

EFFECT OF WARM MIX ASPHALT ADDITIVES AND MARGINAL AGGREGATES ON MECHANICAL PROPERTIES OF SEMI- FLEXIBLE ASPHALT MIXTURES

Thesis

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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**DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,
SURATHKAL, MANGALORE-575025
OCTOBER, 2024.**

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OCTOBER, 2024.

DECLARATION
by the Ph.D Research Scholar

I hereby declare that the thesis entitled “**EFFECT OF WARM MIX ASPHALT ADDITIVES AND MARGINAL AGGREGATES ON MECHANICAL PROPERTIES OF SEMI-FLEXIBLE 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 *bonafide report of the research work carried out by me*. The material contained in this thesis has not been submitted to any University or Institution for the award of any degree.

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CERTIFICATE

This is to certify that the thesis entitled “EFFECT OF WARM MIX ASPHALT ADDITIVES AND MARGINAL AGGREGATES ON MECHANICAL PROPERTIES OF SEMI-FLEXIBLE ASPHALT MIXTURES” submitted by **DOMA HEMANTH KUMAR (177095CV003)** as the record of research work carried out by him, *is accepted as Thesis submission* in partial fulfilment of the requirements for the award of degree of **Doctor of Philosophy**.



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Dedicated to
my father,
D Nageswara Rao

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ABSTRACT

Semi-Flexible Asphalt (SFA) mixture is a wearing course in which Open-Graded Asphalt (OGA) mixes having air voids of 20-35% are grouted with cement mortar. In the present work, an effort was made to assess the effect of the Sand-Cement (S/C) ratio in determining the optimal grout proportions. Taguchi technique combined with Grey Relational Analysis (GRA) was used to obtain the optimal grout proportion. The optimum grout was obtained for an S/C ratio of 0.6, a water-to-cement (W/C) ratio of 0.40, and a polycarboxylic ether-based superplasticizer (SP) content of 0.75% by weight of cement. The SP content was identified as the most influencing factor, along with the S/C ratio. To investigate the effect of aggregate gradation and bitumen type on the mechanical properties of SFA mixtures, a new aggregate gradation with neat and modified bitumen was used to prepare OGA mixtures and later grouted with optimal grout proportion. The Marshall Stability, compressive strength, Indirect Tensile Strength, Cantabro loss, fatigue resistance, moisture and Oil spillage resistance tests were conducted. The results showed that the SFA mixtures prepared with Polymer-Modified Bitumen (PMB) and the new aggregate gradation have better mechanical properties, implying the significance of bitumen type and aggregate gradation.

Due to the enormous generation of construction and demolition waste, processing and utilising recycled aggregates in pavement layers, particularly in asphalt layers, is deemed necessary to reduce the disposal problem and depletion of natural resources. Evaluating the performance of asphalt mixtures with recycled aggregates is complex due to the heterogeneity of materials. Therefore, the potential of utilizing the recycled aggregates in semi-flexible asphalt mixtures was explored along with the ferrochrome slag (FCS) aggregate. Though the FCS aggregates exhibited good mechanical and engineering properties, studies on the utilization of ferrochrome slag aggregate are limited. Therefore, in the next phase of this research, the Natural Coarse Aggregates (NCA) in OGA were replaced by Recycled Concrete Aggregates (RCA) (50% and 100%) and Ferrochrome Slag aggregate (FCS) (100%), and the effect on the mechanical properties of SFA mixtures were evaluated. The RCA was obtained by crushing the laboratory-prepared concrete specimens and passing them through the jaw crusher, followed by the ball-milling. SFA with 100% FCS exhibited higher stability,

compressive strength, moisture resistance, fatigue life and rutting resistance due to strong aggregate having good impact value. At the same time, SFA with marginal aggregates (RCA and FCS) met the requirements of IRC SP 125.

With the objective to reduce working temperatures of OGA mixtures, three Warm Mix Asphalt (WMA) additives, Sasobit (3%), Rediset (0.8%) and Zycotherm (0.1%), were added to PMB 40. The SFA mixtures prepared using WMA-modified binders were evaluated, and concluded that the SFA with Sasobit exhibited better mechanical properties than other mixtures, while the SFA with Rediset exhibited lower mechanical properties; however, all the SFA mixtures satisfied the specifications of IRC SP 125 2019. In the present study, a new approach, based on percentage coating, was adopted to determine working temperatures. The WMA additives reduced mixing and compaction temperatures by 30 °C and 28 - 33 °C.

In the final phase, Semi-Flexible Asphalt (SFA) mixtures were prepared using marginal aggregates (50% RCA, 100% RCA, and 100% FCS) combined with WMA-modified binders. The incorporation of WMA additives allowed for a reduction in mixing and compaction temperatures by 25–35°C and 28–33°C, respectively. However, the mixtures 50RCA-R, 100RCA-S, 100RCA-R, and 100RCA-Z showed higher Cantabro weight loss, indicating lower durability, and were therefore excluded from further evaluation. The 100FCS-S mixture exhibited the highest fatigue life across all stress levels. The rut depth and DS results for SFA mixtures with FCS displayed similar values, emphasizing the significant influence of the aggregate quality or type. Only the mixtures 50RCA-S, 50RCA-Z, 100FCS-S, 100FCS-R, and 100FCS-Z met the IRC requirements. Among these mixtures, SFA mixtures prepared with Sasobit additive and FCS aggregate performed better than other additives and marginal aggregates.

Keywords: Semi-Flexible Asphalt Mixture, Grout, Open-Graded Asphalt mixtures, Warm Mix Asphalt Additives, Marginal Aggregates, Working Temperatures, Coating

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NOTATIONS

AE/C	Asphalt Emulsion-to-Cement
C&D	Construction and Demolition
CAEP	Cement Asphalt Emulsion Paste
CS	Compressive Strength
CT	Compaction Temperatures
DS	Dynamic Stability
FA	Fly-Ash
FCS	Ferrochrome Slag aggregate
FL	Fatigue Life
GGBS	Ground Granulated Blastfurnace Slag
G_{mb}	Bulk Specific gravity
G_{mm}	theoretical maximum specific gravity
GRA	Grey Relational Analysis
GRC	Grey Relational Coefficient
GRG	Grey Relation Grade
Gr-I	IRC SP 125 recommended aggregate Gradation
Gr-II	New aggregate gradation based on SFPCM
GRO	Grey Relational Order
G_{sb}	bulk specific gravity of aggregate
HMA	Hot Mix Asphalt
IS	Indian Standard
ITS	Indirect Tensile Strength
MCDM	Multi-Criteria Decision Making Method
MS	Marshall Stability
MT	Mixing Temperature
NCA	Natural Coarse Aggregates
NMAS	Nominal Maximum Aggregate Size
OBC	Optimum Binder Content
OCE	Optimum Compaction Effort
OGA	Open-Graded Asphalt
OPC	Ordinary Portland Cement
PET	Polyethylene Terephthalate

