EXPERIMENTAL INVESTIGATION OF STONE MATRIX ASPHALT MIXTURES

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

GOUTHAM SARANG

DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA
SURATHKAL, MANGALORE -575 025
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DECLARATION

By the Ph.D Scholar

I hereby declare that the Research Thesis entitled **“Experimental Investigation of Stone Matrix Asphalt Mixtures”** which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy** in **Civil Engineering**, *is a bona fide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

(GOUTHAM SARANG)
Register No. 110645CV11F02
Department of Civil Engineering
NITK Surathkal

Place: NITK Surathkal
Date: 05-05-2015

CERTIFICATE

This is to certify that the Research Thesis entitled **"Experimental Investigation of Stone Matrix Asphalt Mixtures"** *submitted by* **Goutham Sarang** (Register Number: **110645 CV11F02**) as the record of research work carried out by her, is accepted as the Research Thesis submission in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy.**

Dr. A.U Ravi Shankar
Research Guide
(Signature with date and seal)

Dr. K. N. Lokesh
Chairman-DRPC
(Signature with date and seal)

DEDICATED TO MY WELLWISHERS...

ACKNOWLEDGEMENT

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ABSTRACT

Stone Matrix Asphalt (SMA) is gap graded bituminous mixture, having higher proportions of coarse aggregates and bituminous binder, yielding better rut resistance and durability than conventional dense graded mixes. The skeleton of coarse aggregates has stone on stone contact between them, which is a major requirement for this mixture. The gap graded aggregate structure and higher binder and filler content may lead to drain down in loose SMA at elevated temperatures, and it is controlled generally by using a suitable stabilizing additive in the mixture.

In the current study, SMA mixtures were prepared with two aggregate gradations having two nominal maximum aggregate sizes, 16mm and 13.2mm, and are named as SMA 1 and SMA 2. Viscosity Graded (VG) 30 bitumen, Crumb Rubber Modified Bitumen (CRMB) and Polymer Modified Bitumen (PMB) of two grades, 40 and 70, were used as binders, and three types of fibers, pelletized Cellulose Fiber (CF), Coconut Coir (CC) and Sisal Fiber (SF), and Shredded Waste Plastics (SWP) were used in mixtures with VG 30 bitumen to control drain down. Fiber content was limited as 0.3% by weight of mixture, based on drain down test results, whereas SWP content was selected 4, 8, 12 and 16 % by weight of bitumen. Drain down was within specified limits for all mixtures and decreased with increase in fiber and SWP content. The specimens were prepared as per Marshall mix design and were compacted in Superpave Gyratory Compactor (SGC). The performance of these mixtures were assessed in laboratory through Volumetric and Marshall properties, Indirect Tensile (IDT) strength, rutting and fatigue behaviour and moisture susceptibly characteristics. In general, mixes with PMB 40 and CF, showed better properties among mixes with modified binder and fiber additives respectively. In case SWP mixtures, 8 and 12% plastic content produced better mixtures. For all mixture types, SMA 1 gradation showed better results than SMA 2, except for moisture susceptibility, where both gradations performed almost same. Cost analysis of all prepared mixtures was carried out based on the standard rates, and cost for one cubic meter mixture was determined.

Keywords: Stone Matrix Asphalt, stone to stone contact, drain down, fiber additives, modified bitumen, Shredded Waste Plastic

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NOMENCLATURE

AASHTO	Association of State Highway and Transportation Officials
AR	Asphalt Rubber
ASTM	American Society for Testing and Materials
CC	Coconut Coir
CF	Cellulose Fiber
CPOH	Contractor’s Profit and Overhead
CR	Crumb Rubber
CRMB	Crumb Rubber Modified Bitumen
FL	Fatigue Life
G_b	Specific Gravity of Bitumen
G_{mb}	Bulk density of compacted specimen
G_{mm}	Maximum theoretical density of the mixture
G_{sb}	Bulk specific gravity of aggregates
G_{se}	Effective specific gravity of aggregates
HMA	Hot Mix Asphalt
HMP	Hot Mix Plant
IDT strength	Indirect Tensile strength
IRC	Indian Roads Congress
ITS	Indirect Tensile Strength
LAA	Los Angeles Abrasion
LVDT	Linear Variable Deflection Transducer
MoRT&H	Ministry of Road Transport and Highways
MQ	Marshall Quotient
MS	Marshall Stability
NMAS	Nominal Maximum Aggregate Size
OAC	Optimum Asphalt Contents
OBC	Optimum Bitumen Content
P_b	Bitumen content percentage by total weight of mixture
PET	Poly-Ethylene Terephthalate

PG	Performance Grade
PMA	Polymer Modified Asphalt
PMB	Polymer Modified Bitumen
P_{mm}	Percentage by weight of total loose mixture
P_s	Aggregate content, per cent by total weight of mixture
PWD	Public Works Department
RAP	Recycled Asphalt Pavement
RS	Retained Stability
SBS	Styrene Butadiene Styrene
SF	Sisal Fiber
SGC	Superpave Gyratory Compactor
SMA	Stone Matrix Asphalt
SOR	Schedule of Rates
SWP	Shredded Waste Plastics
TPH	Tonne per Hour
TSR	Tensile Strength Ratio
V_a	Air Voids in Total Mix
VCA	Voids in the Coarse Aggregates
VCA_{DRC}	Voids in the coarse aggregate in the dry rodded condition
VCA_{MIX}	VCA of the mixture
VFB	Voids Filled with Bitumen
VG	Viscosity Graded
VMA	Voids in Mineral Aggregates
W_a	Weight of specimen in air
W_{ssd}	Saturated Surface Dry (SSD) weight of specimen
W_w	Weight of specimen in water

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Transportation infrastructure is considered as one of the major backbones for the development of any country. Road transportation is generally the most effective and preferred mode of transport, for both freight and passenger movement, due to easy accessibility and adaptability to individual needs. In India, roads carry over 65% of total goods and 85% of total passenger traffic, and they play a vital role in the economic development and social integration, with a share of 4.8% in the Gross Domestic Product (based on in 2011-12 data) of the country. India has one of the largest road networks of over 46.99 lakh km length comprising 96,214 km National Highways and Expressways, 1.48 lakh km State Highways and 44.55 lakh km other roads (Major District Roads, Other District Roads and Village Roads). Even though National Highways constitute about 2% of the total road network, they carry about 40% of the total road traffic. The large-scale industrialization and commercial activities has resulted in an unprecedented traffic growth in India in the recent past and it was approximately 10% per annum during 2002 – 2012 period, substantiating the need of road development (Ministry of Road Transport and Highways (MoRT&H) 2015).

Most of the Indian roads are flexible types with sub base, base and surface course over the compacted subgrade layer. Conventional Hot Mix Asphalt (HMA) mixtures with dense aggregate gradation are generally used in the pavement surface course. Asphalt or bituminous mixtures are intended to render a resilient, relatively waterproof, load-distributing medium with considerable stability and durability. The high volume of vehicular traffic and increasingly heavy axle loads witnessed on Indian highways have brought the existing arterial road network to such a crippling stage that heavy investments are needed for restoring it to a desired serviceability level. Repeated application of traffic loads and climatic factors such as temperature variation and moisture can cause structural distress to asphalt pavements in the form of fatigue cracking, rutting along wheel tracks, ravelling and potholes. Hence, improving the performance and durability of pavements is considered as a serious concern by pavement engineers and this leads to the development of modified bituminous binders, stabilizing additives and new high performance bituminous mixtures.

1.2 STONE MATRIX ASPHALT

Stone Matrix Asphalt (SMA) is a bituminous mixture with gap graded aggregate structure, having mainly two components, a higher proportion of coarse aggregate, and rich binder mastics (bitumen and mineral filler). The aggregates are arranged in a way to create stone to stone contact between them, leading to a coarse aggregate skeleton. The load distribution in SMA is through this stone to stone contact as depicted in Figure 1.1 and this provides better rut resistance and strength to the mixture. The coarse aggregate skeleton contributes to the shear strength and effective loading distribution pattern of vehicles to endure heavier traffic loads compared to the dense graded mixtures. The rich binder mortar in SMA consists of bituminous binder, mineral filler and generally a stabilizing additive also, and provides durability to the mixture due to higher binder and filler content. The stabilizing additive is used to control drain down, which is a usual phenomenon in gap graded mixtures with higher bitumen and filler content like SMA, where a portion of bitumen and fines may be separated and flow down from the mixture during the elevated temperatures of production, transportation and placement (Brown 1992a, Brown and Manglorkar 1993, Rademaker 1996, Qiu and Lum 2006, Tashman and Pearson 2012).

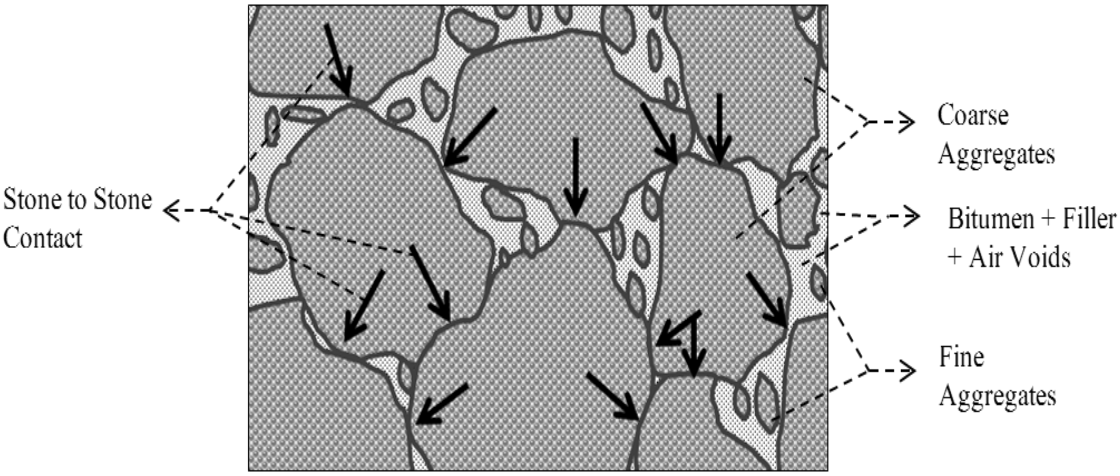


Fig. 1.1 Stone to Stone Contact between Coarse Aggregates

1.2.1 Brief History

SMA was developed in Germany during the 1960s by Zichner from the Central Laboratory for Road Construction at the Strabag Bau AG, as a mean to bring down the wear and damage caused due to the usage of studded tyres. One of the initial SMA blends proposed by Zichner in 1971 had approximately 70% coarse fraction along with 8% binder, 12% filler material and 10% crushed sand with a stabilizer additive (Blazejowski 2010). The acronym of SMA is derived from its German origin term ‘Splitt Mastix’, in which Splitt means crushed stone chips and Mastix means the thick asphalt cement and filler (Kennepohl and Davidson 1992). Even though the studded tyres were banned later, the use of SMA was continued in Europe, including the Scandinavian countries, Austria, Poland, etc., along with Germany, due to the mixture’s additional benefits of rut resistance and durability.

In 1990, Association of State Highway and Transportation Officials (AASHTO) led a European Asphalt Study Tour to exchange ideas and experience with the construction industry and highway agencies in Europe, on design methods, production and placement of bituminous mixtures and pavements. The group included 21 members from agencies including the Federal Highway Administration (FHWA), National Asphalt Pavement Association (NAPA), Strategic Highway Research Program (SHRP), The Asphalt Institute (AI) and Transportation Research Board (TRB) and visited six European nations, namely Sweden, Denmark, Germany, France, United

Kingdom and Italy considering the similarities they share with the United States of America (USA) (AASHTO Report). The success of SMA pavements in Europe, prompted them to adopt the technology to leading to the construction of SMA sections in the US during 1990s (Brown et al. 1997). Wisconsin started the first SMA project followed by Michigan, Georgia, Missouri, etc. and their early specifications were primarily influenced from the Germany and Sweden SMA specifications. The successful usage of this paving mixture was reported from Japan in 1990 (Brown and Manglorkar 1993). SMA mixture also acquired considerable attention in Canada and in this period, the Ministry of Transportation of Ontario constructed three trial sections (Kennepohl and Davidson 1992). Presently many countries, including Australia, China, Czech Republic, India, Ireland, Netherlands, New Zealand, Saudi Arabia, South Korea, Taiwan, etc. have developed specification for SMA and the mixture is considered as an ideal choice for heavy duty bituminous pavements (Blazejowski 2010).

1.2.2 Concept of SMA

The development of SMA was aimed to have a bituminous mixture, resistant to the wearing caused by the studs in the tyres and sufficiently durable to provide a long service life. Zichner was of the opinion that, coarse aggregates with good resistance to dynamic fragmentation or crushing can guarantee high wearing resistance, and those aggregates should be the major constituent material in the mixture, with a higher mastic content for durability. Therefore, SMA can be defined as a bituminous mixture with gap graded aggregate structure with high contents of coarse aggregate fractions, filler, binder and mostly a stabilizing additive.

The coarse aggregate skeleton is the main component in SMA, which is a structure of aggregates of suitable size that rest against each other and are mutually interlocked. In the mixture, based on the function, aggregates can be classified as those forming skeletons and carrying loads (called as active aggregates) and those filling in the voids in the skeleton without carrying loads (called as passive grains) (Blazejowski 2010). If some aggregates (assuming a spherical shape) are compacted in a cubical pot as shown in Figure 1.2 and loaded, it provides the maximum possible compressive strength, by virtue of the full and uninterrupted contact between the aggregates. When the similar feature is assumed for an aggregate skeleton in a pavement surface, the load is transferred by the coarse aggregates through their contact points (Figure 1.3).

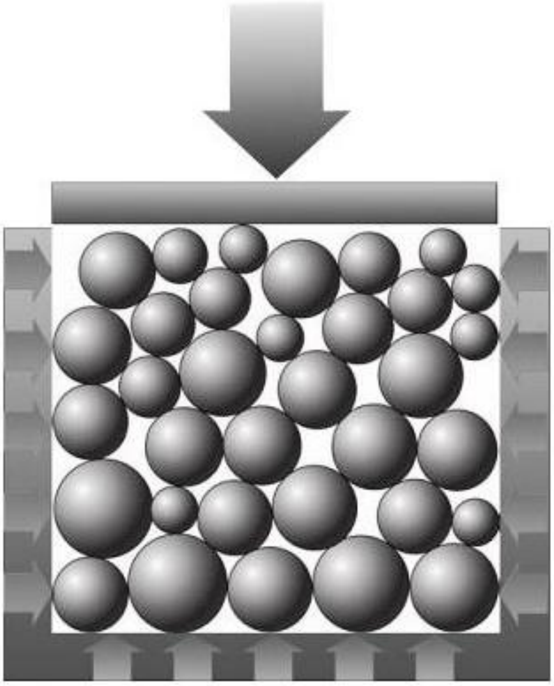


Fig. 1.2 Vertically Loaded Aggregates with Confinements at Sides

(Source: Blazejowski 2010)

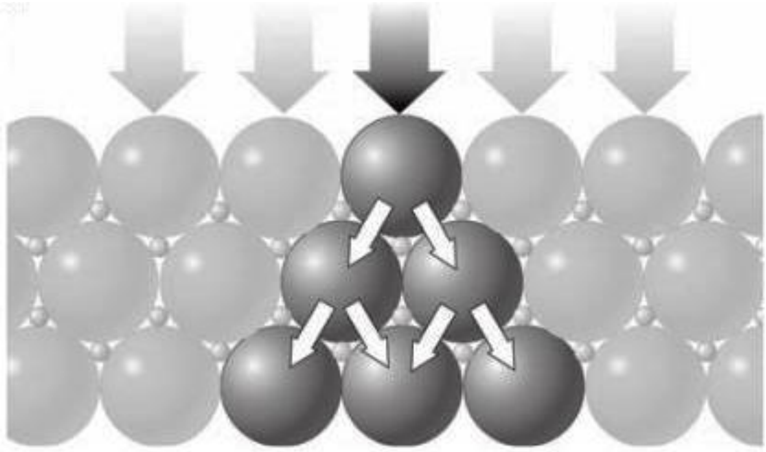


Fig. 1.3 Load Distribution in Aggregates through Contact Points

(Source: Blazejowski 2010)

The absence of this stone to stone contact between the coarse aggregates, makes the fine or passive aggregates doing the function, which weakens the pavement structure. The use of gap graded aggregate gradation is essential to ensure the sufficient quantity of active aggregates and to avoid the possibility of losing stone to stone contact. The compactive effort in SMA mixtures should be limited only until the direct contact occurs between active aggregates, because excess compaction may lead to the breakdown of aggregates.

1.2.3 SMA in India

In India, the first field trial section for the design and construction of SMA surfacing was constructed between Khajuri Chowk and Brij Puri Chowk on Road No. 59 in Delhi in October 2006 (Highway Research Record 2007). The test section was laid by Central Road Research Institute (CRRI), New Delhi, in one of the busiest corridors with mixed traffic conditions including heavy vehicles. These test sections were planned to monitor for their performance, at six months interval (pre monsoon and post monsoon) to find out the performance of SMA surfacing. The Indian Roads Congress (IRC) has issued a specification for SMA in 2008 (IRC SP 79 2008) based on the guidelines by Kandhal (2007) and the same has been adopted by the MoRT&H also and published in the latest revision of specification for road and bridge works (MoRT&H 2013). Even though some studies were conducted on SMA by some institutes in the recent past, the mixture was not exploited to its best in India.

1.3 OBJECTIVES AND SCOPE OF THE WORK

The current study is aimed to prepare Stone Matrix Asphalt mixtures of two aggregate gradations using different types of binders and stabilizing additives, with the following objectives.

- Determination of volumetric properties and Marshall characteristics at varying bitumen contents
- Assessment of Indirect Tensile strength and rutting resistance
- Evaluation of fatigue behaviour

- Assessment of moisture susceptibility characteristics
- Cost analysis of SMA mixtures

The scope of the present study includes the review of previous research works to identify various materials, aggregate gradation and methods that can be used in SMA mixtures. SMA mixtures were prepared by adopting two aggregate gradations and using different bituminous binders and stabilizing additives. Aggregate gradations with Nominal Maximum Aggregate Size (NMAS) 16mm and 13.2mm were adopted for the current study. A conventional bituminous binder, Viscosity Graded (VG) 30 bitumen, which is commonly used in India in bituminous mixtures, and two modified binders, Polymer Modified Bitumen (PMB) 40 grade and Crumb Rubber Modified Bitumen (CRMB) 60 grade, were used. Other than pelletized Cellulose Fiber, two natural fibers, Coconut Coir (CC) and Sisal Fiber (SF), were tried as a stabilizer material with VG 30 bitumen. Shredded Waste Plastics (SWP) in different percentages (4, 8, 12 and 16 % by weight of bitumen) were also incorporated in SMA by the dry process method. Cylindrical specimens with 100mm diameter were prepared in Superpave Gyratory Compactor (SGC) for most of the tests. The laboratory performance of SMA mixtures was evaluated by determining volumetric and Marshall properties, Indirect Tensile strength, rutting resistance, fatigue behaviour and moisture susceptibility characteristics. Cost analysis was also carried out and determined the rate for construction for each SMA mixture.

1.4 ORGANIZATION OF THESIS

The dissertation has been divided in to 7 chapters. **Chapter 1** introduces Stone Matrix Asphalt, including the principle of the mixture, its brief history and objectives and scope of the present research. **Chapter 2** provides a review of various literatures on SMA, which includes different materials used in SMA and observations made by researchers and practitioners. **Chapter 3** details about the materials used in the current study, aggregate gradation and the methodology adopted to prepare and test SMA mixtures. **Chapter 4** focuses on SMA mixtures prepared with conventional binder and fiber additives, including the laboratory tests and cost analysis. In **Chapter**

5, testing and cost analysis of SMA mixtures with different modified bituminous binders are provided. Laboratory observations and cost calculation of SMA mixtures with different proportions of Shredded Waste Plastics as additives are discussed in **Chapter 6**. **Chapter 7** discusses and concludes the present study on SMA with different bituminous binders and stabilizing additives.

CHAPTER 2

REVIEW OF LITERATURE

SMA is accepted as an alternative to conventional dense graded mixtures due to its durability and rutting resistance. Originally developed in Germany, the use of SMA has spread throughout Europe, the USA, and many other countries. Different countries involved in laboratory and field studies on SMA and developed technical specification and requirements for the same.

2.1 MIXTURE COMPONENTS

The mixture components used generally in SMA are aggregates and filler, binder material and stabilizing additive. Many researchers prepared SMA mixes by changing these varieties, by using different types of aggregates and gradation, different types mineral fillers in different proportions, different types of binders and by varying the quantity, different types of stabilizing additives and by varying the quantity. Brown (1992) 93-4 discussed the SMA sections constructed in five different states of USA. Different types of crushed aggregates were used, all having Los Angeles Abrasion (LAA) value 20 – 30 % and the binder used included AC-20, AC-30, penetration grade 85-100 and multigrade asphalt cement. Cellulose fiber at 0.3% by weight of mix and mineral fiber at 7 – 8 % by weight of binder were used as stabilizing additvies. Brown and Manglorkar (1993) used granite and local silicious gravel aggregates along with cellulose fibers and a mineral fiber. Brown and Mallick (1994) used granite and traprock as the aggregate material, and agricultural lime as the filler material in SMA. AC – 20 asphalt binder was used for all the mixes and Marshall method of compaction was adopted to prepare specimens. To determine the best suited SMA mix in Illinois (US), Rademaker (1995) investigated with three types of aggregates and three types of modifiers (polymerized asphalt, mineral fiber and cellulose fiber). SMA mixtures from eleven field test sections in Florida, US were duplicated by West (1995) in the laboratory by keeping the average of the field data for gradation, binder content and in-place density as the target. The experimental SMA mixtures were prepared using aggregates from six different sources. Brown and Cooley (1999) used different types of aggregates, mineral fillers, asphalt binders and stabilizing additives to prepare SMA mixes. Aggregates included traprock, granite (two different sources), limestone (two different sources), Florida limestone (or limerock), blast furnace slag, and siliceous gravel. Eleven different, mineral fillers that had been used in SMA for previous cases, were used for the project and they include limestone dust, marble dust, traprock dust, south-eastern fly ash, Georgia fly ash, aglime, diabase, wimpey, Dankalk, Oyta, and Faxekalk. Three different binder types were used: AC-20, AC-20M1 (Styrene Butadiene Styrene (SBS) modified) and AC-20M2 (polyo1efin modified). The three binder Performance Grades (PG) were 64-22 for the non-modified, 70-28 for the SBS modified, and 70-22 for the polyolefin modified. Three major stabilizing additive types were used during the laboratory study of this project: cellulose fibers, mineral fibers (slag wool and rock wool), and polymers (SBS and polyolefin). Mohammad et al. (1999) prepared SMA mixtures with limestone, sandstone and novaculite aggregates using different binders and observed the best rut resistance for mixtures with sandstone. Gatchalian (2005) used different aggregate types, including Uncrushed River Gravel, Crushed Limestone, Crushed Glacial Gravel, Crushed Traprock, Crushed Granite etc. with varying shape characteristics, in SMA by maintaining the same gradation. For all the mixtures, PG 64-22 asphalt, limestone filler, cellulose fiber stabilizing additive and 1% (by weight of aggregates) of hydrated lime were used. Celaya and Haddock (2006) used different gravel and dolomite aggregates available in Indiana, US and steel slag along with modified PG 76-22 binder and mineral fiber. The binder modification served as the stabilizing additive. West and Moore (2006) prepared SMA using aggregates from five different sources with varying LAA values with Boral Materials Type C Fly Ash mineral filler. PG 76-22 asphalt binder modified with SBS was used as the binder and 0.3% (by weight of mixture) cellulose fiber as the stabilizing additive. In another study, West and James (2006) used Lime Kiln Dust as mineral filler instead of common rock dust, and PG 67-22 asphalt binder. Prowell et al. (2009) tried Diabase, Columbus granite, Ruby granite, limestone and gravel aggregates along with PG 76-22 and PG 64-22 binders, and 0.3% cellulose fibers by total weight of mixture. Punith et al. (2012) evaluated polymerized SMA mixtures with hydrated lime content using moist aggregates and three different Warm Mix Asphalt (WMA) additives. The experimental design included two aggregate sources, two hydrated lime contents, three WMA additives and control mixture. Crumb Rubber (CR) passing 75μ sieve was used to prepare four types of modified binders (i.e., PG 64-22 + 10% CR, PG 64-22 + 15% CR, PG 64-22 + 20% CR and PG 76-22 + Fibers). Muniandy et al. (2009, 2012) checked the suitability of local industrial and by-products wastes such as steel slag, ceramic waste, coal fly ash, limestone, and rejected ceramic raw material as mineral fillers in SMA by comparing with a control mixture having limestone filler.

2.2 AGGREGATE CHARACTERISTICS

It is an undoubtful fact that, aggregate gradation has an important role in the performance of HMA's (Brown and Bassett 1989, Kim et al. 1992, Sridhar et al. 2007). Compared to other bituminous mixtures, aggregate gradation is more significant for SMA. The basic principle of SMA lies on the coarse aggregate skeleton, and it is very important to achieve the same with good quality aggregates for any SMA mixture. Coarse aggregates with LAA value less than 30% generally gives the mixture a better performance, whereas the usage of inferior quality aggregates may lead to aggregate break down during mixing and compaction, which could alter the mix gradation, potentially causing a loss of stone to stone contact between the coarse aggregate particles (Brown 1992b, Prowell et al. 2009). According to a common 30-20-10 thumb rule, the SMA mixture should have 30%, 20% and 10% materials passing through standard sieves 4.75mm, 2.36mm and 75μ respectively (Scherocman 1991).

In earlier researches, aggregate gradation changes were mainly accomplished by varying the Nominal Maximum Aggregate Sizes (NMAS) and the quantity of material passing 4.75mm and 75μ sieves. Brown (1992a) altered the percenatge passing 4.75mm and 75μ sieves by 26 – 46 % and 6.4 – 14.4 % respectively and Brown and

Manglorkar (1993) reduced this range to 24 – 39 % for 4.75mm and 7.4 – 11.6 % for 75μ sieves. Changes in material quantities passing these sieves, result in a significant change in Voids in Minaral Aggregate (VMA) and an increase in these quantities caused increased stability, but affected the Voids in Coarse Aggregate (VCA). The authors suggested that the per cent passing through 4.75mm sieve should be below 30% (and preferably below 25%). For mixtures evaluated by Brown and Mallick (1994), stone-on-stone contact in the coarse aggregate portion began to occur at around 30% passing the 4.75 mm sieve. The dry rodded test was observed to be an easy way to determine the VCA necessary for stone-on-stone contact. In creep test conducted on SMA, the strain and modulus values were found to be optimum for mixes with approximately 25% passing the 4.75 mm sieve. From the material and mixture properties data of 86 SMA projects in US, Brown et al. (1997b) observed that more than 80% of the mixtures were prepared with 25 – 35 % of the material passing the 4.75 mm sieve and 7 – 11 % of the material passing the 0.075 mm sieve.

Rademaker (1996) used two different types of mixture gradations (small and large) by varying the aggregate sizes used for blending. From different field trial sections it was observed that large SMA performed better and its construction cost was not significantly higher compared to fine SMA. Cooley and Brown (2003) also tried the concept of ‘fine’ SMA, prepared with 4.75mm or 9.5 mm NMAS using hard angular traprock aggregates and limestone dust mineral filler. Fine SMA’s performed equally or better than conventional SMA’s and the authors suggested their use for thin overlays. But Schmiedlin and Bischoff (2002) reported that the SMA with larger maximum size aggregate impeded crack development more than the mixture with smaller sized aggregate. Five aggregates with a range of LAA values, and three gradations with 19, 12.5 and 9.5 mm NMAS were selected by Xie (2006). Qiu and Lum (2006) adopted Bailey method to develop aggregate gradation for SMA and tried six gradations with varying design unit weights using crushed granite aggregates. Two aggregate gradations were suggested by IRC for SMA with NMAS 19mm (known as 19mm SMA) and 13mm (known as 13mm SMA), as listed in Table 2.1. 19mm SMA is recommended for binder (intermediate course) with thickness 45-75mm and 13mm SMA for surface course with a thickness of 40-50mm. Sivan and Mathew (2009) used fifteen different aggregate gradations, including IRC specified gradation, to prepare SMA mixes.

Table 2.1 Aggregate Gradation for SMA Suggested by IRC

IS Sieve (mm)	**Cumulative % by weight of total aggregate passing**	
	19mm SMA	**13mm SMA**
26.5	100	-
19	90-100	100
13.2	45-75	90-100
9.5	25-60	50-75
4.75	20-28	20-28
2.36	16-24	16-24
1.18	13-21	13-21
0.6	12-18	12-18
0.3	10-20	10-20
0.075	8-12	8-12

In bituminous mixtures, aggregates may be subjected to degradation or break down in laboratory and field during compaction works and it will be more in the case of SMA mixtures due to its gap graded aggregate structure. Brown and Cooley (1999) observed 5 – 10 % aggregate breakdown for even hard aggregates (for LAA ≤30%) and excessive breakdown made it difficult to meet the VMA requirements. Gatchalian (2005) used conventional methods and advanced imaging techniques to evaluate aggregate characteristics and their resistance to degradation in SMA mixtures. Resistance to abrasion of aggregates from different sources and types with various shape characteristics were measured using Micro-Deval test and their changes in characteristics were examined by aggregate imaging system. The resistance of aggregates to degradation in SMA was evaluated through the analysis of aggregate gradation before and after compaction using conventional mechanical sieve analysis and X-ray Computed Tomography (CT) methods. The author concluded that the aggregate degradation can be measured in terms of abrasion, breakage, and loss of texture. SMA using aggregates with higher resistance to abrasion and impact retarded cracks better than those having least abrasion and impact resistant aggregates (Schmiedlin and Bischoff 2002). Celaya and Haddock (2006) observed that a combination of the results from the LAA test, Micro-Deval abrasion test and SGC degradation test can be adopted to select suitable coarse aggregates for use in SMA mixtures.

Brown and Haddock (1997) suggested a method to determine stone to stone contact of coarse aggregate in SMA mixture. VCA of coarse aggregates only fraction of SMA was determined first and then compared with VCA of the entire mixture, and the former should always be greater than the latter. Five different methods to find VCA of coarse aggregate fraction were tried to find out the best and practical one. Aggregate breakdown was also checked in each case. The results indicated that the SGC and dry-rodded methods produced the best results. Brown and Cooley (1999) also tried different methods to determine when the stone-on-stone contact exists in a coarse aggregate fraction. Different methods were selected on five types of aggregates and it was observed that the dry-rodded test was the easiest of the methods to use and provided reasonable results. Qiu and Lum (2006) observed that the coarse aggregate stone to stone contact was developed when the VCA was in the range of 95 – 105 % of the rodded unit weight and those mixtures exhibited excellent rutting characteristics. Tashman and Pearson (2011) applied conventional laboratory tests and advanced imaging techniques to experimentally verify the VCA method in SMA. Five different coarse aggregate skeletons were examined to establish relationships between VCA ratio, microstructure parameters and the mechanical response of SMA. X-ray CT and image analysis techniques were adopted to non-destructively quantify the microstructure of SMA mixtures. The air void size distributions were quantified with the Weibull cumulative distribution function to describe the packing of the SMA mixtures and to verify the existence of a stone to stone contact between coarse aggregate. The dynamic modulus and static creep tests were carried out to estimate the mechanical response of the mixture. The results showed that the VCA method reasonably identified mixtures with a stone-on-stone coarse aggregate skeleton. The authors recommended that the VCA method should be modified to include a lower critical VCA ratio and mechanical testing should be incorporated to ensure optimal performance of SMA.

Some researchers have investigated the feasibility of replacing the scarce aggregates in SMA with other suitable materials. Adriana (2007) combined four types of Recycled Asphalt Pavement (RAP) at four levels (0%, 10%, 20% and 30%) with four aggregate sources. Xue et al. (2009) used Municipal Solid Waste Incinerator fly ash as a partial replacement of fine aggregate or mineral filler, and Basic Oxygen Furnace slag as a part of coarse aggregates, along with limestone aggregates to obtain 13mm SMA gradation. Behnood and Ameri (2012) prepared SMA mixture with two types of steel slag obtained from various steel industries in Iran as coarse and fine aggregates, and compared with a control mixture with limestone aggregates. In substitution of the natural aggregates, Pasetto and Baldo (2012) tried two types of Electric Arc Furnace steel slags, along with natural sand and limestone aggregates to prepare SMA mixtures.

2.3 BITUMINOUS BINDERS

Generally harder grades of bituminous binders at a comparatively higher proportion perform well in SMA. Usage of AC-20, AC-30, 85-100 pen, and Multigrade asphalt binders at 5.9 – 7.0 % (by weight of mix) was reported during the beginning of 1990s in the USA (Brown 1992b, Brown et al. 1997b, West 1995).

Certain commercial polymers were also used with bitumen in some cases. When stabilizing additives (fibers in most of the cases) were used in SMA mixture with conventional binders, usage of polymerized bituminous binders eliminated the necessity of stabilizers. Generally agencies specify a minimum binder content for SMA, but Brown et al. (1997a) were of the opinion that, the minimum binder content requirement is not needed if the mixture achieves the minimum VMA. Brown and Cooley (1999) used a conventional bitumen, an SBS modified bitumen and a polyolefin modified bitumen and suggested PG binders for SMA, as specified by Superpave binder grading system, based on the climate in which it is used. Texas DoT recommends a harder PG binder (PG 76-22) in SMA and some researchers have tried the same and even higher graded binders (Tashman and Pearson 2011, Guercio et al. 2014). Comparatively softer PG binders like PG 67-22 (Cooley and Hurley 2004, Muniandy and Huat 2006) and PG 64-22 (Gatchalian 2005, West and James 2006) were also reported to be successful in SMA. Prowell et al. (2009) used both PG 76-22 and 64-22 with different aggregate types to prepare SMA mixtures for airfield pavements. In many countries, the usage of Suerpave and PG binder system are limited and they widely adopt the penetration graded bituminous binders for paving mixtures including SMA. Bitumens with penetration values varying from 50 to 70, known as 60/70 bitumen, were reported in various studies on SMA, with suitable stabilizing additives (Asi 2006, Behnood and Ameri 2012, Nejad et al. 2010, Fakhri et al. 2012, İskender 2013). Even the softer binder 80/100 was tried by some researchers including Suchismita et al. (2010), Muniandy and Aburkaba, (2012), Muniandy et al. (2014), etc. SMA mixes were prepared by AI-Hadidy and Tan (2011) using penetration grade 20–30, 40–50 and 70–100 binders.

