-9%	1117.00	166.45	14.90	14126	14056
		168.67	15.10	13985	
		369.64	33.09	7832	7894
		370.63	33.18	7956	
		558.13	49.97	3844	3748
		559.78	50.11	3651	

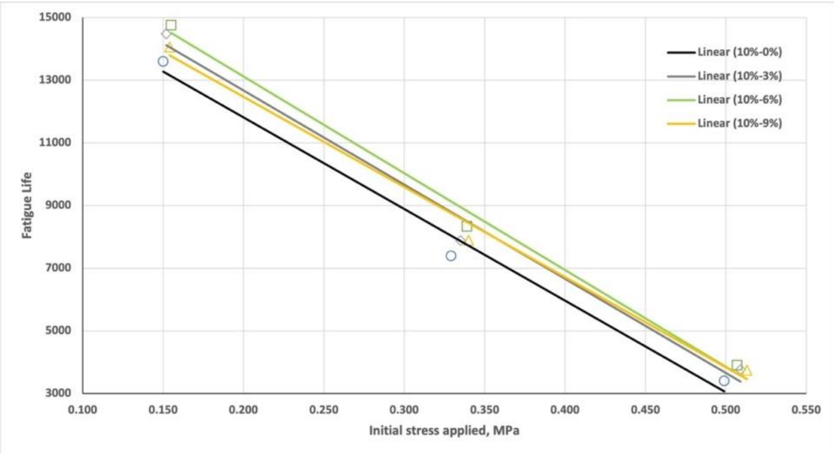

Figure 5.8 FL of SMA mixtures with 10% RAP

Table 5.12 Fatigue Life of SMA Mixtures with 20%-0% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
20%-0%	1117.00	167.23	14.97	13992	14175
		168.29	15.07	14358	
		372.13	33.32	8108	7862
		374.59	33.54	7615	
		560.26	50.16	3576	3802
		563.38	50.44	4027	

Table 5.13 Fatigue Life of SMA Mixtures with 20%-3% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
20%-3%	1117.00	169.17	15.15	14753	14537
		171.78	15.38	14320	
		370.16	33.14	8274	8162
		371.37	33.25	8049	
		558.26	49.98	3921	4130
		562.14	50.33	4339	

Table 5.14 Fatigue Life of SMA Mixtures with 20%-6% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
20%-6%	1117.00	170.45	15.26	14934	14898
		168.34	15.07	14862	
		372.12	33.31	8663	8502
		366.73	32.83	8341	
		557.58	49.92	4415	4369
		559.17	50.06	4322	

Table 5.15 Fatigue Life of SMA Mixtures with 20%-9% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
20%-9%	1117.00	171.32	15.34	14432	14490
		170.11	15.23	14547	
		369.89	33.11	8291	8360
		370.37	33.16	8428	
		557.48	49.91	4396	4184
		558.91	50.04	3971	

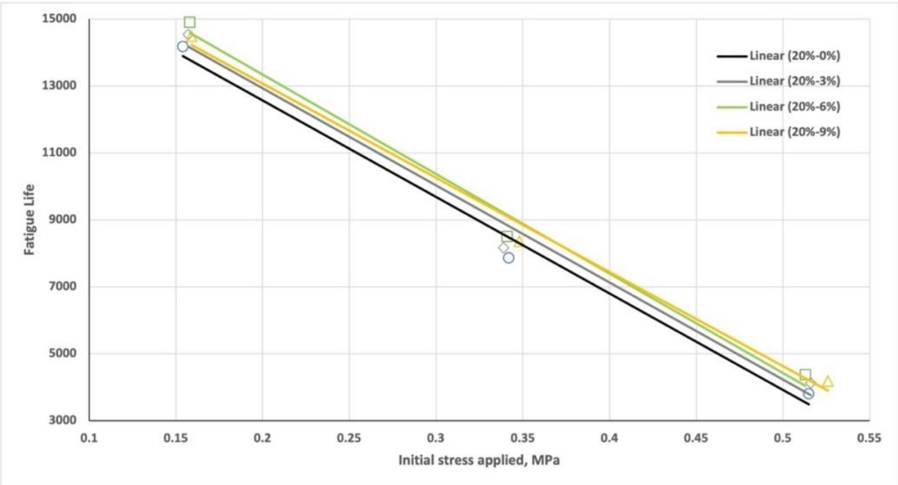

Figure 5.9 FL of SMA mixtures with 20% RAP

Table 5.16 Fatigue Life of SMA Mixtures with 30%-0% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
30%-0%	1117.00	168.45	15.08	16835	16954
		167.36	14.98	17072	
		371.48	33.26	9273	9191
		370.14	33.14	9108	
		556.87	49.85	5153	5090
		557.45	49.91	5026	

Table 5.17 Fatigue Life of SMA Mixtures with 30%-3% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
30%-3%	1117.00	168.34	15.07	17395	17251
		169.16	15.14	17107	
		368.11	32.96	9689	9616
		369.72	33.10	9542	
		558.95	50.04	5484	5548
		557.29	49.89	5612	

Table 5.18 Fatigue Life of SMA Mixtures with 30%-6% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
30%-6%	1117.00	171.21	15.33	17893	18015
		169.93	15.21	18136	
		369.68	33.10	9927	10081
		371.29	33.24	10235	
		558.18	49.97	6038	5933
		560.12	50.15	5828	

Table 5.19 Fatigue Life of SMA Mixtures with 30%-9% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
30%-9%	1117.00	170.67	15.28	17233	17330
		168.35	15.07	17427	
		369.15	33.05	9103	9228
		372.02	33.31	9352	
		559.34	50.08	5801	5634
		561.36	50.26	5466	

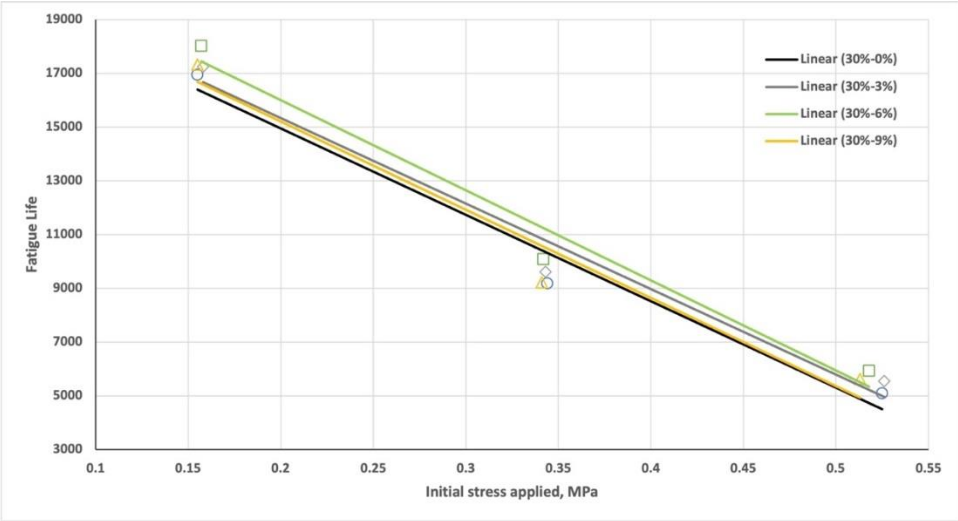

Figure 5.10 FL of SMA mixtures with 30% RAP

Table 5.20 Fatigue Life of SMA Mixtures with 40%-0% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
40%-0%	1117.00	168.92	15.12	15281	15424
		169.47	15.17	15567	
		368.93	33.03	8534	8586
		369.68	33.10	8638	
		557.36	49.90	4463	4375
		558.71	50.02	4287	

Table 5.21 Fatigue Life of SMA Mixtures with 40%-3% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
40%-3%	1117.00	167.46	14.99	15587	15708
		168.56	15.09	15829	
		368.97	33.03	8689	8723
		369.39	33.07	8757	
		558.77	50.02	4624	4553
		559.98	50.13	4481	

Table 5.22 Fatigue Life of SMA Mixtures with 40%-6% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
40%-6%	1117.00	169.67	15.19	16012	15970
		170.13	15.23	15927	
		369.19	33.05	9106	9062
		370.81	33.20	9017	
		558.13	49.97	4872	4902
		559.68	50.11	4931	

Table 5.23 Fatigue Life of SMA Mixtures with 40%-9% RAP

Mixture	Load for IDT Strength (kg)	Load Applied (kg)	Percentage of Load Applied (%)	FL	Average FL
40%-9%	1117.00	169.58	15.18	15683	15587
		170.32	15.25	15490	
		368.47	32.99	8762	8642
		369.56	33.09	8521	
		558.42	49.99	4328	4409
		559.33	50.07	4489	

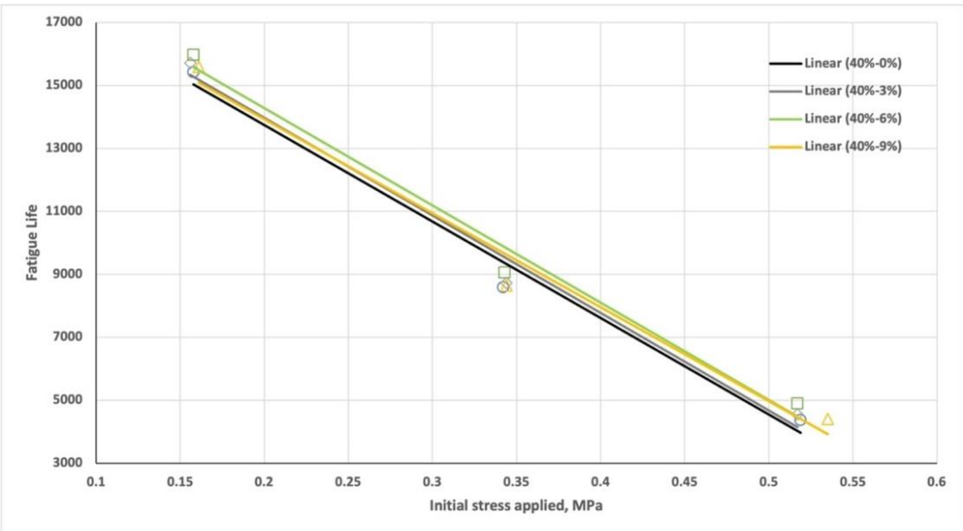

Figure 5.11 FL of SMA mixtures with 40% RAP

5.3.8 Workability

By subjecting the mixtures to 225 gyrations in the SGC, the workability characteristics were assessed using the Bahia-Friemel and Locking Point methods. The Bahia-Friemel approach revealed that 49-74 gyrations were needed to obtain 92% G_{mm} and the Locking Point method showed that 59 to 79 gyrations were required to achieve the locking point. The 40%-0% mixture required the most gyrations to reach 92% G_{mm} and the locking point, indicating that it was less workable than the other mixtures. The same trend was also observed in the computed values of CDI and TDI. Using the Bahia-Friemel method, the CDI and TDI values for the 40%-0% mixture were the highest at

290 and 604, respectively. Using the Locking Point method, the CDI and TDI values for the 40%-0% mixture were the highest at 478 and 517, respectively. For a given RAP content, the workability trend was found to increase with an increase in CNSL dosage but decreased with an increase in RAP content. Figures 5.12 to 5.14 show the values of the number of gyrations to 92% G_{mm}, CDI and TDI using the Bahia-Friemel method. Figures 5.15 to 5.17 show the values of the number of gyrations to 92% G_{mm}, CDI and TDI using the Locking Point method.