PG	Performance Grading
PMB	Polymer Modified Bitumen
PSA	Paper Sludge Ash
RAP	Reclaimed Asphalt Pavement
RCA	Recycled Concrete Aggregates
RLT	Repeated Load Testing
RMS	Retained Marshall Stability
RSM	Response Surface Methodology
S/C	Sand-to-Cement
S/N	Signal-to-Noise
SAC	Sulphoaluminate Cement
SBS	Styrene-Butadiene-Styrene
SEM	Scanning Electron Microscope
SF	Silica Fume
SFA	Semi-Flexible Asphalt
SFPCM	Semi-Flexible Pavement Construction Manual
SP	Superplasticizer
TG	Trial Gradation
TSR	Tensile Strength Ratio
V _a	Air Void content
VCA _{DRC}	Voids in the Coarse Aggregates in the dry-rodded condition
VCA _{MIX}	Voids in the Coarse Aggregates of the mixture
VFB	Voids Filled with Bitumen
VG	Viscosity Grade
VMA	Voids in Mineral Aggregates
W/C	Water-to-Cement
WMA	Warm Mix Asphalt
WOGA	WMA-modified Open Graded Asphalt
WRT	Wheel Rut Tester

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Transportation and infrastructure play a vital role in a country's development and directly contribute to the gross domestic product. Road transport is a preferred and dominant mode of choice due to higher accessibility and connectivity. India has a road network of 63.72 lakh km and second largest network globally. The total road construction from 2015 to 2019 noted a 15.7% growth rate, while the length of National Highways reached 1.32 lakh km with a growth rate of 35% (MoRTH 2022a). The National Highways of 5835 km in length were constructed in nine months of FY 2021-22 and achieved the highest construction rate of 37 km/day (MoRTH 2022b). The roads, particularly National Highways, were constructed at a higher pace to facilitate freight and passenger services, aiming for corridor-based development.

The roads are of two types based on structural behaviour; flexible and rigid pavement. The rigid pavement consists of a concrete slab constructed over a sub-base or base layer on the compacted subgrade. The flexible pavement comprises the sub-base, base, bituminous base course and asphaltic surface course over the compacted subgrade layer. Fig. 1.1 depicts the typical cross-section of flexible pavement. The bituminous base course is designed to be a resistant layer by limiting the horizontal tensile strain at the bottom. The surface course, such as stone matrix asphalt and bituminous concrete, is designed to be a rut resistant layer. However, the other surface courses, such as open-graded friction course and porous asphalt mixture, are selected based on the specific field conditions and requirements.

1.2 SEMI-FLEXIBLE ASPHALT MIXTURES

Flexible pavement provides good riding quality, high skidding resistance, and easy maintenance. However, with rapidly increasing traffic, the occurrence of rutting and cracking has become obvious (Moghaddam et al. 2011). There is a need for a new type of

surface course, called a Semi-Flexible Asphalt (SFA) mixture, to overcome the drawbacks and enhance the performance of both flexible and rigid pavement (Mayer and Thau 2001). The SFA or Grouted Macadam is a surface course consisting of Open-Graded Asphalt (OGA) mixtures with an air void content of 20-35%, grouted with cement paste/mortar (Oliveira 2006). The OGA provides flexibility and skid resistance, and the grouting provides rigidity and the capacity to carry heavy traffic without rutting, together to achieve a joint-free, rut-resistant pavement (Mayer and Thau 2001; Setyawan 2009). Furthermore, the SFA is resistant to abrasion, heat, and fuel spillage, making it ideal for use in airports, ports, and other locations where slow and heavy vehicles pass (Mayer and Thau 2001).

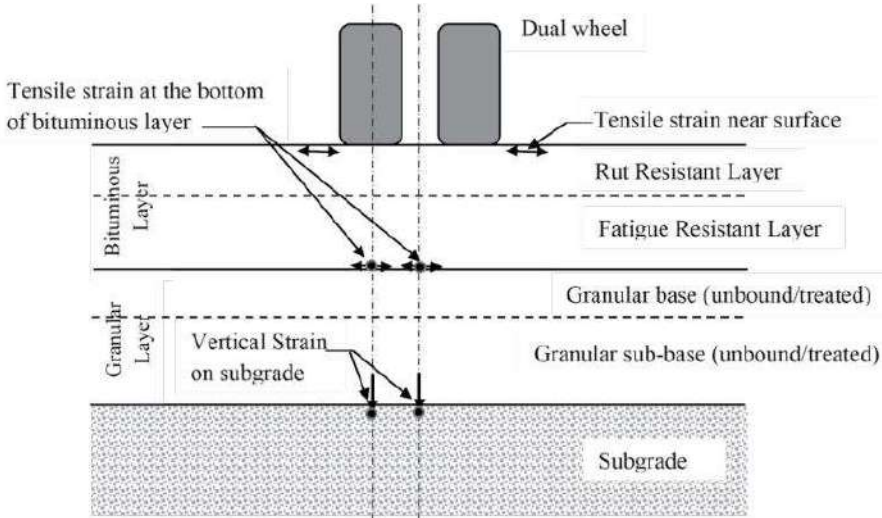


Fig. 1.1 Typical cross-section of flexible pavement (IRC 37 2018)

The OGA possesses a large porous structure, ensuring the stone-on-stone contact bears the traffic load and provides the voids for grout to permeate readily. Grout is a highly dense and low viscous packing material generally employed to fill the gaps between aggregates to form a proper bonding and to hold aggregate skeleton. It primarily consists of water, cement, sand, fly ash, silica fume, and other cementitious materials. The superplasticizers may increase the flowability at lower water content and compressive strength. Fig 1.2 depicts the typical laboratory preparation of SFA specimens. The SFA wearing course shall be constructed in two stages on two test sections in Surat, Gujarat state, India, as depicted in Fig. 1.3. The bituminous mix having air voids was laid on the

cleaned surface of the existing bituminous surface and compacted, as depicted in Fig. 1.3 (a) and (b). Once the bituminous surface reached ambient temperature, the thoroughly mixed grout was poured on and spread uniformly over the bituminous surface, as depicted in Fig. 1.3 (c). This surface layer was cured for three days, and the finished surface can be seen in Fig. 1.3 (d).

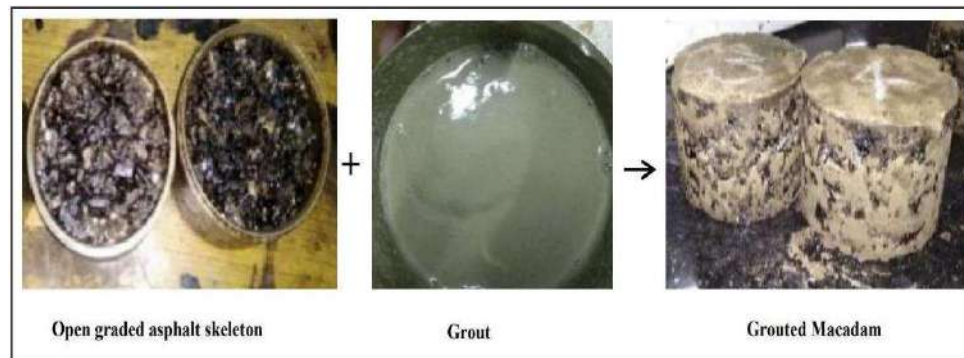


Fig. 1.2 Preparation of SFA (Saboo et al. 2019a)



Fig. 1.3 (a) Laying OGA mixture (b) Compaction of OGA mixture (c) Grout poured on OGA layer (d) Finished SFA mixture layer (Bharath et al. 2020)

The concept of SFA mixtures, known as resin modified pavement, dates back to the 1960's in France and is used as a surface layer resistant to fuel, oil spillage and abrasion

(Anderton 2000). As France succeeded in implementing SFA mixtures, the Africa, North America, USA and countries of European Union also adopted and were successful. However, SFA mixtures were called by various names; resin modified pavement or Salviacim (France and Europe), Cement Grouted Bituminous Mixture (CGBM), Grouted Macadam and Asphalt-Portland Cement Concrete Composite (APCCC), Cement Grouted Open-Graded Pavement, Composite Cement Asphalt Mixture (CCAM) and Densiphalt (Al-Qadi et al. 1994; Hassani et al. 2020; Zachariah et al. 2020).