2.3.1 Modified Bitumen

Generally at low temperature, bituminous binders are very hard and brittle, whereas it become very soft and deformable when the temperature is high, and hence the issues of both low temperature cracking and excessive deformation (during increased temperature) should be addressed simultaneously (Jew et al. 1986). Properties of bitumen and bituminous mixes can be improved by incorporating certain additives or a blend of additives. Bitumen treated with these additives or modifiers is known as "Modified Bitumen" and is expected to provide higher life mixtures depending upon the degree of modifications and type of additives used. Tia et al. (1994) reported that Haas et al. (1983) defines these modifiers as: "An asphalt cement additive is a material which would normally be added to and/or mixed with the asphalt before mix production, or during mix production, to improve the properties and/or performance of the resulting binder and/or the mix, or where an aged binder is involved, as in recycling, to improve or restore the original properties of the aged binder."

Based on Thompson and Hoiberg (1979), Yildirim (2007) reported that the processes of modifying bituminous binders with natural and synthetic polymers were patented from 1843. Alexander (1968) reported the usage different types of modifiers by many researchers and practitioners since 1940s to improve the performance of bituminous binders (Clinebell and Stranka 1951). The possible advantages of binders and pavements with commonly used modifiers like rubber and polymer include increase in softening point, viscosity, ductility, fracture toughness, elastic modulus, flexural strength, creep resistance, reduction in embrittlement by aging, rut susceptibility and low temperature cracking, enhanced Marshall stability, resilient modulus, tensile strength and traction, and overall improvement in performance both in the laboratory and field (Alexander 1968, Shim-Ton et al. 1980, Denning and Carswell 1981, Kortschot and Woodhams 1984, Jew et al. 1986, Carpenter and VanDam 1987, Lee and Demirel 1987, Shuler at al. 1987, Nahas et al. 1990, Choquet and Ista 1992, Dhalaan et al. 1992, , Tia et al. 1994, Zaman et al. 1995, Hossain et al. 1999, Palit et al. 2004, Hamzah et al. 2006).

Bituminous binders subjected to suitable modification can prevent drain down in SMA mixtures without any stabilizer, in addition to enhancing the mixture performance. Polymer Modified Bitumens (PMB) are considered to provide additional resistance to bleeding, taking out some of the risk associated with high binder contents (Stuart et al. 2001, Shukla and Jain 1989) and this prompted researchers to use different types of PMB in SMA. The most commonly used PMB type in SMA is with an elastomeric polymer SBS (Allen 2006, Pasetto and Baldo 2012, Cao et al. 2013). Brown and Cooley (1999) reported that SMA incorporating SBS PMB produced mixes that were more rut resistant than SMA with unmodified binder. Researchers used SBS and other polymer based PG binders including PG 70-28, 76-28 and 76-22 in SMA mixtures (Xie et al. 2005, Celaya and Haddock 2006, Croteau and Hanasoge 2006, Vargas-Nordcbeck 2007 and Ishai et al. 2011) and in most of the cases, no other stabilizing additives were required. Lin et al. (2004) used four types of commercially available Polymer Modified Asphalt (PMA) in SMA. The base binder was AC 20 and it was modified with two types of SBS polymers (linear and radial) in two proportions (3 and 6 %). The authors used an approach of modified toughness for the evaluation and observed that PMA provided better modified toughness, which indicates higher stiffness of SMA mixtures. Tayfur et al. (2007) observed least permanent deformation for SMA mix with SBS polymer, compared to mixtures with other polymer and fiber additives. Ghasemi and Marandi (2011) added different combinations of SBS polymer and recycled glass powder with penetration grade 60/70 bitumen and evaluated their advantages in SMA mixtures through Marshall stability, indirect tensile strength and resilient modulus tests. The additives improved the performance and also provided better mechanical and physical characteristic of both binder and mixture. Hao et al. (2011) observed that the addition of SBS and Trinidad Lake Asphalt in SMA mixture satisfied the requirement, but a combination of both additives showed better performance. In an investigation, Al-Hadidy and Tan (2009) and Al-Hadidy and Yi-qiu (2010) compared SMA mixtures having SBS PMB and starch with control mixture. The SBS modified binder resulted in mixes having lesser drain down and increase in stability, Marshall Quotient, rut resistance and resilient modulus, in comparison with the other mixtures. Similar observations for SMA with SBS PMB were made by Mokhtari and Nejad (2013) also, compared to control mix and mix with Fischer–Tropsch wax added bitumen. Ramzanpour and Mokhtari (2011) observed that the effect of Rheofalt (added in three dosages 5, 10 and 15%) in SMA with AC – 60/70 asphalt was more than that of SBS (5% by weight of binder) in terms of moisture resistance, whereas SBS was more capable in improving the Marshall and rutting properties. An evaluation of control and SBS SMA mixtures through Marshall Quotient approach, repeated creep test, indirect tensile strength test and Wheel tracking tests showed the higher performance for polymer added mixtures (Sengul et al. 2013). SBS content of 6.5% was used in PMB by Khodaii et al. (2013) and Haghshenas et al. (2015).

Researchers have also tried to use rubber modified bitumen in SMA with an aim to avoid stabilizing fibers and to improve the mix properties (Jain et al. 2004). Generally the required rubber is collected from used tyres and they were observed to be performing better than conventional SMAs (Sharma and Goyal 2006). The natural rubber improves the rutting resistance and ductility, whereas the processed tyre rubber reduces reflective cracking and rutting in SMA mixtures (Ahmadinia et al. 2012).

Tyre processing includes punching, splitting, chopping, grinding, and cutting tyres into shredded or “crumb” rubber, as well as chemically altering tyres. Mechanical sizing, including chopping and grinding, is generally used to prepare Crumb Rubber (CR) by reducing the size of the tyres. Additional grinding and screening operations are carried out to obtain the desirable size range. The rubber modified binder prepared by wet process (by dissolving crumb rubber in the bitumen as binder modifier) is commonly named as “Asphalt Rubber” (AR) (Epps 1994, Hossain et al. 1995, Chesner et al. 1997). Kamaraj et al. (2004) used natural rubber powder in SMA and it controlled drain down and provided resistance to deformation. Similar performance was obtained by Kumar et al. (2007) for SMA mixtures with Crumb Rubber Modifed Bitumen (CRMB) compared to mixes with natural and patented fibers. Chiu and Lu (2007) modified conventional bituminous binder using coarse and fine ground tyre rubber after grinding, in different proportions for preparing SMA mixture. It was observed that, only fine rubber could produce a suitable mixture satisfying all volumetric requirements, and it showed better moisture and rutting resistance than the conventional SMA with mineral fiber as stabilizing additive. Dong and Tan (2011) reported that the pavement performance of AR SMA is very excellent, compared to the other two SMA’s frequently used in Beijing region. Punith et al. (2012) also observed that PG 64-22 bitumen modified with CR helps the SMA mixtures to meet the drain down requirements. Oda et al. (2012) observed improved fatigue behaviour for SMA mixtures with AR compared to fiber added mixes. Peralta et al. (2012) tried to characterize the interactions between bitumen and rubber in the production of AR and a good correlation between the rheological properties of the materials and the physical changes during the process was observed.

2.4 STABILIZING ADDITIVE

Stabilizer materials are generally incorporated in SMA mixtures in order to control the mastic drain down, and they may also improve the mixture performance. Suitable fibers are commonly used for this purpose from olden days, and AASHTO (1990) reported the wide use of cellulose and rock wool mineral fibers, and less often certain polymers, to control drain down of SMA mixtures in Europe. Researchers have reported the usage of (0.2 – 0.5 %) of different cellulose and mineral fibers and polymers in various trials conducted in the US (Brown 1992b, Brown and Manglorkar 1993, Rademeker 1996, Brown et al. 1997b). Brown and Mallick (1994) has observed that the type and amount of stabilizer significantly affects the drain down of SMA mixtures. The mixtures with no additive and 0.3% (by weight of binder) polymer (Vestoplast) resulted in the maximum drain down, whereas for SMA with 8% polymer and with 0.1% (by weight of binder) of mineral and European cellulose fibers produced intermediate drain down. The minimum drain down was obtained for fiber additives at 0.3% dosage. West (1995) conducted drain down test with different stabilizers including, 0.3% (by weight of total mixture) of cellulose, nylon, polyester, polypropylene fibers, 0.4% slag wool fiber, 12% (by weight of binder) ground tyre rubber, 5% (by weight of binder) Novophalt and 7% (by weight of binder) Vestoplast. Only cellulose fibers, Novophalt, polyester fibers and tyre rubber added mixtures showed drain down less than 0.3% at the highest binder content tested (6.5%). Tests conducted on mixtures with these additives at a constant binder content of 6% showed that, Novophalt, tyre rubber and Vestoplast performed a good job in increasing the tensile strength and decreasing the failure strain. When mixtures were prepared at varying binder contents to create 6 – 7 % air voids, highest tensile strength was observed for SMA mixes with tyre rubber and Novophalt. Brown and Cooley (1999) used different stabilizing additives viz. cellulose fibers, mineral fibers (slag wool and rock wool), and polymers (SBS and polyolefin), and observed that the stabilizer type has significant effect in the low, intermediate and high temperature performance of SMA fine mortar. Along with cellulose and mineral fiber stabilizers, Schmiedlin and Bischoff (2002) used thermoplastic and elastomeric polymer stabilizers at low and high contents in SMA test sections. The authors reported that the mix temperature should be properly maintained, especially in the case of mixtures with polymers. Behbahani et al. (2009) evaluated the performance of SMA mixtures with two types (Germany and Iran) of cellulose fibers and mineral fiber added at proportions 0.1, 0.2, 0.3, 0.4 and 0.5 % by weight of mixture.

2.4.1 Fibers in Bituminous Mixtures

Bituminous mixture is strong in compression, but weak in tension, as in the case of cement concrete. According to McDaniel (2015), incorporation of suitable fibers having good tensile properties results in the increase of the tensile strength of a mixture. This is accomplished by the transfer of stresses to the strong fibers, reducing the stresses on the relatively weak asphalt mix. Fibers were used in pavements as a reinforcement and crack retarding material from olden days. Researchers reported the treatment of fiber in the early years in the US including the usage of asbestos fiber in the 1920s and cotton fibers during 1930s (Maurer and Malasheskie 1989, Serfass and Samanos 1996, Al-Qadi et al. 2008, McDaniel 2015).

Based on the availability and suitability, different types of fibers including asbestos, metallic wire etc. were used in bituminous mixtures (Kietzman 1960, Tons and Krokosky 1960). Maurer and Malasheskie (1989) used different fabrics and polyester fiber in pavements and observed that the fiber-reinforced bituminous concrete performed well and the method of random inclusion of fibers was cost effective, easy to apply and not causing any delay in construction compared to the other methods adopted in that study. Polyester and Polypropylene fibers were observed to be increasing the fracture energy by 50 – 100 % when incorporated in bituminous mixtures (Jenq et al. 1993) and similar improvement was observed with nylon fibers also by Lee et al. (2005). Huang and White (1996) concluded that bituminous overlays modified with polypropylene fiber were stiffer and having increased fatigue life compared to conventional overlays. Polypropylene and aramid fibers improved the performance of bituminous mixture by controlling major pavement distresses like permanent deformation, fatigue cracking, and thermal cracking (Kaloush et al. 2010). Glass fibers were also used successfully in asphalt concrete in combination with Polypropylene fibers (Abtahi et al. 2013). Jahromi and Khodaii (2008) obtained improvement in mechanical properties like fatigue characteristics, deformation etc. with the usage of carbon fibers in bituminous mixture. Tapkin (2008) observed that polypropylene fibers stabilized bituminous mixtures possessed increased Marshall and fatigue properties. Xu et al. (2010) studied the reinforcing effects and mechanisms of polyester, polyacrylonitrile, lignin and asbestos fibers in asphalt concrete mixtures under temperature and water effects, and observed that fibers resulted in significant improvement in mixture's rutting resistance, fatigue life, and toughness.

Compared to dense graded mixtures fibers are generally recommended in SMA as a drainage inhibitor, and most commonly cellulose and mineral fibers were used for this purpose (Lin et al. 2004, Chiu and Lu 2007, Ramzanpour and Mokhtari 2011). Researchers have also tried using some other types of fibers, other than conventional ones, in SMA mixtures. Putman and Amirkhanian (2004) found that waste fibers, produced from manufacturing processes such as scrap tyre processing and automotive carpet manufacturing, are successful in SMA, by comparing their performance with conventional cellulose and other polyester fibers, which are specifically produced for use in HMA. SMA mixtures containing waste fibers showed similar resistance to permanent deformation and moisture susceptibility as that of conventional mixtures and improved toughness. Muniandy and Huat (2006) used cellulose oil palm fiber, extracted from empty fruit branch of the oil palm, in different proportions (0.2%, 0.4%, 0.6%, 0.8% and 1.0% by weight of aggregates) as a stabilizer in SMA. The fatigue life, tensile stress and stiffness showed improvement with fiber addition, and the better results were obtained at the fiber content of 0.6%. When the fiber was pre-blended in PG 64-22 binder, its properties improved to PG 70-22 grade. Naturally occurring jute fibers coated with low viscosity binder was used by Kumar et al. (2004, 2007), instead of costly imported fibers with paving grade bitumen 60/70. The drain down, moisture susceptibility, rutting and fatigue characteristics showed that, the costly fibers can be replaced with treated jute fibers. Xue et al. (2009) used polyester fiber extracted from recycled raw materials with 6.35mm length, whereas Mahrez and Karim (2010) tried glass fiber in SMA with 80/100 penetration grade bitumen. Stiffness properties and resistance to permanent deformation increased for mixes having glass fiber content within 0.2%. It was observed to be capable of resisting the structural distress in pavements due to increased traffic loading and improving the fatigue life. Improved resilient properties of SMA mixtures having 60/70 and 80/100 penetration grade binders with 0.3% coconut fiber stabilizer was reported by Suchismita et al. (2010). Out of three natural fibers (coconut, oil palm fibers and jute fibers), two waste fibers (fibers extracted from refrigerator door panels (FERP), and old machinery belts (FEMB)) and an artificial fiber (glass fiber) used in SMA, Raghuram and Chowdary (2013) observed better drain down and performance characteristics for the jute fiber and FERP. SMA with natural fibers showed more rutting resistance than the mixtures with waste and artificial fibers.

2.5 WASTE PLASTICS IN BITUMINOUS MIXTURES

The proper disposal of waste is one of the major problems causing environmental degradation all around the world, and the issue is more critical for non-biodegradable waste like plastics. It is a source of continuing pollution and poisons the environment for decades. During 2013-14, the total consumption of plastic in India was 11 million tonnes and it is reported that the quantity of plastic waste generated in the country is more than 15,000 tonnes per day. About 60% of the total plastic waste is only collected and recycled and the rest remains uncollected and littered (Javadekar 2015 a and b). Environmental hazards due to waste plastics can be addressed to a large extent by using them effectively in road construction and it is a widely accepted, eco-friendly method of waste disposal.

The incorporation of different types of virgin or recycled polymers improves the performance of bituminous mixtures, and this can be accomplished either by wet process or by dry process. In wet process, polymers can be directly added and mixed with hot bitumen, whereas they are first mixed with hot aggregates in dry process, and then bitumen is added. As reported by Little (1993), Felsinger Group from Austria conducted a study in 1989 and concluded that recycled low density polyethylene can be added as a modifier to prepare bituminous binder with equal performance of binder produced by virgin polymer. Liang et al. (1993) observed that recycled polythene did not show much reduction in the quality of modified bitumen, but significant material cost saving was possible, when compared to the addition of virgin polymer. Addition of recycled or waste Low Density Poly-Ethylene (LDPE), High Density Poly-Ethylene (HDPE), plastics and Poly Vinyl Chloride (PVC) with bitumen improves the stability, tensile strength, stiffness, void characteristics, Marshall quotient and moisture resistance of bituminous mixtures (Panda and Mazumdar 2002, Hınıslıoglu and Agˇar 2004, Bose et al. 2005, Rahman et al. 2013). Bituminous binder modified with shredded waste polythene caused increase in storage stability, resistance to aging, viscosity, degradation, and temperature susceptibility, compared to the unmodified binder and this modified binder was observed to be improving the performance of bituminous mixture based on the results from dynamic creep test, indirect tensile test, resilient modulus test, and Hamburg wheel track test (Punith and Veeraragavan 2007, 2010a, 2010b). Even though many research works have been carried out using wet process, comparatively limited studies are reported with the method of dry process for incorporation of waste polymer in bituminous mixtures. Zoorob and Suparma (2000) used recycled plastic pellets with 5 – 2.36 mm size in dense graded bituminous mixture as a replacement to same size aggregates. The mixture was named as ‘plastiphalt’ and was observed to having increased strength and improved deformation capacity. Hassani et al. (2005) replaced different percentages of 4.75 – 2.36 mm aggregates with Poly-Ethylene Terephthalate (PET) granules in asphalt concrete and determined the volumetric and Marshall properties. Some researchers have observed that coating shredded plastic over the hot aggregate provides the mixture better strength and performance than blending it with bitumen, and also it helps in the usage of higher quantity of polymers (Vasudevan et al. 2006, 20010, Ravi Shankar et al. 2013). Awwad and Shbeeb (2007) have observed that the polymer coating over aggregates provides a rougher surface structure and better adhesion between aggregates and bitumen, and this improves the engineering properties of the mixture. Addition of waste plastics and waste polymeric packaging material by dry process was reported to be improving the impact value, abrasion value and water absorption of aggregates (Sabina et al. 2009), along with increasing the stability, tensile strength, moisture susceptibility, rut resistance thereby improving the pavement performance (Jain et al. 2011). A study conducted by Aslam and Rahman (2009) showed that most of the commonly used polymers do not cause any evolution of gas around 130 to 140 °C and at this temperature, plastic will be in the molten form having well binding property. IRC also suggests the usage of waste plastics shredded into size between 2.36mm and 600µ, by the dry process method (IRC SP 98 2013).

Limited studies were reported with the addition of waste polymers in SMA mixtures also. Little (1993) conducted experiments on two types of SMA mixtures with recycled LDPE additives and they were observed to be performing better than mixes without polymer. Casey et al. (2008) modified bituminous binder by adding some commonly available recycled polymers in different proportions, to use in SMA mixes, and the binder and mixture performances were assessed. Punith et al. (2010) incorporated reclaimed polyethylene obtained from carry bags in SMA by blending with penetration grade 60/70 bitumen (5% by weight of bitumen) and also by shredding and mixing with aggregates (0.3% by weight of mixture). Both methods controlled the mixture drain down and performed better than conventional SMA with cellulose fiber additive. Incorporation of waste plastic bottles (PET) at various percentages (2, 4, 6, 8 and 10 % by weight of bitumen) in aggregates-bitumen blend was effective in retarding the drain down and improved mixture's Marshall characteristics, stiffness and resistance against permanent deformation (Ahmadinia et al. 2011, 2012). Similar observation was made by Moghaddam and Karim (2012) and Moghaddam et al. (2014) with the addition of waste PET flakes (at dosages 0.2, 0.4, 0.6, 0.8 and 1 % by weight of aggregates), obtained from PET bottles, in SMA using dry process method.

2.6 DRAIN DOWN IN SMA MIXTURES

Drain down is one of the major problems associated with SMA, but the usage of proper stabilizing additive can prevent it to a certain extent. Different types of cellulose and mineral fibers are reported as the common stabilizers in SMA from earlier days and a few researchers tried polymers to control drain down.

Brown and Mallick (1994) used two types of fibers (European cellulose and mineral fiber) and one type of polymer (vestoplast) to evaluate the drain down potential of SMA mixtures with two types of aggregates (gravel and limestone) and mineral fillers (baghouse fines and marble). The mixtures were prepared at different gradations having three different fine contents (50, 30 and 20 % passing 4.75mm sieve) and tested in a wire mesh basket with 1/4 inch by 1/4 inch openings. It was observed that, drain down is significantly affected by the type of filler, per cent passing the 4.75mm sieve (higher per cent passing-lower drain down), binder content (higher binder content-higher drain down), type of stabilizer, and amount of stabilizer (higher stabilizer content-lower drain down). The authors suggest the test to be conducted for a duration of one hour and at the mixture temperature anticipated in the field. Out of different types of stabilizers tried by West (1995) cellulose fiber was observed to be the most efficient one, followed by LDPE, polyester fibers and Ground Tyre Rubber. Brown et al. (1997b), Brown and Cooley (1999) and Mohammad et al. (1999) observed that the fibers performed better than polymers in reducing drain down.

2.7 PERFORMANCE CHARACTERISTICS

Researchers have tried to assess the laboratory and field performance of SMA mixtures and pavements using different methods, mainly which are commonly used for dense graded mixtures. Generally SMA mixtures are designed based on volumetric properties including the air voids, VMA, etc. and by considering the minimum bitumen content requirement (Stuart 1992). The bitumen content required to produce 3 – 5 % air voids with 50 blows of Marshall compactive effort (on either side of the specimen) was considered. Even though SMA should produce lesser air voids compared to dense graded mixtures, Brown (1992b) recommended a minimum of 3% to prevent the potential of rutting problems, and this should be near to 4% in hotter climates.

Brown and Manglorkar (1993) determined Marshall stability and flow, gyratory properties, resilient modulus (at different temperatures), static and dynamic confined creep and indirect tensile strength of SMA, to assess the potential of these properties to predict the mixture performance. Authors observed that conventional Marshall stability tests were not suitable for determining the performance of SMA mixtures. Hence evaluation of SMA should be done by measuring their resistance to permanent deformation (rutting), fatigue behaviour, moisture susceptibility characteristics etc. Brown and Mallick (1994) conducted dynamic creep tests to predict the optimum gradation for SMA using two aggregate types. Partl et al. (1995) used long-term oven aging, low temperature cracking, resilient modulus, rutting, and moisture sensitivity to evaluate SMA mixtures from filed and laboratory.

From West's (1995) studies, the rutting resistance of SMA mixtures did not appear to be sensitive to low air void contents. The most important aggregate characteristic related to rutting resistance was Dry VMA (DVMA) from the Gyratory Testing Machine (GTM) aggregate degradation test. Greater rutting resistance is produced with aggregate blends that have low DVMA (high aggregate densities). Other characteristics were identified to have an effect on rutting included LAA, particle index, aggregate shear strength, and the change in per cent passing the major aggregate size. The commonly used wet-dry indirect tensile strength ratio was satisfactory for evaluating moisture damage potential of SMA mixtures. Moisture damage potential was increased for mixtures containing aggregates prone to degradation as indicated by the LAA test or the GTM aggregate degradation test. SMA mixtures were more permeable than Superpave mixes with similar void contents and similar nominal maximum size aggregates and the permeability was very sensitive to the air void content. It increased rapidly at approximately at 6 to 6.5 per cent air voids, and hence the mixture should be constructed to a lesser air void content (Brown and Cooley 1999). Wheel tracking test indicated better performance of SMA mixtures and generally finer mixes showed higher VMA and asphalt contents along with increased rutting. Analysis of data on material and mixture properties from 86 SMA projects in US and performance evaluation done by Brown et al. (1997b) on the basis of several factors including rutting, cracking, ravelling and fat spots showed that: a) Approximately 30% of the mixtures had less than 3% air voids during construction and 60% of the mixtures exceeded 6% asphalt content, b) Over 90% of the projects had rutting measurements less than 4 mm, whereas 25% of the projects had no measurable rutting, c) Raveling was not observed, but fat spots, caused by segregation, drain down, high asphalt content, or improper type or amount of stabilizer, appeared to be the biggest performance problem.

Dynamic creep test results conducted on SMA mixtures with cellulose and mineral fibers showed that variation of fiber type and content can lead to considerable changes in the rutting performance (Behbahani et al. 2009). Nejad et al. (2010) carried out indirect tensile tests on SMA mixtures comprising different NMAS in three different temperatures. Stiffness modulus, fatigue lives and fatigue prediction equation of the mixtures were developed and characterized in terms of aggregate gradation type, coarseness and fineness of gradation, temperature and asphalt content. Stiffness modulus and fatigue life decreased with the increase in temperature and the effects of coarseness and fineness of aggregate gradation were significantly higher than the effects of asphalt content on fatigue life.

2.8 COMPARISON WITH DENSE GRADED MIXES

Based on the laboratory and field performance and previous experiences, researchers compared SMA mixtures with conventionally using dense graded bituminous mixes. Even though SMA was having lesser stability values than dense graded mixes, it cannot be considered as an indication of SMA’s weaker performance (Brown and Manglorkar 1993). SMA mixtures appeared to be more resistant to cracking than dense mixtures (Brown et al. 1997a). From the study of Schmiedlin and Bischoff (2002), the SMA was noted to be better performers than the standard Asphalt Concrete pavements, considering all types of distress over the five-year study period. SMA showed 30% to 40% lesser crackings compared to the standard pavements.

Smith et al. (2006) conducted a thorough evaluation of SMA and conventional HMA mixture performance on Wisconsin highways with different traffic conditions, collection and review of unit costs, and full-scale life cycle costing to determine the cost-effectiveness of SMA pavements. For all scenarios, authors recommended SMA over the other, based on the findings. In a study, Asi (2006) fabricated specimens for normally used dense graded mixtures and SMA mixtures at their Optimum Bitumen Contents (OBC) (5.3% for dense graded mixtures and 6.9% for SMA mixtures). Test results showed that although the dense graded mixtures had higher compressive and tensile strengths, SMA mixtures showed higher durability and resilience properties and proved its superiority in rutting resistance in the field study. Therefore, these properties, (durability, resilience and rutting resistance) give SMA mixtures advantages over dense graded mixtures, especially in hot weather climates. Prowell et al. (2009) concluded that, SMA offers equal rutting performance and improved resistance to cracking, moisture damage etc. when compared to conventional dense graded mixes.

In a long term field study, Zeng and Gan (2009) observed certain reflective transverse cracks on some sections of Lin-Chang Expressway in China, and the cracks were much less in SMA section compared to the section with a conventional dense graded mixture. The split test in different aging degree also showed that SMA had better long-term performance of anti-reflective crack than the other one. SMA is generally costlier than dense graded mixtures because of the higher coarse aggregate and binder content and also due to the need of a stabilizer material. But from the studies it was observed that the increased cost of SMA is justifiable on a life-cycle basis (Brown et al. 1997a, Rademaker 1995).

2.9 COMPACTION METHODS

Compaction of hot bituminous mixtures in field has a significant role in the performance and durability of that pavement. It can be defined as a stage of construction, which transforms the mix from its very loose state into a more coherent mass, thereby permitting it to carry traffic loads (Francken 1998). The goal of any bituminous mix design is to combine aggregates and bitumen in an optimum proportion to form a mixture which could deliver a desired level of performance. It is very important to adopt a suitable method to prepare a realistic test specimen in the laboratory which represents the structure of the mixture when laid in the field (Khan 1998). In India, Marshall mix design is the most commonly adopted bituminous mixture design procedure, in which mixes are prepared using impact compaction. In this method, 75 Marshall blows are provided on either sides of the specimen for preparing conventional dense graded mixtures. Whereas in the case of gap graded mixtures, it is reduced to 50 blows, because of its aggregate structure which leads to severe break down of aggregates at higher compaction levels.

2.9.1 Superpave Gyratory Compactor

In flexible pavements, field density is obtained due to the primary compaction during construction period and secondary compaction caused by the running traffic. From past experience it is observed that, field density of most of the bituminous pavements are remarkably higher than the laboratory design density due to rapidly increasing traffic loads with higher tyre pressures. Increasing the compactive effort in Marshall method leads to break down of aggregates, which is one of the main drawback associated with it. This aggregate degradation is experienced in a severe manner for mixtures like SMA with gap graded structure, which causes changes in the original gradation and in the volumetric properties (Collins et al. 1997). Compared to fine aggregates, coarse aggregates are adversely affected by break down, and when the original gradation becomes finer, the dust material passing 75µ sieve may increase above the critical limits. These issues made the highway engineers and researchers to develop new mix design approaches. The concept of developing a bituminous mix design method in laboratory, which yields approximately the same density expected in the field, without causing severe aggregate breakdown, led to the development of Gyratory Compactors. Various agencies like Texas Highway Department, US Army Corps of Engineers, etc. developed different types of gyratory compactors and Superpave Gyratory Compactor (SGC) was one among them (Philippi 1957, McRae et al. 1958).

The SGC compacts the laboratory specimen with gyratory action rather than impact compaction as is done with Marshall hammer, and also simulates field compaction with rollers in terms of aggregate particle orientation. In this, a mix is subjected to two kinds of stresses during compaction: one is the constant vertical stress and the other is a shearing stress (Sadasivam 2004). Button et al. (1994) fabricated bituminous samples in different compaction devices in laboratory and they were compared with samples extracted from field, and the results were statistically analyzed. Gyratory method was found to be often producing specimens similar to pavement cores, whereas those from Marshall rotating base compactor were having the least probability of matching with field specimens. From studies it is observed that, gyratory method of compaction can reduce the aggregate degradation significantly (West and Moore 2006).

Researchers had used different gyrations to prepare SMA samples and to assess their performance. Xue et al. (2009) conducted a comparative study on the performance of two SMA mixes designed using Superpave and Marshall mix design procedures. Samples from both mixes were prepared at the design asphalt contents and aggregate gradations, and were subjected to evaluation tests including Marshall stability, water sensitivity, resilient modulus, fatigue life and rutting. In all performed tests Superpave mixtures proved their superiority over Marshall mixtures. Xie (2006) prepared SMA mixes with five aggregate types and three aggregate gradations by giving 65 and 100 gyrations in SGC and 50 Marshall blows. West and Moore (2006) also prepared SMA mixtures with five aggregate sources using a 50-blow Marshall compaction and 50, 75, and 100 gyrations with an SGC. OBC and aggregate breakdown in each case were determined and laboratory rutting tests were conducted using the Asphalt Pavement Analyzer. The number of gyrations required to achieve the same density as the Marshall hammer for the SMA mix designs with the five aggregates varied inversely with their LAA values. A design compactive effort of 100 gyrations was recommended for mixtures with coarse aggregate having LAA value less than 30%, and 70 gyrations was recommended for mixtures having coarse aggregate with LAA value greater than 30% (Prowel et al. 2009). Behnood and Ameri (2012) prepared SMA samples in Gyratory compactor with a steel mold of inside diameter 150 mm. The bottom of the mold was shifted horizontally to provide a rotation angle of 1.25 degrees and the speed of gyrations (revolutions) was 30 rpm.

2.10 SUMMARY OF LITERATURE REVIEW

SMA is a well performing gap graded mixture superior to conventional dense graded mixtures. The principle of SMA lies on the coarse aggregate skeleton and high asphalt content. The stone to stone contact between the coarse aggregates forms a skeleton and adds strength and provides an efficient network for load distribution to the mixture, whereas the bitumen content provides durability. Because of the increased quantity of coarse aggregates and bitumen, SMA mixes are costlier than dense graded mixtures. But this additional cost for construction will be compensated with the increased performance. To maintain the coarse aggregate skeleton, literature suggests limiting the 4.75mm sieve passing aggregates to 30%. The drain down problem due to the gap graded structure and the presence of high bitumen and filler content should be prevented by using proper stabilizing additive or modifiers. Generally mineral or cellulose fibers are used for stabilizing SMA mixes. From literature it is observed that, usage of suitable modified bituminous binders or inclusion of certain non-conventional additives like waste plastic, coir fibers, etc. can control drain down problems. Compaction with Marshall fifty blows on either sides of the specimen causes aggregate degradation in SMA mixtures. Mix preparation using SGC with suitable gyrations, was observed to be causing less aggregate break down and these mixes were performing better than Marshall mixes. For better performance, hard aggregates (with LAA value ≤ 30%) should be used in SMA and 100 gyrations can be given in SGC for to prepare these mixes.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 MATERIALS

For any bituminous mixture, the types and properties of materials used for it, is very important. In this investigation, aggregates, bituminous binder, mineral filler, stabilizing additive, etc. are used to prepare SMA mixture.

3.1.1 Aggregates

Aggregates are the main ingredients of bituminous mixture, which generally comes around 80-85 % of the mixture. The quality of aggregates is very important for SMA mixtures and should be hard, durable and clean. In this study crushed granite rocks collected from stone crushing plant near Karkala, Karnataka were used after ensuring their suitability in SMA based on IRC guidelines. Physical properties of aggregates were tested as per IS 2383 methods and were observed to be satisfying the specification. The test results are presented in Table 3.1.

Table 3.1 Properties of Coarse Aggregates

Property	**Test**	**Method**	**Results**	**IRC Specifications**
Strength	Aggregate Impact Value	IS 2386 (P-4)	20.1%	24% maximum
	Los Angeles Abrasion Value	IS 2386 (P-4)	21.6%	25% maximum
Water Absorption	Water Absorption	IS 2386 (P-3)	0.18%	2% maximum
Particle shape	Combined Flakiness and Elongation Index	IS 2386 (P-1)	26.3%	30% maximum

3.1.2 Bituminous Binder

In this study, one conventional bitumen and three types of modified bitumen were used as the binder material in SMA mixtures. Viscosity Graded bitumen 30, a commonly used bitumen type in India, was the normal bitumen used in this study. Modified bitumen types including Polymer Modified Bitumen (PMB) grades 40 and 70, and Crumb Rubber Modified Bitumen (CRMB) grade 55 were also used to prepare SMA mixtures. The bitumen types used in the study were supplied by Mangalore Refineries and Petroleum Limited and Hincol, Mangalore, Karnataka. Each bitumen was tested for different properties as per IS codes and found to be satisfying IS 73 (2013) and IRC SP 53 (2002) specifications for normal bitumen and modified bitumen types respectively. The properties of bitumen are listed in Tables 3.2 and 3.3.

Table 3.2 Properties of Normal Bitumen (VG 30)

Property Tested	**Test Method**	**Results Obtained**	**IS 73 Requirements**
Penetration at 25°C, 0.1 mm, 100g, 5s	IS 1203	61	45 Minimum
Softening point, (R&B), °C	IS 1205	53	47 Minimum
Ductility at 25°C (5 cm /minute pull), cm	IS 1208	> 100	-
Specific Gravity	IS 1202	1.00	-
Flash point, COC, °C	IS 1448	249	220 Minimum
Absolute Viscosity at 60°C, Poises	IS 1206 Part 2	2950	2400 – 3600
Kinematic Viscosity at 135°C, cSt	IS 1206 Part 3	380	350 Minimum
Test on residue from rolling thin film oven test:			
Viscosity ratio at 60°C	IS 1206 Part 2	3.1	4.0 Maximum
Ductility after thin film oven test at 25°C, cm	IS 1208	55	40 Minimum

Table 3.3 Properties of Modified Bitumen

Property tested	**Test method**	**Results**		
		CRMB	**PMB 40**	**PMB 70**
Penetration at 25^{0}C, 0.1 mm, 100g, 5s	IS 1203	45 (30-50)	38 (30-50)	61 (50-80)
Softening point, (R&B), °C	IS 1205	69 (Min. 60)	67 (Min. 60)	62 (Min. 55)
Flash point, COC, °C	IS 1209	283 (Min. 220)	251 (Min. 220)	243 (Min. 220)
Elastic recovery of half thread in ductilometer at 15°C, per cent	Annex 2 of IRC SP 53	61 (Min. 60)	87 (Min. 60)	79 (Min. 60)
Thin film oven tests and test on residue:				
a) Loss in mass, per cent	IS 9382	0.084 (Max. 1)	0.049 (Max. 1)	0.068 (Max. 1)
b) Increase in softening point, °C	IS 1205	3 (Max. 5)	3.2 (Max. 5)	4 (Max. 6)
c) Reduction in penetration of residue, at 25°C per cent	IS 1203	41 (Max. 35)	24 (Max. 35)	22.5 (Max. 35)
d) Elastic recovery of half thread in ductilometer at 25°C, per cent	Annex 2 of IRC SP 53	33 (Min. 50)	64 (Min. 50)	65 (Min. 50)

3.1.3 Mineral Filler

Finely divided mineral matter is generally used as mineral filler in bituminous mixtures. In this study granite stone dust and hydrated lime were used for this purpose, limiting the quantity of lime to 2% by weight of aggregates. Hydrated lime provides better resistance to degradation of mixture in the presence of moisture by increasing the stiffness, strength, and toughness of the mastic, and produces better resistance to stripping by improving the asphalt-aggregate interfacial bonding (Kim et al. 2008). This also improves the permanent deformation characteristics and fatigue endurance of bituminous mixtures, particularly at higher temperatures (Mohammad et al. 2000). The filler material was graded as per Table 3.4 suggested by IRC.