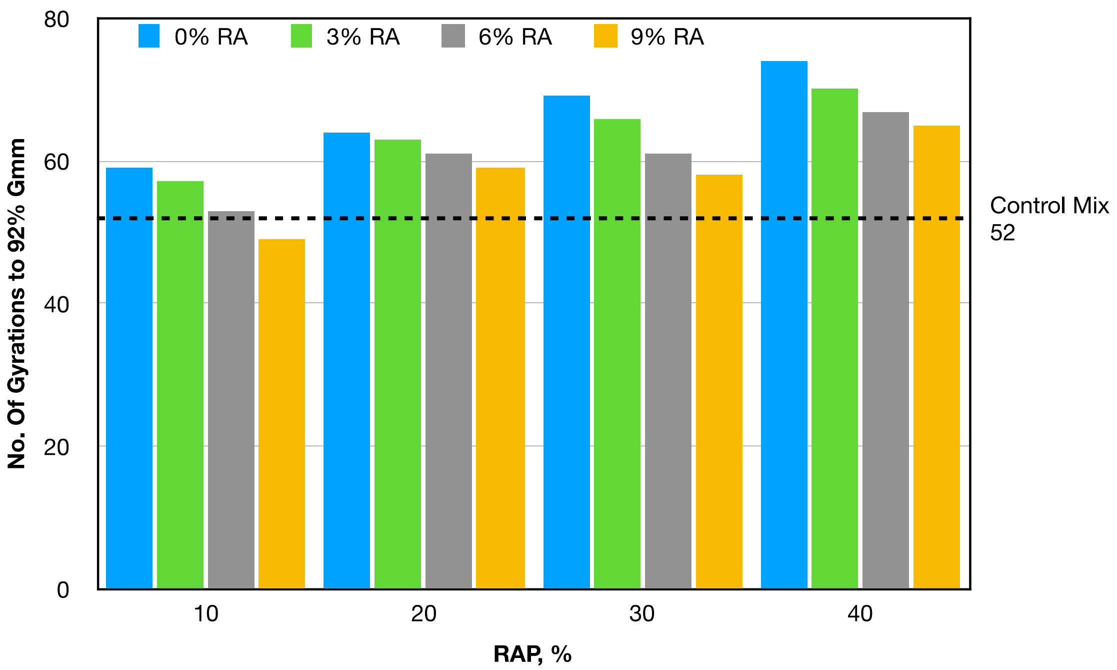

Figure. 5.12 No. of Gyrations to 92% G_{mm}

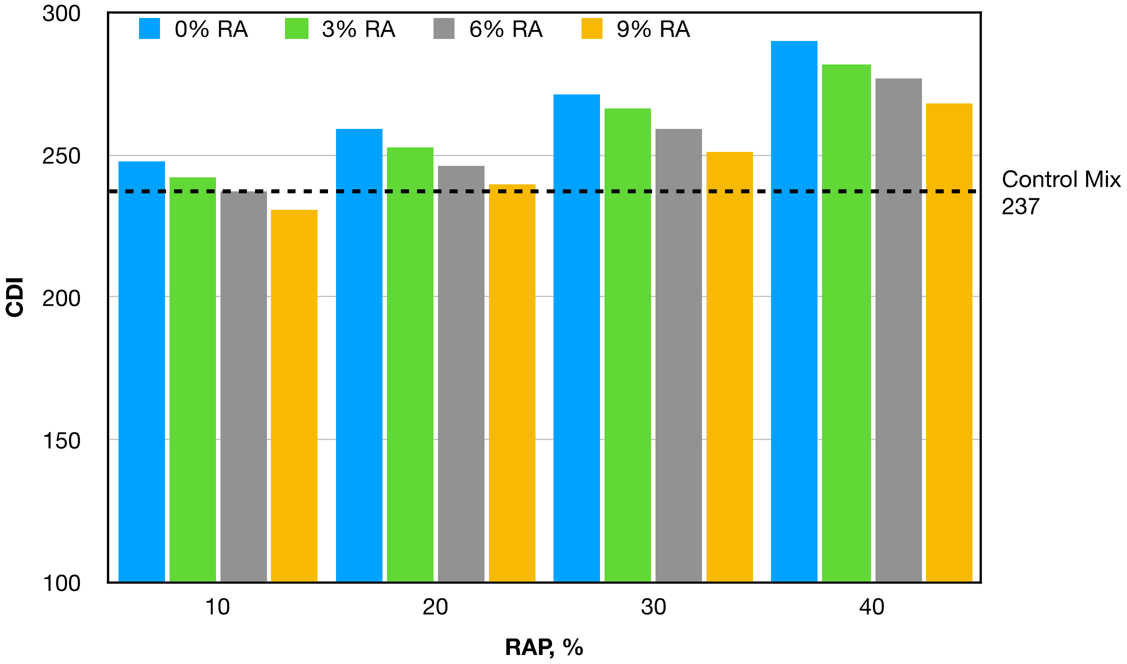

Figure. 5.13 Construction Densification Index (CDI) – Bahia-Friemel Method

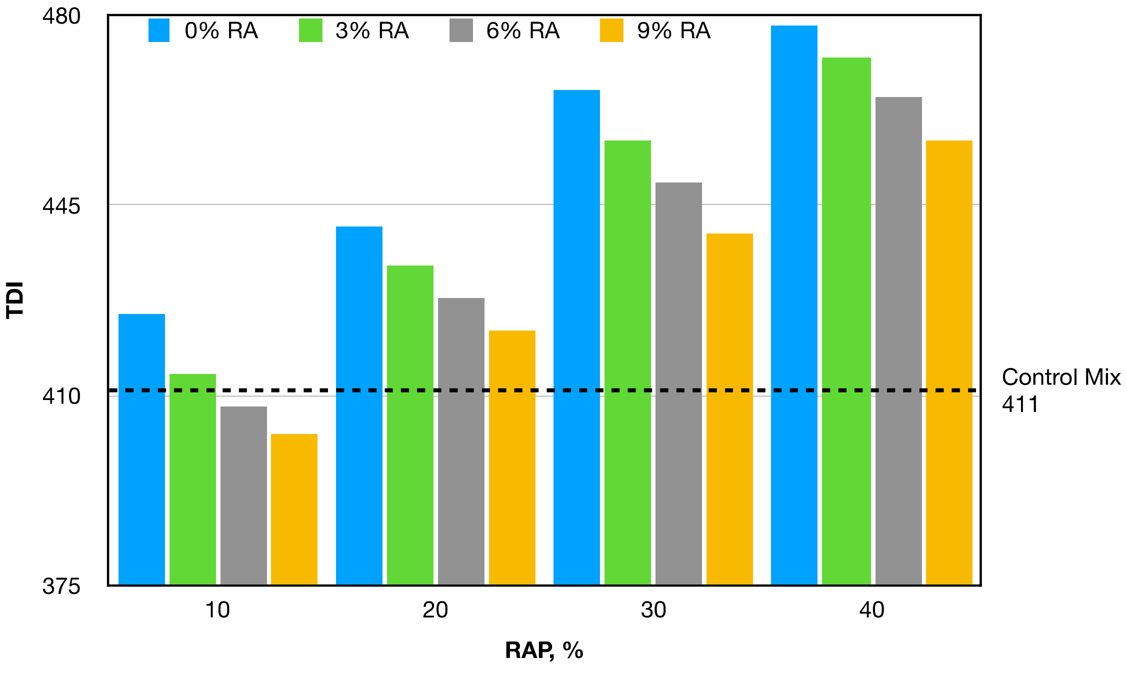

Figure. 5.14 Traffic Densification Index (TDI) – Bahia-Friemel Method

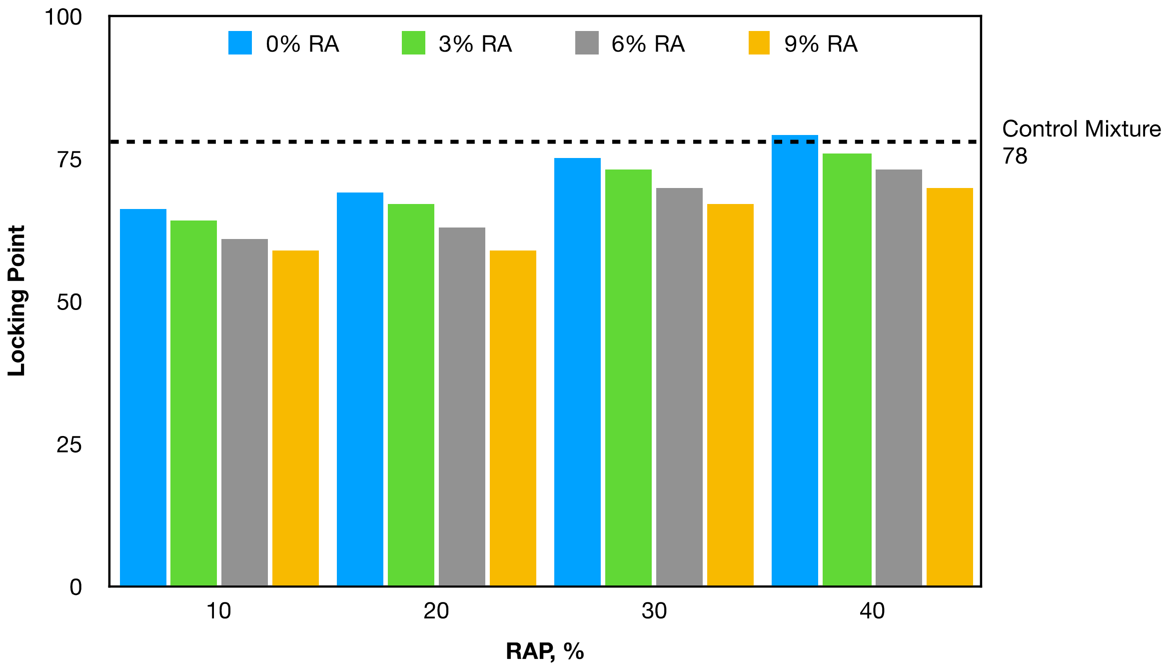

Figure. 5.15 Number of Gyrations to Locking Point

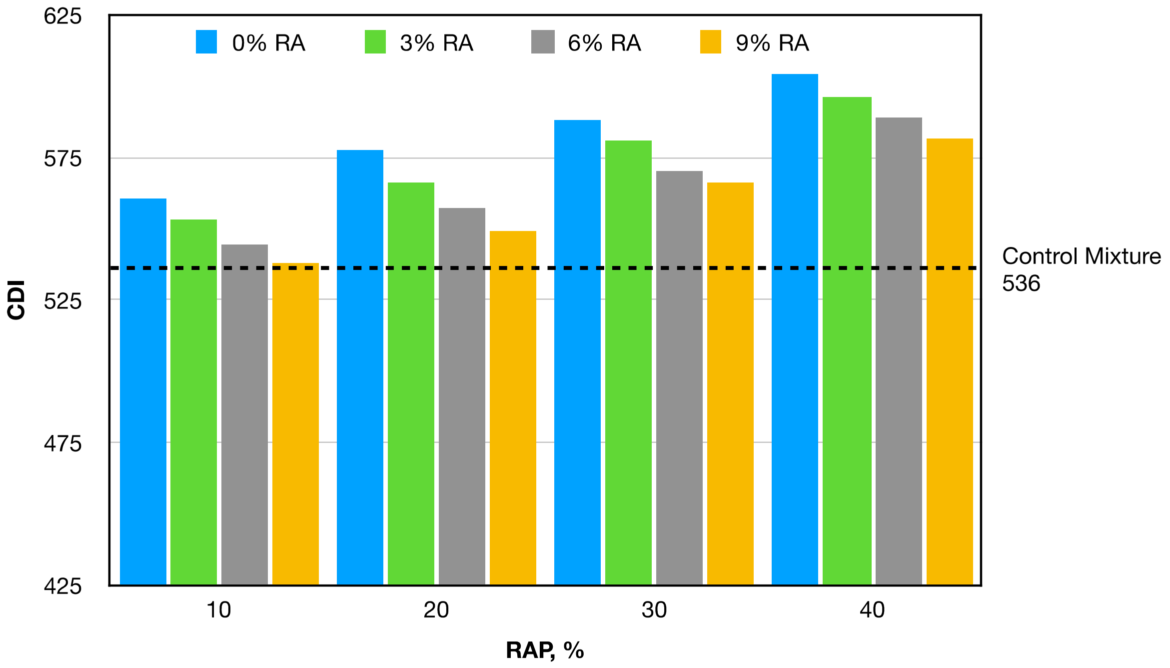

Figure. 5.16 Construction Densification Index (CDI) – Locking Point Method

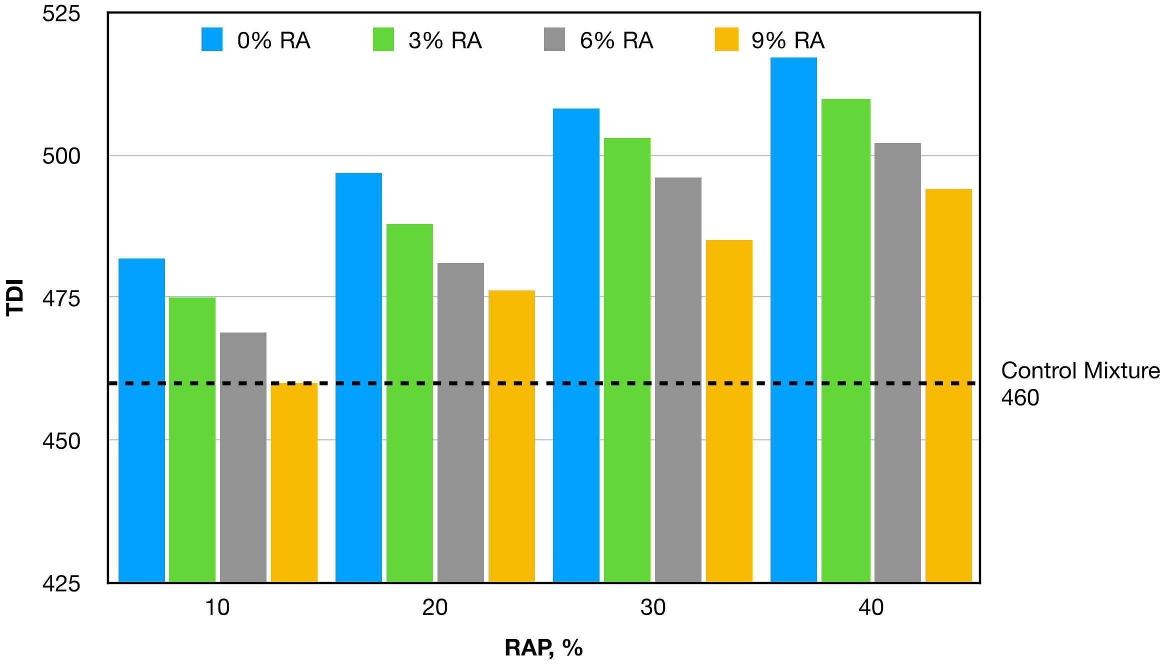

Figure. 5.17 Traffic Densification Index (TDI) – Locking Point Method

5.3.9 Moisture Susceptibility

5.3.9.1 Retained Marshall Stability

RMS tests were conducted on the RAP mixtures prepared at OBC, and the MS values of unconditioned and conditioned sets of specimens are shown in Figures 5.18 to 5.21. The RMS values are shown in Table 5.24. The RMS values were observed to be affected by both the rejuvenator dosage and RAP contents. The RMS increased with a rejuvenator dosage of up to 6% because of the activation of the RAP binder and better lubrication of the aggregate particles. But, at rejuvenator dosages of 9%, the mixture was too flexible and the mixture failed at lower MS values. The RMS increased with an increase of RAP up to 30% and decreased at 40% RAP content because of the improper blending of the mixture. The highest RMS of 95.69% was obtained for the 30%-6% mixture.