1.3 MARGINAL AGGREGATES

Ahlich and Rollings (1994) defined marginal aggregates as aggregates which do not meet the requirements of the concerned code or standard. Using industrial by-products and Construction and Demolition (C&D) waste has been a common practice in asphalt and concrete pavements. The performance of industrial by-products, such as blast furnace arc slag and ferrochrome slag, was studied in preparing the asphalt and concrete mixtures. The production of C&D waste in India from demolition, renovation and natural disasters was around a minimum of 12 million tons annually (CPCB 2017). Jain et al. (2019) estimated C&D production in India to be 750 million tons by 2050. Concrete contributes to 35% of total C&D, including masonry, bricks, metal, asphalt and wood (CPCB 2017). Considering 50% of concrete as coarse aggregates, India generates 131 million tons of Recycled Concrete Aggregates (RCA) yearly.

On the other hand, Ferrochrome Slag (FCS) is an industrial by-product generated worldwide during ferrochrome alloy production, an essential constituent in stainless steel. Approximately 80% of ferrochrome reserves are used in producing stainless steel, contributing to the anti-corrosion characteristic of stainless steel (Holappa 2013). According to Global Stainless-Steel Expo 2023, the demand for stainless steel was 3.7 MT in 2022 and is predicted to increase to 12.5 MT by 2040 in India. Due to this expected demand in stainless steel production, ferrochrome alloy production increases FCS production. One tonne of ferrochrome alloy produces about 1.2-1.5 T of FCS.

Therefore, using RCA and FCS in asphalt, concrete and SFA mixtures has become a necessary common practice to avoid the disposal problem and maximize the utilization of RCA and FCS.

1.4 WARM MIX ASPHALT

Due to rapid urbanization, increased heavy vehicular traffic and traffic growth rate, using modified bitumen became inevitable to enhance the performance and life span of Hot Mix Asphalt (HMA) mixtures. The modified binders generally have high viscosity, which demands mixing temperatures of more than 150 °C (Li et al. 2016; Shang et al. 2011). The higher mixing temperatures increased gas emissions and fuel consumption (Pérez-Martínez et al. 2014). Jamshidi et al. (2013) mentioned that lowering working temperatures by 10 °C reduces carbon dioxide emissions by one kg/ton and fuel consumption by one litre. With this objective, the working temperatures were reduced using Warm Mix Asphalt (WMA) technology. The temperature reduction may range from 10-90°C depending on the type and dosage of WMA additive added to the binder or mixture (Cheraghian et al. 2020). The WMA additives are categorized into three groups, as shown in Fig. 1.4. The foaming additives improve the workability and coating due to the evaporation of water in the foamed asphalt binder. The organic additives reduce the working temperature by reducing the viscosity of the binder. The chemical additives improve the coating of aggregate by reducing surface tension, thus reducing working temperatures. The WMA additive (sasobit) significantly reduced energy consumption and carbon emissions (Liu et al. 2023). The WMA additives reduced 80% of harmful gas emissions, such as asphalt fume and benzopyrene, compared with HMA mixtures (Liu et al. 2023).

1.5 NEED AND SIGNIFICANCE OF THE PRESENT INVESTIGATION

Due to heavy and slow-moving traffic, asphalt pavements undergo rutting and fatigue failures, while concrete pavements have joints reducing riding quality and higher construction cost and time. SFA mixtures are suited for wearing course applications as their properties strike a balance between concrete and asphalt mixtures.



Fig. 1.4 Categorization of WMA technology (Cheraghian et al. 2020)

As the asphalt skeleton of the OGA mixture provides flexibility, the effect of gradation and bitumen type used to prepare the OGA mixtures on the mechanical properties of SFA must be investigated. The grout composition and formulation should be examined as the grout improves the rigidity of SFA mixtures. On the other hand, the usage of marginal aggregates should be investigated to meet the enormous demand for natural aggregates due to the increased construction rate and to save natural aggregates. Investigating alternate or marginal aggregates, such as industrial by-products and RCA, is necessary to reduce the depletion of natural coarse aggregates. Unlike HMA mixtures, the OGA skeleton of marginal aggregates is reinforced by grout, thus increasing the possibility of utilizing various marginal aggregates. The effect of WMA additives on OGA and SFA mixtures should be assessed to facilitate the construction of the OGA layer at lower working temperatures.

1.6 RESEARCH OBJECTIVES AND SCOPE

The main objectives of the current study are to assess the effect of aggregate gradation, bitumen type and WMA additives on the mechanical properties of SFA mixtures and also to assess the impact of potential replacement of natural coarse aggregates while preparing OGA mixtures on mechanical properties of SFA mixtures.

The specific objectives are identified as follows:

1. To assess the effect of the Sand-to-Cement (S/C) ratio in the selection of optimal grout mix using the Taguchi technique in conjunction with Grey Relational Analysis (GRA).
2. To evaluate the effect of aggregate gradation and bitumen type on the mechanical properties of SFA mixtures
3. To replace the natural coarse aggregates with recycled concrete aggregates and ferrochrome slag aggregates in preparing the OGA mixtures and evaluate the effect on mechanical properties of SFA mixtures.
4. To assess the effect of WMA additives on the mechanical properties of SFA mixtures.
5. To evaluate the effect of WMA additives and marginal aggregates on the mechanical properties of SFA mixtures.

The grout will be prepared using the specified quantity of cement, sand, water and superplasticizers. In conjunction with GRA, the Taguchi technique is adopted to determine the effect of the S/C ratio in selecting optimal grout composition. The S/C ratio, Water-to-Cement (W/C) ratio and superplasticizer (SP) content will be optimized simultaneously to achieve the minimum fluidity and higher compressive strength (CS). The grouts will be tested for fluidity and CS at seven days of curing. After selecting the optimal grout proportion, the OGA specimens will be prepared using two aggregate gradations. One of the two aggregate gradations is a new gradation developed, while the other is recommended by IRC SP 125. An unmodified binder, Viscosity Grade (VG) 30 and a Polymer Modified Bitumen (PMB) 40 are used to prepare the OGA mixtures of two gradations. Three SFA mixtures using two gradations and two binders will be prepared and compared to evaluate the effect of gradation and bitumen type on the mechanical properties.