Table 3.4 Gradation Requirement for Mineral Filler

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

3.1.4 Stabilizing Additives

Due to the problem of the drain down associated with SMA mixtures, a suitable stabilizing additive is generally used. Cellulose, mineral and polymer fibers are typically suggested in this regard, by different countries and institutions, and IRC recommends using cellulose fiber in pelletized form.

3.1.4.1 Fiber Materials

In this investigation, non-conventional fiber materials like Coconut Coir (CC) and Sisal Fiber (SF) were tried as stabilizer material in SMA, along with the IRC recommended Cellulose Fiber (CF), in pellet form. The CF used in the study is a blend of 66.6% by weight ARBOCEL ZZ 8-1 and 33.3% by weight of VG 30 bitumen. CC was brought from Thiruvananthapuram, Kerala and SF from Mumbai, Maharashtra, and both fibers were manually cut into small pieces of length less than 35mm, to ensure proper mixing with the aggregates and binder. The fibers used in this study are shown in Figure 3.1 (a-c), and their properties are listed in Table 3.5 and Table 3.6 (Common Fund for Commodities (CFC) 2004).

(a) Pelletized Cellulose Fiber

(b) Coconut Coir

(c) Sisal Fiber

Fig. 3.1 Fiber Additives used in SMA

Table 3.5 Properties of Cellulose Fiber

Property	**Description**
Colour and Shape	Grey, cylindrical pellets
Pellet length	2 – 10 mm
Thickness	3.5 ± 1 mm
Bulk density	490 – 570 gm/l
Length to diameter ratio	0.80 – 2.22

Table 3.6 Properties of Coconut Coir and Sisal Fiber

(Source: CFC 2004)

Property	**Coconut Coir**	**Sisal Fiber**
Diameter (mm)	0.10-0.50	0.05-0.25
Density (g/cc)	1.25-1.50	1.35-1.60
Tensile Strength (MPa)	130-210	520-700
Chemical Composition		
Cellulose (%)	35-45	55-70
Hemi-cellulose (%)	16-24	12-18
Lignin (%)	35-50	8-15

3.1.4.2 Waste Plastic

Incorporation of Waste Plastics in road construction is widely accepted as an eco-friendly method. In this study, Shredded Waste Plastic (SWP), with properties listed in Table 3.7 (Punith and Veeraragavan 2010), was tried as a stabilizing additive in SMA mixtures. Plastic wastes, mainly containing polyethylene, polypropylene, etc. were cleaned and shredded into small pieces as shown in Figure 3.2 and the material was supplied by K K Plastic Waste Management Ltd., Bangalore, Karnataka.

Table 3.7 Properties of Shredded Waste Plastics

(Source: Punith and Veeraragavan 2007)

Properties	Values
Density	0.95g/cc
Tensile strength at break	2.542MPa
Elongation at break	> 500%
Young’s modulus	0.8MPa
Impact strength	0.86 Joule
Melting point	130°C

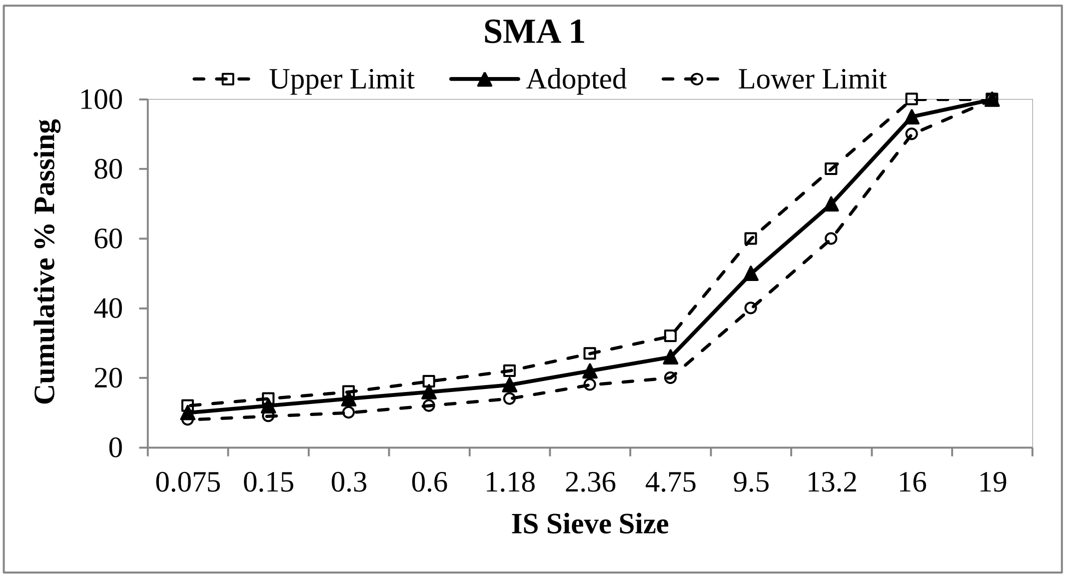
Fig. 3.2 Shredded Waste Plastics

3.2 AGGREGATE GRADATION

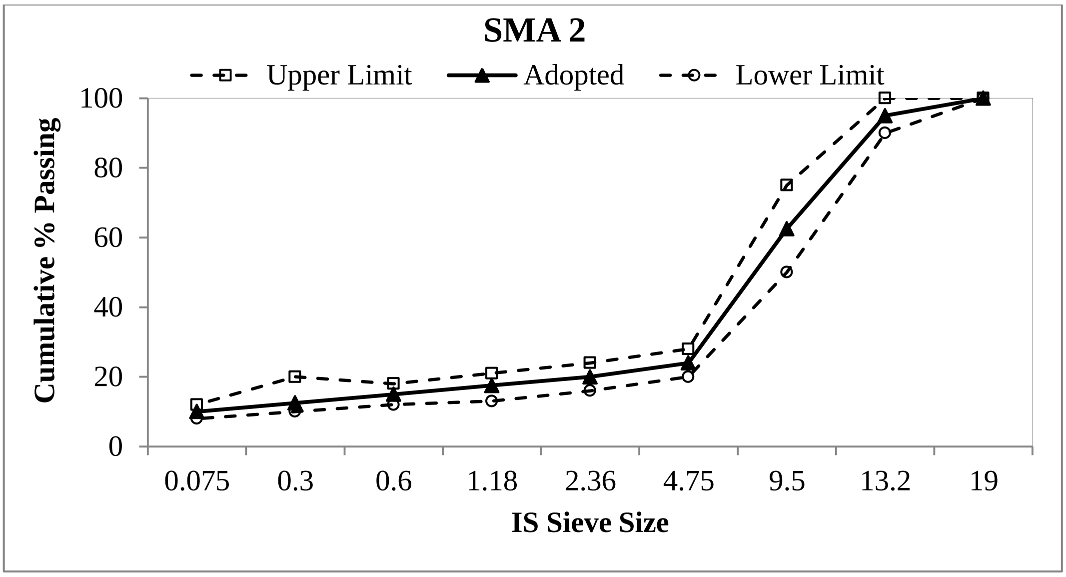
In order to prepare SMA mixtures, two aggregate gradations with two Nominal Maximum Aggregate Size (NMAS), were considered for the study. The gradation with 16mm NMAS, named as SMA 1, was adopted from Chinese specifications for SMA, and the one with 13.2mm NMAS, named as SMA 2, was adopted from IRC guidelines (JTG F40-2004, IRC SP 79-2008). The gradation ranges and adopted values for SMA 1 and SMA 2 are presented in Table 3.8 and Figures 3.3 (a-b). The collected aggregates were sieved as per the sieve sizes in the adopted gradation and material retaining on each sieve were separated. During mixture preparation, these separated aggregates were mixed based on the gradation requirement, and this way of aggregate mixing helped to maintain uniformity in all mixtures.

Table 3.8 Aggregate Gradation of SMA Mixtures

Mixture	SMA 1	SMA 2
IS Sieve Size (mm)	Cumulative % by weight of total aggregate passing	
19	100	100
16	90-100	-
13.2	60-80	90-100
9.5	40-60	50-75
4.75	20-32	20-28
2.36	18-27	16-24
1.18	14-22	13-21
0.6	12-19	12-18
0.3	10-16	10-20
0.15	9-14	-
0.075	8-12	8-12



(a) SMA 1



(b) SMA 2

Fig. 3.3 Aggregate Gradations for SMA Mixtures

3.3 MIXTURE NOTATIONS

In this current investigation, mixtures were prepared with three fiber additives, three modified bitumen and four levels of SWP dosage for both SMA 1 and SMA 2 aggregate gradations. For convenience to describe, these mixes are named as listed in Table 3.9.

Table 3.9 SMA Mixture Constituents and Notations

Aggregate Gradation	**SMA 1**	**SMA 2**
Mixture Constituents	**Notations**	
VG 30 Bitumen + Cellulose Fiber	1-CF	2-CF
VG 30 Bitumen + Coconut Coir	1-CC	2-CC
VG 30 Bitumen + Sisal Fiber	1-SF	2-SF
CRMB (No Stabilizing Additive)	1-CB	2-CB
PMB 40 (No Stabilizing Additive)	1-P40	2-P40
PMB 70 (No Stabilizing Additive)	1-P70	2-P70
VG 30 Bitumen + 4% SWP	1-W4	2-W4
VG 30 Bitumen + 8% SWP	1-W8	2-W8
VG 30 Bitumen + 12% SWP	1-W12	2-W12
VG 30 Bitumen + 16% SWP	1-W16	2-W16

3.4 METHODOLOGY

Marshall's method of mix design as per the specification laid down by the Asphalt Institute (AI) in Manual Series – 2 (MS – 2) was adopted for the present study. The SMA mixture requirement specified by IRC is presented in Table 3.10. Loose SMA mixtures were used to determine the maximum theoretical density (G_{mm}), drain down and stripping behaviour. Cylindrical specimens were prepared to evaluate the volumetric properties, Marshall characteristics, Indirect Tensile (IDT) strength Fatigue behaviour and moisture susceptibility characteristics of SMA mixtures. The test specimens were prepared in Troxler 4140 Superpave Gyratory Compactor (SGC), shown in Figure 3.4, by adding 5.0, 5.5, 6.0, 6.5, and 7.0 per cent of bitumen by total weight of mixture, and 100 gyrations were provided to compact the specimen. In order to study the rutting behaviour, rectangular slab specimens were prepared.

Table 3.10 SMA Mixture Requirements as per IRC

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

Fig. 3.4 Superpave Gyratory Compactor

Following procedure was adopted for mix preparation and compaction.

Loose Mixture Preparation:

- The aggregates were proportioned and mixed as per the adopted gradation and heated to a temperature of 150 – 170 °C.
- For mixes with waste plastic, SWP were added in different percentages (4, 8, 12 and 16 % by weight of bitumen) to heated aggregates and properly mixed.
- The bitumen heated to 150 – 165 °C was added to the hot aggregates in required quantity (5.0, 5.5, 6.0, 6.5 and 7.0 per cent by weight of mix) and was thoroughly mixed by maintaining a temperature of 150 – 165 °C.

- For modified bitumens, the aggregate and binder temperature should be raised to 165 – 185 °C and the mixture temperature to 150 – 170 °C.

Compaction in SGC:

- The mix was placed in a pre-heated SGC mould (Figure 3.5) of diameter 100mm. The mould with a puck inserted received the asphalt for making specimens.

Fig. 3.5 SGC Mould (100mm Diameter)

- After levelling the top surface, the mould was kept inside the Superpave and the glass door was closed.
- In the menu status the pressure was set to 600kPa, angle of gyration to 1.25°, gyration rate to 30 rpm, number of gyrations to 100 and number of dwell gyrations to 10.
- When the START button was pressed, the ram moved down to apply the fixed pressure of 600kPa to the mix. The mould then tilted 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 was gyrated at 1.25° about the original central axis at 30rpm.

- As the specimen was being compacted, its height was measured after each gyration and displayed to the nearest 0.1 mm. The dot matrix printer printed the data.
- After completion of 100 gyrations and 10 dwell gyrations, the ram automatically moved up.
- Then the mould was taken out and the specimen was removed through the top of the mould with the extruder.
- The diameter, weight in air and weight in water of the specimens were noted.

3.4.1 Drain Down

American Society for Testing and Materials (ASTM) describes drain down as the portion of bituminous mixture which separates itself from the sample as a whole and is deposited outside the wire basket during the test. The material which drains may be composed of either asphalt binder or a combination of asphalt binder, additives, or fine aggregate.

Drain down test was conducted as per ASTM D 6390 in a wire basket made up of standard sieve cloth of 6.3 mm size as shown in Figure 3.6. The test was conducted on loose mixtures at OBC and 7 % bitumen content to ensure that the mastic draining property of the SMA mixtures was within acceptable levels. About 1000g of SMA mixture was prepared and poured in the wire basket, and the basket was hung in the oven maintained at 160°C (anticipated plant production temperature) with a catch plate kept below the basket. The ratio of weight of material drained after the test period of one hour to the total mixture weight expressed in percentage is termed as drain down. The test was repeated at a test temperature of 170°C, and the average value was considered. It also provided an evaluation of the drain down potential of SMA mixture produced in the field.

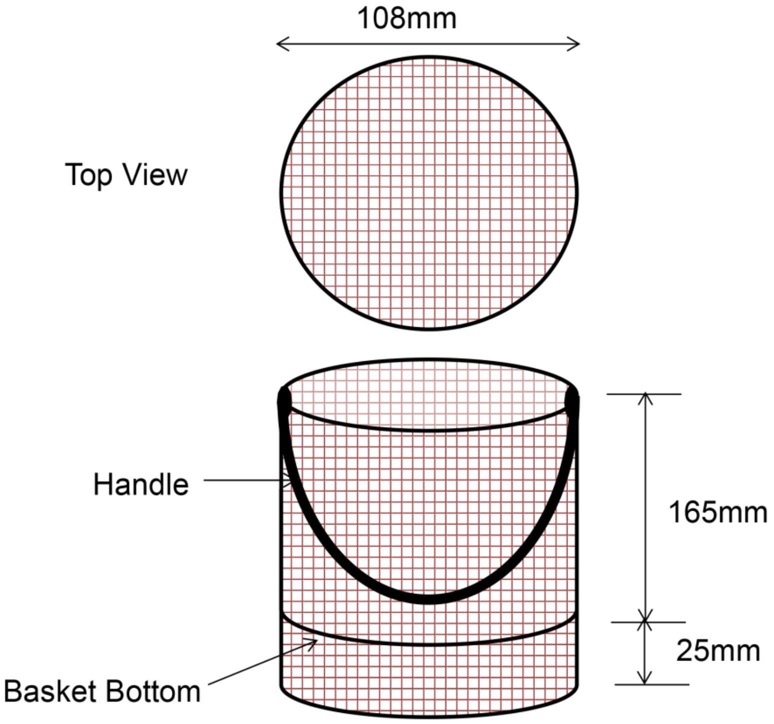


Fig. 3.6 Wire Basket Assembly for Drain down Test

3.4.2 Volumetric Properties

Maximum Theoretical Density

Maximum Theoretical Density of the mixture (G_{mm}) is measured for the mixture of aggregates and bitumen in loose uncompacted form, since it can provide the value after the absorption of bitumen by aggregates. Loose SMA mixtures were prepared to determine G_{mm} and the test was conducted as per ASTM D 2041, using Asphalt Mixture Density Tester shown in Figure 3.7 and the procedure is described below.

1. The SMA mixture was prepared using oven-dry aggregates, and the particles were separated by hand, taking care to avoid fracturing the aggregates, so that the particles of the fine aggregate portion were not larger than about 6 mm. The mixture was cooled to room temperature.
2. The sample was placed directly into a cylindrical container of the Asphalt Mixture Density Tester. The container was weighed with the mixture and the net mass (mass of mixture only) was designated as A.

3. Sufficient water was added at a temperature of approximately 25°C to cover the mixture completely and then the container was closed with lid.
4. The container was placed in the machine with the mixture and water, and agitation was started immediately to remove air trapped in the mixture by gradually increasing the vacuum pressure (using a vacuum pump connected to it) until the residual pressure manometer reads 3.7 ± 0.3 kPa. The vacuum was achieved within 2 minutes. Once the vacuum was achieved, vacuum and agitation were continued for 15 ± 2 minutes.
5. The vacuum pressure was gradually released using the bleeder valve and the weighing in water was done. For determining the weight in water, the container and contents were suspended in water for 10 ± 1 minutes, and then the mass was determined. The mass of the container and mixture under water was designated as C.

The maximum specific gravity of the mixture was calculated using Equation 3.1.

$$G_{mm} = \frac{A}{[A-(C-B)]} \tag{3.1}$$

where:

G_{mm} = Maximum theoretical density of the mixture,

A = Mass of dry sample in air, g,

B = Mass of bowl under water, g, and

C = Mass of bowl and sample under water, g.

The theoretical maximum density for SMA mixtures with 6% and 6.5% bitumen content by weight of mixture were determined by the specified method. The effective specific gravity of the aggregates was determined using Equation 3.2 for each case and the average of the two values were considered.

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

G_{se} = Effective specific gravity of aggregates

G_{mm} = The Average theoretical maximum specific gravity determined as per ASTM D2041.

P_{mm} = Percentage by weight of total loose mixture

P_b = Bitumen content percentage by total weight of mixture

G_b = Specific Gravity of Bitumen

The G_{mm} of mixtures with different bitumen contents was then calculated as follows (Equation 3.3):

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

P_s = Aggregate content, per cent by total weight of mixture

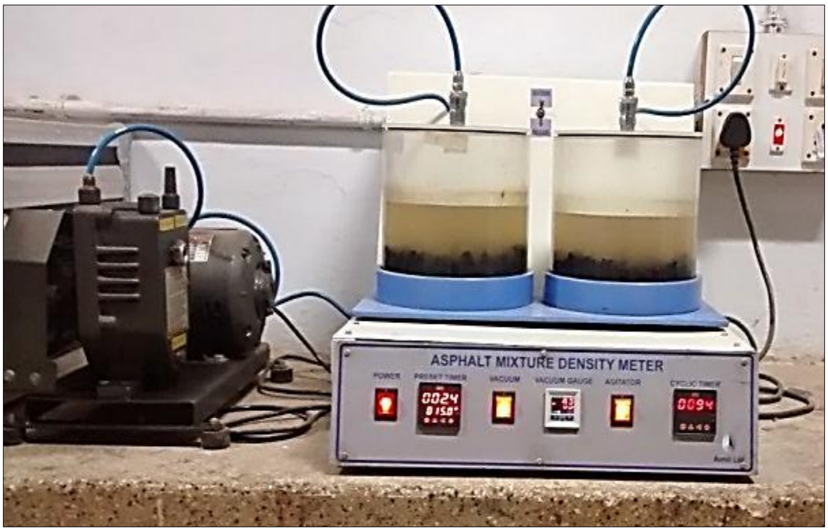


Fig. 3.7 Asphalt Mixture Density Tester

Bulk Specific Gravity of Aggregates

The bulk specific gravity of aggregates (G_{sb}) for each specimen was calculated by knowing the specific gravities of the different materials used. It was calculated from 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 = % by weight of coarse aggregates in total aggregate

W_2 = % by weight of fine aggregates in total aggregate

W_3 = % by weight of filler in total aggregate

W_4 = % by weight of lime in total aggregate

G_1 = Specific gravity of coarse aggregates

G_2 = Specific gravity of fine aggregates

G_3 = Specific gravity of filler

G_4 = Specific gravity of lime

Bulk Density of Compacted Sample

Bulk density of each compacted specimen (G_{mb}) was calculated from Equation 3.5.

$$G_{mb} = \frac{W_a}{W_{ssd} - W_w} \tag{3.5}$$

where,

W_a = Weight of specimen in air

W_w = Weight of specimen in water

W_{ssd} = Saturated Surface Dry (SSD) weight of specimen

Air Voids in Total Mix (V_a)

Voids in total mix are the volume of small pockets of air between the coated aggregate particles throughout a compacted mix, expressed as a percentage of bulk volume of compacted mix. Equation 3.6 was used to determine V_a.

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

where,

G_{mm} = Maximum theoretical density of the mixture

G_{mb} = Bulk density of the compacted specimen

Voids in Mineral Aggregates (VMA)

VMA is the volume of inter granular void space between the aggregate particles of the compacted paving mixture that includes the air voids and the volume of the asphalt not absorbed into the aggregates. Equation for VMA is given in below (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 aggregate

Voids Filled with Bitumen (VFB)

VFB is the percentage of the volume of the air voids that is filled with bitumen and was calculated using Equation 3.8.

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

Voids in the Coarse Aggregates (VCA)

The coarse aggregates were washed and the dry rodded unit weight was determined in accordance with ASTM C 29. A measure of known volume (about 10L) and weight was used for this experiment. The oven- dried coarse aggregates were filled up to 1/3rd of the measure, levelled with finger and compacted by giving 25 strokes of the tamping rod evenly distributed over the surface. The remaining portion was also filled in the same manner and the weight of measure and aggregates was taken. The unit weight of coarse aggregates by the dry rodding procedure (Y_S) was calculated as:

$$\mathrm{Y_s} = \frac{\mathrm{G} - \mathrm{T}}{\mathrm{V}} \tag{3.9}$$

Y_S = Unit weight of the coarse aggregate in dry rodded condition, kg/m^3

G = Mass of the measure plus aggregate, kg

T = Mass of the measure, kg

V = Volume of the measure, m^3

The dry rodded VCA of the coarse aggregate was calculated using the following Equation (3.10)

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

$\mathrm{VCA_{DRC}}$ = Voids in the coarse aggregate in the dry rodded condition

$\mathrm{G_{ca}}$ = Bulk specific gravity of the coarse aggregate

$\mathrm{Y_w}$ = Unit weight of water (998 kg/m^3)

$\mathrm{Y_s}$ = Unit weight of coarse aggregate fraction in dry-rodded condition (kg/m^3)

The VCA of the mixture ($\mathrm{VCA_{MIX}}$) is calculated using Equation (3.11).

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

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

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

A sample calculation for the volumetric properties of SMA mixture is presented in Appendix I.

3.4.3 Marshall Characteristics

Marshall test is generally conducted as a part of the Marshall mixture design to evaluate the resistance of bituminous mixtures to plastic flow. The test was conducted as per ASTM D 6927. The prepared specimens were kept immersed in a thermostatically controlled water bath at 60±1 ºC for 30 to 40 minutes. The specimens were taken out, placed in Marshall test head (Figure 3.8) and tested to determine Marshall Stability (MS) value which is a measure of strength of the mixture. It is the maximum resistance in kN, which it will develop at 60ºC when tested in the standard Marshall equipment. MS was calculated using Equation 3.12. Flow value is the total deformation, occurring in the specimen between no load and maximum load during the test. The test specimens were prepared with varying bitumen content in 0.5 per cent increments over a range that gives a well-defined maximum value for specimen density and stability. The Marshall Quotient (MQ) was calculated from the stability and flow values (Equation 3.13).

Fig. 3.8 Marshall Test Setup

$$\text{Marshall Stability, MS (kN)} = 0.0808 \times (\text{Proving Ring Reading}) - 0.0176 \qquad (3.12)$$

$$\text{Marshall Quotient, MQ (kN/mm)} = \frac{\text{Marshall Stability}}{\text{Flow}} \qquad (3.13)$$

3.4.4 Optimum Bitumen Content

Any bituminous mixture should have necessary binder to coat the aggregates completely and to fill a desired portion of VMA, but its quantity should not be high to result into problems like instability, bleeding etc. The Optimum Binder Content or Optimum Bitumen Content (OBC) for SMA mixtures is usually selected to produce 3.0–4.0% air voids. Marshall stability and flow values are generally measured for information, but not used for acceptance. The binder content (5.0, 5.5, 6.0, 6.5 and 7 %) was plotted against air voids and the binder content corresponding to the specified air voids (4%) was found from the plots. In the present study the binder content at 4% of air voids was taken as OBC for SMA mixtures. All the properties obtained at OBC were compared with the specification values to ensure that they are in the required limits.

3.4.5 Indirect Tensile Strength

Indirect Tensile (IDT) strength is a measure of tensile strength of bituminous mixtures, measured along the diametrical plane of cylindrical specimen. This value provides an assessment of relative quality of bituminous mixtures and estimate of their rutting or cracking characteristics.

IDT strength of SMA mixtures was determined as per ASTM D 6931. The specimens prepared at OBC were kept in water bath at 25°C for about one hour (more than 30 minutes, but lesser than 2 hours is recommended). The specimen was placed over the bottom loading strip and then the upper portion of mould was lowered for the top loading strip to touch the specimen. The specimen was adjusted to align the loading strips along its diametrical plane, and then the testing mould was placed in the Marshall stability testing equipment as shown in Figure 3.9. A vertical compressive load was applied, by maintaining a deformation rate of 50mm/minutes and the maximum load required for specimen failure was noted. The IDT strength was calculated using Equation 3.14.

$$S_t = \frac{2000\,P}{\pi D t} \tag{3.14}$$

S_t = Tensile strength (kPa)
P = Failure load (N)
D = Diameter of specimen (mm)
t = Thickness of specimen in (mm)

Fig. 3.9 IDT Strength Test Setup

3.4.6 Rutting Resistance

Due to the increased traffic loads, surface and other layers of bituminous pavements deform leading to longitudinal depression along the wheel path, commonly known as rutting or permanent deformation. Nevelt and Thanfold (1988) defined rutting as the accumulation of unrecoverable strain in lesser magnitudes due to the heavy loads coming over the pavements. In this study, the behaviour of SMA mixtures to permanent deformation was assessed by rutting test conducted on Wheel Tracking Device, shown in Figure 3.10. Slab specimen of dimensions 600mm × 200mm × 50mm casted specifically for the purpose is used for the test. As presented in Figure 3.11, the device consists of a rubber wheel with 200mm diameter and 50mm thickness, a cantilever loading arm to provide load to the wheel and a confined mould in which the specimen is rigidly restrained on all sides and placed on a platform. A motor and a reciprocating device give to and fro travel to the platform with specimen for a distance of 600mm, with the loaded wheel kept in static position above the specimen surface. The depth of deformation caused by this movement is measured by means of two LVDTs (Linear Variable Deflection Transducers) fixed on either sides of the wheel and the readings are displayed.

Fig. 3.10 Wheel Tracking Device

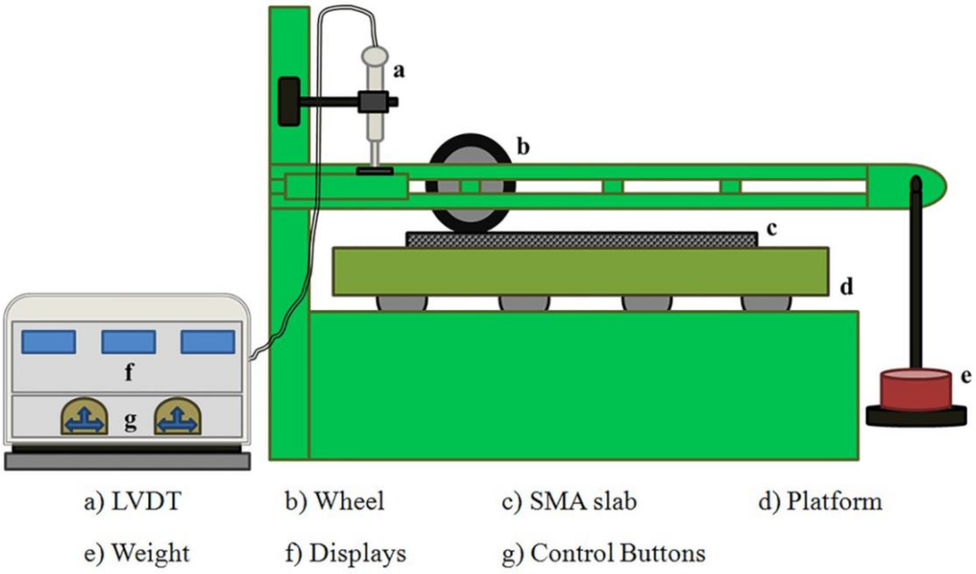


Fig. 3.11 Sketch of Wheel Tracking Device

The slabs for each SMA mixture were prepared at the corresponding OBC and bulk density values. The aggregates required for the rutting sample was taken by measuring the required quantities according to the adopted gradation using these bulk density values and volume of mould (6000cm^3).

The procedure carried out is briefed here:

1) The aggregates were heated and mixed uniformly. Required amount of SWP was added to hot aggregates and mixed thoroughly for SMA mixtures with SWP. Then the bitumen heated was mixed with the hot aggregate (Figures 3.12 and 3.13). For mixtures with fibers, required quantity of fiber was also added and mixed.
2) This loose SMA mixture was compressed in a sturdy steel mould (600 × 200 × 50 mm) using a static compression machine to the required density and thickness (Figures 3.14 and 3.15).
3) The compacted specimen is shown in Figure 3.16. After 24 hours of casting, the slab was placed in the machine and all the sides were encased with confining plates.
4) The static wheel was brought into contact with slab surface. Depending upon stress level to be maintained, the weight pads on the cantilever were adjusted.
5) LVDTs were fixed on both sides and connected to the control unit. The speed of specimen platform was adjusted to required level.
6) The slab was subjected to reciprocating load repetitions for 10000 passes and the depression on the slab surface was recorded. Water was applied externally to the specimen. A set of specimens after test are presented in Figure 3.17.

Fig. 3.12 Mixing of Aggregates for Rutting Sample

Fig. 3.13 SMA Mix Preparation for Rutting Sample

Fig. 3.14 Placing of Mix for Preparation of Rutting Sample

Fig. 3.15 Compaction of Rutting Slab

Fig. 3.16 Compacted Rutting Slab Specimen

Fig. 3.17 Rutting Specimens after Test

3.4.7 Fatigue Behaviour

Fatigue cracking due to repeated loading, has been an everlasting issue in the design and performance of bituminous pavements. The repeated application of damage inducing stress (and strain), first results in the initiation of microcracks, which, if not healed, cause to form macrocracks, ultimately leading to pavement failure (Tarefder et al. 2013). Fatigue behaviour of SMA mixtures was assessed using Repeated Load Testing machine shown in Figure 3.18 (Ravi Shankar et al. 2013). The device is a modified version of similar equipment reported by Palit et al. (2001). This is a dynamic diametrical tensile test and the load is applied to the cylindrical specimen in a positive sinusoidal pattern. The dynamic loading is applied using the hydraulic loading system present in the machine, and is transferred to the specimen through a movable shaft. A cooling system is attached to control temperature of the machine and the pressure can be adjusted to maintain balance between input and output loads. The specimen arrangement is sown in Figure 3.19. The specimen is fixed in between two steel strips present at the top and bottom of the testing setup. The position of the specimen is adjusted in such a way that, it is exactly below the loading shaft and to apply the load along its diametrical plane. Two vertical and two horizontal LVDTs are connected with the specimen to measure the deflections. The machine is capable of applying load with frequency from 1 to 10 Hz and rest period 0 to 0.9 seconds. The machine is attached with a PC and can be controlled using a software ‘fatigue 4.0’, which is also used to provide various input values.

Fig. 3.18 Repeated Load Testing Machine

Fig. 3.19 Specimen Arrangement in Repeated Load Testing Machine

In this study, SMA specimens at OBC were tested with loadings approximately 15%, 33.3% and 50% of the corresponding IDT strength failure loads. The specimens were subjected to 1Hz frequency and 0.9 s rest period, and number of cycles required for failure was considered as Fatigue Life (FL).

Other than the mixture characteristics, applied load is also a significant factor affecting the FL of the mix, along with the dimensions of the tested specimen, and hence FL value alone cannot be used to represent the fatigue behaviour of a mixture. Since the applied load is a fraction of IDT strength, the FL may be higher for a weak mixture with lesser IDT strength and lesser applied load, and to the contrary a lower FL value may be obtained for a strong mixture. In order to obtain a more accurate picture about the fatigue behaviour of SMA mixtures, the FL values were related with the corresponding tensile stress, which includes load applied to the specimen and its dimensions. The tensile stress was calculated using Equation 3.15.

$$\text{Tensile Stress (kPa)} = \frac{2000\ \text{P}}{\pi \text{dt}} \tag{3.15}$$

where,

P = load applied to the specimen in fatigue test, N
d = diameter of the specimen, mm
t = thickness of the specimen, mm

3.4.8 Moisture Susceptibility

Moisture susceptibility of bituminous mixtures is one of the main reasons for distresses in flexible pavements, which leads to loss of strength, stripping, ravelling, fatigue damage and permanent deformation. The detrimental effects of water in bituminous mixtures and the pavement distresses due to it were recognized from the 1930s itself. The moisture damage can be defined as the degradation of the mechanical properties of the material due to the presence of moisture in its microstructure (Caro et al. 2008, Hamzah et al. 2015). The moisture susceptibility of

SMA mixtures was assessed using three parameters, Retained Stability (RS), Tensile Strength Ratio (TSR) and stripping.

3.3.8.1 Retained Stability

Retained stability test is a way of assessing the moisture susceptibility of bituminous mixtures based on Marshall stability values. In this test Marshall stability values for two sets of SMA specimens were considered, unconditional and conditional sets. Values determined as per ASTM D 6927 were taken as the unconditioned Marshall stability, whereas the other set of specimens were conditioned by keeping in water bath at 60°C for 24 hours. These specimens were tested for stability after conditioning and the ratio of conditioned stability to unconditioned stability is termed as Retained Stability. From this test the effect of hot water immersion for 24 hours on the stability of SMA specimens is obtained, which provides an indication of the mixtures' moisture susceptibility.