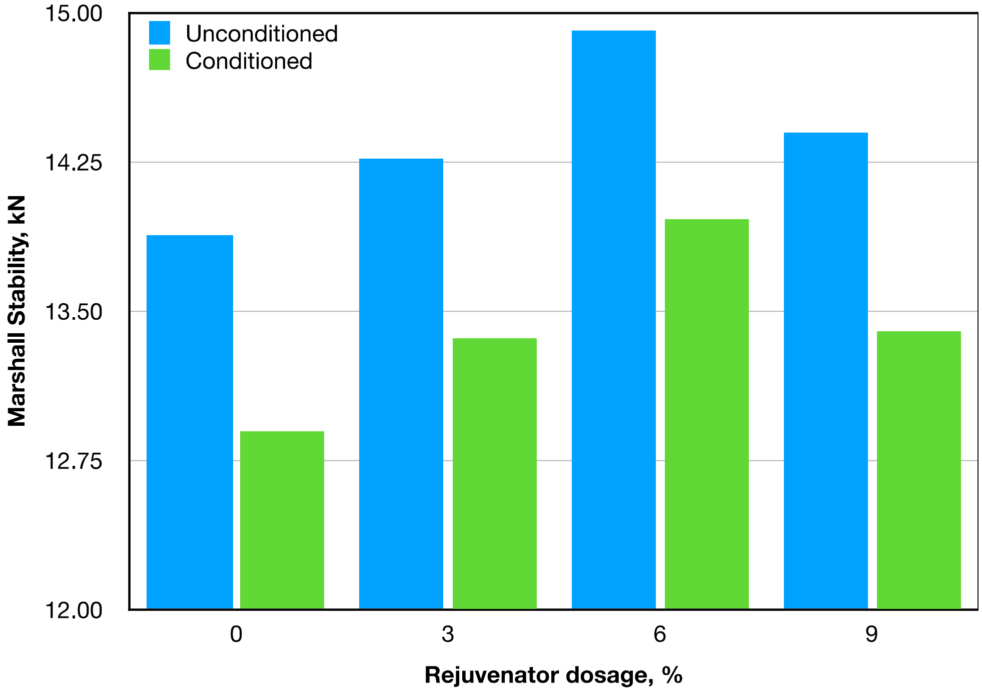

Figure. 5.18 Unconditioned and Conditioned MS of 10% RAP mixtures

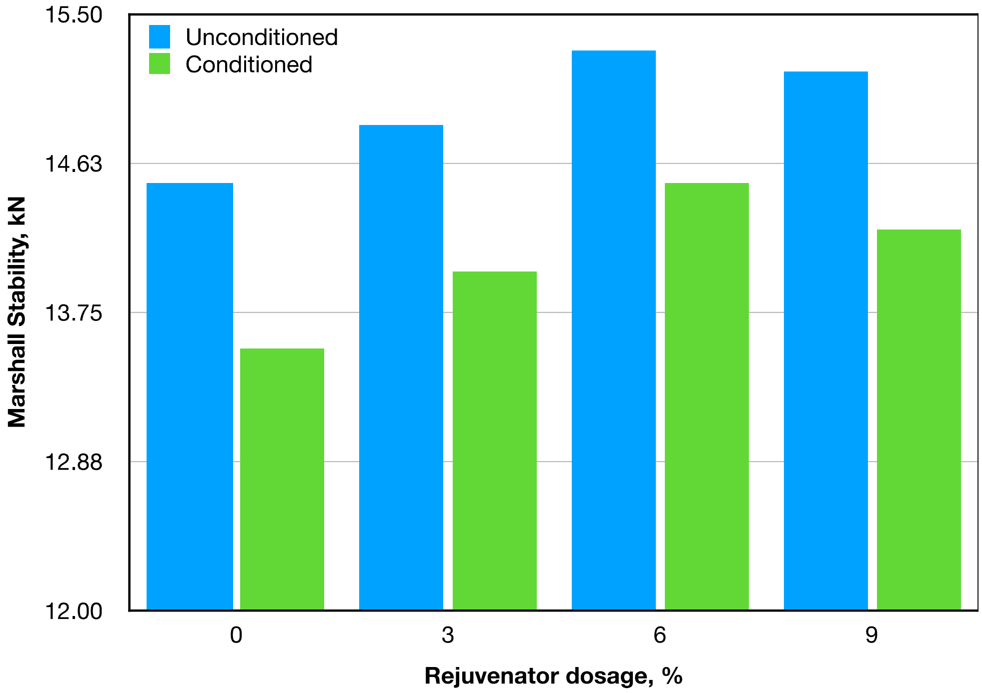

Figure. 5.19 Unconditioned and Conditioned MS of 20% RAP mixtures

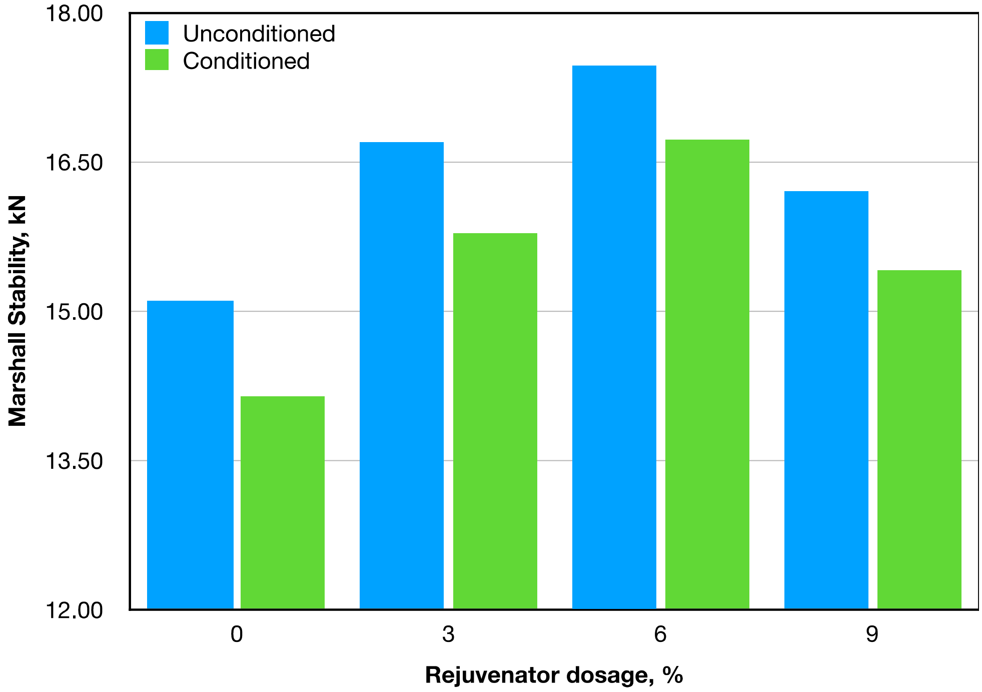

Figure. 5.20 Unconditioned and Conditioned MS of 30% RAP mixtures

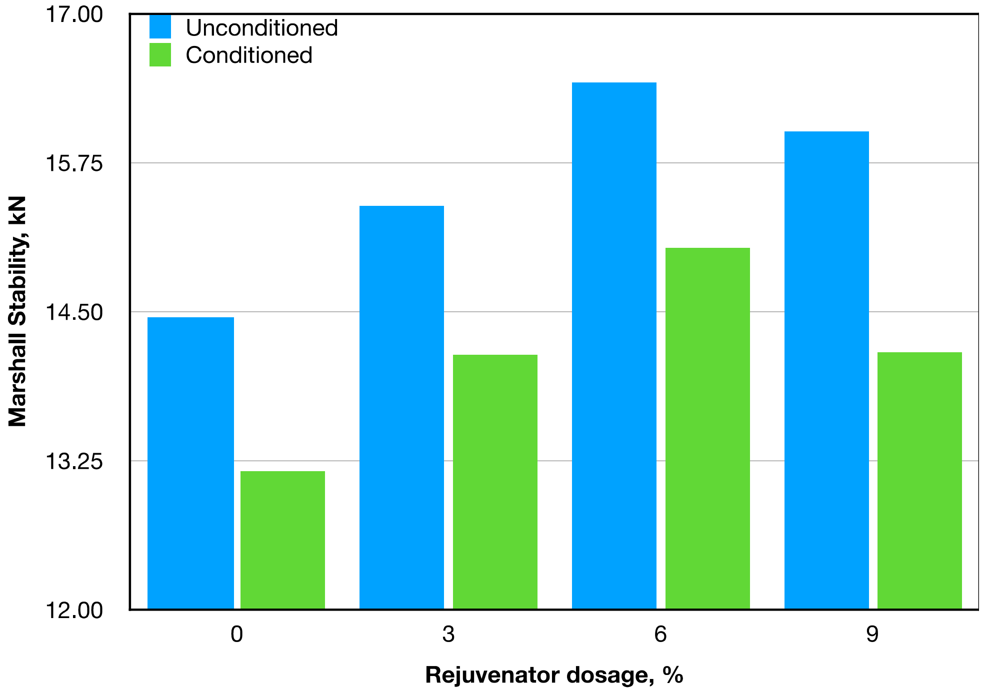

Figure. 5.21 Unconditioned and Conditioned MS of 40% RAP mixtures

Table 5.24 Retained Marshall Stability of SMA Mixtures

RAP, %	Rejuvenator dosage			
	0%	**3%**	**6%**	**9%**
10	92.91	93.69	93.65	93.08
20	93.38	94.12	94.90	93.89
30	93.65	94.51	95.69	95.05
40	91.03	91.89	91.56	88.35

5.3.9.2 Tensile Strength Ratio

IDT tests were conducted on cylindrical specimens prepared at 7% air voids on both unconditioned and conditioned set specimens to determine the effect of moisture. The TSR values followed the same trend as IDT at 4% air voids for both unconditioned and conditioned specimens. The TSR values of the mixtures are shown in Table 5.25. The maximum TSR obtained was 92.47% for the 30%-6% mixture. The minimum requirement of TSR is 85% as per AASHTO T 283 and all the mixtures satisfied this requirement. Figures 5.22 to 5.25 show the values of IDT of mixtures at 7% air voids for both the unconditioned and conditioned set of specimens.