In the next phase, the possibility of replacing the Natural Coarse Aggregates (NCA) with RCA and FCS is examined. The mechanical properties of SFA mixtures will be evaluated by conducting marshall stability, compressive strength, indirect tensile strength, moisture resistance, durability (cantabro abrasion tests), wheel rut tester and repeated load testing (fatigue resistance). Three WMA additives, such as Sasobit, Rediset and

Zycotherm, will be added to PMB 40 in connection with the fourth and fifth objectives. Using WMA-modified binders, the SFA mixtures are to be prepared, cured for 28 days and tested for mechanical properties. To accomplish the fifth objective, the SFA mixtures will be prepared with combinations of marginal aggregates and WMA-modified binders, and the mechanical properties will be evaluated.

1.7 ORGANIZATION OF THESIS

Chapter 1 introduces the concepts of SFA mixtures and WMA technologies. It outlines the research objectives and scope of the study. **Chapter 2** presents the literature review on the composition and properties of grout and SFA mixtures. It includes the significance and suitability of alternate aggregates in SFA mixtures and the effect of WMA additives on asphalt mixes. **Chapter 3** describes the materials, gradations, testing procedures and methodology adopted in the investigation. **Chapter 4** explores optimization of grout formulations by examining the influence of SP content, S/C ratio, and W/C ratio, aiming to identify the optimal grout composition through a systematic optimization approach. Following this, **Chapter 5** shifts the focus to the key components of OGA mixtures, including aggregate gradation and binder type, and presents findings on how these factors impact the mechanical properties of SFA mixtures. Once the effects of aggregate gradation have been thoroughly assessed, the next phase involves investigating the impact of different aggregate types, specifically marginal aggregates. Thus, **Chapter 6** reports on the outcomes of incorporating RCA and FCS into SFA mixtures to improve sustainability.

To further enhance the safety of the work environment, the integration of WMA technology is explored, aiming to lower the production temperatures of OGA mixtures. **Chapter 7** addresses this aspect by examining the implementation of WMA additives and their influence on the properties of SFA mixtures. Finally, Chapter 8 extends this investigation by evaluating the combined effects of WMA additives and the use of marginal aggregates on the mechanical performance of SFA mixtures, thereby advancing the research toward more sustainable and safer construction practices. **Chapter 9** presents the

conclusions, recommendations, lessons learned, practical applications and future scope of the research work.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

The present investigations aimed to design and evaluate the performance of the Semi-Flexible Asphalt (SFA) mixtures. This chapter discussed the contribution of various past studies in using SFA mixture as a pavement layer. Further, this chapter discussed the selection and preparation of grout and Open-Graded Asphalt (OGA) mixtures, utilizing alternate aggregates and Warm Mix Asphalt (WMA) additives, and the review connected to different aspects of SFA mixtures.

2.2 GROUT

2.2.1 Composition and Optimization

The composition and optimization of grout mixes adopted to prepare SFA mixtures were presented in Table 2.1. It was observed that the W/C ratios ranging from 0.30 to 0.72 and Sand-to-Cement (S/C) ratios ranging from 0.15 to 0.67 were adopted to prepare the grout. However, the studies focused on S/C ratio and its effect on selecting the optimal grout were limited. The superplasticizers such as latex modifier, polycarboxylate-based, polycarboxylate ether-based, modified polycarboxylate ether-based, sulfonated naphthalene-based superplasticizers, viscosity modifying agents and polymer-modified additives were used in various dosages to reduce the water requirement and achieve higher flowability at lower water contents. The fluidity ranged from 8 to 110 seconds with these admixtures and superplasticizers. The Compressive Strength (CS) of grout at 7- and 28-day curing periods ranged about 3.9-90 MPa and 5.8-91MPa, respectively, while the geopolymer grout exhibited CS of 108 MPa at 28-day curing period. The selection of W/C ratio, S/C ratio, superplasticizer and its dosages depended on the grout requirements such as high early strength, high performing grout and geopolymer grout. However, the grout composition was optimized based on one or more factors: fluidity, CS and flexural strength, as tabulated in Table 2.1.

Table 2.1 Composition and properties of grout from various research papers

Type of Grout	Composition	W/C ratio	S/C ratio	SP* Type or additives (by weight of binder)	Fluidity (s)	CS (MPa)*	Remark (optimization)	Author
CAEP and Cement Paste	Ordinary Portland Cement (OPC), Asphalt Emulsion	0.34 (W/C); 0.2-0.6 (AE/C)*	-	Polycarboxylate SP, Oraganic Defoaming agent, viscosity modifying agent	-	-	Based on fatigue life of SFA mixtures	(Alae et al. 2022; Zarei et al. 2022)
Cement mortar	cement, sand, Zeolite (0-25% replacement of cement)	-	0.50	-	-	-	-	(Hamzani et al. 2021)
Cement paste	Cement, filler	0.36	-	various admixtures	12	27 (3 days)	-	(Gong et al. 2022)
Cement paste and cement with waste plastic	Cement	0.35	-	Polycarboxylate ether based SP-1.0%	12.6	40 (7 days) 57 (28 days)	Response Surface Methodology to optimize the FA, regular and irradiated PET	(Khan et al. 2022)
Cement mortar	Cement, FA, sand	0.60	0.30	Sulfonated naphthalene-based SP -1%	27	12.8 (7 days) 19.6 (28 days)	Based on fluidity and CS	(Kaushik and Siddagangaiah 2022)
Cement mortar	Portland cement, FA, sand, mineral powder	0.55-0.65	15-25% (sand content)	-	10-20	17-28	Based on fluidity, CS and flexural strength	(Zhang et al. 2022)
Polymer modified mortar	Cement, sand, polymer modified additive	18-35% (water content)	-	-	10-110	23-68	Based on fluidity and CS (7 days)	(Shukla et al. 2021)
Cement mortar	Cement, sand, mineral powder	0.50-0.70	8-24%	SF, Emulsified asphalt, waterborne epoxy resin	8.33-17.5	16-31.45 (7 day)	Orthogonal array (L9)	(Jiahong 2021)

Type of Grout	Composition	W/C ratio	S/C ratio	SP* Type or additives (by weight of binder)	Fluidity (s)	CS (MPa)*	Remark (optimization)	Author
Cement mortar	Cement, fine aggregate	0.3	-	Various admixtures	14			(Tan et al. 2021a)
Cement paste	OPC, FA, Silica Fume (SF)	0.32	-	Water reducing chemical admixture-1%	16-33	7-15 (7 days) 12-20 (14 days) 15-30 (28 days)	Based on fluidity and CS	(Gupta and Kumar 2021)
Cement mortar	OPC, SF, FA, sand	25-41%	-	SP	8-20	3.9-68 (7 days) 5.8-85 (28 days)	Based on fluidity	(Othman et al. 2020)
Latex-modified cement mortar	OPC, sand, fines	0.72	0.49	latex modifier	12.1-12.8	23.5-24.1 (7 days)	Based on fluidity, compressive and flexural strengths	(Luo et al. 2020)
Polymer modified mortar	Cement, sand	20%	-	Polymer additive	55	65 (7 days)	Based on fluidity and full-depth grouting	(Bharath et al. 2020)
Cement paste	Cement	0.31	-	Polycarboxylate ether-based SP-1.43%	15.4	20.8 (1 day) 51.49 (7 days) 57.91 (28 days)	Based on fluidity and CS using RSM	(Imran et al. 2020)
Cement paste	OPC, Sulphoaluminate Cement (SAC), FA, SF	0.3	-	Polycarboxylate-based SP -1%	15-46	44-80 (1 day) 52-90 (7 days) 56-91 (28 days)	Based on fluidity less than 16 s	(Chen et al. 2020)
Cement paste	OPC, Paper Sludge Ash (PSA), SF	0.5	-	Modified polycarboxylate ether-based SP	15-18	17-33 (28 days)	Based on fluidity, CS and FS	(Hail et al. 2020)