3.3.8.2 Tensile Strength Ratio

The Tensile Strength Ratio (TSR) of bituminous mixtures is an indicator of their resistance to moisture susceptibility. The test was carried out according to AASHTO T 283 specifications, by loading a Marshall specimen with compressive load acting parallel to and along the vertical diametric-loading plane. This method covers preparation of compacted bituminous mixtures and the measurement of the change of diametric tensile strength resulting from the effects of water saturation and laboratory accelerated stripping phenomenon with freeze-thaw cycle. The result may be used to predict long-term stripping susceptibility of bituminous mixtures and evaluate liquid anti-stripping additives that are added to bitumen or pulverized mineral materials such as hydrated lime, which are added to the mineral aggregate.

The test is similar to IDT test mentioned in section 3.2.5, but in this test, the specimens are prepared with 7±0.5 % air void content to maximise the effect of moisture action. SGC specimens were prepared at OBC, by providing lesser number of gyrations to produce the required air void content. The number of gyrations for each mixture was estimated based on the method suggested by AI Superpave series (SP) 2 manual.

It suggests a relation between the actual density of specimen at design air voids (G_{mb}) and the density estimated based on the diameter and height of the specimen after the design number of gyrations (100 in this case) (Est. G_{mb}), using a Correction Factor, C as presented in Equation 3.16.

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

The required actual density of specimen at 7% air voids (G_{mb} at 7%) is 93% of the G_{mm}. The same Correction Factor (from Equation 3.16) can be applied to estimate the density of specimen at 7% air voids based on diameter and height (Est. G_{mb} at 7%), as shown in Equation 3.17.

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

From this Est. G_{mb} at 7%, corresponding estimated height of specimen for 7% air voids (Est. h at 7%) can be calculated. The gyrations v/s height data of specimen at design air voids can be used to identify the number of gyrations required producing a height of Est. h at 7% and the same can be adopted to prepare specimens at 7% air void content.

Test procedure for determination of Indirect Tensile Strength is as follows:

1) Specimens for each SMA mixture were prepared at corresponding OBC by applying the number of gyrations to produce 7% air voids.
2) Two sets of specimens were prepared for testing, i.e. one to be tested dry and the other to be tested after partial saturation and moisture conditioning with a freeze-thaw cycle.
3) One set of specimens were brought to temperature of 25±1°C, by keeping them in water bath maintained at test temperature for 2 hours. These specimens are called as unconditioned specimens.

4) Another set of specimens were placed in the vacuum container (Figure 3.20) filled with water at room temperature for 30 minutes. The vacuum was removed and specimens were submerged in water for 5 to 10 minutes.
5) Then specimens were placed in plastic bags containing 10 ±0.5 ml of water and sealed and kept in freezer at temperature of -18 ±3°C for minimum period of 16 hours (Figure 3.21).

Fig. 3.20 Vacuum Container to Keep Specimens

Fig. 3.21 Specimens in Freezer

6) The specimens were then kept in water bath for 24 ±1 hours maintaining 60 ±1°C temperatures. This complete process in steps (3), (4), (5) and (6) is called a freeze and thaw cycle.
7) The specimens were then kept in another water bath for 2 hours maintaining temperature of 25 ±1°C. These specimens are called conditioned specimens for ITS test.
8) The conditioned and unconditioned specimens were tested for ITS using the same mould and method adopted for IDT strength mentioned in section 3.2.5, and ITS was calculated using Equation 3.18.

$$\mathrm{ITS} = \frac{2000\,\mathrm{P}}{\pi \mathrm{Dt}} \tag{3.18}$$

where,

ITS = Indirect Tensile Strength (kPa)
P = Failure load (N)
D = Diameter of specimen (mm)
t = Thickness of specimen in (mm)

9) The ratio of the ITS value of the conditioned subset to that of the unconditioned subset is termed as Tensile Strength Ratio (TSR) and is calculated using Equation 3.19

$$\mathrm{TSR} = \frac{\mathrm{S_2}}{\mathrm{S_1}} \mathrm{x}\, 100 \qquad 3.19$$

where,

S_1 = average tensile strength of the dry (unconditioned) subset, kPa
S_2 = average tensile strength of the conditioned subset, kPa

3.3.8.3 Stripping

The development of good adhesion between aggregate and binder is one of the paramount functions of bituminous material (Mina et al. 2006). The effectiveness of bituminous coating on the stone aggregate lies in its strong and durable adhesion to the aggregate surface under varying climatic and traffic conditions, and this plays a very significant role in the satisfactory performance and durability of the roads. Boiling test as per ASTM D 3625 was conducted to assess the stripping potential of SMA mixtures. About 250g of loose SMA mixture was prepared at OBC and was allowed to cool to a temperature of 85 – 100 °C. A clean container, half filled with distilled water, was kept for boiling. The mixture was placed in the boiling water and the container was boiled for 10 minutes ± 15 seconds (Figure 3.22). Then the container was removed and skimmed off the free bitumen from the water surface to prevent recoating. After cooling, the water was decanted and the mixture was placed on a white paper towel and the surface was observed. The stripping area and the per cent of stripping were determined based on visual observation.

Fig. 3.22 Boiling Test

3.4.9 Cost Analysis

Cost analysis of SMA mixtures was carried out using the latest Schedule of Rates (SOR) different Public Works Departments (PWD) under Government of India. Most of the rates were adopted from the SOR of Central PWD and the analysis was also based on it. Some missing rates were decided as per the SOR of Mangalore PWD, Karnataka state and also from the information provided by the material suppliers. In India, required aggregate gradation for pavement mixtures are achieved by blending different sizes of aggregates and this blending proportion is achieved during laboratory mix design, before construction. In order to calculate cost of mixes, arbitrary blending proportions of different sizes of aggregates were assumed for SMA 1 and SMA 2, as listed in Table 3.11. The proportion of 6mm aggregates, stone dust and lime were maintained same for both gradations and only the proportions of 20mm, 12.5mm and 10mm aggregates were varied. But this blending proportion may change depending on the gradation of aggregates using for mix preparation.

Table 3.11 Assumed Blending Proportion for SMA Mixtures for Cost Analysis

Aggregate	**20mm**	**12.5mm**	**10mm**	**6mm**	**Stone Dust**	**Lime**
SMA 1	35	35	0	10	18	2
SMA 2	0	50	20	10	18	2

In the cost calculation, different material costs, their carriage rates, necessary machinery and labour charges and miscellaneous charges are included, and these rates are presented in Table 3.12 to 3.15. The carriage rates for fibers, coir and SWP are arbitrarily assumed. Even though the Hot Mix Plant (HMP) and paver finisher have 100 Tonne per Hour (TPH) capacity, their output is assumed as 75 TPH. The loading rate for tipper is assumed as 10% of its carriage cost. Along with these, 1% of the total cost is considered as water charges and 15% of the total cost (including water charge) as the Contractor’s Profit and Overhead (CPOH) charges.

Table 3.12 Basic Cost of Materials Used

Material	Unit	Rate per Unit (Rupees)
20mm Aggregate	cum	1,800.00
12.5mm Aggregate	cum	1,750.00
10mm Aggregate	cum	1,890.00
06mm Aggregate	cum	1,550.00
Stone dust	cum	1,100.00
Dry Hydrated Lime	quintal	230.00
VG 30 Bitumen	tonne	41,000.00
Modified Bitumen CRMB 60	tonne	52,747.00
Modified Bitumen PMB 40	tonne	59,000.00
Modified Bitumen PMB 70	tonne	58,000.00
Shredded Waste Plastics	tonne	40,000.00
Cellulose Fiber Pellets	tonne	1,50,000.00
Coconut Coir	tonne	500.00
Sisal Fiber	tonne	1,500.00

Table 3.13 Carriage Rates for Materials

Material	Unit	Carriage Rate per Unit (Rupees)
Aggregate below 40mm size	cum	106.49
Lime	cum	106.49
Cement	tonne	94.65
Bitumen	tonne	106.49
Stone dust	cum	106.49
Fiber, Coir, Shredded Waste Plastic	tonne	106.49

Table 3.14 Rates for Machineries

Machinery and Description	Unit	Rate per Unit (Rupees)
Hot mix Plant 100 TPH capacity (Output 75 TPH)	hour	17,500.00
Paver finisher Hydrostatic with sensor control 100 TPH (Output 75 TPH)	hour	2,700.00
Generator 250 KVA	hour	700.00
Front end loader 1 cum bucket capacity	hour	900.00
Tipper -5 Cum	tonne-km	3.00
Vibratory roller 8 to 10 tonne	hour	1,300.00
Smooth Wheeled Roller 8 to 10 tonne	hour	450.00
Tandem Road Roller	hour	1,150.00

Table 3.15 Labour Rates

Labour Description	Unit	Rate per Unit (Rupees)
Mate	day	363.00
Beldar (working with HMP, mechanical broom, paver, roller, asphalt cutter and assistance for setting out lines, levels and layout of construction)	day	329.00
Skilled beldar (for checking line and levels)	day	363.00

The cost required for preparation, laying and compaction of 450 tonnes of mixture was determined and then per cubic meter rate was calculated. Since the total quantity considered for all SMA mixtures was same (450 tonnes), the machinery and labour charges were same for all cases, and were obtained as Rs. 1,56,960 and Rs. 6,725.92 respectively (The detailed calculation for the same are shown in Appendix II).

In order to calculate cost for each mixture, first the quantity of each aggregate size (20, 12.5, 10 and 6 mm), stone dust, lime, bitumen and stabilizing additive (fiber or SWP) for the producing 450 tonnes of the mixture was calculated using the adopted gradation, density, OBC and stabilizer content. Then the cost for each material and their carriage can be determined using the corresponding unit rates. Since the unit material and carriage rates for aggregates and stone dust were provided in volume (in cubic meter), instead of weight in the SOR, the quantity of these materials were converted in terms of volume. Similarly after determining the cost for 450 tonnes of mixture, which was converted to determine the cost per cubic meter of the material (A sample cost calculation is provided in the Appendix III).

CHAPTER 4

STONE MATRIX ASPHALT WITH FIBER ADDITIVES

4.1 GENERAL

Different types of fibers are generally used in SMA to control drain down and many agencies suggest the same. IRC suggests using cellulose fiber in pellet form in SMA for this purpose as a stabilizing additive, when a conventional bituminous binder is used. Mineral fibers, cellulose fibers etc. are commonly used and some researchers have tried the possibility of other different fibers.

4.2 CELLULOSE, COCONUT AND SISAL FIBERS

Cellulose fibers are plant based fibers generally extracted from different parts of plants including wood, bark, leaves, etc. High absorption property of cellulose fibers helps in increasing the binder quantity and retaining them with the aggregates in bituminous mixtures McDaniel (2015). Along with these properties, the abundant availability of cellulose fiber also made it a common stabilizing additive in SMA to control drain down. Cellulose fiber coated with low viscosity bituminous binder and made into small pellets is also used for this purpose. The pelletized fiber is not susceptible to humidity and allows rapid dispersion and a more homogeneous mixture, compared to the loose fibers. Coconut is one of the main crops in many parts of India, and the fiber is obtained from the fibrous mesocarp forming the bark of coconut. It has higher lignin content which offers the fiber a greater hardness and strength. Ngesa et al. (2011) observed that during mixing process, the coir fiber could withstand 150°C temperature for a duration of 20 minutes without altering any mechanical properties. Hadiwardoyo (2013) found that after preparation of bituminous mixture with coir fibers, 90 – 95 % of the fiber was retained without getting disintegrated. Sisal is a perennial plant which can grow in variety of weather climates including hot climates in dry areas unsuitable for other crops. Sisal fiber obtained from leaves of the plant and is considered as a hard fiber with high strength and durability (Weindling 1947).

4.3 EXPERIMENTAL INVESTIGATION

SMA mixtures were prepared with VG 30 bitumen and adopting aggregate gradations SMA 1 and SMA 2, and with the intention of controlling drain down, three types of fibers, cellulose, coconut coir and sisal were added. As suggested by IRC cellulose fiber was added in pellet from, whereas other fibers were used in loose form. Required quantity of fibers were uniformly spread in the aggregate – bitumen mix, and thorough mixing was done simultaneously to prepare a uniform mixture without fiber segregation.

Drain down test of SMA mixtures with fiber additive was conducted for loose mixtures prepared with fiber contents 0.2, 0.3 and 0.4 % by weight of mixture and minimum three trials were conducted. Cylindrical specimens were prepared in SGC with Optimum Fiber Content (OFC) determined from drain down test at bitumen contents 5.0, 5.5, 6.0, 6.5 and 7.0 per cent by weight of mixture, to check volumetric and Marshall properties. IDT strength, fatigue, retained stability and TSR tests were conducted on cylindrical specimens prepared at respective OBC for each mixture, whereas rutting test was conducted on specially prepared slab specimens.

4.4 RESULT AND DISCUSSION

4.4.1 Drain Down

Drain down test was conducted for SMA mixtures with 7% bitumen content and fiber contents 0.2, 0.3 and 0.4 % by weight of mixture and the results are presented in Figure 4.1. IRC recommends a maximum allowable drain down of 0.3%, whereas a generally recommended limit is 0.2%. Based on the results, the fiber content was fixed as 0.3% for each fiber and further tests were conducted with this dosage. After determining OBC from volumetric properties, drain down was checked for each mixture at corresponding OBC, and the results are presented in Figure 4.2.

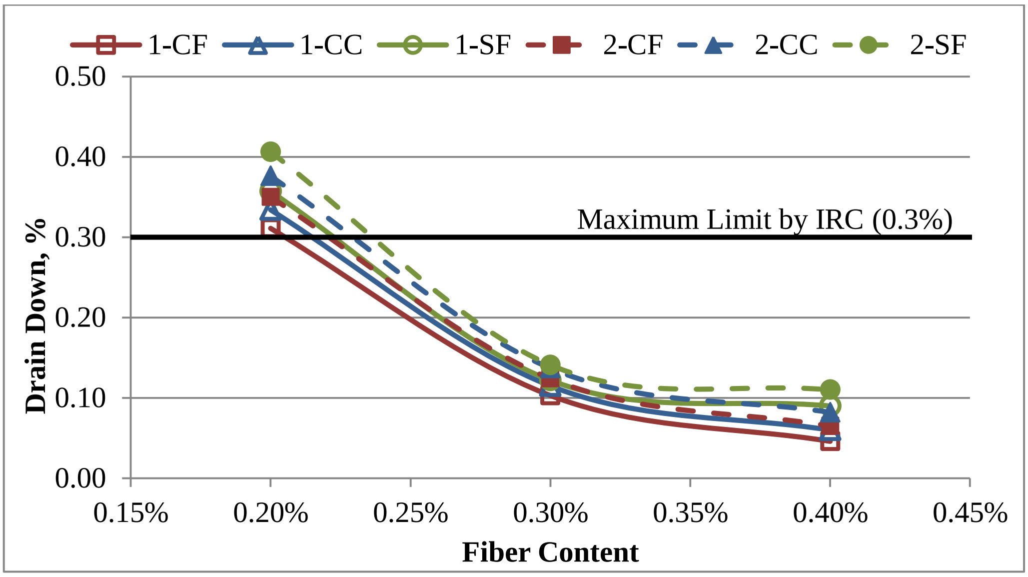


Fig. 4.1 Drain Down of SMA mixtures with Fibers

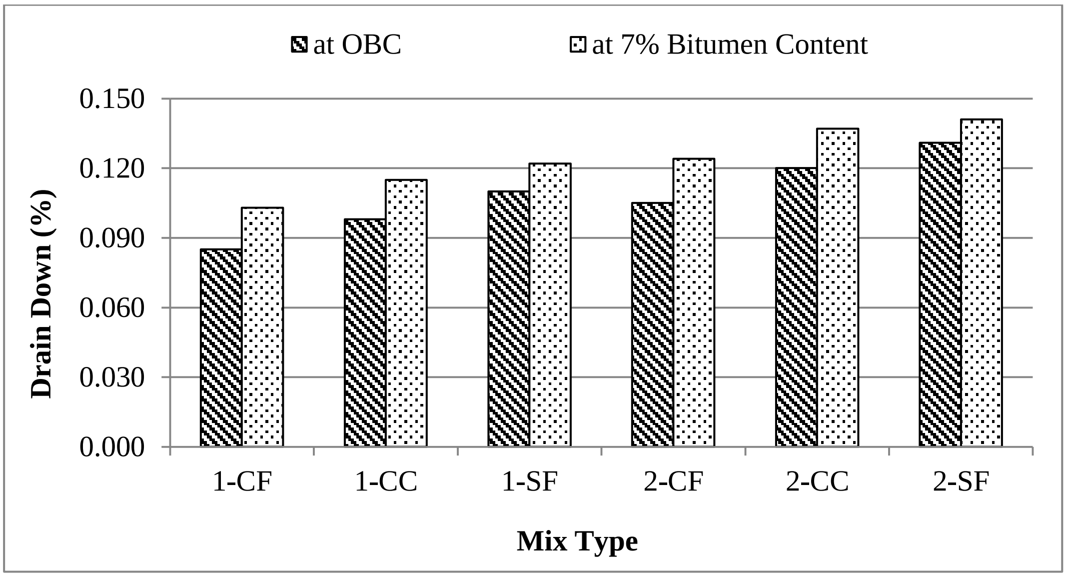


Fig. 4.2 Drain Down of SMA mixtures with 0.3% Fiber Content

4.4.2 Volumetric and Marshall Properties

Volumetric properties and Marshall characteristics of both SMA 1 and SMA 2 mixtures with cellulose fiber, coir fiber and sisal fiber are presented in Tables 4.1 –

4.6 and Figures 4.3 – 4.6. G_{mm} was observed to be decreasing with bitumen content for all the six mixtures, whereas G_{mb} increased with bitumen content first, attained a maximum value and then decreased, which is shown in Figure 4.3. Air voids were decreasing with bitumen content, following the general trend in bituminous mixtures, and the values were in the range 6.21 – 3.00 % and 6.46 – 3.06 % for SMA 1 and SMA 2 gradations respectively. VMA was observed above 17% for all mixtures, as presented in Figure 4.4, satisfying the requirement by IRC. Since VCA_{DRC} depends only on aggregate type and gradation, it does not change with bitumen and stabilizer materials. In this study it was obtained as 43.16 and 40.85 % for SMA 1 and SMA 2 respectively. VCA_{MIX} was observed to be lesser than the corresponding VCA_{DRC} value for all mixtures (Figure 4.5), ensuring the presence of stone to stone contact in them. From Figure 4.6, Marshall stability values were observed to be higher for SMA 1 mixtures compared to SMA 2 mixes, and this may be due to the increased number of coarse aggregate sizes in SMA 1 gradation. The flow values were comparatively lesser for SMA 2 mixtures for all types of fibers.

Table 4.1 Properties of SMA 1 Mixture with Cellulose Fiber (1-CF)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.487	2.468	2.449	2.430	2.412
G_{mb} (g/cc)	2.333	2.343	2.350	2.345	2.336
V_v (%)	6.19	5.07	4.05	3.53	3.13
VMA (%)	18.23	18.32	18.51	19.13	19.84
VFB (%)	66.01	72.33	78.15	81.57	84.22
VCA_{MIX} (%)	39.06	39.13	39.28	39.74	40.27
VCA_{MIX}/ VCA_{DRC}	0.905	0.907	0.910	0.921	0.933
Marshall Stability (kN)	11.05	13.03	15.57	14.24	11.62
Flow Value (mm)	2.71	2.94	3.23	3.32	3.40
Marshall Quotient (kN/mm)	4.08	4.44	4.82	4.29	3.42
OBC (%)	6.04				

Table 4.2 Properties of SMA 1 Mixture with Coconut Coir (1-CC)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.482	2.463	2.444	2.426	2.407
G_{mb} (g/cc)	2.328	2.339	2.346	2.337	2.332
V_v (%)	6.21	5.04	4.03	3.64	3.13
VMA (%)	18.40	18.46	18.66	19.38	19.99
VFB (%)	66.28	72.69	78.39	81.22	84.37
VCA_{MIX} (%)	39.20	39.24	39.39	39.92	40.38
VCA_{MIX}/ VCA_{DRC}	0.908	0.909	0.913	0.925	0.936
Marshall Stability (kN)	9.79	11.40	13.93	11.97	9.47
Flow Value (mm)	2.80	2.96	3.18	3.41	3.56
Marshall Quotient (kN/mm)	3.50	3.85	4.38	3.51	2.66
OBC (%)	6.10				

Table 4.3 Properties of SMA 1 Mixture with Sisal Fiber (1-SF)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.485	2.466	2.447	2.428	2.410
G_{mb} (g/cc)	2.331	2.340	2.347	2.340	2.337
V_v (%)	6.21	5.08	4.06	3.61	3.00
VMA (%)	18.32	18.41	18.60	19.28	19.81
VFB (%)	66.10	72.38	78.16	81.26	84.85
VCA_{MIX} (%)	39.13	39.20	39.34	39.85	40.25
VCA_{MIX}/ VCA_{DRC}	0.907	0.908	0.912	0.923	0.933
Marshall Stability (kN)	10.77	12.64	15.05	13.81	11.33
Flow Value (mm)	3.03	3.21	3.42	3.60	3.70
Marshall Quotient (kN/mm)	3.56	3.94	4.40	3.83	3.06
OBC (%)	6.12				

Table 4.4 Properties of SMA 2 Mixture with Cellulose Fiber (2-CF)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.484	2.464	2.445	2.427	2.408
G_{mb} (g/cc)	2.327	2.335	2.343	2.340	2.330
V_v (%)	6.32	5.25	4.20	3.57	3.24
VMA (%)	18.46	18.60	18.76	19.29	20.05
VFB (%)	65.78	71.79	77.62	81.47	83.85
VCA_{MIX} (%)	37.61	37.71	37.84	38.24	38.82
VCA_{MIX}/ VCA_{DRC}	0.921	0.923	0.926	0.936	0.950
Marshall Stability (kN)	9.78	11.82	13.87	12.68	10.65
Flow Value (mm)	2.59	2.81	3.02	3.14	3.23
Marshall Quotient (kN/mm)	3.77	4.20	4.59	4.04	3.29
OBC (%)	6.12				

Table 4.5 Properties of SMA 2 Mixture with Coconut Coir (2-CC)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.479	2.460	2.441	2.423	2.404
G_{mb} (g/cc)	2.319	2.325	2.337	2.334	2.328
V_v (%)	6.46	5.49	4.26	3.66	3.18
VMA (%)	18.73	18.95	18.95	19.49	20.13
VFB (%)	65.49	71.02	77.54	81.23	84.22
VCA_{MIX} (%)	37.81	37.98	37.98	38.40	38.89
VCA_{MIX}/ VCA_{DRC}	0.926	0.930	0.930	0.940	0.952
Marshall Stability (kN)	8.32	10.03	12.12	10.69	9.16
Flow Value (mm)	2.71	2.83	3.10	3.31	3.42
Marshall Quotient (kN/mm)	3.07	3.55	3.90	3.23	2.68
OBC (%)	6.19				

Table 4.6 Properties of SMA 2 Mixture with Sisal Fiber (2-SF)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.481	2.462	2.443	2.425	2.406
G_{mb} (g/cc)	2.323	2.328	2.339	2.336	2.333
V_v (%)	6.38	5.43	4.28	3.67	3.06
VMA (%)	18.59	18.83	18.90	19.44	19.97
VFB (%)	65.68	71.15	77.37	81.13	84.69
VCA_{MIX} (%)	37.71	37.89	37.95	38.35	38.76
VCA_{MIX}/ VCA_{DRC}	0.923	0.928	0.929	0.939	0.949
Marshall Stability (kN)	9.55	11.26	13.33	12.14	10.24
Flow Value (mm)	2.91	3.07	3.33	3.52	3.64
Marshall Quotient (kN/mm)	3.28	3.66	4.00	3.45	2.82
OBC (%)	6.22				

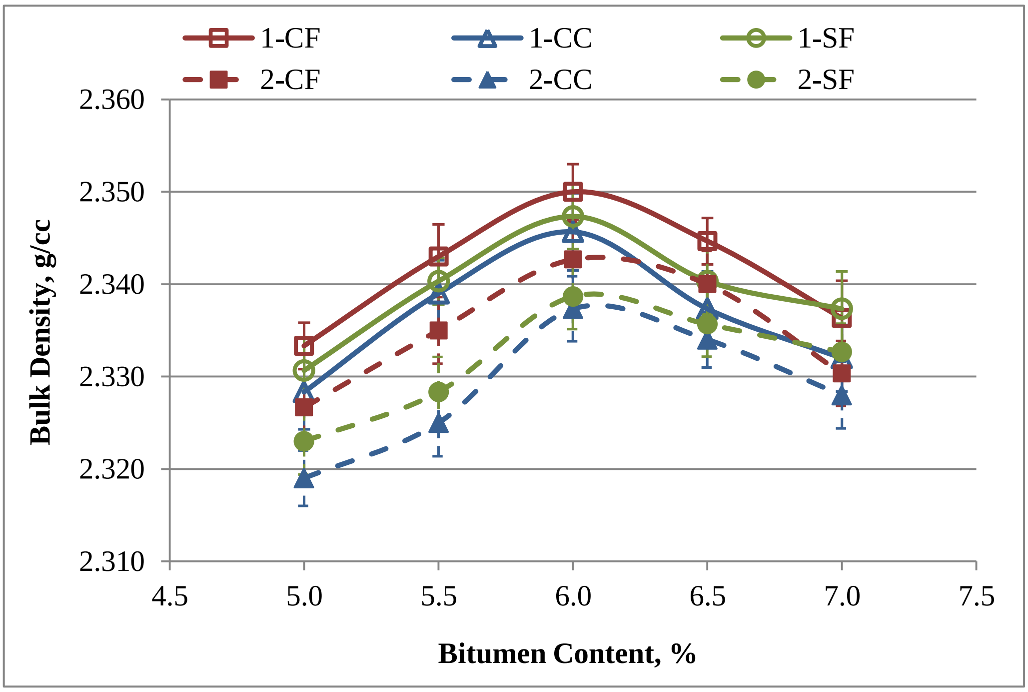


Fig. 4.3 Bulk Density of SMA Mixtures with Fiber Additives

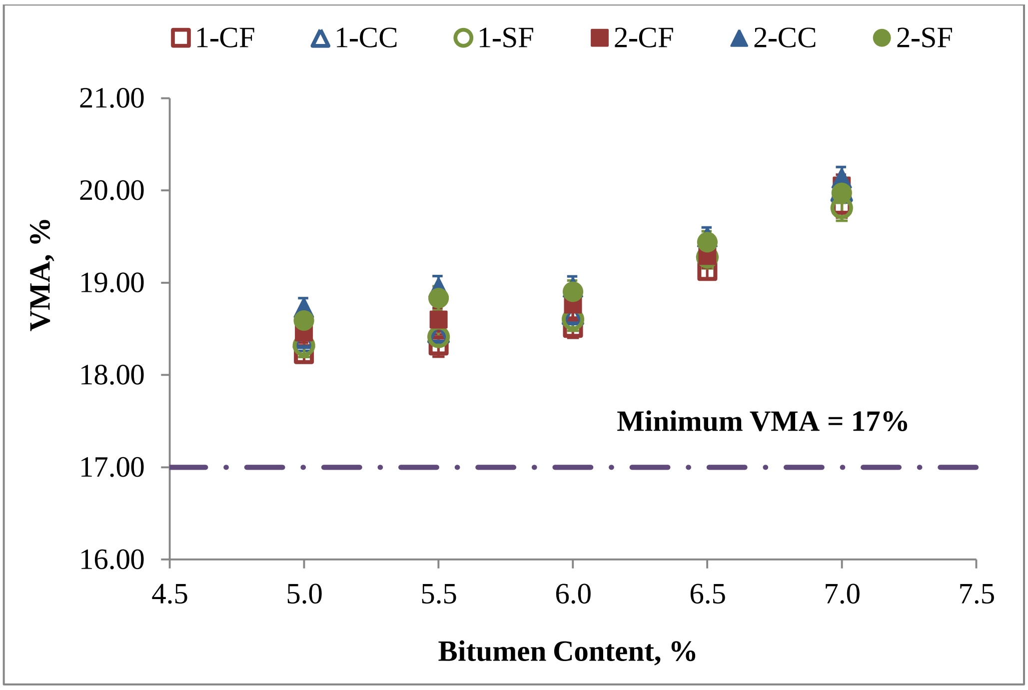


Fig. 4.4 VMA of SMA Mixtures with Fiber Additives

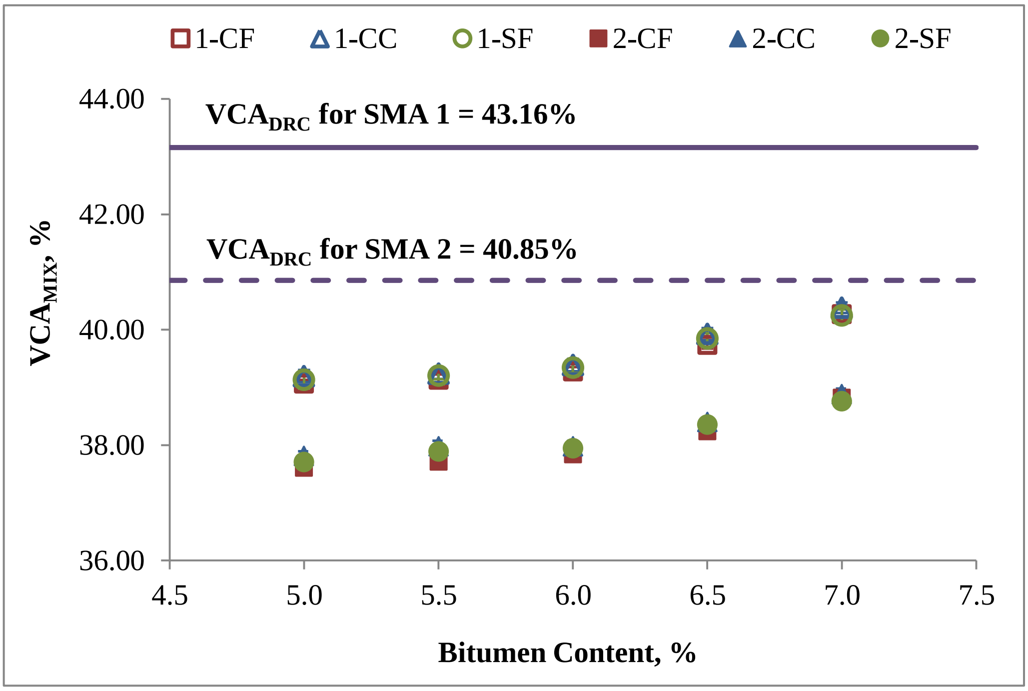


Fig. 4.5 VCA Values of SMA Mixtures with Fiber Additives

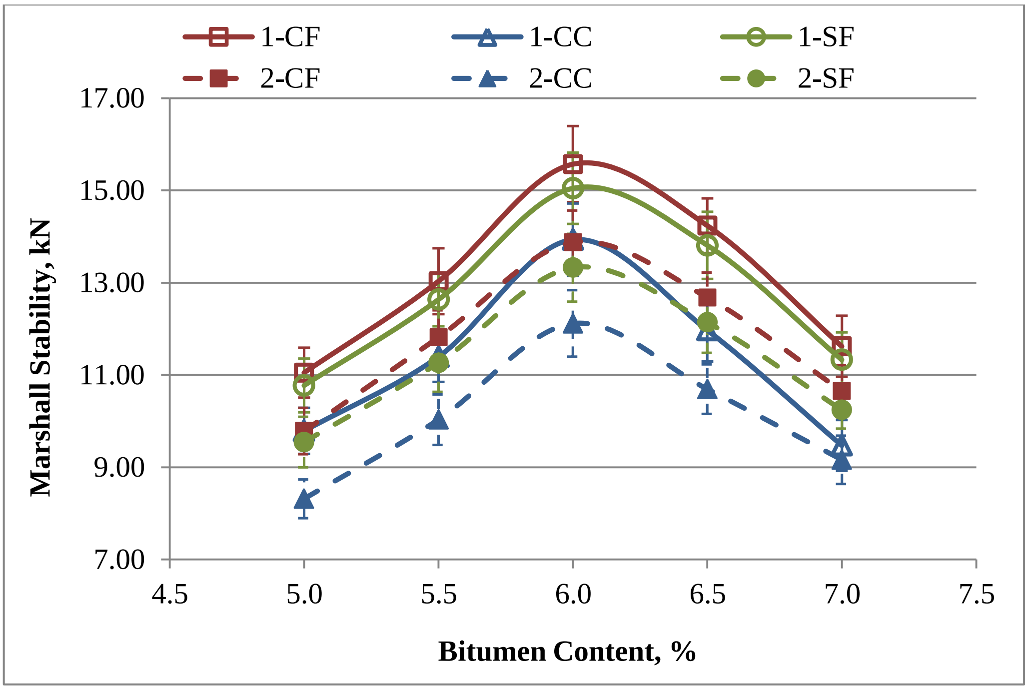


Fig. 4.6 Marshall Stability of SMA Mixtures with Fiber Additives

In SMA 1 mixtures, OBC was determined as 6.04, 6.10 and 6.12 % for CF, CCF and SF respectively, whereas it was respectively 6.12, 6.19 and 6.22 % for SMA 2 mixes. The SF had the thinnest structure compared to other fibers, resulting in more number of fibers in mixtures with more specific surface are and causing the highest OBC. Since CF is in pelletized form with a coating of bitumen, the amount of bitumen to be added is lesser, hence producing lesser OBC. Properties of mixes at OBC are presented in Table 4.7. Highest density and stability values were obtained for CF mixtures which are due to the improved properties of Cellulose Fiber. Increased tensile strength of Sisal Fiber provided better properties for SF mixtures when compared to mixes with Coir. Fibers generally result in strength improvement through bridging effect, and this gets enhanced with the presence of more number of fibers, in the case of SF mixtures.

Table 4.7 Properties of SMA Mixtures with Different Fibers at OBC

Mixture	1-CF	1-CC	1-SF	2-CF	2-CC	2-SF
OBC	6.04	6.10	6.12	6.12	6.19	6.22
G_{mm} (g/cc)	2.447	2.441	2.442	2.441	2.434	2.435
G_{mb} (g/cc)	2.350	2.345	2.347	2.343	2.338	2.339
V_v (%)	3.98	3.91	3.91	4.01	3.95	3.95
VMA (%)	18.55	18.77	18.73	18.85	19.09	19.08
VFB (%)	78.55	79.15	79.12	78.75	79.30	79.29
VCA_{MIX} (%)	39.30	39.47	39.44	37.91	38.09	38.08
VCA_{MIX}/ VCA_{DRC}	0.911	0.915	0.914	0.928	0.932	0.932
MS (kN)	15.62	13.91	15.10	13.89	11.96	13.20
Flow Value (mm)	3.25	3.23	3.47	3.06	3.20	3.42
MQ (kN/mm)	4.81	4.31	4.35	4.54	3.74	3.86

4.4.3 Indirect Tensile Strength

IDT strength was determined for SMA mixtures at OBC and the results are presented in Figure 4.7. Tensile strength was found to be higher for SMA 1 mixtures for all types of fibers and this can be attributed to the presence of more coarse aggregate sizes in the mixture compared to SMA 2. CF mixtures produced the highest strength among all mixtures and CC had the least. This difference among SMA mixtures is due to the variation in properties of fibers used.