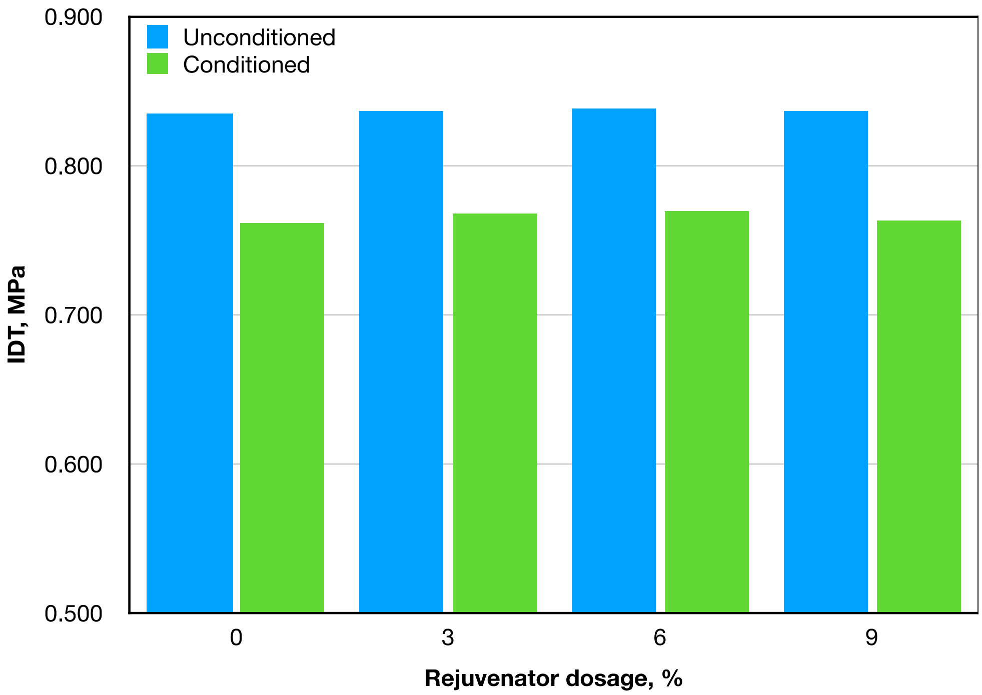

Figure. 5.22 Unconditioned and Conditioned IDT of 10% RAP mixtures

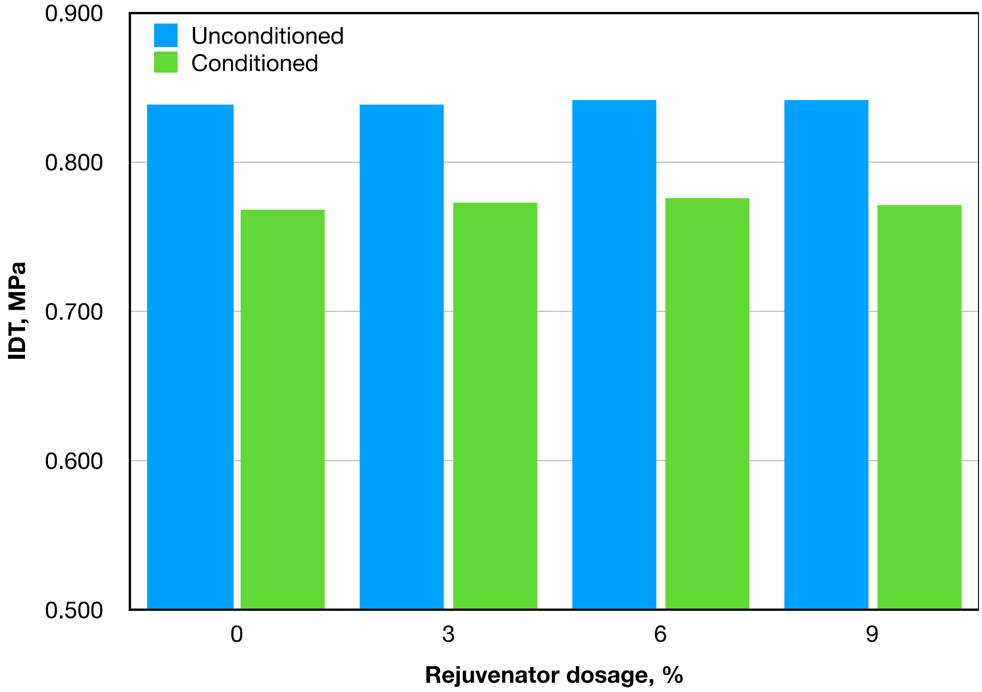

Figure. 5.23 Unconditioned and Conditioned IDT of 20% RAP mixtures

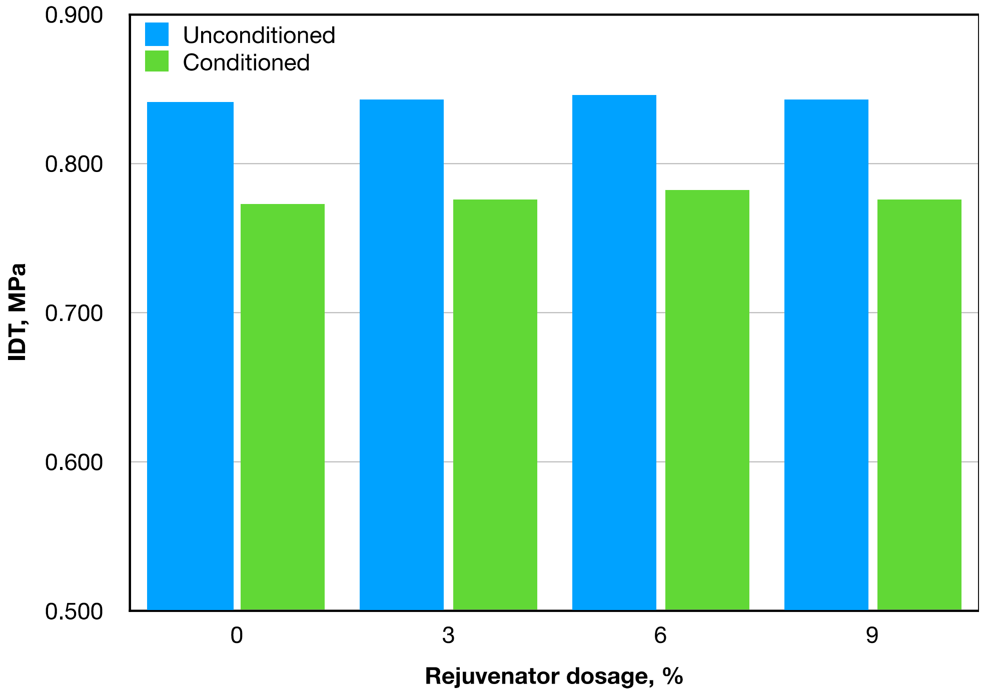

Figure. 5.24 Unconditioned and Conditioned IDT of 30% RAP mixtures

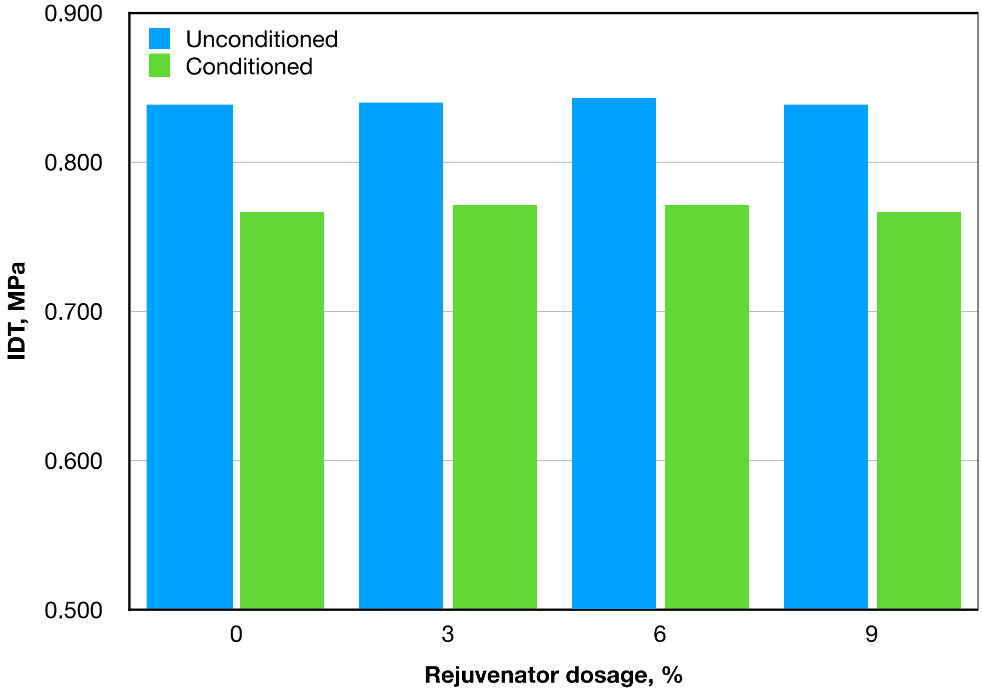

Fig. 5.25 Unconditioned and Conditioned IDT of 40% RAP mixtures

Table 5.25 TSR, % of SMA Mixtures

RAP, %	Rejuvenator dosage			
	0%	**3%**	**6%**	**9%**
10	91.26	91.62	91.68	91.27
20	91.50	92.01	92.17	91.69
30	91.93	92.14	92.47	91.97
40	91.59	91.88	91.54	91.39

5.3.9.3 Stripping

All the mixtures prepared at their corresponding OBC were subjected to boiling test in accordance with ASTM D 3625 in their loose condition and visually observed for stripping of bitumen from the surface. It was observed that all the mixtures tested had a stripping area of less than 5%.

5.4 SUMMARY

In this chapter, SMA mixes were prepared with RAP contents of 10%, 20%, 30% and 40%. A by-product of the production of cashewnut called the Cashewnut Shell Gel

(CNSL) was used as the rejuvenator at percentages of 0, 3, 6 and 9% by weight of bitumen. A total of 17 mixture combinations were prepared and the mixture produced using only natural aggregates and cellulose fibre but without a rejuvenator was used as the control mixture. The drain down tests conducted on the mixes showed a decrease in the drainage susceptibility of the mixtures with an increase in the RAP content which may be due to the presence of higher aged binder in the mixture making it stiffer. However, the drain down increased with an increase in the rejuvenator content which may be due to decrease in the viscosity of the aged binder. The OBC values reduced with an increase in the RAP and rejuvenator contents. This may be due to the combined effect of higher bitumen content at higher RAP percentages and decrease in the viscosity of the aged binder due to an increase in the rejuvenator content. In terms of volumetric properties, all the mixtures satisfied the minimum VMA requirement of 17% except 40%-6% and 40%-9% mixtures. Due to the increase in the stiffness of the mixture because of an increase in the RAP contents, the specific gravity of the compacted specimens also increased. The Marshall stability of the mixtures for a particular RAP content increased with an increase in the rejuvenator content up to 6%. At 9% rejuvenator level, the Marshall stability reduced, which may be due to the high fluidity of the mixture. The highest Marshall stability obtained was for 30%-6% mixture. The IDT values increased with an increase in the RAP content up to 30%. With reference to an increase in rejuvenator content, the IDT values increased up to 6% and reduced at 9%. The rutting characteristics of the mixes showed a decrease in the rut depth of the mixtures with an increase in the RAP content, which may be due to the higher stiffness of the mixtures. But, with an increase in the rejuvenator content, the rut depth increased which may be due to the reduction in the stiffness of the mixtures, making them more flexible. The FL of the mixtures increased with an increase in the rejuvenator content up to 6% and reduced at 9% rejuvenator level. The FL of the mixtures increased with an increase up to 30% RAP content and reduced at 40% RAP content. This may be due to the high stiffness of the mixture. The highest FL was observed at all stress levels of 15%, 33% and 50% for 30%-6% mixture. The moisture susceptibility of the mixtures in terms of Retained Marshall Stability increased with an increase in the RAP content up to 30% and rejuvenator up to 6%. The highest Retained Marshall Stability recorded was for 30%-

6% mixture. The RMS values obtained were in the range of 88.35% to 95.69%. The Tensile Strength Ratio also followed the same trend the IDT at 4% air voids. The range of TSR values was 91.39% to 92.47%. The highest TSR was obtained for 30%-6% mixture and the lowest was obtained for 40%-9% mixture. The stripping test conducted using the boiling test method showed that the stripping percentage was less than 5%.