Type of Grout	Composition	W/C ratio	S/C ratio	SP* Type or additives (by weight of binder)	Fluidity (s)	CS (MPa)*	Remark (optimization)	Author
Geopolymer paste	FA, SF, Ground Blast slag Furance (GGBS), Metakaolin	0.27-0.52	-	Liquid activator (Potassium silicate)	9-608	36-108 (28 days)	Based on fluidity, initial setting time, CS	(Thao et al. 2020)
Cement mortar	Cement, sand, micro silica, FA	0.55	0.67	SP-0.5%	6	-	Fluidity	(Reddy and Reddy 2023)
Cement asphalt emulsion paste	OPC, SF, aluminite powder, Slow setting cationic asphalt emulsion	AE/C: 20-60%	-	Polycarboxylate viscosity modifying agent	10-13	11-12.5 (7 days) 17.5-19 (28 days)	Based on performance of SFA mixtures	(Zarei et al. 2020)
Cement mortar	Cement, sand	0.3	-	various admixtures	14	25-82	-	(Hong et al. 2020)
Cement mortar	OPC	0.6	0.5	-	11.6	10.4 (7 days) 30.7 (28 days)	-	(Zhang et al. 2019)
Cement slurry	Readily available grout material	0.3	-	-	13	-	-	(Gong et al. 2019)
Cement paste	JGM-301 grout material	0.31	-	-	10.3	34.5 (3 days) 42.3 (28 days)	-	(Cai et al. 2019)
Cement paste	Portland cement, sand slag	0.3	-	Polycarboxylic ether SP-0.35	3.5 (4mm dia. orifice Marsh cone)	-	Based on full-depth grouting	(Mukherjee and Sahoo 2019)
Cement mortar	OPC, sand	0.5, 0.6	0.3	Naphthalene based SP (2%), Polycarboxylate SP (1-1.5%)	10-14	20.32-24.93	Based on fluidity and CS	(Saboo et al. 2019a)

*NOTE: For CS: curing period is mentioned in parentheses; AE/C, Asphalt Emulsion-to-Cement; SP, Superplasticizer;

Saboo et al. (2019a) formulated a mathematical program based on the requirements of optimal grout mix and obtained the solution (optimal grout mix) using the optimization technique. The W/C ratio, sand size, and SP contents were selected as input parameters, and the proportions or contents were based on the experimental work. The constant S/C ratio of 0.3 was considered based on the literature. The optimal grout proportions obtained were checked for full-depth grouting. It was observed that the polycarboxylate-based SP improved the CS and reduced the water demand significantly compared to naphthalene-based SP. Hlail et al. (2020) replaced cement using PSA and SF with 5-20% and 2.5-10%. The fluidity had increased with PSA and SF; however, the increment was marginal. The SP improved the fluidity and flexural strength. The effect of PSA and SF on compressive strength was ambiguous. The optimum contents of PSA and SF were recommended to be 15% and 2.5%, respectively.

Chen et al. (2020) prepared the grout using SAC to achieve high early strength. The FA, SF and superplasticizer were also used to improve the fluidity. The FA improved the fluidity but reduced the compressive strength compared to the grout with 100% SAC. The SF reduced the early strength; however, no effect was observed on compressive strength at 28 days. The composition of the grout was selected solely based on fluidity being less than 16 seconds (Oliveira 2006). The grout prepared with 70% SAC, 30% FA, 1% SP and 0.30 W/C ratio exhibited the same strength of 56 MPa at 1- and 28-day curing period. Luo et al. (2020) prepared grout with the latex modifier to improve the flexural strength and adhesion between the asphalt and grout. The latex modifier has improved flexural and compressive strength but increased fluidity. The grout with latex modifier exhibited 70% higher flexural strength than those without, while the compressive strength was enhanced by about 2.5%.

Imran et al. (2020) adopted Response Surface Methodology (RSM) to optimize the W/C ratio and superplasticizer content in achieving highly flowable grout. The range of W/C ratios and superplasticizer contents considered were 0.25-0.45 and 0-2%, by weight of binder, respectively. The fluidity decreased with an increase in the W/C ratio and SP content. The grout with higher SP content dosages (more than 1.5%) exhibited bleeding issues. The CS had improved with a reduction in the W/C ratio. However, this initial

increase in CS had with SP content later reduced, due to bleeding issues. The targeted fluidity range was 11-16 s, and the maximum CS was at 1, 7 and 28 days. Based on these requirements, the optimum combinations were obtained as the W/C ratio of 0.36 and SP content of 1.43%. The grout at optimal composition had the fluidity of 16 s, CS of 20.8 MPa, 51.5 MPa and 57.9 MPa at 1, 7 and 28 days, respectively.

Zhang et al. (2022) optimized the grout proportions of W/C, mineral powder and sand content using orthogonal arrays (L9). The W/C ratios of 0.55-0.65, 5-15% of mineral powder, and 15-35% of sand content were optimized based on fluidity. The CS was most to least influenced, in the order, by sand content, mineral powder and W/C ratio, respectively. The fluidity was most and least affected by mineral powder and sand content. The influential factors of fluidity and CS were determined; however, the best optimal mix was solely selected based on fluidity. Jiahong (2021) also reported similar results on influencing factors of fluidity based on the orthogonal arrays (L9). In contrast to Zhang et al. (2022), it was observed that the CS was most and least affected by mineral powder and sand, respectively. The recommended sand content was 16% based on the reduced drying shrinkage of grout. The optimal grout mix was determined by analysing the experimental results rather than by optimization technique.

Khan et al. (2022) investigated the cement replacement with fly ash, normal and irradiated polyethylene terephthalate (PET) powder using the RSM. The PET content increased the fluidity (i.e., reduced the flowability) and reduced the CS and drying shrinkage. Interestingly, the FA increased the fluidity and improved the CS and drying shrinkage. However, the grout containing 5% PET and 10% FA achieved the targeted fluidity and improved CS and drying shrinkage. The irradiated PET improved the grout properties more than the normal PET. Based on RSM, the optimal irradiated PET and FA contents were obtained as 4.75 and 10%, respectively, meeting the requirements of fluidity (11-16 s), CS (7 MPa-1 day, 35 MPa-7 day, 60 MPa-28 day), drying shrinkage, and flexural strength (3 MPa).

2.2.2 Effect on Mechanical Properties of SFA Mixtures

As the grout reinforces the OGA skeleton, the strength of the grout highly influences the performance of SFA mixtures. Zarei et al. (2020) prepared Cement Asphalt Emulsion Paste (CAEP) with varied AE/C of 20-60%. The AE/C content increased the fluidity and flexural strength but reduced the compressive strength; the changes in strength seemed to be marginal. However, the pull-off tensile strength improved significantly, attributed to enhanced bonding between grout and asphalt. The rutting resistance, Marshall Stability (MS), Indirect Tensile Strength (ITS), and moisture resistance of SFA mixtures were reduced with increasing AE/C content and inferior to the SFA grouted with cement paste; but satisfied the requirements. The flexural strength at -10 °C was expected to improve with increased AE/C content as grout exhibited better pull-off tensile strength, and the same was observed. The flexural strength of SFA mixtures was better than Hot Mix Asphalt (HMA) mixtures but reduced with increased AE/C content. Hence, based on the performance of SFA mixtures, the 40% AE/C content was recommended as the optimal dosage to prepare the CAEP.