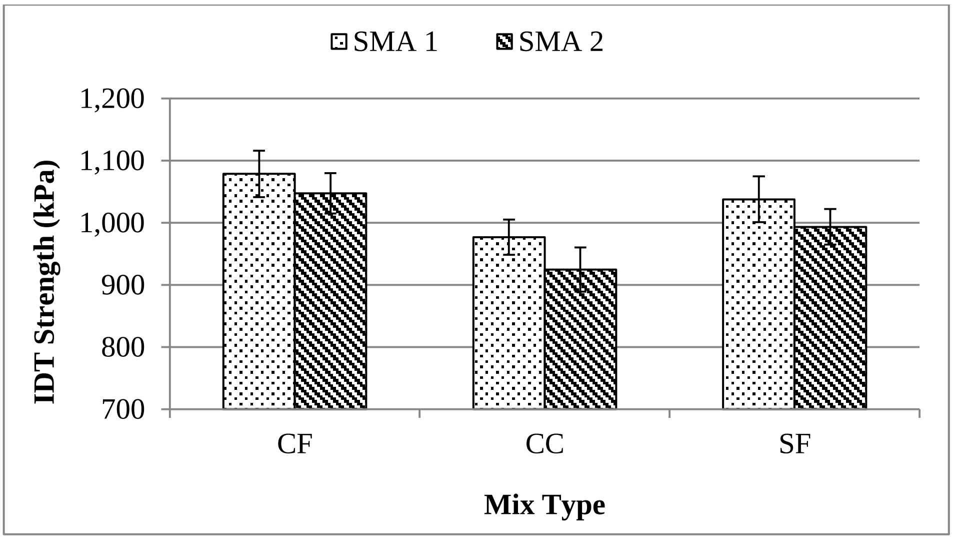


Fig. 4.7 IDT Strength of SMA Mixtures with Fiber Additives

4.4.4 Rutting Resistance

The rut deformation for each SMA mixture was determined from Wheel Tracking Device and the results are presented in Figure 4.8. The deformation recorded at all cycles was lesser for CF mixtures, which is an indication of better rut resistance. The improved rut resistance for these mixtures is due to the properties of fiber and its pellet forms. The increased properties of SF, including tensile strength, make its mixture more rut resistant than CF mixtures. The test was conducted for 10,000 wheel passes, and the final deformation for SMA 1 was 4.36, 4.86 and 4.63 mm respectively for mixes with CF, CC and SF, whereas it was respectively 4.92, 5.37 and 5.17 mm for SMA 2 mixtures.

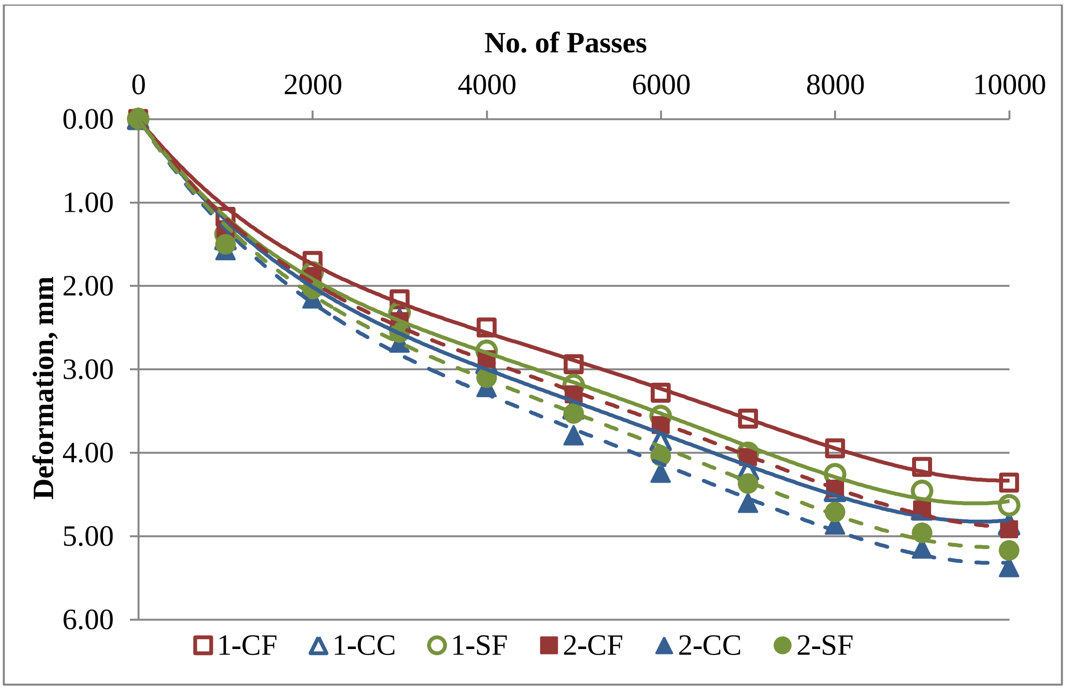


Fig. 4.8 Rutting Deformation of SMA Mixtures with Fiber Additives

4.4.5 Fatigue Behaviour

Both SMA 1 and SMA 2 specimens prepared at OBC for different fibers were tested for approximately 15, 33.3 and 67 % of the corresponding IDT failure loads and the results are presented in Table 4.8. For a particular mixture, with the increase in applied load (or load fraction), the specimen fails faster with lesser number of cycles, providing lesser FL. The improved fatigue behaviour of SMA 1 mixtures, due to their aggregate structure compared to SMA 2, is evident from the increased FL values obtained for these mixes. For SMA 1 gradation FL was observed to be the highest for CF compared to other mixes at 15 and 33 % load level, whereas it was slightly lesser for 50% load level. In the case of SMA 2 gradation for 33 and 50 % load levels, CF was having the highest FL and for 15%, SF was having the same. The dimensions of the test specimen and the load applied to it, also affect the FL value and hence FL was represented along with the tensile stress value as shown in Figure 4.9. This gives a clear indication of the fatigue behaviour of mixes and shows that CF mixes are having better fatigue behaviour than other two fibers.

Table 4.8 FL of SMA Mixtures with Fiber Additives

Mixture	Load for IDT Strength (kg)	Applied Load (kg)	Applied Load Fraction (%)	Fatigue Life
1-CF	1214.63	615.26	50.65	1908
		411.78	33.90	4784
		182.35	15.01	9245
1-CC	1097.62	547.61	49.89	1765
		366.28	33.37	4583
		165.15	15.05	8976
1-SF	1174.29	590.3	50.27	1911
		388.22	33.06	4710
		177.44	15.11	9167
2-CF	1113.52	561.63	50.44	1786
		374.53	33.63	4623
		169.44	15.22	8819
2-CC	1005.68	510.58	50.77	1682
		327.55	32.57	4456
		152.31	15.14	8817
2-SF	1098.52	541.62	49.30	1760
		358.16	32.60	4597
		157.84	14.37	8955

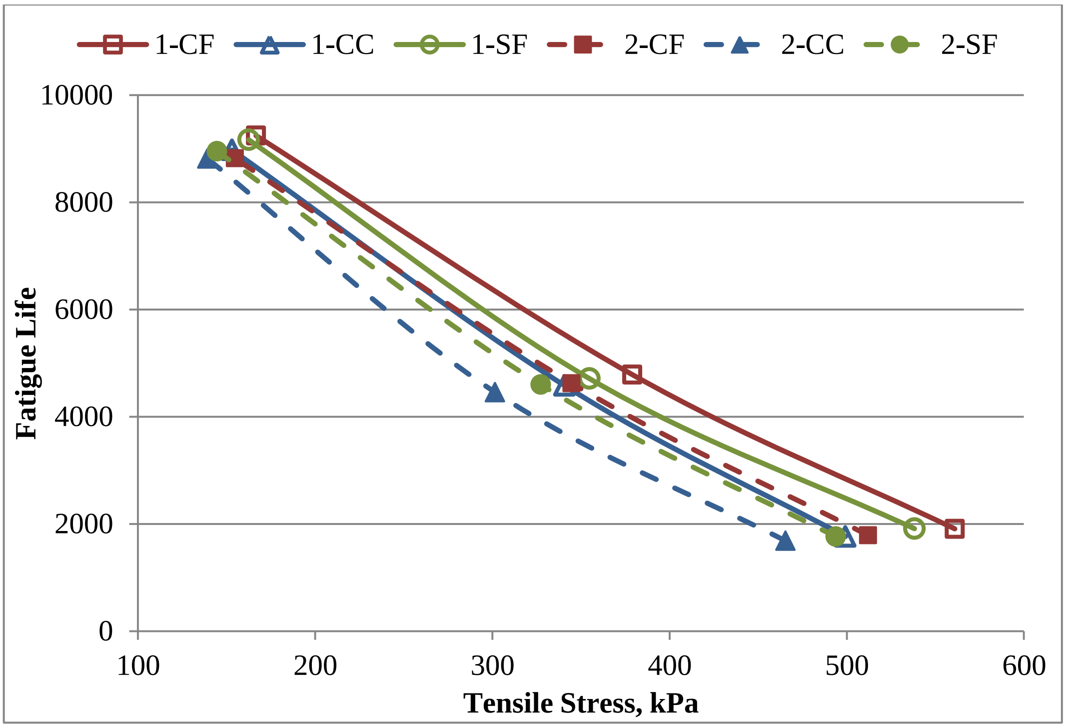


Fig. 4.9 Variation of Tensile Stress with FL for Mixtures with Fiber Additives

4.4.6 Moisture Susceptibility

4.4.6.1 Retained Stability

Retained stability test was conducted for SMA mix specimens prepared using different fibers at OBC and the results are presented in Figure 4.10 and Table 4.9. All mixtures with fiber additives showed good resistance to moisture with retaining the stability value by a minimum of 89% even after conditioning. Even though the normal and conditional stability values were higher for CF mixes compared to other mixes, retained stability value remained almost same in the range 89.4 – 92.0 % for all fibers, and even for both gradations.

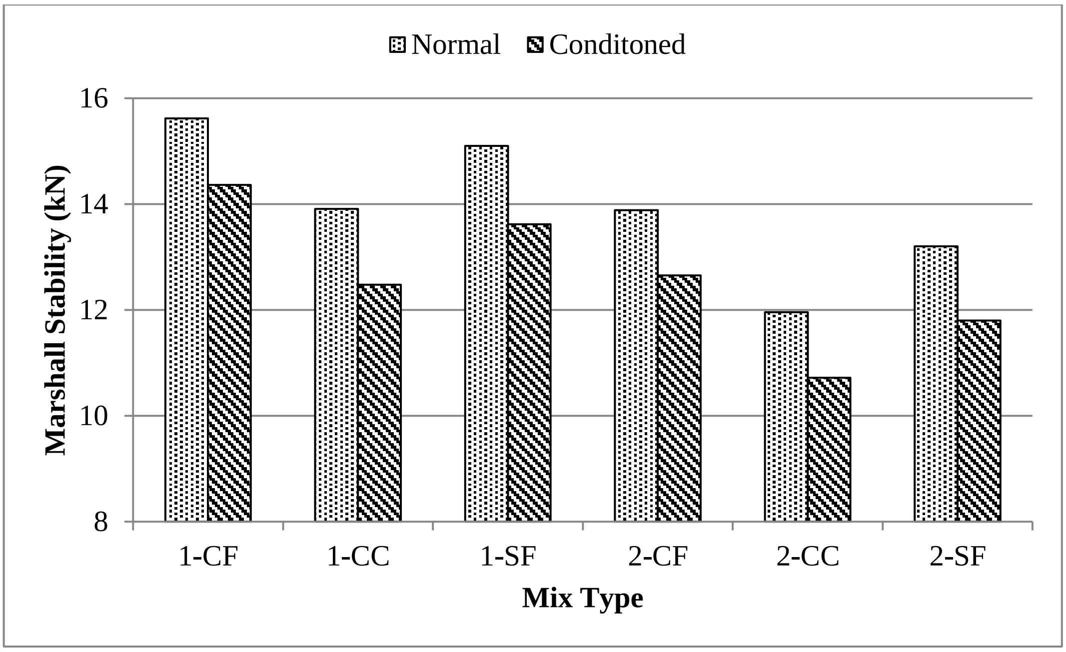


Fig. 4.10 Stability of Normal and Conditioned SMA Mixtures with Fiber Additives

Table 4.9 Retained Stability of SMA Mixtures with Fiber Additives

Mix Type	1-CF	1-CC	1-SF	2-CF	2-CC	2-SF
RS (%)	91.94	89.72	90.19	91.10	89.63	89.37

4.4.6.2 Tensile Strength Ratio

ITS test was conducted on SMA specimens prepared with 7% air voids for both unconditioned and conditioned cases to determine the moisture resistance of mixtures in terms of TSR and the results presented in Figure 4.11 and Table 4.10 are obtained. As observed in the case of IDT strength at 4% air voids, both conditioned and unconditioned ITS values (at 7% void content) were higher in the for CF mixtures. But the reduction in strength after conditioning through a freeze thaw cycle was almost same for all fiber added mixtures and the TSR was obtained as 87.5 – 89.3 %.

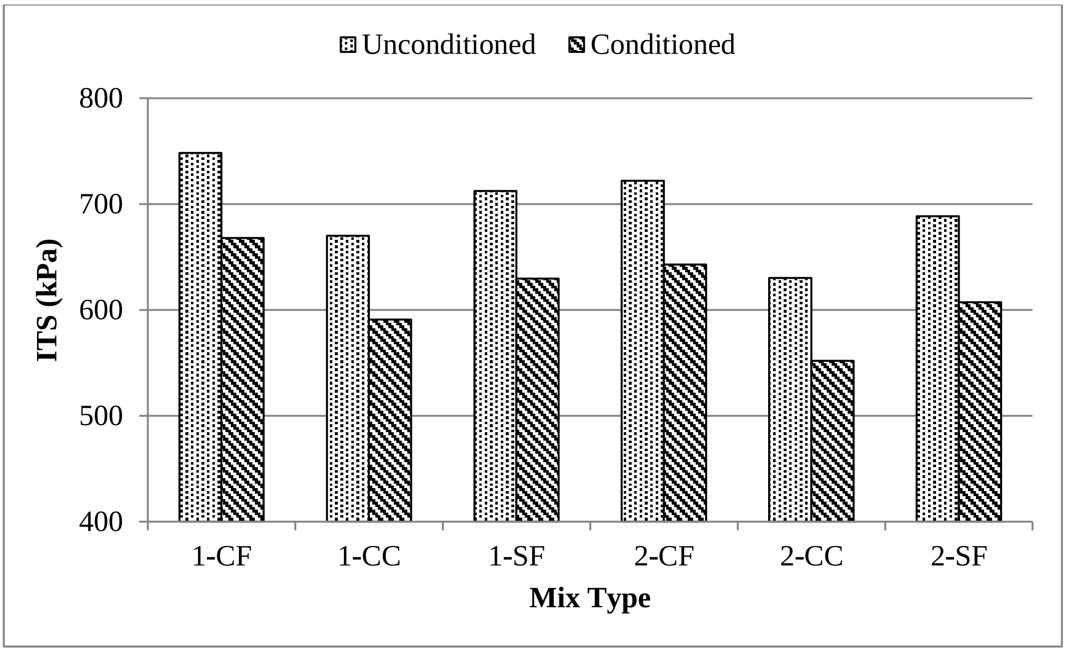


Fig. 4.11 ITS of Conditioned and Unconditioned SMA Mixtures with Fiber Additives

Table 4.10 TSR of SMA Mixtures with Fiber Additives

Mix Type	1-CF	1-CC	1-SF	2-CF	2-CC	2-SF
TSR (%)	89.24	88.19	88.35	89.02	87.59	88.20

4.4.6.3 Stripping

Boiling test was carried out on all loose SMA mixtures at their corresponding OBC and the stripping was visually observed. All mixes were observed to be resistant to stripping with about 3-4 % stripped surface area.

4.4.7 Cost Analysis

The cost analysis was conducted for all mixtures with fiber additives and the cost of materials used for preparing 450 tonnes of each mixture and their carriage costs are listed in Table 4.11. The cost per m^3 of each SMA mixture was calculated by adding machinery and labour charges, water charges and CPOH charges, and the results presented in Figure 4.12. The highest cost was obtained for CF mixtures due to the increased price of PCF. Other fiber mixtures can be produced with nearly similar cost, about 10% lesser than that of CF.

Table 4.11 Material and Carriage Cost for SMA Mixtures with Fiber Additives

Mixture	Cost of Materials and Carriage (Rs.)			
	Aggregates including Stone Dust and Lime	Bitumen	Fiber	Total
1-CF	4,99,770.34	11,18,014.32	2,02,643.76	18,20,428.42
1-CC	4,99,476.85	11,28,188.17	818.76	16,28,483.78
1-SF	4,99,364.79	11,32,072.74	2,168.76	16,33,606.29
2-CF	5,02,312.56	11,32,072.74	2,02,643.76	18,37,029.06
2-CC	5,01,926.08	11,45,391.24	818.76	16,48,136.08
2-SF	5,01,791.89	11,50,015.72	2,168.76	16,53,976.37

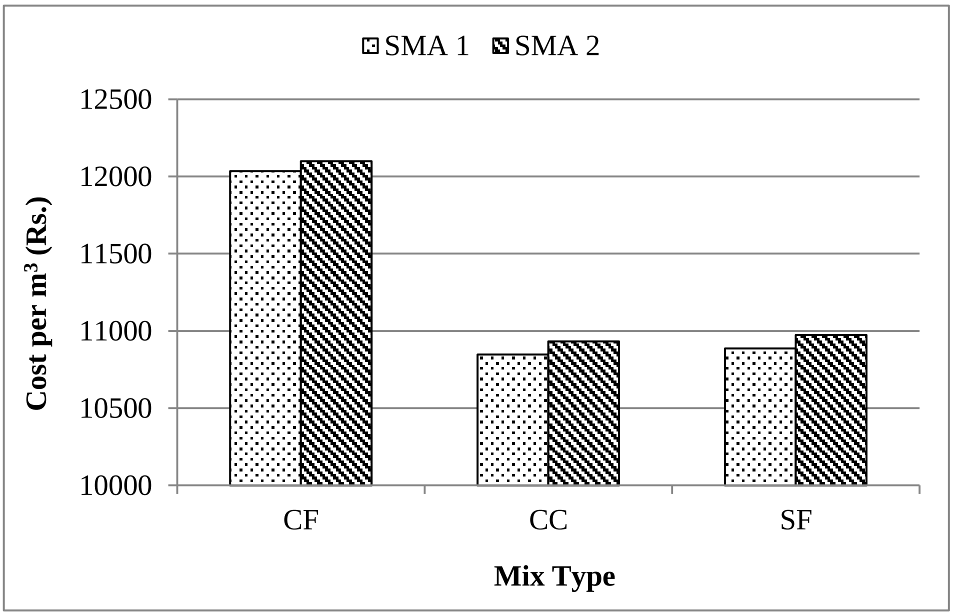


Fig. 4.12 Cost of SMA Mixtures with Fiber Additives

4.5 SUMMARY

In this chapter the preparation and laboratory performance of SMA mixtures with CF, CC and SF additives were discussed. Many countries and transportation agencies suggests cellulose fiber as a stabilizer additive in SMA. IRC also suggest using cellulose fiber in pelletized form for the same and hence CF mixtures prepared in this study can be considered as control SMA mixtures. Drain down test had proved that, CF, CC and SF can be used as stabilizing additives, since they are able to control drain down in the SMA mixture with VG 30. Based on the results by considering a safer drain down limit of 0.2% and the suggestion by IRC, the fiber content was fixed as 0.3% by weight of mix for all the three types of fibers. Out of the three fibers used, CF produced SMA mixture with better volumetric and Marshall properties, by virtue of the fiber properties and the pelletized structure. The increased density and strength of SF compared to CC made the SMA mixtures with SF superior to that with CC. Moreover, the increased number of SF in the mixture provided higher networking effect compared to CC. Considering all the mixtures in both gradations, usage of CC and SF fiber could produce mixes with 86 – 97 % Marshall stability of conventional CF mixtures. For both gradations, CF mixtures had the least OBC values and the highest was obtained for SF, due to the higher number and surface area compared to CC. The highest IDT strength was also observed for CF mixtures (1078.7kPa for SMA 1 and 1047.2kPa for SMA 2) and mix with SF showed more strength than CC mixture. The IDT strength decrease from CF mixtures was only 40 – 54 kPa for SF mixes whereas this difference was 101 – 123 kPa for CC mixes. In rutting test, deformation was lesser for CF mixtures at all wheel passes indicating their higher rut resistance capacity. CC mixtures showed the maximum deformation among all mixes tested with both aggregate gradations. For fatigue behaviour also similar trend as in the case of other properties was followed, by obtaining better characteristics for CF mixtures. Among loose fibers, SF specimens performed well by withstanding for more number of cycles in all cases, even though higher load was applied to them compared to CC specimens. Higher stability values were obtained for CF mixture specimens before and after conditioning and SF mixes showed a decrease of just 0.5 – 0.9 kN from these values. Even though stability values were lesser for CC mixes, they showed retained stability similar to SF mixtures, and for all mixtures it was in the range 89.3 – 92.0 %. Moisture resistance of SMA mixtures with fiber additives was evident also from the TSR, where all specimens showed a value higher than 87.5%.

The cost per cubic meter was obtained as more than 12,000 Rs. for CF mixtures, whereas CC and SF showed lesser (by 9 – 10 % compared to CF) cost.

All laboratory test conducted in the study indicated that SMA 1 gradation produced better mixtures than SMA 2, except in the case of moisture resistance, which was observed to be similar for both gradations. The better performance of SMA 1 mixtures is due to the higher NMAS and the presence of more coarse aggregate sizes, compared to SMA 2. The cost of SMA 2 mixtures for one cubic meter was 60 – 90 rupees higher than that of corresponding SMA 1 mixes.

CHAPTER 5

STONE MATRIX ASPHALT WITH MODIFIED BITUMEN

5.1 GENERAL

Mixtures prepared with bitumen modified with suitable additives in appropriate proportions perform better than mixes with conventional bitumen. Modified bituminous binders are expected to produce SMA mixtures without severe drain down, even in the absence of any stabilizing additive.

5.2 EXPERIMENTAL INVESTIGATION

SMA mixtures were prepared with aggregate gradations SMA 1 and SMA 2, using three types of modified bituminous binders, PMB 40, PMB 70 and CRMB 60, without any stabilizing additives. Drain down test of SMA mixtures with modified binders was conducted for loose mixtures prepared at 7% bitumen content. Cylindrical specimens were prepared in SGC at bitumen contents 5.0, 5.5, 6.0, 6.5 and 7.0 per cent by weight of mix, to check volumetric and Marshall properties. Cylindrical specimens were prepared at respective OBC for each mixture for IDT strength, fatigue, retained stability and TSR tests and slab specimens were used for rutting test.

5.3 RESULT AND DISCUSSION

5.3.1 Drain Down

Drain down test was conducted for SMA mixtures with different SWP contents at 7% bitumen content and the results were observed as depicted in Figure 5.1. After fixing OBC, drain down was determined for each mixture at corresponding OBC, and the values are shown.

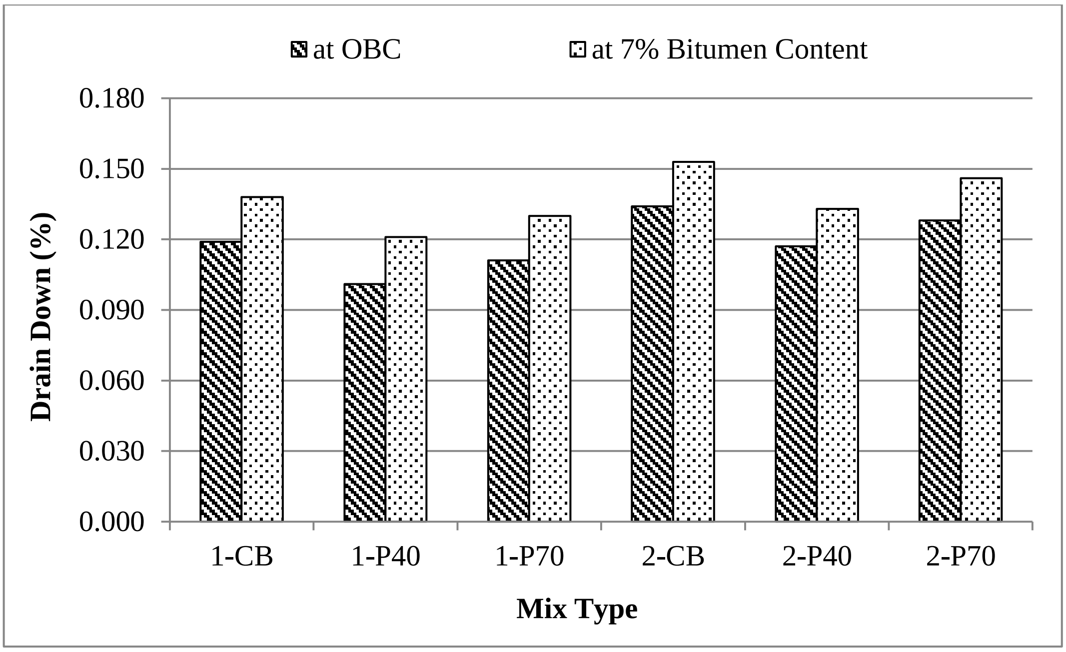


Fig. 5.1 Drain Down of SMA mixtures with Modified Bitumen

5.3.2 Volumetric and Marshall Properties

Volumetric properties and Marshall characteristics of both SMA 1 and SMA 2 mixtures with CRMB, PMB 40 and PMB 70 are presented in Tables 5.1 – 5.6 and Figures 5.2 – 5.5. G_{mm} followed the general trend of decreasing with bitumen content for all mixtures, whereas G_{mb} increased with bitumen content first and decreased after reaching maximum value at about 6% bitumen content as in Figure 5.2. Air voids also followed the general trend, providing values in the range 3.27 – 6.33 % and 3.21 – 6.47 % for SMA 1 and SMA 2 gradations respectively, and VMA was obtained as more than 17% (Figure 5.3). VCA_{DRC} was obtained as 43.16 and 40.85 % for SMA 1 and SMA 2 respectively, as mentioned in previous chapter. It can be seen from Figure 5.4 that VCA_{MIX} values lesser than these VCA_{DRC} values indicates the presence of stone to stone contact in the SMA mixtures. As in the case of volumetric properties, Marshall stability values were also observed to be better for SMA 1 mixtures compared to SMA 2 mixes, as presented in Figure 5.5. Flow was in the range 2.97 – 4.08 mm and 2.91 – 3.86 mm for SMA 1 and SMA 2 respectively.

Table 5.1 Properties of SMA 1 Mixture with CRMB (1-CB)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.492	2.473	2.454	2.436	2.417
G_{mb} (g/cc)	2.337	2.348	2.355	2.344	2.331
V_v (%)	6.20	5.04	4.04	3.77	3.58
VMA (%)	17.84	17.88	18.09	18.92	19.80
VFB (%)	65.22	71.84	77.69	80.06	81.90
VCA_{MIX} (%)	38.77	38.81	38.96	39.58	40.23
VCA_{MIX}/ VCA_{DRC}	0.898	0.899	0.903	0.917	0.932
Marshall Stability (kN)	12.53	15.57	16.05	15.34	13.13
Flow Value (mm)	2.98	3.27	3.65	3.77	3.91
Marshall Quotient (kN/mm)	4.21	4.76	4.40	4.07	3.36
OBC (%)	6.06				

Table 5.2 Properties of SMA 1 Mixture with PMB 40 (1-P40)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.507	2.488	2.469	2.450	2.432
G_{mb} (g/cc)	2.351	2.365	2.372	2.364	2.352
V_v (%)	6.23	4.95	3.92	3.54	3.28
VMA (%)	17.36	17.30	17.48	18.22	19.05
VFB (%)	64.09	71.42	77.59	80.58	82.80
VCA_{MIX} (%)	38.42	38.38	38.51	39.06	39.68
VCA_{MIX}/ VCA_{DRC}	0.890	0.889	0.892	0.905	0.919
Marshall Stability (kN)	15.31	17.19	18.60	16.72	14.86
Flow Value (mm)	3.15	3.50	3.76	3.81	3.95
Marshall Quotient (kN/mm)	4.86	4.91	4.94	4.38	3.76
OBC (%)	5.92				

Table 5.3 Properties of SMA 1 Mixture with PMB 70 (1-P70)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.496	2.476	2.458	2.439	2.421
G_{mb} (g/cc)	2.338	2.353	2.359	2.351	2.340
V_v (%)	6.33	4.97	4.00	3.61	3.32
VMA (%)	17.83	17.71	17.94	18.66	19.46
VFB (%)	64.50	71.93	77.72	80.68	82.95
VCA_{MIX} (%)	38.77	38.68	38.85	39.39	39.99
VCA_{MIX}/ VCA_{DRC}	0.898	0.896	0.900	0.913	0.927
Marshall Stability (kN)	13.14	15.26	17.60	15.94	14.33
Flow Value (mm)	3.08	3.52	3.80	3.89	4.08
Marshall Quotient (kN/mm)	4.26	4.33	4.64	4.10	3.52
OBC (%)	6.00				

Table 5.4 Properties of SMA 2 Mixture with CRMB (2-CB)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.488	2.469	2.450	2.432	2.414
G_{mb} (g/cc)	2.327	2.338	2.348	2.343	2.333
V_v (%)	6.46	5.31	4.19	3.64	3.34
VMA (%)	18.17	18.23	18.33	18.91	19.70
VFB (%)	64.45	70.89	77.14	80.75	83.03
VCA_{MIX} (%)	37.40	37.44	37.52	37.96	38.57
VCA_{MIX}/ VCA_{DRC}	0.915	0.917	0.918	0.929	0.944
Marshall Stability (kN)	11.98	12.5	14.91	13.73	11.52
Flow Value (mm)	2.91	3.17	3.53	3.68	3.77
Marshall Quotient (kN/mm)	4.12	3.95	4.22	3.73	3.05
OBC (%)	6.14				

Table 5.5 Properties of SMA 2 Mixture with PMB 40 (2-P40)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.501	2.482	2.463	2.444	2.426
G_{mb} (g/cc)	2.344	2.357	2.366	2.353	2.348
V_v (%)	6.27	5.01	3.94	3.72	3.22
VMA (%)	17.59	17.55	17.70	18.57	19.18
VFB (%)	64.36	71.47	77.72	79.96	83.24
VCA_{MIX} (%)	36.95	36.93	37.04	37.70	38.17
VCA_{MIX}/ VCA_{DRC}	0.905	0.904	0.907	0.923	0.934
Marshall Stability (kN)	12.72	14.92	16.71	15.88	13.65
Flow Value (mm)	2.92	3.34	3.58	3.70	3.81
Marshall Quotient (kN/mm)	4.36	4.47	4.66	4.29	3.58
OBC (%)	6.08				

Table 5.6 Properties of SMA 2 Mixture with PMB 70 (2-P70)

Property	**Bitumen content by weight of aggregate**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.491	2.472	2.454	2.435	2.417
G_{mb} (g/cc)	2.332	2.345	2.352	2.346	2.337
V_v (%)	6.41	5.15	4.14	3.64	3.30
VMA (%)	18.02	17.99	18.18	18.81	19.56
VFB (%)	64.42	71.37	77.24	80.64	83.13
VCA_{MIX} (%)	37.28	37.26	37.40	37.89	38.46
VCA_{MIX}/ VCA_{DRC}	0.913	0.912	0.916	0.927	0.942
Marshall Stability (kN)	12.08	13.09	15.85	14.23	12.56
Flow Value (mm)	3.00	3.35	3.63	3.75	3.85
Marshall Quotient (kN/mm)	4.02	3.90	4.37	3.80	3.26
OBC (%)	6.12				