The workability characteristics of the mixtures were evaluated using the Bahia-Friemel method and the Locking Point method. Using the Bahia-Friemel method, the number of gyrations required to achieve 92% G_{mm} varied from 49 for 10%-9% mixture to 74 for 40%-0%. This shows that the 10%-9% mixture is a tender mixture because of the lesser number of gyrations required and the 40%-0% mixture has very poor workability characteristics due to the stiffness imparted by high RAP content and also due to the lack of the rejuvenator. The locking point method confirmed the findings of the Bahia-Friemel method with the 10%-9% mixture requiring 59 gyrations and the 40%-0% mixture required the highest number of gyrations at 79. The CDI values obtained were in the range of 231 to 290. The lowest value of 231 was obtained for 10%-9% mixture while the highest value of 290 was for 40%-0% mixture. A lower value of 231 indicates high workability while a higher value of 290 indicates low workability of the mixture. Similarly, the CDI values obtained using the Locking point were 538 and 604 for 10%-9% mixture and 40%-0% mixture, respectively. The TDI values were higher for mixes with higher RAP contents, indicating higher resistance of the mixture to breakdown of aggregates due to the movement of traffic. This may be due to the stiffness of the mixtures at higher RAP contents. The TDI values obtained using the Bahia-Friemel method were in the range of 403 to 478. The lowest value of 403 was observed for 10%-9% mixture and the for the 40%-0% the value obtained was 478. The same trend was observed for the mixes using the Locking Point method. For 10%-9% mixture, the TDI value was the lowest at 460 indicating low resistance of the mixture to deformations caused by traffic movement. However, the 40%-0% mixture showed the highest resistance to deformation caused by traffic movement as indicated by the highest TDI value of 517.

CHAPTER 6

DISCUSSIONS AND CONCLUSIONS

6.1 DISCUSSIONS

6.1.1 SMA Mixtures With Stabilising Additives

6.1.1.1 Drain-down

The drain-down of all the mixes at 7% bitumen content with stabilising additives was evaluated at fibre contents of 0.0%, 0.1%, 0.2%, 0.3%, 0.4% and 0.5%, respectively. The drain-down values reduced with an increase in the fibre content. The minimum fibre content at which the drain-down was observed to be lesser than the maximum permissible drain-down was 0.3%. Hence, the OFC was 0.3% for all the mixtures with fibres. The values of drain-down at 170°C were higher than that at 160°C due to the effect of temperature. However, at fibre contents of 0.3% and above, the mixes with fibres satisfied the requirements of drain-down.

6.1.1.2 Optimum Binder Content

The bitumen content corresponding to 4% air voids was taken as the OBC. The OBC of SMA-PMB was the lowest at 6.10% and that of SMA-CF was the highest at 6.17%. The increase in the OBC of SMA-CF may be due to the smaller diameter of coconut fibres resulting in a higher surface area. The higher OBC of mixes with natural fibres may also be due to the possible absorption of bitumen by the fibres.

6.1.1.3 Voids in the Coarse Aggregates

All the mixes satisfied the condition of ratio of VCA_{mix} to VCA_{DRC} less than one, ensuring the presence of stone skeleton. The values of VCA_{mix} at all bitumen contents were the highest for SMA-CF, which may be due to the lower density of coconut fibres resulting in a higher volume of fibres in the mixture. On the other hand, the values of VCA_{mix} of SMA-PMB were the lowest at all bitumen contents, which may be due to the absence of any externally added fibres.

6.1.1.4 Marshall Stability

The MS value of SMA-PMB was the highest, which may be due to the improved characteristics of PMB 40 bitumen compared to conventional bitumen. Among the mixes with VG 30 bitumen, SMA-PF produced the highest load at failure followed by SMA-AF and SMA-CF. Among the natural fibres, the higher result observed in the case of SMA-AF may be due to the better characteristics of Areca fibres compared to coconut fibres.

6.1.1.5 Indirect Tensile Strength (IDT)

The IDT value of SMA-PMB was the highest, which may be due to the better ductility characteristics of PMB 40 bitumen. Among the mixes with VG 30 bitumen, SMA-PF sustained higher tensile loads due to the uniform distribution of cellulose fibres and the formation of a network of fibres in the mixture compared to the mixtures with Areca and Coconut fibres.

6.1.1.6 Rutting Characteristics

The rutting characteristics showed that SMA with PMB showed the highest resistance to rutting with a rut depth of 4.41 mm followed by SMA-PF at 4.87 mm. Among the mixtures with natural fibres, SMA-AF performed better with a rut depth of 5.24 mm. The rutting behaviour of the mixture with coconut fibre, SMA-CF, however, was close to the failure criterion of 6 mm at 5.69 mm.

6.1.1.7 Fatigue Characteristics

The results of the fatigue tests on the SMA mixture prepared with PMB showed the highest resistance to fatigue failure at all stress levels. The fatigue life of the mixture prepared using pelletised cellulose fibre was comparable to that of SMA-PMB. Among the mixes with natural fibres, SMA-CF showed higher fatigue life compared to that of SMA-AF. This may be due to the application of higher stresses during the fatigue testing of SMA-AF resulting in lower number of repetitions to failure.

6.1.1.8 Workability Characteristics

The workability characteristics of the mixes prepared determined in terms of number of gyrations required to achieve 92% G_{mm} were 49, 52, 58 and 61 for SMA-PMB, SMA-PF, SMA-AF and SMA-CF, respectively. The workability characteristics using the locking point followed the same trend as the number of gyrations to achieve 92% G_{mm} and the values were 74, 78, 81 and 83 for SMA-PMB, SMA-PF, SMA-AF and SMA-CF, respectively. Similarly the CDI values for all the mixtures were in the range 306-358 using the Bahia-Friemel method and 843-892 using the locking point method. The mixture SMA-PMB showed the highest resistance to traffic loading as indicated by the highest TDI values using both the Bahia-Friemel and locking point methods. The least resistance was shown by SMA-CF with the lowest values of 724 and 441 using the Bahia-Friemel and locking point methods, respectively.

6.1.1.9 Moisture Susceptibility Characteristics

All the SMA mixtures satisfied the minimum requirement of TSR of 85%. The mixture with SMA-PMB retained the highest tensile strength at about 92% and SMA-CF retained the lowest tensile strength at 87.55%. The moisture susceptibility in terms of RMS was in the range 89-92%, with SMA-PMB retaining the highest stability and SMA-CF, the lowest.

6.1.2 SMA Mixtures With RAP and Rejuvenator

6.1.2.1 Drain-down

The drain down of all the mixes with RAP contents of 10%, 20%, 30% and 40% were determined using CNSL as the rejuvenator and at 7% bitumen contents. The drain-down increased with an increase in the dosage of the rejuvenator, which is due to the activation of the aged binder by the rejuvenator. However, with an increase in the RAP content, the drain-down decreased due to the presence of a higher aged binder content which is stiff and hence it does not drain. The drain-down of the control mixture was 0.257% and the highest drain-down was obtained for the 10%-9% bituminous mixture. After the determination of the OBC of all the mixtures, the drain-down was checked at OBC values and plant production temperatures of 160°C and 170°C, respectively. The drain-down of the mixtures at 160°C was lower than that of the mixtures at 170°C, which is due to the effect of elevated temperature. All the mixtures produced satisfied the maximum permissible drain-down of 0.3% as per IRC SP 79 2008.

6.1.2.2 Optimum Binder Content

The OBC of the mixtures was affected by both the CNSL dosage as well as the RAP content. For any particular RAP content, the OBC decreased because of the increase in the rejuvenator dosage. Similarly, an increase in the RAP content reduced the OBC of the mixture, which is due to the higher binder content contributed to the mixture by the RAP. However, it is to be noted that the mixtures 40%-6% and 40%-9% did not satisfy the requirement of minimum bitumen content of 5.80% as per IRC SP 79 2008. The mixture 40%-3% required an OBC of 5.81%, which just satisfies the minimum bitumen content.

6.1.2.3 Voids in the Coarse Aggregates

The VCA_{DRC} and VCA_{mix} were determined for all the mixtures. With the increase in both RAP and CNSL dosage, the VCA_{mix} increased. The VCA_{DRC} of the control mixture was 41.230%. All the mixtures had a VCA_{mix} value lesser than VCA_{DRC} and the ratio of VCA_{mix}/ VCA_{DRC} is less than 1, which confirms the presence of the stone-to-stone contact and aggregate skeleton.

The VMA values of all the mixtures were higher than the minimum VMA requirement of 17%, except for 40%-6% and 40%-9% mixtures.

6.1.2.4 Marshall Stability

The MS values of the mixtures increased with an increase in the CNSL dosage up to 6%, which may be due to the activation of the RAP binder and better lubrication of the aggregate surface leading to higher density values and MS. The MS values also increased with the increase in RAP content up to 30% and decreased with the addition of 40% RAP which may be due to improper blending of the mixture, causing it to fail at lower loads. The highest MS value was noted for 30%-6% mixture at 17.47 kN.

6.1.2.5 Indirect Tensile Strength (IDT)

The IDT values increased with the increase in RAP content up to 30% due to the stiffness of the aged binder present in the bitumen. Similarly, the IDT values increased with an increase in the CNSL dosage up to 6% and decreased at 9% dosage, which may be due to the mixture being too flexible. Similar to MS, the maximum IDT value observed was for the mixture 30%-6%.

6.1.2.6 Rutting Characteristics

The rutting characteristics of the mixtures produced showed a similar trend as IDT with respect to increase in the RAP content. The rut depths of the mixtures decreased with an increase in the RAP content. The maximum rut depth was recorded for the mixture 10%-9% at 6.15 mm, which was more than the maximum permissible rut depth of 6 mm. With the increase in the RAP content, the stiffness of the mixtures increased, which reduced the rut depth of the mixtures. The Dynamic Stabilities of the mixtures increased with an increase in the RAP content.

6.1.2.7 Fatigue Characteristics

The FL of the mixtures increased with respect to RAP content up to 30% and decreased at 40% RAP content, which may be due to the problems associated with blending. Similarly, for all the RAP contents, the FL decreased at 9% CNSL dosage, which may be due to the mixture becoming flexible.