Thao et al. (2020) prepared geopolymer grout using fly ash, GGBS, Metakaolin, SF and potassium silicate (liquid activator) with a molar ratio of 1.6. As geopolymer grouts have lesser initial setting time, the fluidity, initial setting time and CS were used to select the final grout composition. The SFA mixtures grouted with GGBS and FA exhibited higher compressive strength and fluidity than mixtures with GGBS, FA, metakaolin and SF. The metakaolin and SF improved the CS of grout but reduced the flowability. Hamzani et al. (2021) prepared grout by replacing cement with 0-25% zeolite powder and investigated the performance of SFA mixtures. It was observed that the modulus of elasticity and compressive and flexural strengths were initially improved and then reduced with increased zeolite content. On the other hand, drying shrinkage had decreased initially and then increased. The strength improvement was attributed to the silica in zeolite reacting with calcium hydroxide to form calcium-silicate-hydrate. In the case of higher dosages of zeolite, excessive unreacted zeolite hindered the strength. Hence, the zeolite content of 15% replacing the cement was recommended.

Jiahong (2021) prepared three types of SFA mixtures grouted with mortars having admixtures, SF (5%), emulsified asphalt (4%) and waterborne epoxy resin (6%). The silica fume and emulsified asphalt improved the flexural tensile strength of SFA mixtures, while the epoxy resin reduced the same. It was worth mentioning that the epoxy resin could improve the rigidity of SFA mixtures but impairs cracking resistance. It was concluded that the grout composition would influence the low-temperature cracking resistance of SFA mixtures. Zarei et al. (2022) observed reduced tensile strengths with increased asphalt emulsion contents. The indirect tensile fatigue test results indicated that the fatigue life increased with increased asphalt emulsion content to some extent and then reduced. The crack appeared at the interface between the asphalt layer and grout in the SFA with cement paste. In the case of SFA mixtures with CAEP, the breakage of aggregates and grout and the interface failure indicate a strong bond strength between the asphalt and grout due to asphalt emulsion. Hence, the CAEP grout prepared with the asphalt emulsion to the cement of 0.40 was recommended. Alae et al. (2022) reported that the SFA grouted with CAEP of asphalt emulsion (20-60%) improved the rutting and top-down cracking resistance; however, the rutting depth increased with asphalt emulsion content. The asphalt emulsion content of 0.40 was recommended to improve the rutting and top-down cracking resistance.

2.3 SEMI-FLEXIBLE ASPHALT MIXTURES

2.3.1. Effect of Aggregate Gradation

The fine aggregates, filler, and bitumen generally fill the voids between the coarse aggregates in OGA mixtures and provide flexibility to SFA mixtures (EucoDensit 2000). However, the fine aggregate content in OGA mixtures was reduced to provide high air void content and interconnected air voids (Hou et al. 2016). Higher fine aggregates and fillers demand higher bitumen content to form a thicker asphalt film, increasing the fatigue life of HMA mixes (Anderson and Kennedy 1993; Oliveira 2006). Setyawan (2005) investigated the effect of fine aggregate content on the void content and permeability of porous asphalt skeleton using three different aggregate gradations. It was observed that the fine aggregate content had a stronger influence on permeability than void content; in other words, void interconnectivity was more affected than void content. The smaller change in

fine aggregate content affected the void interconnectivity significantly compared to air voids. The increase in fine aggregate content reduced the air voids.

Ding et al. (2011) evaluated three continuous aggregate gradations with different air voids and a homogenous gradation (similar to a single-sized aggregate gradation). The SFA mixture with homogenous gradation performed better than the same with continuous gradation, attributed to the formation of continuous same-sized voids distributed equally in the former. The increased voids accommodated the higher grout volume and improved the performance of SFA mixtures. Yang et al. (2012) selected the aggregate gradation based on the concept of Main Mineral Aggregate Void Filling, where the volume of fine aggregates, filler and binder should be equal to the volume of coarse aggregates in dry-rodded condition excluding the targeted void content (Jiahong 2021). The proportions of aggregates, filler and binder were adjusted to meet the technical requirements of the OGA skeleton. There was ambiguity regarding the increased optimum binder contents with air voids. The interconnectivity of voids, supposedly assessed by permeability, was not considered. Husain et al. (2014) observed statistically improved compressive strength and abrasion resistance of SFA mixtures with decreased fine aggregate content in the OGA mixture. The reduced fine aggregate content increased the voids in the OGA mixture, which increased the grouting volume, thus improving the performance of SFA mixtures.

Hou et al. (2017) investigated the effect of aggregate gradation on air voids of OGA mixtures and residual voids of SFA mixtures and found bitumen content and fine aggregate content to influence air void content and residual void content significantly. The higher air voids in OGA mixtures need not necessarily promotes a high degree of grouting. It also depended on the interconnectivity and size of voids. The coarse aggregate proportion of 10-5 mm sieves improved the grouting ability with increased interconnectivity of voids. The fine aggregate proportion of 0.30-0.15 mm size had a negligible effect on grouting ability. The fine aggregate proportion of 1.18-0.30 mm size significantly affected the interconnectivity of voids more than void content.

Cai et al. (2017) used two parameters, contributive rate and contributive efficiency, to determine the contribution of grout and asphalt skeleton. The SFA mixture has two

phases, asphalt skeleton and grout. The contributive rate was the influence of each phase, while the contributive efficiency was the ratio of each phase material per volume on the strength of SFA mixtures. Based on the uniaxial compressive test, it was concluded that the contribution of the OGA skeleton was higher than grout. The contribution rate of grout increased marginally from 3% to 5%, with increased void content from 18% to 24%. At the same time, it was worth mentioning that the performance of SFA mixtures improved with void content.

Cai et al. (2019) concluded that the dynamic modulus of SFA mixtures was more influenced by aggregate gradation than voids. Saboo et al. (2019b) adopted a hierarchical ranking strategy to select the OGA skeleton based on the drain down, air voids, permeability, cantabro loss and ITS. The gradation with higher fine aggregate content (more than 17%) produced air voids of 27%. However, due to the lower permeability (i.e., less than 100 m/day), the interconnectivity of voids was assumed poor and, thus, not recommended. It was observed that the coarse aggregate proportion of 10-5 mm size improved the grouting ability with increased interconnectivity of voids. Luo et al. (2020) prepared two SFA mixtures with Nominal Maximum Aggregate Sizes (NMAS) of 16 mm and 13 mm and observed the significant effect of aggregate gradation on the performance of SFA mixtures. The SFA mixture with finer gradation exhibited improved or comparable performance in terms of marshall stability, tensile strength, dynamic stability, low-temperature crack resistance and fatigue. However, it signified the importance of full-depth grouting and air voids, irrespective of void content.