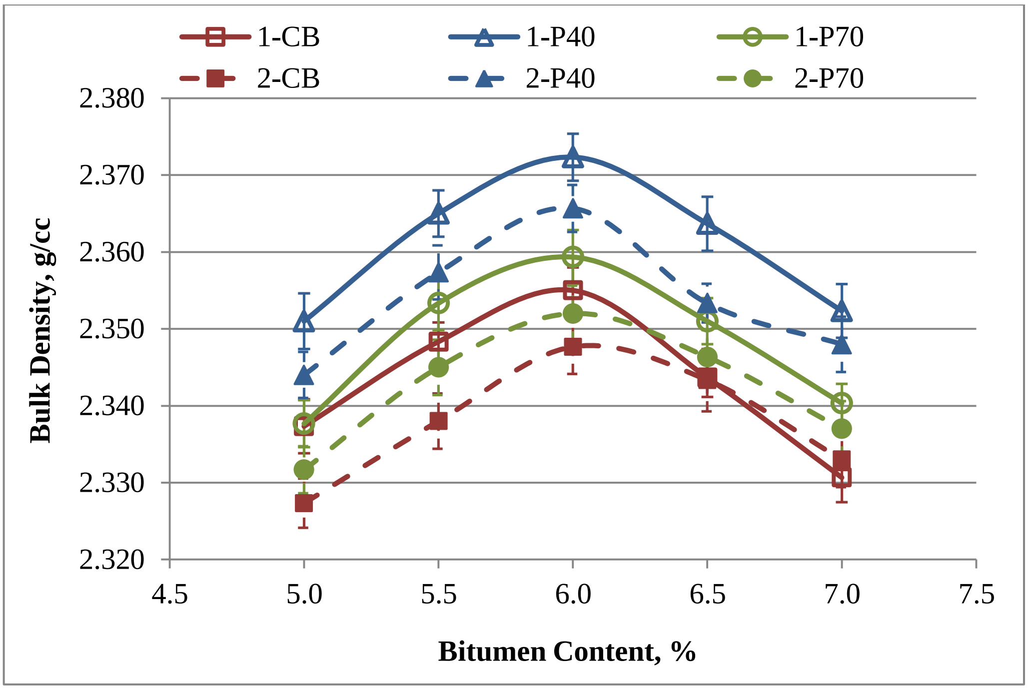


Fig. 5.2 Bulk Density of SMA Mixtures with Modified Bitumen

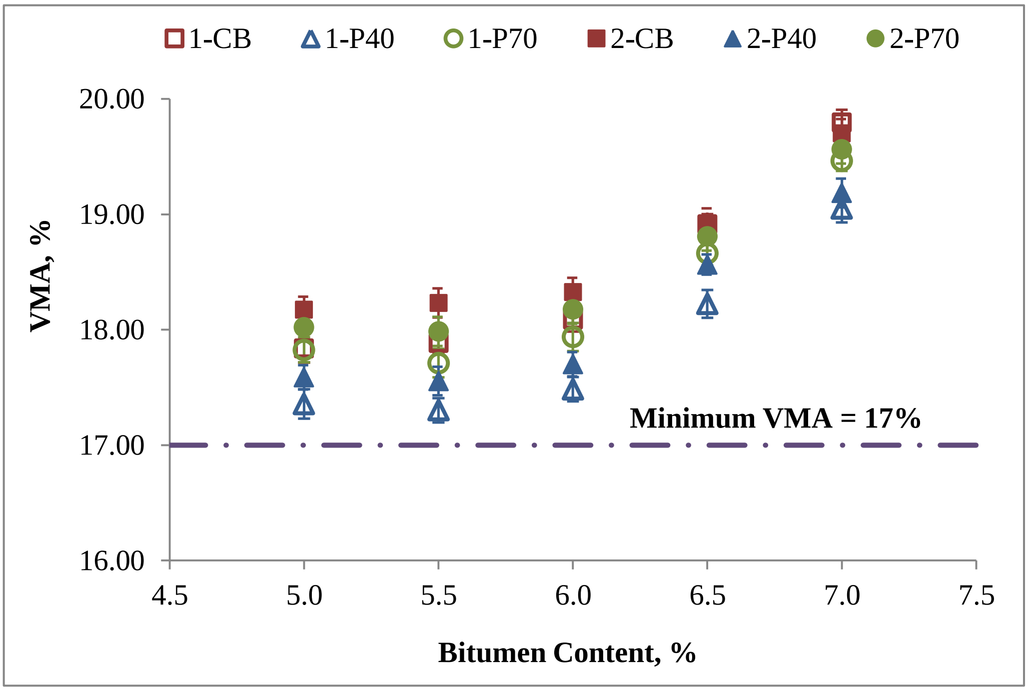


Fig. 5.3 VMA of SMA Mixtures with Modified Bitumen

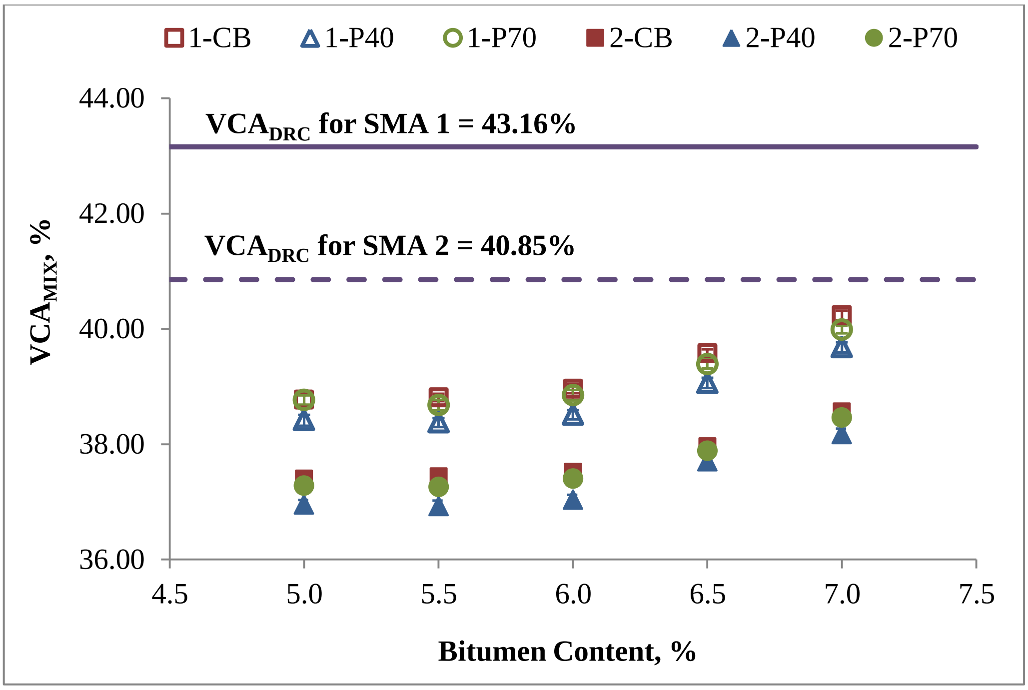


Fig. 5.4 VCA Values of SMA Mixtures with Modified Bitumen

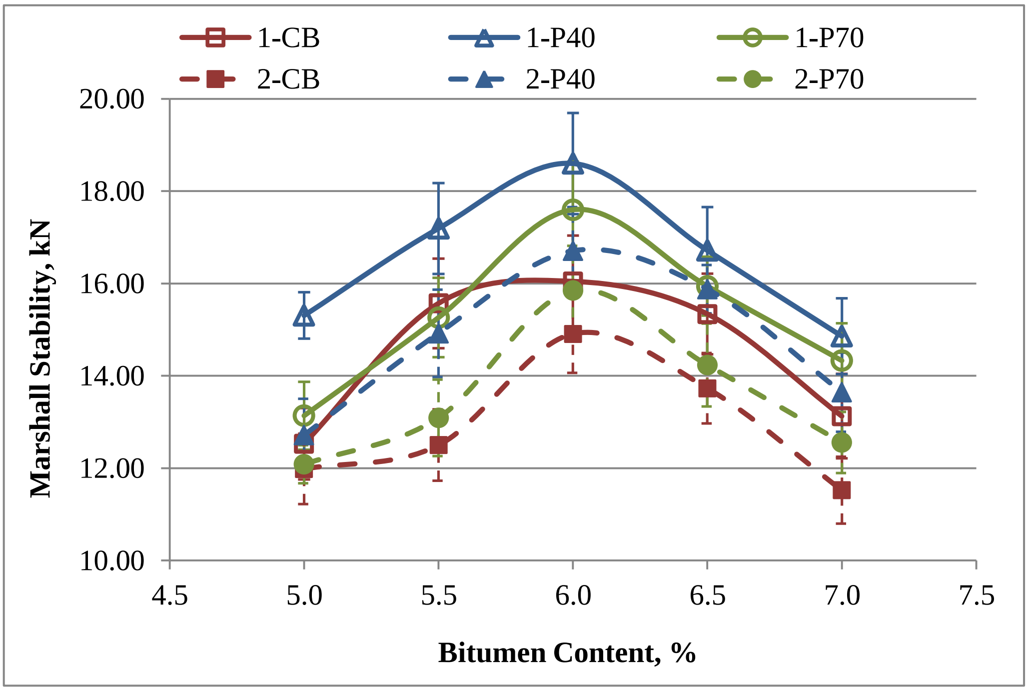


Fig. 5.5 Marshall Stability of SMA Mixtures with Modified Bitumen

In SMA 1 mixtures, OBC was determined as 6.06, 5.92 and 6.00 % for CB, P40 and P70 respectively, whereas it was respectively 6.14, 6.08 and 6.12 % for SMA 2 mixes. Properties of mixes at OBC are presented in Table 5.7

Table 5.7 Properties of SMA Mixtures with Modified Bitumen at OBC

Mixture	**1-CB**	**1-P40**	**1-P70**	**2-CB**	**2-P40**	**2-P70**
OBC (%)	6.06	5.92	6.00	6.14	6.08	6.12
G_{mm} (g/cc)	2.452	2.472	2.457	2.445	2.460	2.449
G_{mb} (g/cc)	2.355	2.372	2.359	2.348	2.365	2.352
V_v (%)	3.97	4.03	3.99	3.98	3.86	3.98
VMA (%)	18.15	17.42	17.94	18.44	17.80	18.29
VFB (%)	78.12	76.85	77.75	78.39	78.33	78.24
VCA_{MIX} (%)	39.01	38.46	38.85	37.60	37.12	37.49
VCA_{MIX}/ VCA_{DRC}	0.904	0.891	0.900	0.920	0.909	0.918
MS (kN)	16.02	18.60	17.60	14.98	16.76	15.87
Flow Value (mm)	3.68	3.74	3.80	3.59	3.61	3.67
MQ (kN/mm)	4.36	4.97	4.63	4.17	4.64	4.33

5.3.3 Indirect Tensile Strength

IDT strength values of SMA mixtures at corresponding OBC are presented in Figure 5.6. As in the case of fiber added mixes, slightly higher tensile strength was obtained for SMA 1 mixtures for all types of bituminous binders compared to SMA 2. As expected, P40 mixtures produced the highest strength among all mixtures and this is due to the characteristics of bitumen.

5.3.4 Rutting Resistance

The rut deformations for SMA mixtures with modified bituminous binders obtained from Wheel Tracking Device are presented in Figure 5.7. The performance was observed to be better for P40 mixtures for both gradations, at all wheel passes. After 10,000 wheel passes, the deformation was obtained as 4.32, 3.59, 4.08, 4.83, 4.29 and 4.66 mm for 1-CB, 1-P40, 1-P70, 2-CB, 2-P40 and 2-P70 respectively.

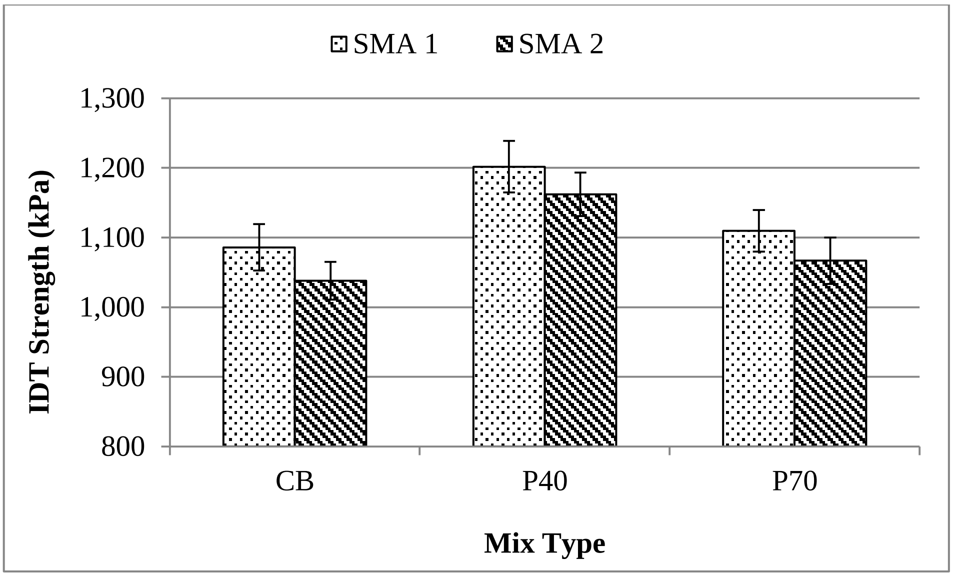


Fig. 5.6 IDT Strength of SMA Mixtures with Modified Binders

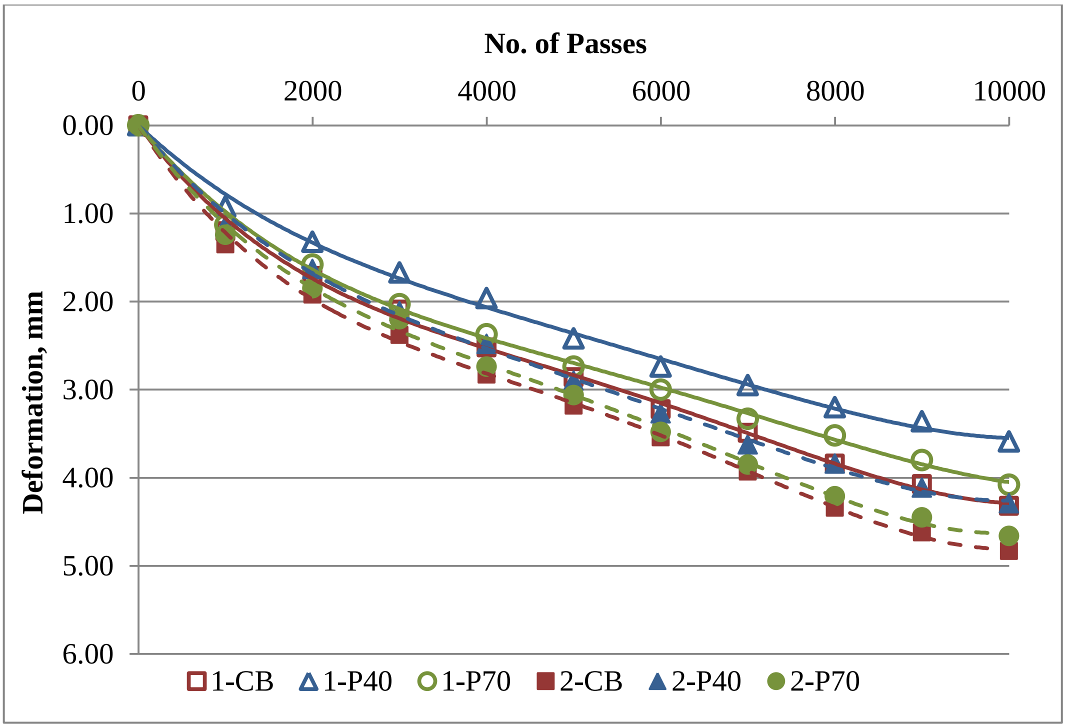


Fig. 5.7 Rutting Deformation of SMA Mixtures with Modified Binders

5.3.5 Fatigue Behaviour

All SMA specimens were tested for fatigue behaviour by applying 15, 33.3 and 50 % of the corresponding IDT failure loads and the results are tabulated in Table 5.8.

Highest FL among all mixes for SMA 1 was observed for P40 (9254 at 15% loading) and for SMA 2 it was 8895 for P70 at same loading level. The slightly lesser FL for SMA mixtures with PMB 40 in some cases is due to the higher load applied to these specimens. In order to obtain an exact idea about fatigue behaviour, variation of FL with tensile stress for mixtures is illustrated in Figure 5.8. From the figure it can be seen that among all mixtures with modified bitumen, the one with PMB 40 had increased FL for both SMA 1 and SMA 2 cases. Whereas, other mixtures (with CRMB and PMB 70) showed almost similar performance with an upper hand for P70 mixes. The improvement with SMA 1 aggregate gradation for all binder types is also clear from the test results.

Table 5.8 FL of SMA Mixtures with Modified Binders

Mixture	Load for IDT Strength (kg)	Applied Load (kg)	Applied Load Fraction (%)	Fatigue Life
1-CB	1228.59	614.5	50.02	1710
		407.69	33.18	4789
		180.19	14.67	9138
1-P40	1393.87	695.28	49.88	1720
		460.5	33.04	4657
		206.62	14.82	9254
1-P70	1286.69	642.84	49.96	1678
		429.93	33.41	4634
		197.75	15.37	9214
2-CB	1137.7	569.24	50.03	1635
		373.16	32.80	4510
		168.34	14.80	8884
2-P40	1284.79	640.16	49.83	1631
		422.37	32.87	4445
		189.36	14.74	8879
2-P70	1185.34	598.65	50.50	1603
		389.23	32.84	4412
		179.52	15.15	8895

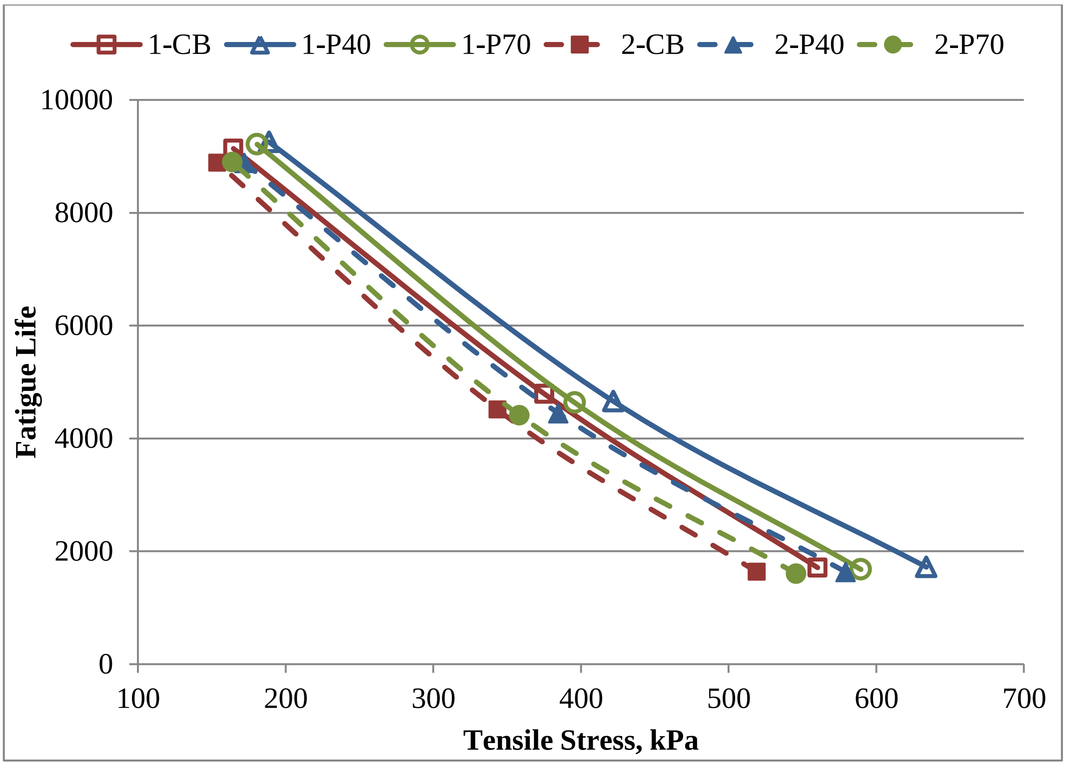


Fig. 5.8 Variation of Tensile Stress with FL for Mixtures with Modified Bitumen

5.3.6 Moisture Susceptibility

5.3.6.1 Retained Stability

Marshall stability of normal and conditioned specimens of SMA mixtures with different modified bitumen at OBC are presented in Figure 5.9 and the Retained Stability (RS) values in Table 5.9. RS was observed to be above 94% for all mixtures indicating their moisture resistance, and the highest value was obtained for 1-P40.

5.3.6.2 Tensile Strength Ratio

ITS values at 7% air voids were determined for all SMA mixtures, with and without conditioning, to determine the moisture resistance of mixtures in terms of TSR and the values shown in Figure 5.10 and Table 5.10 are observed. Highest ITS and TSR values were observed for P40 mixtures in both gradations, whereas these values were similar for other mixtures, and all mixtures with modified bitumen were having more than 92% TSR.

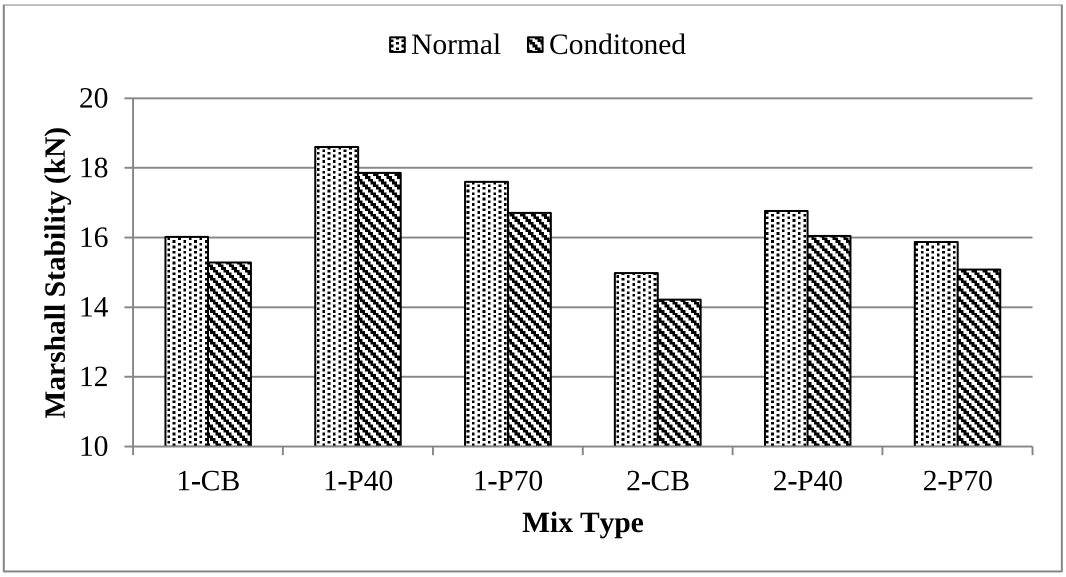


Fig. 5.9 Stability of Normal and Conditioned SMA Mixtures with Modified Bitumen

Table 5.9 Retained Stability of SMA Mixtures with Modified Bitumen

Mix Type	**1-CB**	**1-P40**	**1-P70**	**2-CB**	**2-P40**	**2-P70**
RS (%)	95.40	96.03	94.93	94.91	95.75	95.01

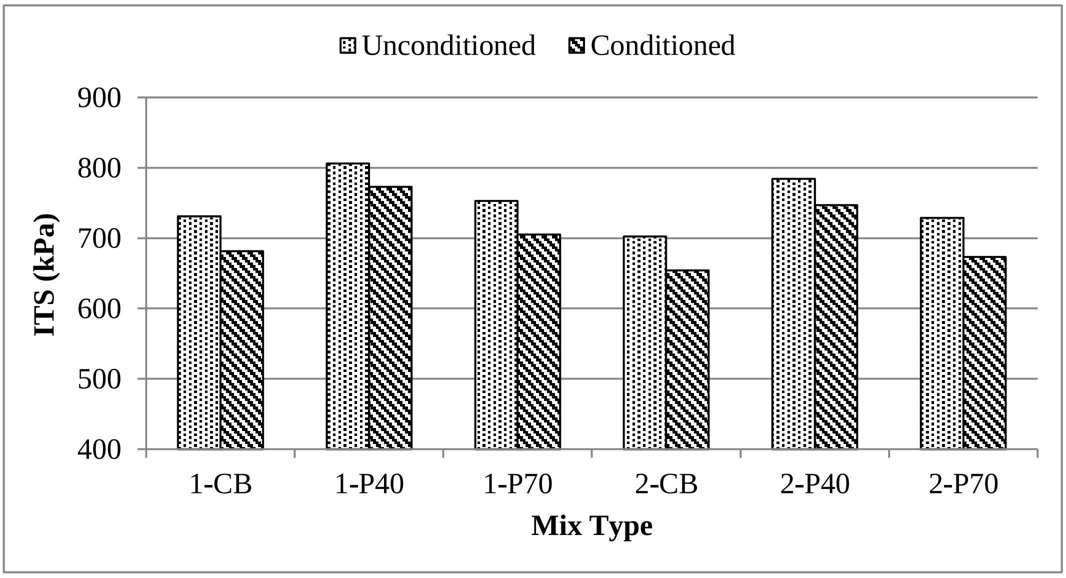


Fig. 5.10 ITS of Conditioned and Unconditioned SMA Mixtures with Modified Bitumen

Table 5.10 TSR of SMA Mixtures with Modified Bitumen

Mix Type	**1-CB**	**1-P40**	**1-P70**	**2-CB**	**2-P40**	**2-P70**
TSR (%)	93.19	95.85	93.66	93.14	95.23	92.38

5.3.6.3 Stripping

Boiling test was conducted for SMA mixtures at OBC to check the stripping behaviour of the mixes. Stripping was observed to be negligible in all mixes with less than 2% stripped surface area, and this is due to the presence of modified bituminous binder in the mixture.

5.3.7 Cost Analysis

The cost of materials required and their carriage rates for preparing 450 tonnes of SMA mixtures with modified bituminous binders are tabulated in Table 5.11. The cubic meter cost for each mixture was then calculated, after considering other necessary charges. From Figure 5.11, it can be seen that, PMB mixtures had the highest cost, due to the usage of costly PMB's. CB mixtures were 6 – 7 % more expensive than P40 mixes.

Table 5.11 Material and Carriage Cost for SMA Mixtures with Modified Bitumen

Mixture	**Cost of Materials and Carriage (Rs.)**		
	Aggregates including Stone Dust and Lime	**Bitumen**	**Total**
1-CB	5,01,301.84	14,40,601.15	19,41,902.99
1-P40	5,02,016.90	15,75,394.83	20,77,411.73
1-P70	5,01,584.66	15,69,921.15	20,71,505.81
2-CB	5,03,842.36	14,59,152.73	19,62,995.09
2-P40	5,04,121.49	16,17,951.50	21,22,072.99
2-P70	5,03,944.35	15,99,208.82	21,03,153.17

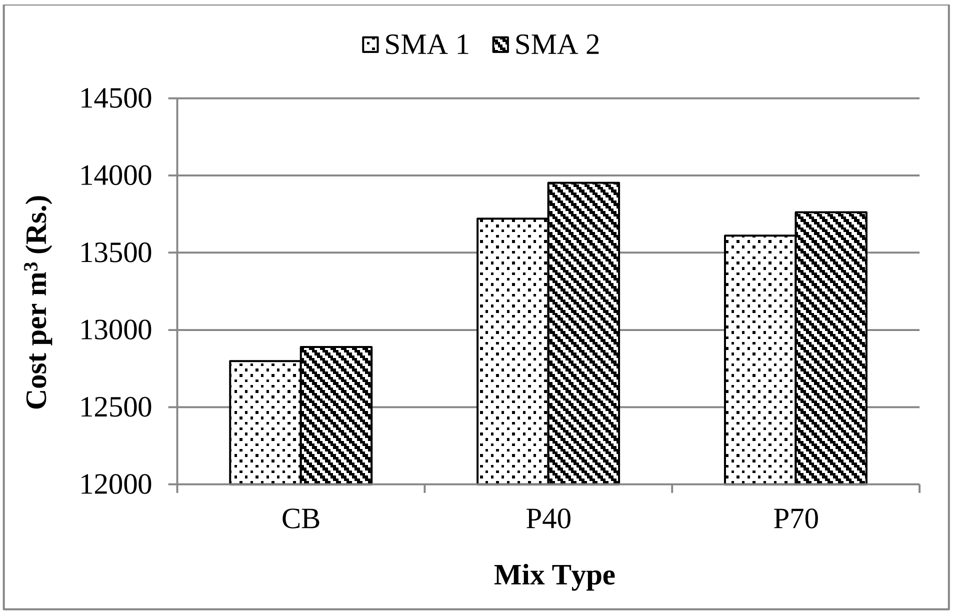


Fig. 5.11 Cost of SMA Mixtures with Modified Bitumen

5.4 SUMMARY

This chapter describes about SMA mixtures prepared with three modified bituminous binders, PMB 40, PMB 70 and CRMB and their performance in laboratory. Drain down test indicated that, with the use of these modified bituminous binders, no stabilizing additive is required to control drain down in the mixture. Volumetric and Marshall properties showed that, for both SMA 1 and 2, PMB 40 produced better mixes compared to other binders. This is due to the improved characteristics of PMB 40 binder as listed in Table 3.3 (Chapter 3). Among all SMA mixtures prepared in the study using modified bitumen, P40 mixes had the minimum OBC (5.923 % for SMA 1 and 6.083% for SMA 2) whereas it was the highest for mixes with CRMB (6.057% for SMA 1 and 6.135% for SMA 2). IDT strength, rutting resistance and fatigue behaviour also showed similar trends for SMA 1 and SMA 2 mixtures. During fatigue test, in some cases (33% load level for SMA 1 and all loading levels for SMA 2) higher FL was not obtained for P40 mixtures, but this is due to the higher load applied to P40 mixes. Marshall stability and ITS values for both conditioned and unconditioned cases also followed trend similar to other properties, but the moisture resistance of the mixtures was almost same irrespective of the binder type. The TSR was observed to be slightly lesser than RS for all mixes. The presence of polymer and rubber particles in the bituminous binder provided higher moisture resistance to the mixture with RS and TSR above 94.9 and 92.3 % respectively. Even though both PMB mixtures showed similar cost, a comparatively decreased price was observed for CB mixtures.

As observed in the case of fiber stabilized SMA mixtures, SMA 1 gradation produced better mixes than SMA 2 and this is due to the higher NMAS and presence of more coarse aggregate sizes in SMA 1 compared to SMA 2. SMA 2 mixtures were 90 – 230 rupees costlier than SMA 1 mixture (for cubic meter of the mix), and the maximum difference was obtained for P40 mixes.

CHAPTER 6

STONE MATRIX ASPHALT WITH SHREDDED WASTE PLASTICS

6.1 GENERAL

It is generally suggested incorporating suitable fibers as stabilizing additives or using modified bituminous binders to control drain down in SMA mixtures. Inclusion of appropriate waste materials as an ingredient in bituminous mixtures to improve their properties has an additional advantage of environmental friendliness. Recently in 2013, the IRC has issued guidelines for the use of waste plastics in bituminous mixtures (IRC SP 98 2013). Incorporating waste plastics in SMA mixtures, in the appropriate form, method and proportion can provide a better performing mixture without any other stabilizer materials.

6.2 EXPERIMENTAL INVESTIGATION

SMA mixtures were prepared with aggregate gradations SMA 1 and SMA 2, using VG 30 bitumen, with shredded waste plastics (SWP) as stabilizing additive. The plastic content used was 4, 8, 12 and 16 % by weight of aggregates. Drain down test of SMA mixtures with different SWP was conducted for loose mixtures prepared at 7% bitumen content. Cylindrical specimens were prepared in SGC at bitumen contents 5.0, 5.5, 6.0, 6.5 and 7.0 per cent by weight of mix, to check volumetric and Marshall properties. Cylindrical specimens were prepared at respective OBC for each mixture for IDT, fatigue, retained stability and TSR tests and slab specimens were used for rutting test.

6.3 RESULT AND DISCUSSION

6.3.1 Drain down

Drain down test was conducted for all SMA mixtures at 7% bitumen content and the results are presented in Figure 6.1. After determining the OBC for each plastic content, drain down was examined at corresponding OBC, and the values are shown.

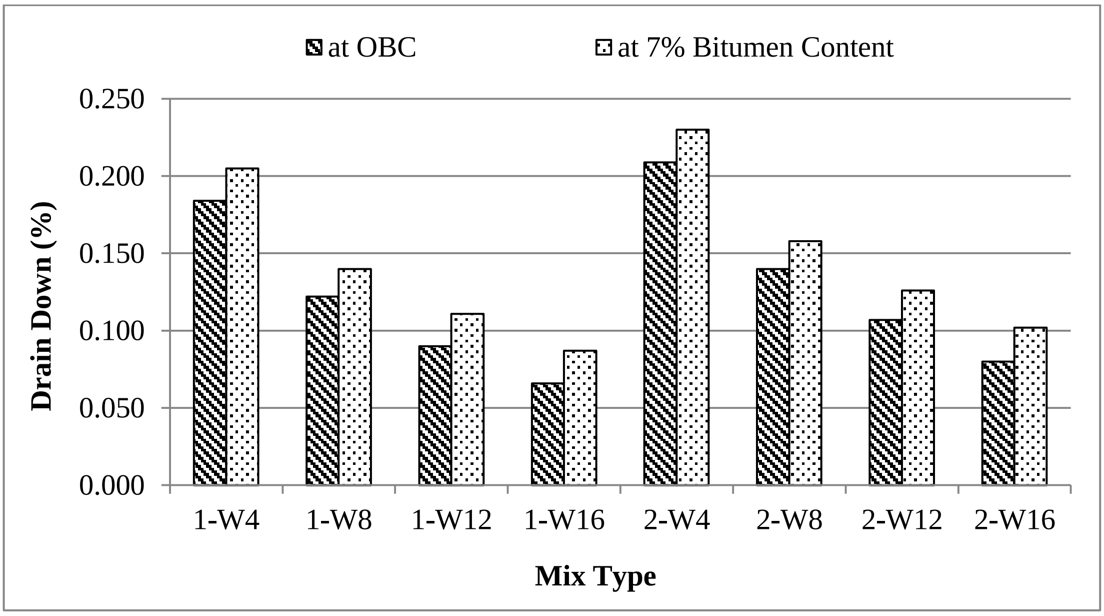


Fig. 6.1 Drain Down of SMA mixtures with SWP

6.3.2 Volumetric and Marshall Properties

Volumetric properties and Marshall characteristics of both SMA 1 and SMA 2 mixtures with different SWP contents are presented in Tables 6.1 – 6.8 and Figures 6.2 – 6.5. In all SWP mixtures, G_{mm} decreased with bitumen content and G_{mb} increased with bitumen content till 5.5 – 6.0 % to reach the maximum value and then decreased, and this trend was similar to SMA mixes with fibers and modified binders. From Figure 6.2, it is also noted that, both G_{mm} and G_{mb} decreased with the increase in SWP content, due to the inclusion of lighter plastic material. Air voids were observed to be decreasing with increase in bitumen content and plastic content, and were in the range 5.81 – 2.84 % for SMA 1 and 6.12 – 2.90 % for SMA 2 gradations respectively. Figure 6.3 shows that all mixes were satisfying the minimum air void requirement of 17%. Stone to stone contact was present in all SMA mixtures since VCA_{MIX} values were lesser than corresponding VCA_{DRC} values (43.16% for SMA 1 and 40.85% for SMA 2), which can be observed from Figure 6.4. Higher Marshall stability values were obtained for SMA 1 mixtures compared to SMA 2 (Figure 6.5), same as in the cases of mixtures with fiber additives and modified bitumen. The stability values increased with SWP content, attained maximum values and then decreased for both gradations. For all mixtures, flow values were obtained slightly lesser for SMA 2 (2.41 – 3.53 mm) compared to SMA 1 (2.58 – 3.71 mm) mixes. Addition of SWP stiffened the mixture, leading to decrease in flow values with the increase in plastic content, at all bitumen contents.