6.1.2.8 Workability Characteristics

The number of gyrations to 92% G_{mm} increased with the increase in RAP content. This may be due to the increase in the stiffness due to the presence of RAP binder. Hence, a higher effort is required to compact the mixtures with higher RAP contents. A similar trend was also observed for the Locking Point method. The values of CDI also increased with increase in the RAP content. A lower CDI value indicates the mixture requires lesser effort to compact than a mixture with a higher CDI value. The CDI values increased with an increase in the RAP content, resulting in the mixtures at higher RAP contents requiring more effort for compaction. A higher TDI value indicates that the mixture offers higher resistance to aggregate degradation. Using both methods, the TDI increased with an increase in the RAP content.

6.1.2.9 Moisture Susceptibility Characteristics

The RMS was affected by both the RAP and rejuvenator contents. The RMS increased with an increase in the RAP content up to 30% and decreased at 40%

content. The RMS followed the same trend as MS values. At a high rejuvenator content of 9%, the mixture becomes flexible, which results in a lower MS value. Hence, the RMS at 9% CNSL is lower than at 6%.

The TSR followed the same trend as IDT, with the highest TSR recorded for 30%-6% mixture. All the mixtures satisfied the minimum TSR requirement of 85% as per AASHTO T 283.

The stripping test on loose mixtures was conducted for all the mixture combinations and the stripping observed was less than 5%, which may be due to the presence of hydrated lime in the mixture. The hydrated lime is a good anti-stripping agent which improves the bonding between the aggregate particles and bitumen.

6.2 CONCLUSIONS

6.2.1 SMA Mixtures With Stabilising Additives

The mixes SMA-AF, SMA-CF and SMA-PF did not satisfy the requirements of drain down at fibre contents of 0.0%, 0.1% and 0.2%. All the mixes satisfied the volumetric (VMA, VCA_{MIX} less than VCA_{DRC}), minimum bitumen content, drain down and tensile strength ratio requirements as per IRC SP 79 2008. The OBC values obtained for mixes with natural fibres were higher than those with SMA-PMB and SMA-PF which may be due to the absorption of bitumen and the specific surface area by the fibres. Further, SMA-CF resulted in higher OBC due to the higher specific surface area of coconut fibres compared to areca fibres used in SMA-AF. The workability studies indicated that SMA-PMB required the lowest energy for compaction and as indicated by both the locking point and Bahia-Friemel methods, SMA-PMB showed the highest resistance to degradation caused by traffic loading. The performance of the SMA mix produced with a synthetic fibre like pelletised cellulose fibre was comparable to that of SMA-PMB. Whereas the results of the SMA mixes prepared with natural fibres were comparable. The SMA mixture with areca fibres satisfies all the volumetric and moisture susceptibility requirements. Hence, areca fibres can be used as a stabilising additive in SMA mixes since the initial cost of procurement of areca fibres is less, and also solves the problem of disposal and environmental pollution.

6.2.2 SMA Mixtures with RAP and Rejuvenator

Based on the results obtained, the mixtures 40%-6% and 40%-9% do not satisfy the minimum binder content requirement. Also, they do not satisfy the minimum requirement of VMA of 17%. Since the values of MS, IDT, fatigue, RMS and TSR have reduced at 40% RAP content compared to 30% RAP, 40% RAP cannot be incorporated in the mixture. Also, the 40% RAP mixtures required a higher effort for compaction, as indicated by the higher values of CDI by both the Bahia-Friemel and Locking Point methods. Though a maximum RAP content of 40% and a CNSL dosage of 3% can be used in the mixture, it is a stiff mixture since it is a stiff mixture. For the mixture 30%-6%, the values of MS, IDT, Fatigue, RMS and TSR are the highest. The 30%-6% mixture also provides a good balance between rutting and fatigue characteristics. Hence, an optimum RAP content of 30% with a CNSL dosage of 6% can be used for the preparation of SMA mixtures.

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APPENDIX I

Blending of aggregate stockpiles to obtain the desired gradation

The aggregate gradation of individual stockpiles used to achieve the required gradation are:

Sieve Size, mm	Aggregate A (20 mm)	Aggregate B (10 mm)	Aggregate C (Dust)
19.0	100.0	100.0	100.0
13.2	94.0	100.0	100.0
9.50	59.0	59.1	100.0
4.75	11.12	4.6	100.0
2.36	5.68	2.36	86.0
1.18	6.68	13.97	41.4
0.60	9.91	8.44	29.0
0.30	10.93	9.48	22.0
0.075	6.81	7.02	18.21

The required gradation was achieved using the trial and error method with the following percentages:

1. 52% of Aggregate A
2. 30% of Aggregate B and
3. 18% of Aggregate C

Sieve Size, mm	Required Gradation	Achieved Gradation
19.0	100	100.00
13.2	90-100	96.88
9.50	50-75	66.41
4.75	20-28	25.16
2.36	16-24	19.14
1.18	13-21	15.12
0.60	12-18	12.91
0.30	10-20	12.49
0.075	8-12	8.93

APPENDIX II

Blending of natural aggregate stockpiles and RAP to obtain the desired gradation

The aggregate gradation of individual stockpiles and RAP used to achieve the required gradation are:

Sieve Size, mm	Aggregate A (20 mm)	Aggregate B (10 mm)	Aggregate C (Dust)	Aggregate D (RAP)
19.0	100.0	100.0	100.0	100
13.2	94.0	100.0	100.0	91
9.50	59.0	59.1	100.0	64
4.75	11.12	4.6	100.0	14
2.36	5.68	2.36	86.0	7.23
1.18	6.68	13.97	41.4	8.34
0.60	9.91	8.44	29.0	10.97
0.30	10.93	9.48	22.0	12.02
0.075	6.81	7.02	18.21	7.89

The required gradation was achieved using the trial and error method with the following percentages for different percentages of RAP.

	Percentages of Aggregates			
Aggregate Stockpiles	**Aggregate A (20 mm)**	**Aggregate B (10 mm)**	**Aggregate C (Dust)**	**Aggregate D (RAP)**
10% RAP	45	28	17	10
20% RAP	32	31	17	20
30% RAP	20	33	17	30
40% RAP	13	31	16	40

APPENDIX III

Calculation of mix design properties of the mixture with Areca fibre

Consider the mixture with 5.0% bitumen content:

Mass of the aggregates in the mixture: 1200 g

Mass of bitumen: 60 g

Mass of fibre at 0.3% by weight of the mixture = 1260 * $\frac{0.3}{100}$ = 3.816 g

Total mass of the mixture = 1263.816 g

Bulk Specific Gravity of the aggregate blend, G_{sb} = 2.702

Maximum theoretical specific gravity, G_{mm} = 2.481 g/cm^3

Bulk density of the compacted specimen, G_{mb} = 2.312 g/cm^3

Air Voids, V_a (%) $= \frac{Gmm - Gmb}{Gmm} * 100$

$= \frac{2.481 - 2.312}{2.481} * 100$

= 6.81%

Aggregate content (%) by weight of the mixture, Ps $= \frac{1200}{1200+63.816} * 100$

= 94.95%

Voids in the Mineral Aggregates, VMA (%) $= 100 - \frac{Gmb * Ps}{Gsb}$

$= 100 - \frac{2.312 * 94.95}{2.702}$

= 18.75%

Voids Filled with Bitumen VFB (%) $= \frac{VMA - Va}{VMA} * 100$

$= \frac{18.75 - 6.81}{18.75} * 100$

= 63.68%

APPENDIX IV

Determination of stone-to-stone contact in the mixture

Determination of voids in the coarse aggregates in the dry rodded condition:

Bulk specific aggregates in the coarse aggregates G_{ca} = 2.744

Unit weight of the coarse aggregates in dry rodded condition, kg/m^3 γ_S = 1609.44

VCA_{DRC}, % $= \frac{G_{ca}\gamma_w - \gamma_s}{G_{ca}\gamma_w} \times 100$

= 41.23

Determination of voids in the coarse aggregates in the mixture:

Mass of coarse aggregates in the mixture, g = 912

Percentage of coarse aggregates in the mixture, P_{ca} % = 72.16

Voids in the coarse aggregates in the mixture

VCA_{MIX}, % $= 100 - (\frac{Gmb}{Gca} * P_{ca})$

VCA_{MIX}, % = 39.20

Since VCA_{MIX} is less than VCA_{DRC}, there exists a stone-to-stone contact in the mixture.

APPENDIX V

Determination of the number of gyrations for preparing specimens at 7% air voids

Consider the mixture with Areca fibre

The actual density of the specimen at OBC, g/cm^3 = 2.335

Height of the specimen after 100 gyrations, cm = 7.06

Diameter of the specimen, cm = 10

Volume of the specimen after 100 gyrations, cm^3 = 554.49

Mass of the specimen, g = 1268

Estimated Density of the specimen based on the dimensions after the design number of gyrations $E_{st}\ G_{mb}$, g/cm^3 = 2.287

Correction factor 'C' $= \frac{\text{Est Gmb}}{\text{Actual Gmb}} = \frac{2.287}{2.335}$

= 0.979

Theoretical maximum specific gravity of the mixture = 2.438

The required actual density of specimen at 7% air voids (G_{mb} at 7%) i.e., 93% of G_{mm}

= 2.267

The same correction factor 'C' can be applied to estimate the density of the specimen at 7% air voids based on the dimensions

$E_{st}\ G_{mb}$ at 7%, g/cm^3 = Correction Factor * G_{mb} at 7% = 2.22

The readings shown in the following table obtained from the gyratory compactor provide the data of height of the specimen versus the number of gyrations.