Cai et al. (2020) prepared three SFA mixtures with OGA skeletons having 22%, 25% and 30% air void content and investigated the interlocking characteristics of OGA skeleton and grout. It was concluded that the SFA with OGA skeleton having 25% voids was the most stable gradation. The higher void content might increase the coarse aggregate and grout contacts. Nonetheless, the gradation had a significant impact on the effective coarse aggregate and grout contacts that were responsible for load transfer. Shukla et al. (2021) evaluated six aggregate gradations to prepare SFA mixtures based on the resilient modulus. It was observed that the gradations with a higher percentage of 9.5 mm sieve

passing (57-84%) might accommodate air voids ranging from 25-30%. However, it significantly reduced the resilient modulus and tensile strength of SFA mixtures. Jiahong (2021) investigated the low-temperature crack resistance of SFA mixtures and concluded that the air void content of OGA mixtures had the most significant influence, followed by the binder and grout type.

Taghipoor et al. (2021) observed that the SFA mixture with coarser gradation has high grouting saturation than those of finer gradation and better rutting resistance. Gong et al. (2022) investigated three aggregate gradations of OGA mixtures with different fine aggregate content and their effect on the performance of SFA mixtures. The SFA mixtures with coarser gradation exhibited lower tensile strength, higher cantabro loss, and higher dynamic stability than those with finer gradation. However, the SFA mixture with finer gradation was recommended based on the overall performance, including low-temperature and flexural strength. The grout was more significant than the asphalt skeleton at high and intermediate temperatures. In contrast, at low temperatures, both the grout and asphalt skeleton affected the performance of SFA mixtures. The gradation type was observed to be the most significant factor than the compaction level. Reddy and Reddy (2023) prepared SFA mixtures using four different aggregate gradations and observed the improved rutting resistance with increased initial voids in OGA mixtures. The rutting resistance reduced with an increased bitumen content, attributed to decreased air voids and thus the reduced grout volume.

2.3.2 Bitumen Type

To prepare the OGA mixtures, the U.S. Army Corps of Engineers' Specification on Resin Modified Pavement recommends that bitumen should have a penetration value of 40-100 (Anderton 2000). Similarly, EucoDensit (2000) recommended bitumen of penetration values of 85-100 and 120-150, depending on weather conditions. However, Oliveira et al. (2006) concluded that stiffer binders yield stiffer SFA mixtures, which improves fatigue life to some extent. Setyawan (2009) evaluated the effect of bitumen type on the mechanical properties of porous asphalt mixture and concluded that the Styrene-Butadiene-Styrene (SBS)-modified binder improved the durability and lower stiffness

modulus. However, the effect of bitumen type on SFA mixtures was not investigated. Several researchers prepared the OGA specimens using a variety of binders, including Asphalt Cement - 20, SBS modified binder, and VG 30 (Al-Qadi et al. 1994; Anderton 2000; Gong et al. 2022; Gupta and Kumar 2021; Kaushik and Siddagangaiah 2022; Mukherjee and Sahoo 2019; Saboo et al. 2019b; Shukla et al. 2021)

Oliveira (2006) stated that the polymer-modified binder significantly improved fatigue life; however, the mechanical characteristics and moisture susceptibility of SFA mixtures require more investigation. Ding et al. (2015) incorporated Reclaimed Asphalt Pavement (RAP) to prepare the SFA mixtures and observed the major crack propagated through the interface of asphalt and hardened grout. It was concluded that a binder having high viscoelasticity would improve the cracking resistance. Afonso et al. (2016) prepared the cold asphalt skeleton using emulsion, compared it with the HMA skeleton, and concluded that the SFA mixtures with the HMA asphalt skeleton outperformed those of the cold asphalt skeleton. Gong et al. (2019) evaluated the cracking resistance of SFA mixtures prepared with modified binders using the semi-circular bending test, and the base binder was SBS-modified binder. The SFA with base binder exhibited higher fatigue life at a lower stress ratio, while the other modified binders performed better at high-stress ratios. It was concluded that the modified binders significantly influenced the cracking resistance

Jiahong (2021) prepared SFA mixtures with a neat binder, SBS-modified asphalt and epoxy-modified asphalt to evaluate the low-temperature cracking resistance. The SFA mixture with SBS-modified binder had improved flexural tensile strength than the same with the neat binder, followed by the epoxy binder. The flexural tensile strength improvement was about 5-7% higher than the neat binder. Table 2.2 presents various researchers' mix design details of the OGA skeleton. Table 2.2 Mix design parameters of OGA mixtures

Table 2.3 Mix design parameters of OGA mixtures

NMAS (mm)	Binder Type	Optimum Binder Content (OBC) (%)	Air Voids (%)	Compaction Effort	Marshall Stability (kN)	ITS (MPa)	Cantabro weight loss (%)	Author
12.5	Penetration Grade 85/100 with fibers; SBS-modified asphalt	4.6-4.8; 4.5-4.6	20-25, 25-30, 30-35	50 blows on each side	-	0.44-0.73; 0.59-0.86	22	(Taghipoor et al. 2021)
19	Penetration Grade 60/70 with zeolite (3-5%)	3.5 (Based on stability)	24.7	-	5.02 (≥ 4.9)	-	-	(Hamzani et al. 2021)
13	SBS modified asphalt	4.2	26	50 gyrations	3.4	0.9	28	(Tan et al. 2021a)
19, 13.2, 12.5	VG 30	2.45, 2.95, 3.75	24.8, 20.8, 16.4	40, 45, 50 blows on one side	-	-	-	(Gupta and Kumar 2021)
16	Penetration Grade 80/100	2.2	26	50 blows on each side	≥ 3.5	-	-	(Alae et al. 2022; Zarei et al. 2022)
13	SBS modified binder	4.2	20.5-26.6	50, 75, 100	-	0.35-0.65	18-43	(Gong et al. 2022)
12.5	VG 30	Based on surface area	30	15 blows on each side	-	-	-	(Kaushik and Siddagangaiah 2022)
13.2	70# petroleum asphalt with epoxy resin	4.2-5.2	18-25	Rut shaper	-	-	-	(Zhang et al. 2022)
19-9.5 (6 gradations)	VG 30	2.0-3.3	25-36	30, 40, 50 blows on one side (based on gradation)	-	-	-	(Shukla et al. 2021)

Table 2.3 Mix design parameters of OGA mixtures

NMAS (mm)	Binder Type	Optimum Binder Content (OBC) (%)	Air Voids (%)	Compaction Effort	Marshall Stability (kN)	ITS (MPa)	Cantabro weight loss (%)	Author
19	Neat bitumen, SBS and Epoxy modified binders	-	24, 28, 32	-	-	-	-	(Jiahong 2021)
9.5	Penetration Grade 60/70	4.2 (Based on literature)	28.4, 25.7, 22.5	15, 25, 35 blows on each side	-	-	-	(Othman et al. 2020)
16, 13	SBS modified asphalt	3.2, 3.4 (Based on asphalt film thickness)	-	50 blows on each side	4.43, 4.15	-	18, 14	(Luo et al. 2020)
13.2	VG 30	2.41	33.5	40 blows on one side	-	-	-	(Bharath et al. 2020)
13.2	SBS-modified bitumen (PG76-22)	3.8	25	Rolling compaction	5.8	-	-	(Xu et al. 2020)
5-10	PG*76-16	3	30	Roller compaction based on targeted air voids	-	-	-	(Chen et al. 2020)
-	SBS-modified bitumen with high viscosity modifier	3.1, 4.1, 3.3	21, 28, 32	Gyratory compacter	-	-	-	(Cai et al. 2020b)
19	Penetration Grade 80/100	2.2 (Marshall mix design)	26.3	Marshall compaction	3.77 (≥ 3.5)	-	-	(Zarei et al. 2020)
19	VG 30	5.2, 5.6, 5.2 (based on air voids,	18, 21, 24	50 blows on each side	7.47-8.43	-	16-23.2	(Zachariah et al. 2020)