Table 6.1 Properties of SMA 1 Mixture with 4% SWP (1-W4)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.478	2.459	2.440	2.421	2.403
G_{mb} (g/cc)	2.334	2.334	2.337	2.332	2.323
V_v (%)	5.81	5.05	4.19	3.70	3.31
VMA (%)	18.14	18.56	18.91	19.55	20.29
VFB (%)	67.97	72.80	77.82	81.10	83.69
VCA_{MIX}	39.00	39.32	39.57	40.05	40.60
VCA_{MIX}/ VCA_{DRC}	0.904	0.911	0.917	0.928	0.941
Marshall Stability (kN)	10.33	11.85	14.28	12.92	10.74
Flow Value (mm)	2.84	3.16	3.48	3.61	3.71
Marshall Quotient (kN/mm)	3.64	3.75	4.11	3.58	2.89
OBC (%)	6.18				

Table 6.2 Properties of SMA 1 Mixture with 8% SWP (1-W8)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.467	2.448	2.430	2.411	2.393
G_{mb} (g/cc)	2.327	2.329	2.333	2.324	2.316
V_v (%)	5.69	4.85	3.97	3.63	3.21
VMA (%)	18.56	18.93	19.27	20.05	20.77
VFB (%)	69.34	74.37	79.39	81.91	84.55
VCA_{MIX}	39.31	39.59	39.84	40.43	40.96
VCA_{MIX}/ VCA_{DRC}	0.911	0.917	0.923	0.937	0.949
Marshall Stability (kN)	12.61	14.86	16.53	15.82	13.76
Flow Value (mm)	2.78	3.10	3.37	3.53	3.64
Marshall Quotient (kN/mm)	4.53	4.80	4.90	4.48	3.78
OBC (%)	6.04				

Table 6.3 Properties of SMA 1 Mixture with 12% SWP (1-W12)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.456	2.437	2.419	2.401	2.383
G_{mb} (g/cc)	2.321	2.325	2.327	2.319	2.311
V_v (%)	5.48	4.62	3.81	3.40	3.03
VMA (%)	18.75	19.25	19.59	20.27	21.07
VFB (%)	70.79	76.02	80.56	83.22	85.62
VCA_{MIX}	39.58	39.85	40.16	40.71	41.28
VCA_{MIX}/ VCA_{DRC}	0.917	0.923	0.931	0.943	0.957
Marshall Stability (kN)	12.25	14.37	15.52	13.91	11.60
Flow Value (mm)	2.72	3.05	3.22	3.50	3.61
Marshall Quotient (kN/mm)	4.51	4.71	4.82	3.97	3.21
OBC (%)	5.88				

Table 6.4 Properties of SMA 1 Mixture with 16% SWP (1-W16)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.443	2.425	2.407	2.389	2.371
G_{mb} (g/cc)	2.316	2.320	2.319	2.312	2.304
V_v (%)	5.22	4.31	3.65	3.23	2.84
VMA (%)	19.16	19.54	20.00	20.73	21.43
VFB (%)	72.73	77.94	81.76	84.42	86.76
VCA_{MIX}	39.85	40.10	40.51	41.07	41.63
VCA_{MIX}/ VCA_{DRC}	0.923	0.929	0.939	0.952	0.965
Marshall Stability (kN)	12.17	14.45	13.79	12.04	10.90
Flow Value (mm)	2.58	2.95	3.05	3.20	3.33
Marshall Quotient (kN/mm)	4.71	4.90	4.53	3.76	3.27
OBC (%)	5.72				

Table 6.5 Properties of SMA 2 Mixture with 4% SWP (2-W4)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.474	2.455	2.437	2.418	2.400
G_{mb} (g/cc)	2.323	2.327	2.330	2.329	2.325
V_v (%)	6.12	5.24	4.37	3.67	3.11
VMA (%)	18.51	18.83	19.16	19.64	20.22
VFB (%)	66.96	72.18	77.19	81.31	84.64
VCA_{MIX}	37.65	37.89	38.15	38.51	38.95
VCA_{MIX}/ VCA_{DRC}	0.922	0.928	0.934	0.943	0.954
Marshall Stability (kN)	8.83	10.17	12.20	11.72	9.46
Flow Value (mm)	2.78	2.98	3.21	3.40	3.53
Marshall Quotient (kN/mm)	3.17	3.41	3.81	3.44	2.68
OBC (%)	6.25				

Table 6.6 Properties of SMA 2 Mixture with 8% SWP (2-W8)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.465	2.446	2.427	2.409	2.391
G_{mb} (g/cc)	2.320	2.323	2.327	2.324	2.321
V_v (%)	5.90	5.02	4.12	3.54	2.94
VMA (%)	18.81	19.14	19.46	20.04	20.61
VFB (%)	68.64	73.79	78.81	82.36	85.74
VCA_{MIX}	37.87	38.13	38.37	38.82	39.26
VCA_{MIX}/ VCA_{DRC}	0.927	0.933	0.939	0.950	0.961
Marshall Stability (kN)	10.91	13.19	14.57	13.97	12.52
Flow Value (mm)	2.70	2.87	3.09	3.28	3.42
Marshall Quotient (kN/mm)	4.04	4.59	4.71	4.25	3.66
OBC (%)	6.12				

Table 6.7 Properties of SMA 2 Mixture with 12% SWP (2-W12)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.453	2.435	2.416	2.398	2.381
G_{mb} (g/cc)	2.316	2.319	2.321	2.318	2.310
V_v (%)	5.59	4.74	3.94	3.35	2.95
VMA (%)	19.09	19.47	19.88	20.47	21.21
VFB (%)	70.72	75.63	80.19	83.62	86.11
VCA_{MIX}	38.09	38.38	38.69	39.15	39.71
VCA_{MIX}/ VCA_{DRC}	0.932	0.939	0.947	0.958	0.972
Marshall Stability (kN)	10.44	12.56	13.83	12.46	9.71
Flow Value (mm)	2.57	2.69	2.94	3.11	3.25
Marshall Quotient (kN/mm)	4.06	4.66	4.71	4.01	2.99
OBC (%)	5.95				

Table 6.8 Properties of SMA 2 Mixture with 16% SWP (2-W16)

Property	**Bitumen content by weight of mix**				
	5.0	**5.5**	**6.0**	**6.5**	**7.0**
G_{mm} (g/cc)	2.440	2.421	2.403	2.386	2.368
G_{mb} (g/cc)	2.307	2.311	2.313	2.307	2.299
V_v (%)	5.46	4.57	3.76	3.31	2.90
VMA (%)	19.60	19.95	20.37	21.08	21.83
VFB (%)	72.16	77.08	81.55	84.32	86.72
VCA_{MIX}	38.48	38.75	39.07	39.61	40.18
VCA_{MIX}/ VCA_{DRC}	0.942	0.949	0.956	0.970	0.984
Marshall Stability (kN)	10.42	12.18	12.86	11.20	9.71
Flow Value (mm)	2.41	2.70	2.83	2.97	3.15
Marshall Quotient (kN/mm)	4.33	4.52	4.55	3.77	3.09
OBC (%)	5.84				

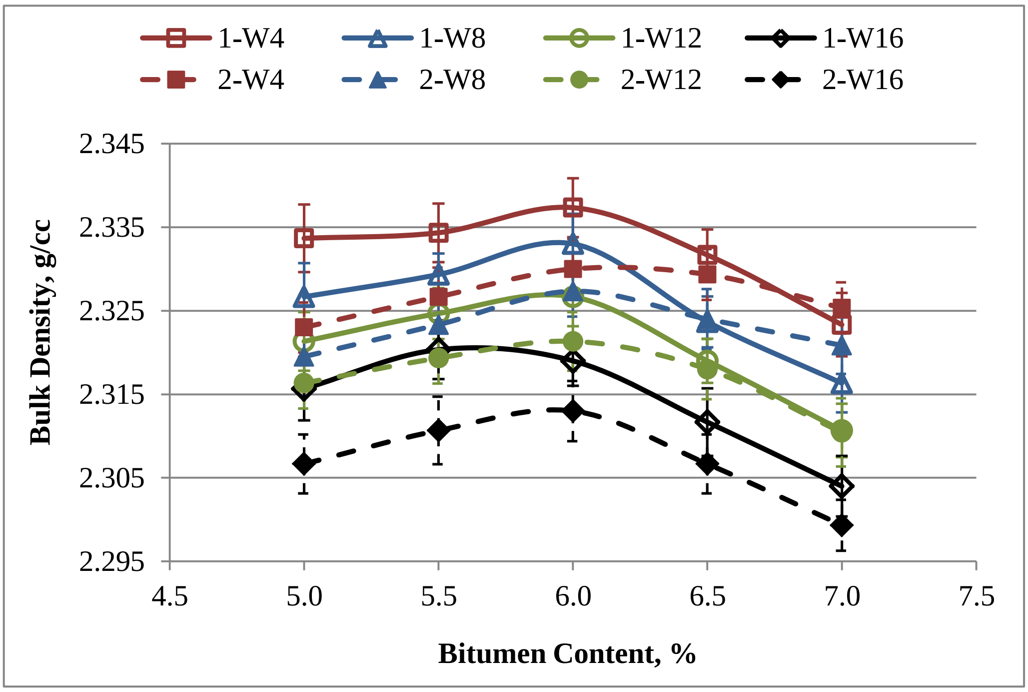


Fig. 6.2 Bulk Density of SMA Mixtures with SWP

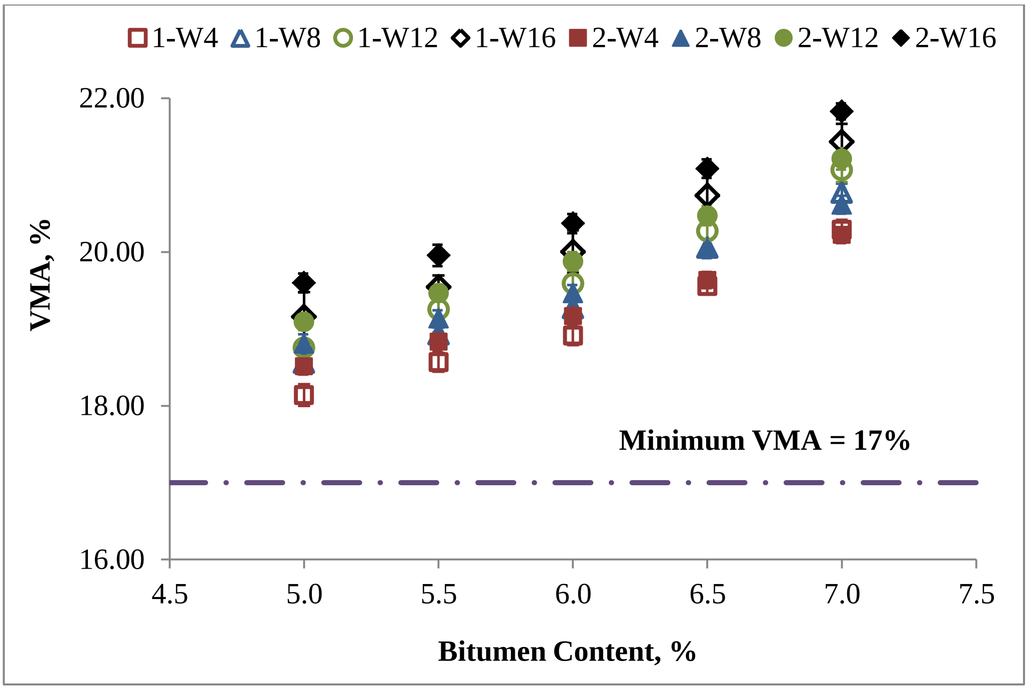


Fig. 6.3 VMA of SMA Mixtures with SWP

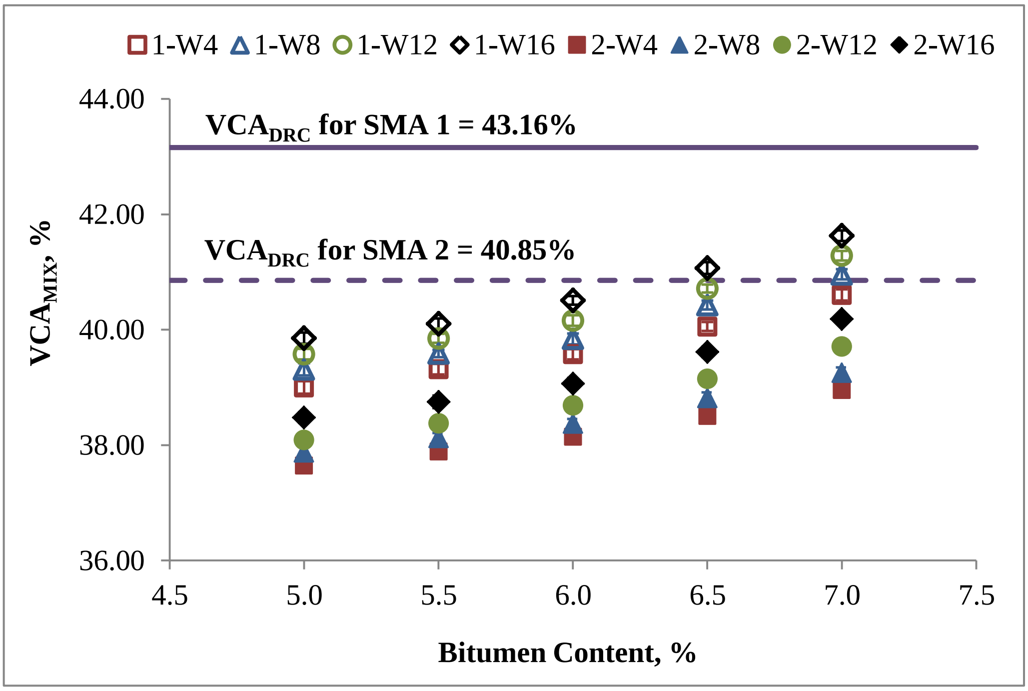


Fig. 6.4 VCA Values of SMA Mixtures with SWP

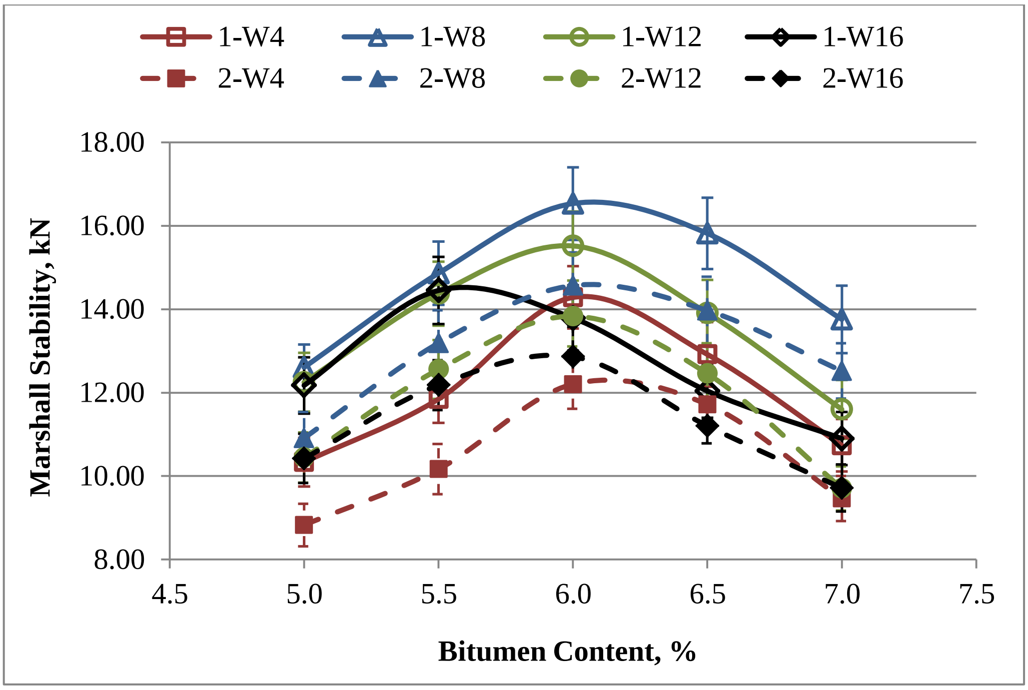


Fig. 6.5 Marshall Stability of SMA Mixtures with SWP

In SMA 1 mixtures, OBC was determined as 6.18, 6.04, 5.88 and 5.72 % for W4, W8, W12 and W16 respectively, whereas it was respectively 6.25, 6.12, 5.95 and 5.84 % for SMA 2 mixes. The addition of SWP to heated aggregates provides a coating over the aggregate surface thus reducing the quantity of bitumen required to coat them. This resulted in the reduction of OBC value with increase in SWP contents for both gradations. Properties of mixes at OBC are presented in Table 6.9. At OBC also, G_{mm} and G_{mb} were observed to be decreasing with the addition SWP. From Figures 6.6 and 6.7, it can be seen that the highest Marshall stability was attained as 16.57kN for SMA 1 and 14.60kN for SMA 2, both at 8% SWP content, whereas Marshall Quotient was maximum for W12 mixes. When SWP content was 16%, mix produced minimum flow values and due to that good Marshall Quotient also was obtained.

Table 6.9 Properties of SMA Mixtures with SWP at OBC

Mixture	1-W4	1-W8	1-W12	1-W16	2-W4	2-W8	2-W12	2-W16
OBC (%)	6.18	6.04	5.88	5.72	6.25	6.12	5.95	5.84
G_{mm} (g/cc)	2.433	2.428	2.423	2.417	2.427	2.423	2.418	2.409
G_{mb} (g/cc)	2.336	2.333	2.327	2.321	2.330	2.327	2.321	2.313
V_v (%)	3.98	3.92	3.97	3.99	4.00	3.96	4.01	3.98
VMA (%)	19.10	19.32	19.48	19.71	19.38	19.58	19.83	20.21
VFB (%)	79.18	79.71	79.60	79.77	79.37	79.78	79.78	80.31
VCA_{MIX} (%)	39.72	39.88	40.06	40.26	38.31	38.46	38.65	38.94
VCA_{MIX}/ VCA_{DRC}	0.920	0.924	0.928	0.933	0.938	0.942	0.946	0.953
MS (kN)	14.25	16.57	15.48	14.41	12.32	14.60	13.82	12.92
Flow Value (mm)	3.54	3.39	3.17	3.00	3.31	3.14	2.91	2.79
MQ (kN/mm)	4.02	4.88	4.89	4.81	3.72	4.65	4.74	4.63

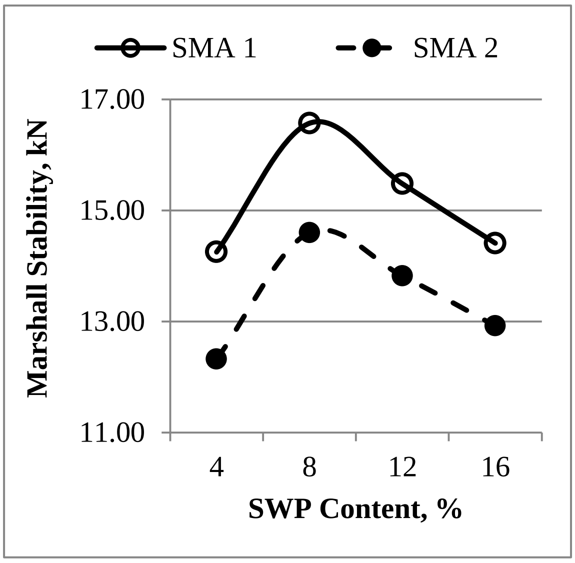


Fig. 6.6 Variation of Marshall Stability with SWP Content

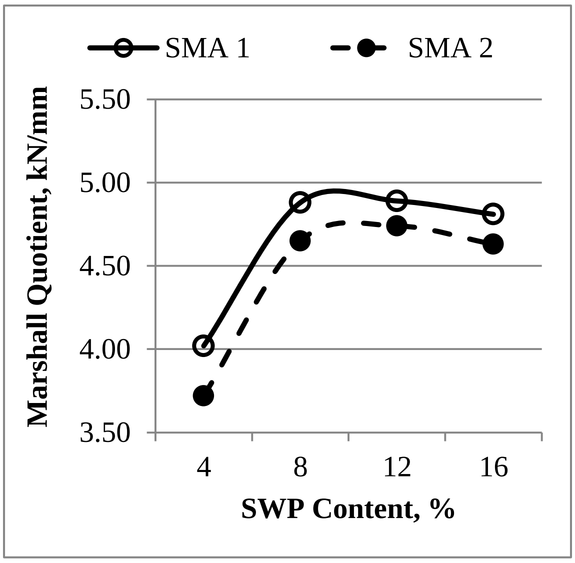


Fig. 6.7 Variation of Marshall Quotient with SWP Content

6.3.3 Indirect Tensile Strength

IDT strength values of SMA mixtures with different SWP contents are depicted in Figure 6.8. Among two aggregate gradations used, higher tensile strength was observed for SMA 1 mixtures. W8 mixtures had the highest IDT strength in both SMA 1 and SMA 2 gradations and W12 mixes also performed well. The presence of excess amount of plastic may be causing the loss of strength at higher SWP contents.

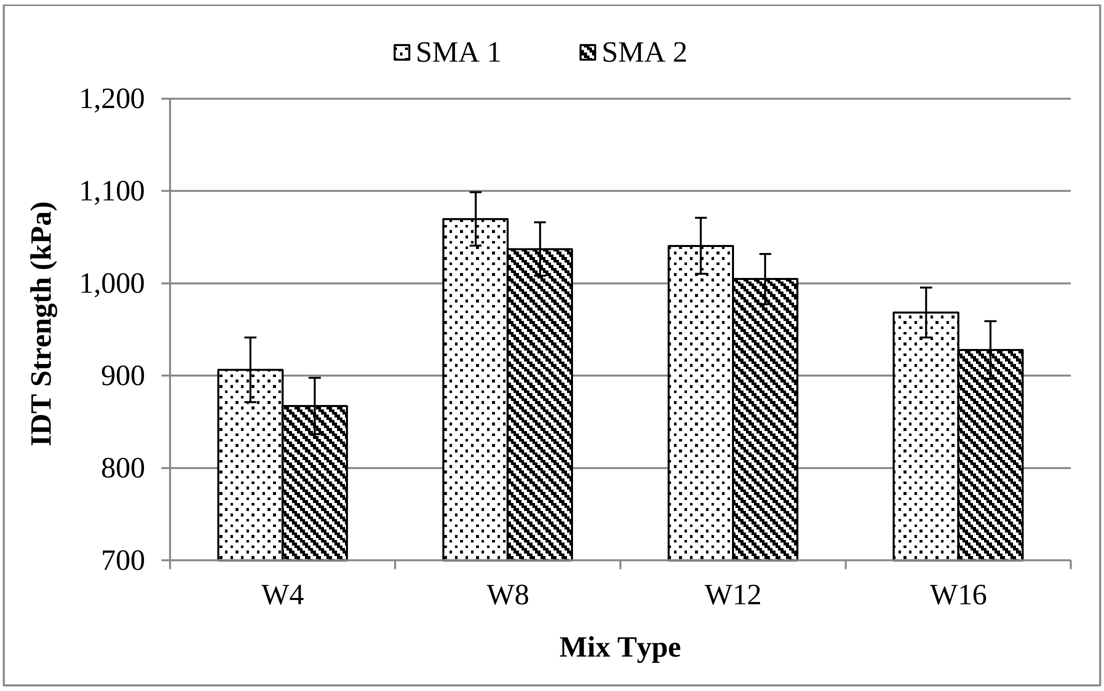


Fig. 6.8 IDT Strength of SMA Mixtures with SWP

6.3.4 Rutting Resistance

The rut deformations observed for SMA mixtures with SWP for different wheel passes are presented in Figure 6.9. At the end of 10,000 wheel passes along the slab surface, the deformation was observed as 5.22, 4.45, 4.63 and 4.98 mm for SWP contents 4, 8, 12 and 16 % respectively for SMA 1 mixtures and 5.73, 4.96, 5.20 and 5.47 for SMA 2 mixes. The highest rut depth of W4 mixes is an indication of lack of plastic content in the mixture to provide better rut resistance, whereas comparable performance was obtained for mixes with SWP contents 8 and 12 %.

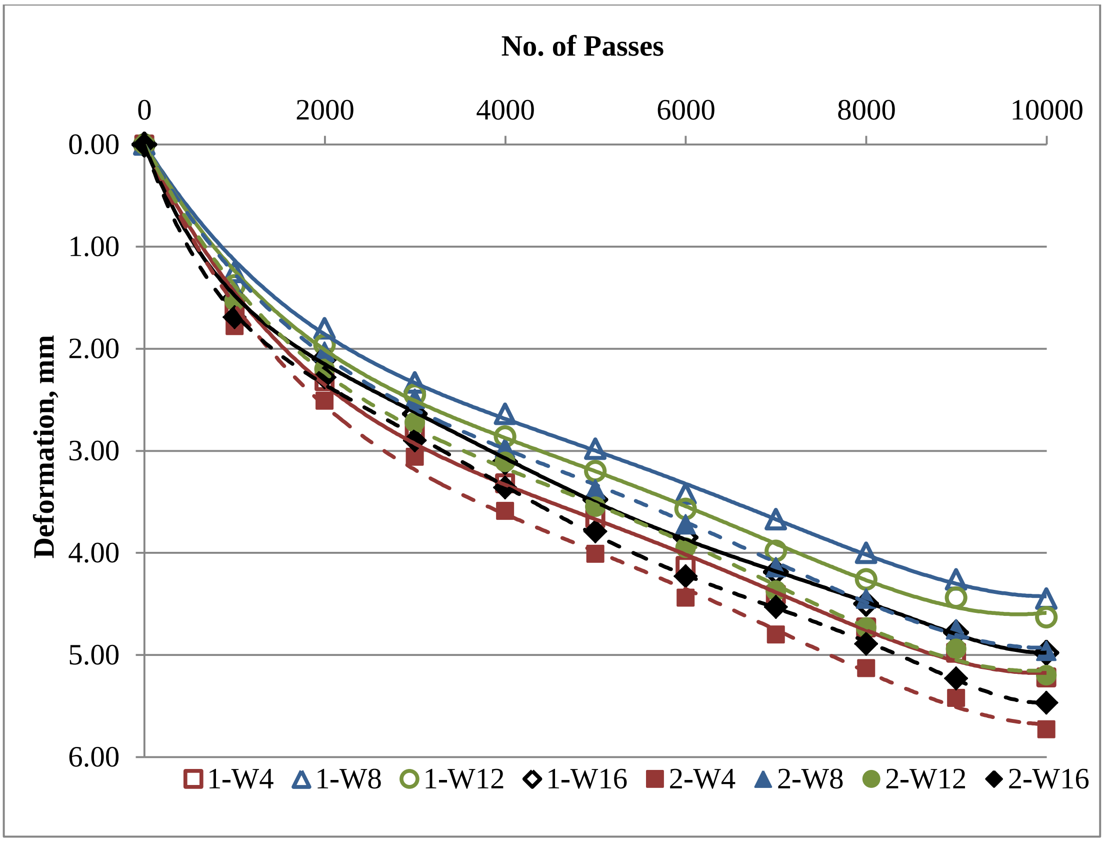


Fig. 6.9 Rutting Deformation of SMA Mixtures with SWP

6.3.5 Fatigue Behaviour

Cylindrical SMA specimens prepared at OBC were tested for fatigue behaviour by applying three fractions of IDT failure load of each specimen. From the results presented in Table 6.10, it can be seen that, among all mixes, 4 and 8% SWP mixes produced the highest FL in different loading level cases. The maximum stress was applied for W8 mixes, higher by 26 – 131 kPa for SMA 1 and 29 – 98 kPa for SMA 2, compared to W4 mixes for which the stress was the minimum. Highest FL was obtained for W4 mixes only when this stress difference was more than 70kPa, and similarly FL was lesser for mixes with 12% SWP, when their stress values were higher (than mix with 4% SWP) by about 50kPa. A combined representation of FL and stress values as in Figure 6.10 explains the fatigue behaviour of SMA mixtures with different SWP contents. It can be seen that SMA 1 mixtures perform much better than SMA 2 and mixes with 8 and 12 % SWP content showed improved fatigue characteristics.

Table 6.10 FL for SMA Mixtures with SWP

Mixture	Load for IDT Strength (kg)	Applied Load (kg)	Applied Load Fraction (%)	Fatigue Life
1-W4	1014.55	498.69	49.15	1914
		331.38	32.66	4928
		158.23	15.60	9088
1-W8	1253.24	638.45	50.94	1836
		412.3	32.90	4755
		186.64	14.89	9194
1-W12	1208.72	604.15	49.98	1812
		390.62	32.32	4711
		176.43	14.60	9123
1-W16	1098.18	554.28	50.47	1747
		372.61	33.93	4534
		164.36	14.97	8890
2-W4	938.63	464.98	49.54	1787
		308.72	32.89	4520
		142.71	15.20	8731
2-W8	1129.33	566.56	50.17	1752
		370.78	32.83	4571
		174.88	15.49	8792
2-W12	1085.89	541.66	49.88	1728
		356.54	32.83	4584
		163.5	15.06	8806
2-W16	991.6	501.20	50.54	1708
		329.41	33.22	4529
		152.58	15.39	8723

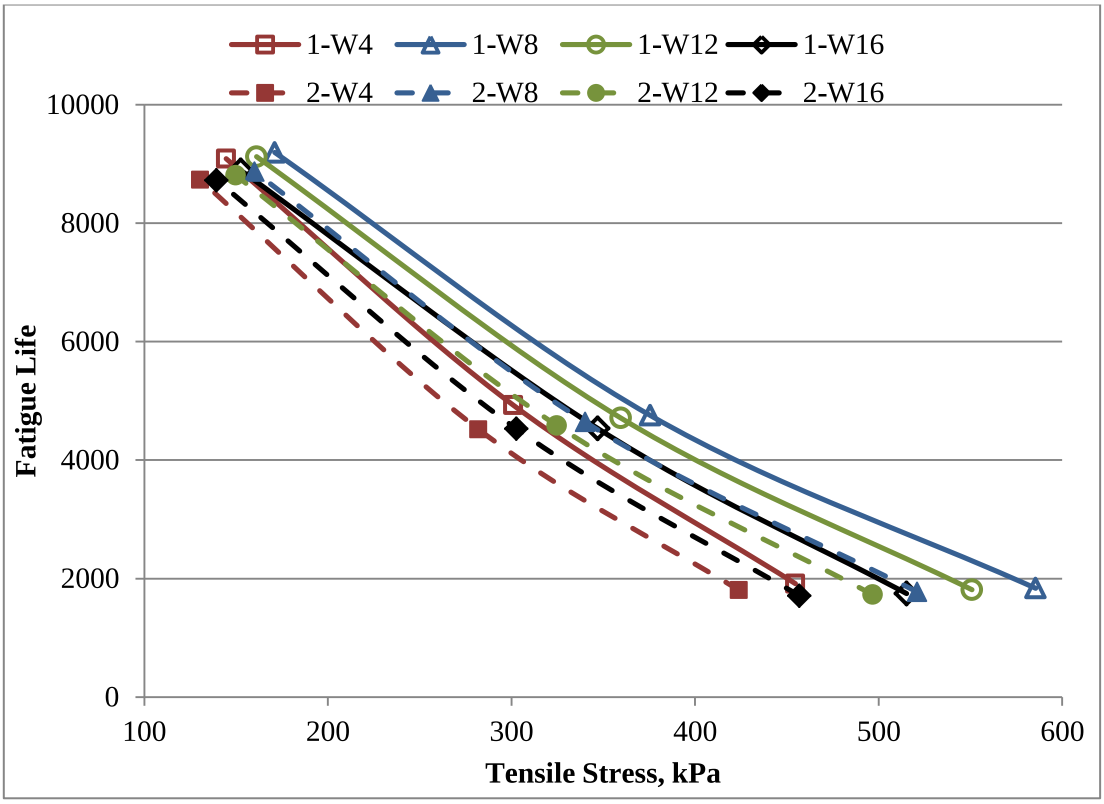


Fig. 6.10 Variation of Tensile Stress with FL for Mixtures with SWP

6.3.6 Moisture Susceptibility

6.3.6.1 Retained Stability

Figure 6.11 and Table 6.11 show the Retained stability test results of SWP added SMA mixtures. Retained stability was observed to be above 87% for all mixtures indicating their better moisture resistance, and the highest value was obtained for W8 and W12 mixtures (about 94%).

6.3.6.2 Tensile Strength Ratio

ITS values for both unconditioned and conditioned specimens prepared at 7% air voids for all SMA mixtures and the corresponding TSR values are presented in Figure 6.12 and Table 6.12 respectively. ITS value at both unconditioned and conditioned were observed to be the highest for W8 mixtures, but the TSR value were similar for mixtures with SWP contents 8, 12 and 16 %.

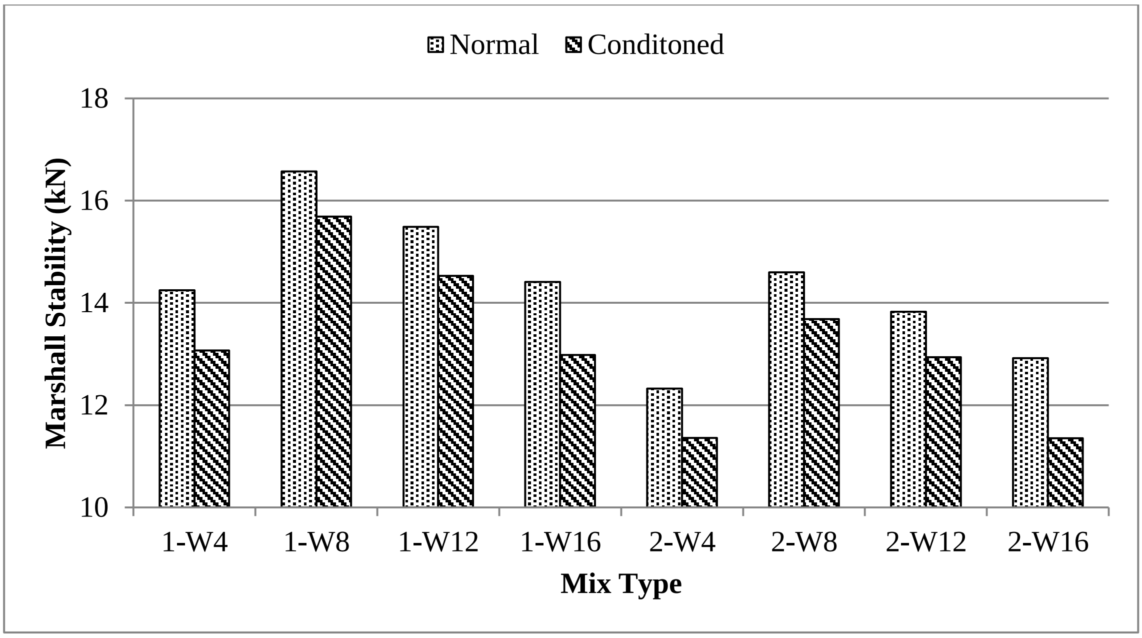


Fig. 6.11 Stability of Normal and Conditioned SMA Mixtures with SWP

Table 6.11 Retained Stability of SMA Mixtures with SWP

Mix Type	**1-W4**	**1-W8**	**1-W12**	**1-W16**	**2-W4**	**2-W8**	**2-W12**	**2-W16**
RS (%)	91.74	94.68	93.83	90.06	92.20	93.71	93.57	87.87

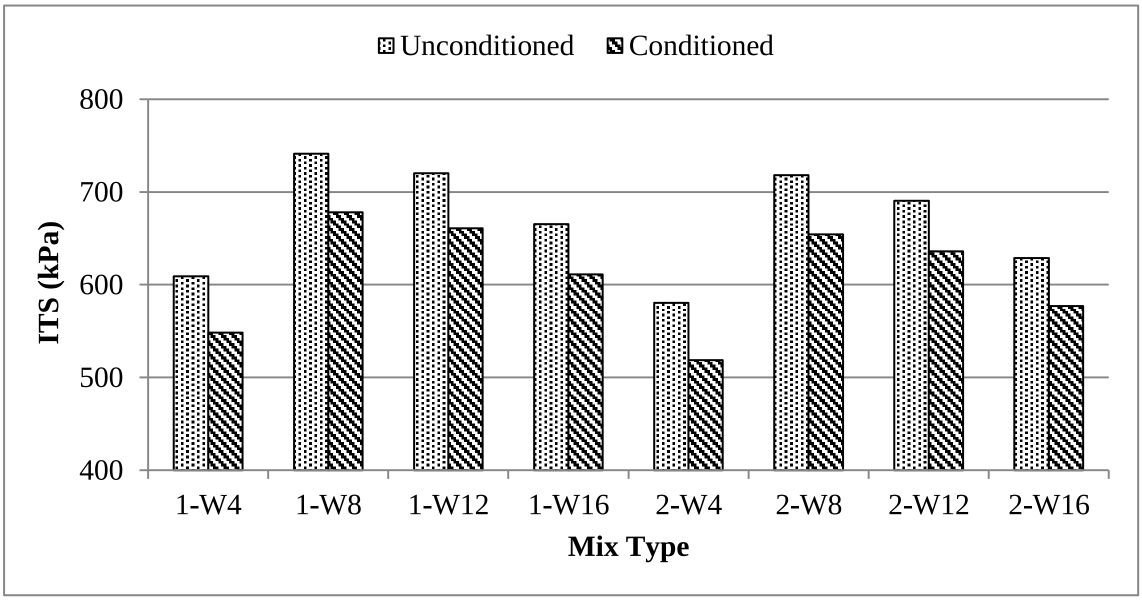


Fig. 6.12 ITS of Conditioned and Unconditioned SMA Mixtures with SWP

Table 6.12 TSR of SMA Mixtures with SWP

Mix Type	1-W4	1-W8	1-W12	1-W16	2-W4	2-W8	2-W12	2-W16
TSR (%)	90.03	91.49	91.73	91.87	89.41	91.11	92.09	91.78

6.3.6.3 Stripping

Stripping behaviour of SMA mixtures with different SWP contents were determined from boiling test. Only W4 mixes were observed to be having some notable stripping, even that was below 5% of the total surface area. Stripping was negligible (less than 2%) for all other mixes with the help of higher SWP content.