No. of Gyrations	1	2	3	4	5	6	7	8	9	10
0	83.70	82.40	81.30	80.40	79.70	79.10	78.70	78.20	77.80	77.50
10	77.20	77.30	76.60	76.40	76.20	76.00	75.80	75.60	75.40	75.30
20	75.10	74.80	74.80	74.60	74.50	74.40	74.20	74.10	74.00	73.90
30	73.80	73.40	73.60	73.50	73.40	73.30	73.20	73.20	73.10	73.00
40	72.90	72.50	72.80	72.70	72.70	72.60	72.50	72.50	72.40	72.40
50	72.30	71.70	72.20	72.20	71.60	72.10	72.00	72.00	71.90	71.90
60	71.80	71.20	71.70	71.70	71.00	71.60	71.60	71.50	71.50	71.50
70	71.40	70.70	71.40	71.30	70.60	71.20	71.20	71.20	71.20	71.10

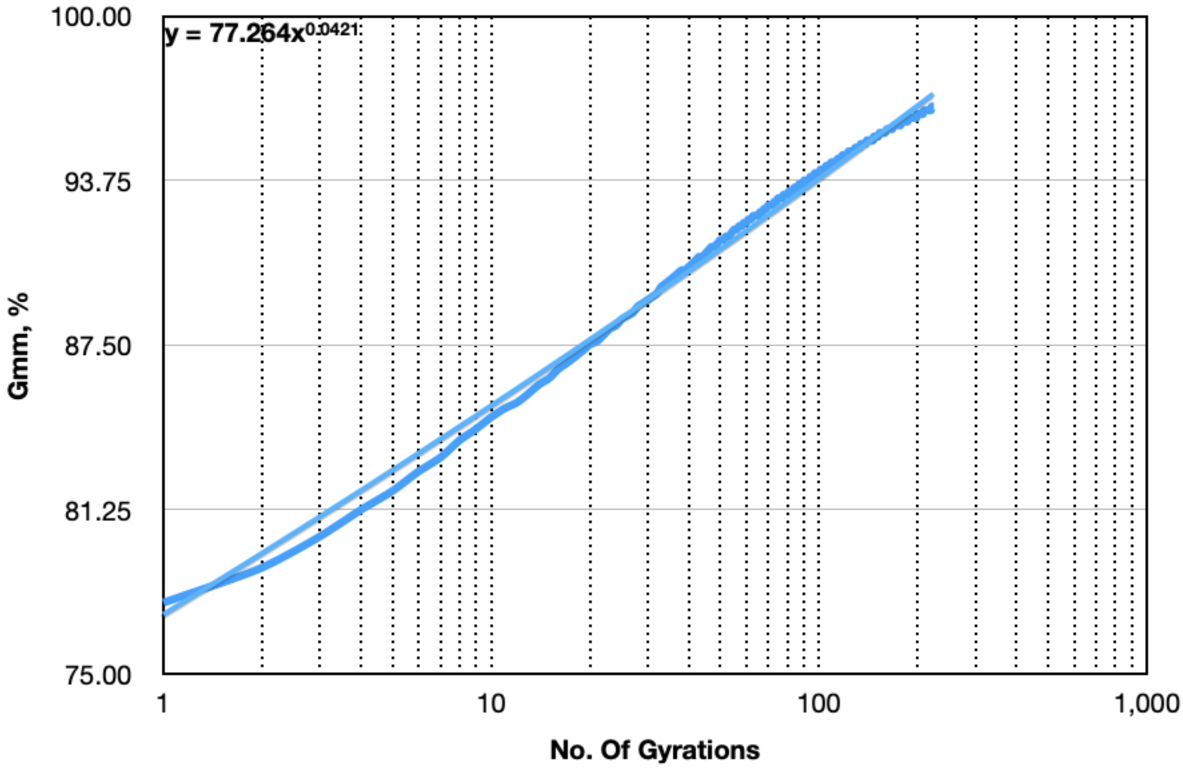
80	71.10	70.40	71.00	71.00	70.30	70.90	70.90	70.90	70.90	70.80
90	70.80	70.80	70.80	70.70	70.00	70.70	70.70	70.60	70.60	70.60

From the aforementioned table, the height of the specimen required to achieve the E_{st} G_{mb} at 7% is noted and the corresponding gyration number is the number of gyrations required to prepare the specimen at 7% air voids.

Hence, the height of the specimen required to achieve a density of 2.22 g/cm^3 is 72.70 mm as shown in the table. The number of gyrations corresponding to the height of 72.70 mm is 44.

APPENDIX VI

Calculation of workability indices of 30% RAP + 6% RA mixture



A1. Densification curve showing the number of gyrations versus G_{mm}, %

Locking Point method:

No. of gyrations required for aggregate locking point = 61

Percentage of G_{mm} at 1st gyration = 77.72

Percentage of G_{mm} at 61st gyration = 92.28

Percentage of G_{mm} at 225th gyration = 96.56

Using the Equation shown in Fig A1, the area under the curve from 1st to 61st gyration is calculated as CDI.

$$CDI = 562.45$$

Using the Equation shown in Fig A1, the area under the curve from 61st to 225th gyration is calculated as TDI.

$$TDI = 443.26$$

Bahia-Friemel method:

No. of gyrations required to achieve 92% G_{mm} = 57

Percentage of G_{mm} at 8^{th} gyration = 83.88

Percentage of G_{mm} at 57^{th} gyration = 92.02

Percentage of G_{mm} at 225^{th} gyration = 96.56

Using the Equation shown in Fig A1, the area under the curve from 1^{st} to 57^{th} gyration is calculated as CDI.

$$CDI = 252.77$$

Using the Equation shown in Fig A1, the area under the curve from 57^{th} to 225^{th} gyration is calculated as TDI.

$$TDI = 485.30$$

LIST OF PUBLICATIONS

Journal

1. Raghuram K. Chinnabhandar, Doma Hemanth Kumar, R. G. Yatish & A. U. Ravi Shankar (2022): Laboratory evaluation of use of areca fibres in SMA mixes, *International Journal of Pavement Engineering*, https://doi.org/10.1080/10298436.2022.2076090

Conference

1. Raghuram K Chinnabhandar, Ravi Shankar, A. U., Chethan, B, A., and Avinash H T. "Comparison of Performance of Stone Matrix Asphalt (SMA) using ViaTop pellets and Sisal Fibers", *Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies (CRSIDE2020),* Conducted by ASCE, Kolkata, West Bengal, India, 2-4 March 2020, Published in *Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies Proceedings (CRSIDE2020), pp 1775-1779.* ISBN: 978-81-954551-0-2

2. Raghuram K Chinnabhandar, Ravi Shankar, A. U., Sai Ganesh, V., Arnet Cleetus. "Laboratory Evaluation on the Use of Natural Fibre in Gap-Graded Asphalt Mixtures", 8th International Conference on Transportation Systems Engineering and Management (CTSEM2021), Conducted by NIT Calicut, Kerala, India, 26-27 August 2021, Accepted for publication as a Book Chapter in Recent *Advances in Transportation Engineering and Management*, Springer Nature. Doi: 10.1007/978-981-19-2273-2.

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5. Basic Statistics
6. Traffic Engineering – I
7. Pavement Evaluation
8. Pavement Management System
9. Traffic Engineering – II
10. Traffic Flow Theory
11. Pavement Construction

Research Publications

International Journal

1. Raghuram K. Chinnabhandar, Doma Hemanth Kumar, R. G. Yatish & A. U. Ravi Shankar (2022): Laboratory evaluation of use of areca fibres in SMA mixes, *International Journal of Pavement Engineering*, https://doi.org/10.1080/10298436.2022.2076090
2. Doma, H. K., Chinnabhandar, R. K., Kondeti, C., & AU, R. S. Effect of Aggregate Gradation and Bitumen Type on Mechanical Properties of Semi-Flexible Asphalt Mixtures. *Case Studies in Construction Materials, https://doi.org/10.1016/j.cscm.2023.e02025*

International Conference

1. Raghuram K Chinnabhandar, Ravi Shankar, A. U., Chethan, B, A., and Avinash H T. "Comparison of Performance of Stone Matrix Asphalt (SMA) using ViaTop pellets and Sisal Fibers", *Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies (CRSIDE2020)*, Conducted by ASCE, Kolkata, West Bengal, India, 2-4 March 2020, Published in *Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies Proceedings (CRSIDE2020), pp 1775-1779.* ISBN: 978-81-954551-0-2

2. Chethan B. A., Ravi Shankar A. U., Raghuram K Chinnabhandar and Avinash H. T. “Strength and Durability Characteristics of Fly Ash Admixed with Black Cotton Soil”, *Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies (CRSIDE2020),* Conducted by ASCE, Kolkata, West Bengal, India, 2-4 March 2020, Published in *Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies Proceedings (CRSIDE2020), pp 1652-1661*. ISBN: 978-81-954551-0-2.

3. Avinash H. T., Ravi Shankar A. U., Chethan B. A., and Raghuram K Chinnabhandar. “Strength and Durability Characteristics of Fly Ash Admixed with Black Cotton Soil”, *Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies (CRSIDE2020),* Conducted by ASCE, Kolkata, West Bengal, India, 2-4 March 2020, Published in *Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies Proceedings (CRSIDE2020), pp 1051-1055*. ISBN: 978-81-954551-0-2.

4. Raghuram K Chinnabhandar, Ravi Shankar, A. U., Sai Ganesh, V., Arnet Cleetus. “Laboratory Evaluation on the Use of Natural Fibre in Gap-Graded Asphalt Mixtures”, 8th International Conference on Transportation Systems Engineering and Management (CTSEM2021), Conducted by NIT Calicut, Kerala, India, 26-27 August 2021, Accepted for publication as a Book Chapter in Recent *Advances in Transportation Engineering and Management*, Springer Nature. Doi: 10.1007/978-981-19-2273-2.

5. Avinash Talkeri, Ravi Shankar A. U., and Raghuram K Chinnabhandar. “Laboratory Investigation of Alkali-Activated Slag Concrete using Reclaimed Asphalt Pavement (RAP)”, 8th International Conference on Transportation Systems Engineering and Management (CTSEM2021), Conducted by NIT Calicut, Kerala, India, 26-27 August 2021, Accepted for publication as a Book Chapter in *Recent Advances in Transportation Engineering and Management*, Springer Nature. Doi: 10.1007/978-981-19-2273-2.

6. B. A. Chethan, A. U. Ravi Shankar, Raghuram K. Chinnabhandar, and Doma Hemanth Kumar. “Alkali Activated Black Cotton Soil with Partial

Replacement of Class F Fly Ash and Areca Nut Fiber Reinforcement", Advances in Construction Technology and Management, Conducted by College of Engineering Pune, Maharashtra, India, 11-12th March 2021, Lecture Notes, Published in *Recent Trends in Construction Technology and Management, pp. 1193-1203,* Springer Nature. https://doi.org/10.1007/978-981-19-2145-2_88