6.3.7 Cost Analysis

The cost analysis was conducted for SMA mixtures SWP using the material and carriage costs presented in Table 6.13, machinery cost, labour charges and other expenses. The cost for cubic meter of mixture with each SWP contents is shown in Figure 6.13. The change in SWP content did not affect the cost significantly, and all mixtures costed from 11100 – 12000 rupees. The cost increase with the increase in SWP content was less, but the gradation change resulted in a variation in price by 70 – 130 rupees, as observed in the case of mixtures with fiber and modified bitumen.

Table 6.13 Material and Carriage Cost for SMA Mixtures with SWP

Mixture	Cost of Materials and Carriage (Rs.)			
	Aggregates including Stone Dust and Lime	Bitumen	SWP	Total
1-W4	4,99,354.12	11,42,246.59	44,578.36	16,86,179.07
1-W8	4,98,791.04	11,18,014.32	87,265.31	17,04,070.67
1-W12	4,98,510.99	10,86,752.83	12,7237.84	17,12,501.66
1-W16	4,98,235.00	10,57,526.12	1,65,087.94	17,20,849.06
2-W4	5,01,883.14	11,56,120.03	45,119.80	17,03,122.97
2-W8	5,01,300.64	11,31,887.76	88,348.18	17,21,536.58
2-W12	5,01,008.85	11,00,441.29	1,28,840.49	17,30,290.63
2-W16	5,00,397.78	10,80,648.52	1,68,697.52	17,49,743.82

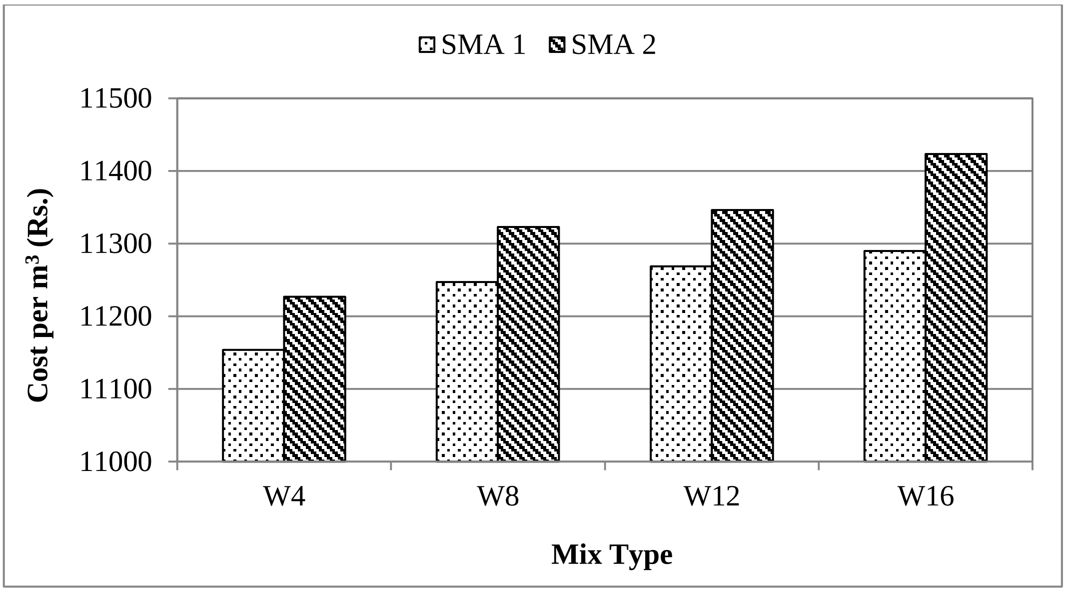


Fig. 6.13 Cost of SMA Mixtures with SWP

6.5 SUMMARY

SMA mixtures were prepared with different SWP contents (4, 8, 12 and 16 % by weight of bitumen) and their laboratory performance is discussed in this chapter. Drain down test had indicated that, SWP incorporated in SMA by dry process method acts as a stabilizer material in the mixture, controlling drain down and it reduces with increase in plastic content. Since SWP is lighter than aggregates and bitumen, its addition reduces the density of the mixture and this led to the reduction of G_{mm} and G_{mb} values with the increase in the SWP content. The increase in SWP content caused decrease in the OBC value for both SMA 1 and SMA 2 gradations, whereas the stability value increased till 8% SWP content and then it decreased. Mix with 8% SWP performed best among all mixes in IDT strength test, followed by W12 mix and the difference in strength between these mixes was 29 – 33 kPa. The same trend was observed for rutting test, with least deformation obtained for W8 mixes. Mix with 12% SWP also performed well in the test whereas W4 mixes showed lesser resistance to wheel passes. Fatigue behaviour was observed to be much better for mixes with 8 and 12 % SWP contents, considering both FL and stress values. Increased FL was obtained for W4 mixes in some loading cases due to the lesser stress, but its overall performance was poor because of the lesser plastic content. Higher plastic content beyond a limit was also not found to be suitable in SMA from the performance of W16 mixes. Stability values of both conditioned and unconditioned specimens were observed to be higher for W8 mixes, but retained stability for almost similar for W8 and W12 mixtures. For normal specimens stability was more for W16 mixes compared to W4, whereas after conditioning the reduction in stability was more for W16 mixes providing lesser retained stability values than that of W4 mixtures. ITS values at 7% air voids for both conditioned and unconditioned specimens were observed to be similar trend as in the case of other properties. The TSR values were observed to be increasing with SWP content, providing maximum value for W16 and W12 mixes in the case of SMA 1 and SMA 2 respectively. But the difference in TSR between mixes with SWP contents 8, 12 and 16 % minimum and even W4 mixes also showed good value indicating its moisture resistance property with lesser plastic content. Considerable difference in cost was not observed between all the four SWP mixtures tried in this study.

CHAPTER 7

DISCUSSION AND CONCLUSIONS

7.1 DISCUSSION

In the present study, SMA mixtures were prepared in two aggregate gradations (SMA 1 and SMA 2) with three fiber additives (Cellulose Fiber in pellet form, Coconut Coir and Sisal Fiber) using VG 30 bitumen, three modified bituminous binders (CRMB, PMB 40 and 70) and Shredded Waste Plastics in four dosages (4, 8, 12 and 16 % by weight of bitumen) as additives using VG 30 binder. All these mixtures satisfied the major requirements suggested for SMA including drain down less than 0.3%, VMA above 17%, VCA_{DRC} value higher than VCA_{MIX} and the minimum TSR of 85%. Some mixtures, especially those with modified binders, performed better than the IRC suggested pelletized CF added mixture.

The drain down criterion was satisfied by mixtures with CRMB and PMBs without any stabilizing additive. SMA with VG 30 having 0.3 and 0.4 % fiber additives (cellulose pellets, coconut coir and sisal) and different SWP contents also controlled drain down. The increase in fiber and SWP quantity stabilize the mixture and control the draining of the mastic material, resulting in a decreasing trend of drain down with the increase in stabilizer content. Fibers were observed to be more successful in controlling drain down compared to modified bitumen and SWP.

The OBC values obtained for SMA 1 mixtures were 6.04, 6.10, 6.12, 6.06, 5.92, 6.00, 6.18, 6.04, 5.88 and 5.72 with CF, CC, SF, CB, P40, P70, W4, W8, W12 and W16 respectively and similarly 6.12, 6.19, 6.22, 6.14, 6.08, 6.12, 6.25, 6.12, 5.95 and 5.84 for SMA 2 mixtures. The absorption property of fibers resulted in their increased OBC values, whereas the presence of SWP reduces the bitumen requirement to coat the aggregates, leading to decrease in OBC.

Mixtures with modified bitumen showed the best volumetric and Marshall properties, due to the presence of polymer/rubber in the bituminous binder. P40 and P70 produced 12 – 21 % higher MS than that of CF mixtures, at corresponding OBC. For SWP mixes, density showed a decreasing trend with increase in plastic content, but the highest Marshall stability was obtained for W8 mixes, which was 5 – 6% higher than that of CF. The reduced flow in CF resulted in a higher MQ and only P40, W8 and W12 mixtures showed improved values than CF, that too by 2 – 4 %.

P40 and P70 mixtures produced IDT strength higher than CF by 2 – 7 %, whereas CB and W8 mixes performed similar to CF. But the difference between these mixtures is not significant, considering the ASTM allowable deviations between the IDT strength values of triplicate specimens of a mixture.

P40 specimens had the minimum rut deformation (10 – 23 % lesser than CF) followed by P70 (3 – 11 % lesser than CF). CB and W8 showed results similar to that of CF, with a maximum difference of 0.17mm, considering all wheel passes.

Fatigue behaviour was obtained to be the best for P40 mixtures and P70 also performed better than other mixtures for all loading levels. It showed an improvement of 4 – 50 % (average 16%) for P40 and 1 – 10 % (average 5%) for P70 mixtures compared to CF mixtures. CF and W8 mixtures showed similar readings (with an average difference of 2%) and were observed to be better than CB mixes. SMA mixtures showed good moisture resistance with both RS and TSR values more than and 87%, but the maximum values were obtained for mixes with modified bituminous binders. Moisture susceptibility was observed to be similar for all fiber added mixtures (RS of 89 – 92 % and TSR of 87 – 90 %), whereas SWP mixes showed better resistance than them, with RS 88 – 95 % and TSR 89 – 92 %.

From cost analysis it was observed that, mixtures with PMB are costlier than CF by 14 – 15 %, whereas mixes with SWP (cost lesser approximately by 6.5% of CF) and other fiber additives (10% lesser cost compared to CF) can be prepared with lesser rates.

For all mixture types, SMA 1 gradation showed better results than SMA 2, except for moisture susceptibility, where both gradations performed almost same. SMA 1 showed a reduction of 0.07 – 0.1 % in OBC value and 0.4 – 0.7 mm in rut deformation after 10000 wheel passes and an increase of 1 – 2 kN in MS, 31 – 53 kPa in IDT strength and 280 – 950 number of cycles in FL, compared to SMA 2 mixtures. The cost per cubic meter of SMA 2 was 60 – 230 rupees higher than that of SMA 1, for different mixtures, mainly due to their increased OBC.

7.2 CONCLUSIONS

In this study, along with modified bituminous binders, a conventional VG 30 bitumen is directly used to produce SMA mixtures with Cellulose Fiber, Coconut Coir, Sisal Fiber and Shredded Waste Plastics. All mixtures prepared in the study, satisfy the requirements of SMA including drain down, VMA, VCA and TSR.

1. Both SMA 1 and SMA 2 mixtures with CRMB and PMBs (without stabilizing additive) and mixtures having VG 30 bitumen with 0.3 and 0.4 % fiber additives (cellulose pellets, coconut coir and sisal) and different SWP contents satisfy the drain down criterion.
2. Mixtures with modified bitumen (especially P40 and P70) have the best volumetric and Marshall properties, with lesser OBC values.
3. The density and OBC of SWP mixes show a decreasing trend with plastic content, but W8 mixture has the highest Marshall stability.
4. P40 mixture has the highest IDT strength and the minimum rut deformation, followed by P70. CB, CF and W8 mixtures represent almost similar results in both tests.
5. Fatigue behaviour is the best for P40, followed by P70 mixture. CF and W8 mixtures show similar performance and are better than CB mixes.
6. SMA mixtures have both RS and TSR above 87%, indicating very good moisture resistance. Among all, the group of mixtures with modified bituminous binder has the best moisture resistance.

7. Moisture susceptibility is similar for all fiber added mixtures, whereas SWP mixes have better resistance than them.
8. For all mixture types, SMA 1 gradation is better than SMA 2, whereas mixtures with both gradations have similar moisture susceptibility.
9. The mixtures with modified binders are expensive, but mixes with SWP and fiber additives cost less.

The entire study concludes that, even though all mixtures satisfy the SMA requirements, the usage of PMB 40 as bituminous binder produces a better mixture, but the cost of the same is also the highest. Pelletized Cellulose Fiber is suggested as the stabilizing additive in SMA having conventional VG 30 bitumen, and produces a good mixture, as expected. But mixture with 8% SWP as a stabilizer performs roughly similar to CF mixtures and their production cost is much lesser, with an additional advantage of environmental friendliness.

7.3 SCOPE FOR FURTHER RESEARCH

- The present work can be extended to determine more dynamic properties of SMA mixtures, including Resilient Modulus.
- Trial sections with SMA mixtures can be constructed in field and evaluation can be carried out for a period of years.
- More waste or marginal materials can be tried in SMA mixtures, including Recycled Aggregates, shingles, slag, waste fibers, etc.

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APPENDIX I

Calculation of Volumetric Properties for 2-CB (SMA 2 Mixture with CRMB)

Consider mixture with 5% bitumen content by weight of mixture

Weight of Aggregates (Including mineral filler) = 1200g

Weight of Bitumen = 63.16g

Total weight of mixture = 1263.16g

Bulk specific gravity of aggregates, G_{sb} = 2.702

Maximum theoretical density of loose mixture, G_{mm} = 2.488g/cc

Bulk Density of Specimen, G_{mb} = 2.327g/cc

Air Voids, V_a (in %) $= \frac{G_{mm} - G_{mb}}{G_{mm}} \times 100\ \%$

= 6.46%

Voids in Mineral Aggregates, VMA (in %) $= 100 - \frac{G_{mb}.P_s}{G_{sb}}$

Aggregate content (% by total weight of mix), P_s = 100 × [1200 ÷ (1200 + 63.16)]

VMA = 18.17%

Voids Filled with Bitumen, VFB (in %) $= \frac{VMA - V_a}{VMA} \times 100$

= 64.45%

Bulk specific gravity of the coarse aggregate, G_{ca} = 2.684

Unit weight of water, Y_w = 998kg/m^3

Unit weight of coarse aggregate fraction in dry-rodded condition, Y_s

= 1584.49kg/m^3

Voids in the coarse aggregate in the dry rodded condition, VCA_{DRC} (in %)

$= \frac{G_{ca}Y_w - Y_s}{G_{ca}Y_w} \times 100$

= 40.85%

Weight of coarse aggregate in the total mixture = 912g

Percent coarse aggregate in the total mixture, P_{ca} = 72.20%

VCA of the mixture, VCA_{MIX} (in %) $= 100 - \left(\frac{G_{mb}}{G_{ca}} \times P_{ca}\right)$

= 37.40%

The specimen has VMA > 17% and $VCA_{DRC} > VCA_{MIX}$

Hence it satisfies the volumetric requirements of SMA.

APPENDIX II

Machinery and Labour Charge Calculation

The total quantity considered for all SMA mixtures is 450 tonnes and the mixture is produced with HMP of 75 TPH output, and is paved with paver finisher of same capacity. Hence for the production and paving operations of 450 tonnes mixture, 6 hours (450 ÷ 75) is required. Along with these machineries, generator, front end loader and tipper are also required for 6 hours. The rollers are actually required only for 3 hours each, but they have to be in site for the entire 6 hours period. In order to incorporate this idle time 65% of the total time (6 hours) is considered and cost is calculated for this period (3.9 hours). The rollers actually required only for three hours each, but they have to be in site for six hours. In order to include this idle time 65% of the total time (6 hours) is considered and cost is calculated for this period (3.9 hours). The tippers are assumed to travel a distance of 10km, so total unit is 4500 tonne-km (450 tonnes × 10km), and 10% of the total expense in tipper is considered as the loading charges. The actual machinery charges for the preparation of 450 tonnes of mixture are calculated as shown in **Tables 1** and obtained as Rs. 1,56,960.

Table 1 Actual Machinery Charges for 450 tonnes of SMA Mixture

Machinery	**Unit**	**Rate per Unit (Rupees)**	**Quantity**	**Total Cost (Rupees)**
Hot mix plant	hour	17,500.00	6	1,05,000
Paver finisher Hydrostatic with sensor control	hour	2,700.00	6	16,200
Generator 250 KVA	hour	700.00	6	4,200
Front end loader 1 cum bucket capacity	hour	900.00	6	5,400
Tipper -5 Cum	tonne-km	3.00	4500	13,500
Loading (10% of total expense in tipper)				1,350
Smooth Wheeled Roller 8 to 10 tonne for initial break down rolling	hour	1,300.00	3.9	1,755
Vibratory roller 8 to 10 tonne for intermediate rolling	hour	450.00	3.9	5,070
Tandem Road Roller for Finish rolling	hour	1,150.00	3.9	4,485
Total Machinery Charges				**1,56,960**

The duration required each labour for the prescribed work is considered based on the SOR data. The calculation actual labour charges for the preparation of 450 tonnes of mixture are presented in **Tables 2,** and the total is obtained as Rs. 6,725.92.

Table 2 Actual Labour Charges for 450 tonnes of SMA Mixture

Labour	**Unit**	**Rate per Unit (Rupees)**	**Quantity**	**Total Cost (Rupees)**
Mate	day	363.00	0.84	304.92
Beldar	day	329.00	14	4,606
Skilled beldar	day	363.00	5	1,815
Total Labour Charges				**6,725.92**

APPENDIX III

Cost Calculation of 1-CF (SMA 1 Mixture with Cellulose Fiber)

Assumed Blending proportion is

20mm: 35%, 12.5mm: 35%, 6mm: 10%, Stone Dust: 18%, Lime: 2%

Material quantity calculation is shown in **Table 3.**

Table 3 Quantity of Bitumen, Fiber and Aggregates

OBC		6.044%
Bulk Density at OBC		2350kg/cum
Weight of Mix		450000kg
Volume of Mix	Weight of Mix ÷ Bulk Density	191.49cum
Weight of Bitumen	Weight of Mix × OBC	27198kg
Fiber %		0.30
Weight of Fiber	Weight of Mix × Fiber %	1350kg
Weight of Aggregates	Weight of Mix – Weight of Bitumen – Weight of Fiber	421452kg

From the total weight of aggregates, weight of different sizes of aggregates, stone dust and lime are determined. Density of aggregates is assumed as 1500 kg/cum, and this is used to convert weight of aggregates into volume (Since the SOR provides unit material and carriage rates for aggregates and stone dust in volume (in cubic meter), instead of weight). Proportion and cost of different aggregate sizes and stone dust are shown in **Table 4.**

Table 4 Cost of Aggregates and Stone Dust Including Carriage

Aggregate Material	Quantity	Unit	Rate per Unit (Rupees)	Total Cost (Rupees)	Carriage Rate (Rupees)	Total Carriage Cost (Rupees)
20mm	98.34	cum	1,800.00	177009.84	115.75	26017.64
12.5mm	98.34	cum	1,750.00	172092.90		
6mm	28.10	cum	1,550.00	43550.04		
SD	50.57	cum	1,100.00	55631.66	106.49	5385.65
Total Cost (Rupees)			**479687.73**			

Quantity of lime = 8429.04kg

Cost of lime = 8429.04 × 2.3 = Rs. 19386.79

Quantity of lime (in volume) = 6.534cum (assuming 1.29 tonne per cum density)

Carriage cost of lime = 6.534 × 106.49 = Rs. 695.82

Total Cost for Lime = Rs. 20082.61

Cost calculation for Bitumen and Fiber are listed in Table 5 and miscellaneous charges in Table 6.

Table 5 Cost of Bitumen and Fiber Including Carriage

Item	Unit	Rate per Unit (Rupees)	Quantity	Total Cost (Rupees)
Bitumen	tonne	27.198	41000	1115118
Carriage of Bitumen	tonne	27.198	106.49	2896.32
Fiber	tonne	1.35	150000	202500
Carriage of Fiber	tonne	1.35	106.49	143.76
Total Cost (Rupees)		**1320658.08**		

Table 6 Miscellaneous Charges Calculation

Item	Cost (Rupees)
Total Material and Carriage Cost	18,20,428.42
Total Labour Charges	6,725.92
Total Machinery Charges	1,56,960.00
Total Cost	**1984114.34**
Water Charge at1%	19841.14
Total Cost including water charge)	**2003955.48**
CPOH at 15%	300593.32
Total Cost including water and CPOH charges	**2304548.81**

Total Cost for 450 Tonnes of Mixture = Total Cost for 191.49cum of Mixture

= Rs. 23,04,548.81

Cost for one cubic meter of Mixture = Rs. 12034.87

LIST OF PUBLICATIONS

Journal

- Goutham Sarang, Mehnaz E. and Ravi Shankar A U. (2014). "Comparison of Stone Matrix Asphalt mixtures prepared in Marshall compaction and gyratory compactor." *International Journal of Civil Engineering Research*, 5 (3), 233–240.
- Goutham Sarang, Lekha B M and A U Ravi Shankar. (2014). "Aggregate and bitumen modified with chemicals for Stone Matrix Asphalt mixtures." *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, 2, 14–20.
- Goutham Sarang, B M Lekha, J S Geethu and A U Ravi Shankar. (2015). "Laboratory performance of stone matrix asphalt mixtures with two aggregate gradations." *Journal of Modern Transportation*, Springer, 23 (2), 130–136.
- Goutham Sarang, Lekha B M, Krishna G, Ravi Shankar A U. "Comparison of Stone Matrix Asphalt mixtures with Polymer Modified Bitumen and plastic coated aggregates." *Road Materials and Pavement Design*, Taylor and Francis. (Under Review)
- Goutham Sarang, Lekha B M, Ravi Shankar A U, Someswara Rao B. "Stone Matrix Asphalt mixtures with cellulose fiber and waste plastics." *Indian Roads Congress Journals*. (Under Review)

Conference

- Goutham Sarang, Lekha B M and Ravi Shankar A U. (2014). "Comparison of bituminous mixtures prepared in Marshall compaction and gyratory compactor." *Colloquium on Transportation Systems Engineering and Management*, NIT Calicut, Kerala, India.
- Goutham Sarang, Lekha B M and Ravi Shankar A U. (2014). "Stone Matrix Asphalt using aggregates modified with waste plastics." *GeoShanghai – 2014, International Conference on Geotechnical Engineering* by ASCE, Shanghai, China.

- Goutham Sarang, Lekha B M, Monisha M and Ravi Shankar A U. (2014). "SMA mixtures with modified asphalt and treated aggregates." *Second T&DI Congress* by ASCE, Orlando, Florida, USA.
- Goutham Sarang, Lekha B M, Ramesh Tejavath, Ravi Shankar A U. "Laboratory performance comparison of Stone Matrix Asphalt mixtures with Polymer Modified Bitumen and cellulose fiber stabilizer" International Conference on Transportation and Development 2016 by ASCE, Texas, USA. (Abstract Accepted).
- Goutham Sarang, Lekha B M, Priyanka B A and Ravi Shankar A U. "Stone Matrix Asphalt mixtures with sisal fiber and Crumb Rubber Modified Binder." International Conference on Sustainable Asphalt Pavement for Developing Countries (ICONSAP) 2016 by CRRI, New Delhi, India. (Abstract Accepted).

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Education

Degree	Subject	University/Institution	Year
PhD	Transportation Engineering (Civil Engineering)	National Institute of Technology Karnataka, Surathkal	2011 – 2015
M Tech	Transportation Systems Engineering	National Institute of Technology Karnataka, Surathkal	2009 – 2011
B Tech	Civil Engineering	University of Kerala/ College of Engineering Thiruvananthapuram, Kerala	2004 – 2008
+2 (XII)	Science (Physics, Chemistry, Mathematics & Biology)	Kerala Higher Secondary Board/ KKV Memorial Panoor Higher Secondary School, Panoor, Kannur, Kerala	2002 – 2004
10th	–	Kerala Board of Public Examinations/ KKV Memorial Panoor Higher Secondary School, Panoor, Kannur, Kerala	2002

Work experience

Positions held	: Site Engineer
Name of the Company	: M/S. ROMAN TARMAT LTD.
Period	: 01 October 2008 to 22 July 2009
Project	: Recarpeting of Runway Along with Related Pavements Upgradation Works at Cochin International Airport (CIAL), Cochin, Kerala

Research Areas

Pavement materials, design and construction, Bituminous mixtures, Soil stabilization

PhD Thesis Title

Experimental Investigation of Stone Matrix Asphalt Mixtures

M Tech Thesis Title Performance of SMA with Waste Plastics (Dry Process) Using Superpave Gyratory Compactor

Undergone subjects in M Tech

1. Pavement Design
2. Traffic engineering and Management
3. Urban Transport Planning
4. Statistical Methods
5. Soil Mechanics
6. Pavement Materials and construction
7. Traffic flow Theory
8. Operational Research
9. Traffic Design and Studio lab
10. Transportation Engineering lab

Research Publications

International Journal

1. Ravi Shankar, A.U., Lekha B. M., Goutham Sarang (2013). "Fatigue and Engineering Properties of Chemically Stabilized Soil for Pavements". *Indian Geotechnical Journal*, Springer, Vol. 43, No. 1, pp. 96–104.
2. Goutham Sarang, Mehnaz E and Ravi Shankar, A U., (2014), "Comparison of Stone Matrix Asphalt Mixtures Prepared in Marshall Compaction and Gyratory Compactor". *International Journal of Civil Engineering Research*, Research India Publications, 5 (3), pp. 233–240.
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4. B.M. Lekha, S. Goutham, A.U.R. Shankar (2015) "Evaluation of lateritic soil stabilized with Arecanut coir for low volume pavements". *Transportation Geotechnics*, Volume 2, March 2015, Pages 20-29.
5. Goutham Sarang, B. M. Lekha, J. S. Geethu, A. U. Ravi Shankar (2015) "Laboratory performance of stone matrix asphalt mixtures with two aggregate gradations". *Journal of Modern Transportation*, Volume 23, Issue 2, pp 130-136.
6. B. M. Lekha, Goutham Sarang, A. U. Ravi Shankar (2015) "Effect of Electrolyte Lignin and Fly Ash in Stabilizing Black Cotton Soil" *Transportation Infrastructure Geotechnology*, Volume 2, Issue 2, pp 87-101.
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8. Lekha B M, Goutham Sarang and Shankar A.U.R. “Experimental investigation on lateritic soil stabilized with cement and aggregates.” *Road Materials and Pavement Design* (Under Review).

National Journal

1. Ravi Shankar, A.U., Koushik, K. and Sarang, G. (2013) “Performance Studies on Bituminous Concrete Mixes Using Waste Plastics”, *Highway Research Journal*, Indian Roads Congress, Vol. 6, No. 1, January – June 2013, pp 1–11.
2. Ravi Shankar, A.U, Lekha B. M, Goutham Sarang, and P. Abhishek (2014). “Performance and Fatigue behavior of semi dense bituminous concrete using waste plastics as modifier”. *Indian Highways*, Indian Roads Congress, Vol 42, No.7, pp. 23–32.
3. Goutham Sarang, Lekha B M, Ravi Shankar A U and Someswara Rao B. “Stone matrix asphalt mixtures with cellulose fiber and waste plastics.” *Indian Roads Congress Journals* (Under Review).
4. Ravi Shankar A U, Durga Prashanth L, Goutham Sarang, Mahesh H M. “Laboratory investigation of recycled aggregates for bituminous concrete mix,” *Indian Roads Congress Journals* (Under Review).
5. Lekha B M, Goutham Sarang and Ravi Shankar A U. “Strength and durability properties of RBI 81 stabilized black cotton soil as a pavement material.” *Indian Roads Congress Journals* (Under Review).

International Conference

1. Lekha B M, Goutham Sarang, Chaitali N and Ravi Shankar A U. “Laboratory investigation on black cotton soil stabilized with non traditional stabilizer”, *International Conference on Innovations in Civil Engineering*, SCMS School of Engineering and Technology, Eranakulam, Kerala, India, 8-9, May 2014.
2. Goutham Sarang, Lekha B M and Ravi Shankar, A U. “Stone Matrix Asphalt using aggregates modified with waste plastics”, *GeoShanghai – 2014, International Conference on Geotechnical Engineering* by ASCE, Shanghai, China, 28-31, May 2014. Published in *Pavement Materials, Structures, and Performance*, Geotechnical Special Publication 239, pp. 9–18.
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4. Goutham Sarang, Lekha B M, Ramesh Tejavath and Ravi Shankar A U. “Laboratory Performance Comparison of Stone Matrix Asphalt Mixtures with Polymer Modified Bitumen and Cellulose Fiber Stabilizer.” *International Conference on Transportation and Development 2016*, Conducted by ASCE, Texas, USA (Abstract Accepted).

5. Lekha B M, Goutham Sarang and Ravi Shankar A U. "Laboratory performance of lateritic soil and soil-aggregate mixture with RBI grade 81." *8th International Conference on Maintenance and Rehabilitation of Pavements (MAIREPAV8) 2016*, Singapore (Abstract Accepted).

National Conference

1. Lekha B M, Goutham Sarang and Ravi Shankar A U. "Stabilization of Lithomargic Clay Using RBI 81 For Pavement Construction", 2nd *National Conference on "Recent Advances in Civil Engineering (RACE – 2013),* Saintgits College of Engineering, Kottayam, Kerala, 6th and 7th September 2013.
2. Lekha B M, Goutham Sarang and Ravi Shankar A U. "Laboratory investigation of soil stabilized with nano chemical", *Indian Geotechnical Conference – 2013* by Indian Geotechnical Society (IGS), Roorkee, India, December 22-24, 2013.
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4. Lekha B M, Goutham Sarang and Ravi Shankar A U. "Laboratory Performance of Black Cotton Soil Stabilized with Terrasil as a Pavement Material" *Colloquium on Transportation Systems Engineering and Management*, NIT Calicut, Kerala, India, May 12-13, 2014.
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6. Goutham Sarang, Lekha B M, Pavan Patil and Ravi Shankar A U. "Experimental Evaluation of Bituminous Concrete Using Chemically Treated Aggregates" *2nd Conference on Transportation Systems Engineering and Management*, NIT Tiruchirappalli, Tamil Nadu, India, May 1-2, 2015.
7. Priyanka B A, Lekha B M, Goutham Sarang and Ravi Shankar A U. "KENPAVE Analysis for Low Volume Roads with Reduced Resilient Modulus Values" *2nd Conference on Transportation Systems Engineering and Management*, NIT Tiruchirappalli, Tamil Nadu, India, May 1-2, 2015.
8. Lekha B M, Goutham Sarang and Ravi Shankar A U. "Effect OF RBI 81 on laterite soil as a pavement material." *53rd Indian Geotechnical Conference 2015*, Conducted by Indian Geotechnical Society, Pune (Full Paper Accepted for Presentation)
9. Goutham Sarang, Lekha B M, Priyanka B A and Ravi Shankar A U. "Stone Matrix Asphalt mixtures with sisal fiber and Crumb Rubber Modified Binder." *International Conference on Sustainable Asphalt Pavement for Developing Countries (ICONSAP) 2016*, Conducted by CRRI, New Delhi, India. (Abstract Accepted).

10. Priyanka B A, Lekha B M, Goutham Sarang and Ravi Shankar A U. "Development of Perpetual Pavements with Cement Treated Base and Rich Bottom Layer using KENPAVE Analysis." *International Conference on Sustainable Asphalt Pavement for Developing Countries (ICONSAP) 2016*, Conducted by CRRI, New Delhi, India. (Abstract Accepted).

Conferences/Workshops Attended

- Workshop on "Tabletop Airports and Safety Aspects", NITK Surathkal, Karnataka, India, 29 – 30, October 2011.
- 2nd National Conference on "Recent Advances in Civil Engineering (RACE – 2013), Saintgits College of Engineering, Kottayam, Kerala, India, 6 – 7, September 2013.
- Training Programme on "How to conduct courses on Environmental Management & Sustainability?", NITK Surathkal, Karnataka, India, 20 – 21, September 2013.
- Short Term on Programme on Urban Transport Systems Planning (UTSP), NIT Calicut, Kerala, India, 25 – 29, November 2013.
- International Conference on Sustainable Innovative Techniques In Civil and Environmental Engineering (SITCEE - 2014) by "Krishi Sanskriti" at JNU, New Delhi, India, 4 – 5, January 2014.
- 74th Annual Session of Indian Roads Congress, Guwahati, Assam, India, 18 – 22, January 2014.
- International Conference on Innovations in Civil Engineering, SCMS School of Engineering and Technology, Eranakulam, Kerala, India, 8 – 9, May 2014.
- Colloquium on Transportation Systems Engineering and Management, NIT Calicut, India, 12 – 13, May 2014.
- First Annual Conference on Innovations and Developments in Civil Engineering, NITK Surathkal, Karnataka, India, 19 – 20, May 2014.
- Second Transportation and Development Institute (T&DI) Congress by ASCE, Orlando, Florida, USA, 8 – 11, June 2014.
- International Workshop on Civil Infrastructure and Structure Materials, NITK Surathkal, Karnataka, India, 28 – 29, July 2014.
- 2nd Conference on Transportation Systems Engineering and Management, NIT Tiruchirappalli, Tamil Nadu, India, 1 – 2, May 2015.

Memberships

- Student Member of American Society of Civil Engineers (ASCE) from May 2013 (Member ID No: 9605727)
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