Table 2.3 Mix design parameters of OGA mixtures

NMAS (mm)	Binder Type	Optimum Binder Content (OBC) (%)	Air Voids (%)	Compaction Effort	Marshall Stability (kN)	ITS (MPa)	Cantabro weight loss (%)	Author
		draindown, cantabro loss)						
13.2	SBS-modified asphalt	3.2	27	50 blows on each side	-	-	-	(Hong et al. 2020)
19	Penetration Grade 80/100	3.4 (draindown and cantabro)	20	75 blows on each side	≥ 3.0	-	4.22	(Zhang et al. 2019)
13	SBS-modified asphalt (base asphalt), modified base asphalt	3.3, 4.2, 4.3 (draindown and cantabro)	25, 23, 22	50 gyrations	-	-	-	(Gong et al. 2019)
9.5	SBS-modified asphalt	4.4 (same bitumen content)	22, 25, 30	Gyratory compactor	-	-	-	(Cai et al. 2019)
13	VG 30	3 (surface area)	28.8	50 gyrations	-	-	-	(Mukherjee and Sahoo 2019)

*PG, Performance Grading

2.3.3 Mechanical Properties of SFA Mixtures

Hamzani et al. (2021) prepared SFA having waste tire rubber powder as a filler (3-5%) and noticed improved drying shrinkage and compressive and flexural strength. However, the modulus of elasticity decreased with increased filler content. Gupta and Kumar (2021) observed improved Marshall stability, compressive strength, ITS and moisture resistance than HMA mixtures. The temperature sensitivity in terms of ITS was less than HMA mixtures. Luo et al. (2020) prepared an SFA mixture with NMAS of 16mm and 13mm and reported improved Marshall stability, split tensile strength and moisture resistance compared with HMA mixtures. It was worth mentioning that the SFA mixtures with NMAS of 13mm exhibited improved or comparable properties to SFA with 16 mm NMAS. Bharath et al. (2020) reported the improved Marshall stability, compressive strength and ITS than bituminous concrete. The Tensile Strength Ratio (TSR) relating to moisture and oil spillage resistance was determined as 96 and 92%, respectively, significantly higher than the HMA mixture. Zhang et al. (2020) observed the improved moisture resistance and tensile strength of SFA mixtures than HMA. Mukherjee and Sahoo (2019) reported significantly improved Marshall stability, ITS, and moisture resistance than HMA mixtures.

2.3.4 Performance of SFA Mixtures

Mukherjee and Sahoo (2019) prepared the SFA mixtures using portland slag cement and observed the rut depth of 0.03 mm at 60 °C measured after 10000 loading cycles. The flexural modulus was 8700 MPa. Cai et al. (2019b) concluded that the higher stiffness of SFA mixtures was not necessarily attributed to the higher initial voids or grout volume. The reinforcing mechanism of the double skeleton might also increase the stiffness. The performance of SFA mixtures at high temperatures was significantly improved due to the grout. However, the same grout affected the performance negatively at low temperatures.

Zhang et al. (2019) observed no statistical difference in the tensile strength at -10 °C of SFA and HMA mixtures, but the stiffness modulus of SFA was 40% lesser than the HMA mixtures. The rutting resistance of SFA mixtures was 16 times higher than HMA mixtures, and the improved moisture resistance in terms of Retained Marshall Stability

(RMS) was also observed. Hong et al. (2020) investigated the freeze-thaw resistance of SFA mixtures using a dynamic elastic modulus test (non-destructive) and observed that the grout resistance to freeze-thaw directly influenced the performance of SFA mixtures. The SFA prepared with high-strength grout exhibited a higher resistance than those with early-strength grout, indicating the significance of grout composition.

The dynamic modulus of SFA mixtures at all frequencies was higher than HMA mixtures, attributed to the higher stiffness of grout and grout acting as secondary reinforcement (Zhang et al. 2020). The variation of the dynamic modulus of SFA mixtures over a wide range of frequencies was comparably lesser than that of HMA mixtures, indicating better temperature resistance of SFA mixtures. Based on the ITS fatigue testing at 20 °C, the SFA mixtures had higher maximum stress than the HMA mixtures. In the post-peak stress region, a sudden drop in stress was observed in SFA mixtures, indicating brittle nature. The fracture work was calculated to assess the fatigue resistance by determining the area under the stress-strain curve. The fracture work of SFA mixtures was 43% lesser than the HMA mixture, indicating inferior fatigue resistance. Similarly, thermal cracking resistance was determined using the ITS testing at -10 °C temperature. It was observed that the fracture work of SFA mixtures was only 4% higher than HMA mixtures, attributed to the brittle nature of asphalt at low temperatures. The dynamic modulus of SFA mixtures was significantly higher than porous asphalt mixtures (Cai et al. 2020a). The loss modulus was always lower than the storage modulus.

SFA mixtures grout with sulphoaluminate cement exhibited high early compressive strength (Chen et al. 2020). But the stiffness modulus was relatively small corresponding to the higher compressive strength. The Indirect Tensile Fatigue test was conducted at a 10 Hz frequency to determine the fatigue life. The load was selected to limit the initial strain ranges from 20 to 200 μ . The increase of 2 μ strain was observed at 400 kPa applied load after 55,000 loading cycles, while at 800 kPa load, the SFA mixtures exhibited a higher fatigue life, implying significantly improved fatigue resistance. While the rutting resistance of SFA mixtures improved considerably, the low-temperature resistance was inferior to the HMA mixtures. The failure temperature of the SFA mixtures was around -17 °C, while the

HMA mixtures' failure temperature was -30 °C. Therefore, it was recommended to use SFA mixtures in hot climate areas and be cautious in cold regions. Wang et al. (2021) evaluated the fatigue resistance of SFA mixtures compared to HMA mixtures by conducting semi-circular bending test. The fatigue life of the SFA mixture was reduced with an increase in stress ratio and a decrease in test temperature. At low temperatures (-5 °C) and a lower stress ratio (0.4), the fatigue resistance of SFA was multifold times that of HMA mixtures. While at intermediate and high temperatures, the fatigue resistance of SFA mixtures was inferior to HMA mixtures. The variation in fatigue resistance was attributed to the rigidity provided by the strength of the grout. It was concluded that the asphalt interface with grout was the source of the crack at low temperatures. In contrast, the grout was responsible for the crack at intermediate and high temperatures. Shukla et al. (2021) observed the reduction in ITS and resilient modulus with an increase in temperature, implying the temperature susceptibility of SFA mixtures. Zhang et al. (2022) observed the improved dynamic stability (rutting resistance) of SFA mixtures with air voids of the OGA skeleton from 18 to 25%, attributed to the increased grouting volume. Gupta and Kumar (2021) observed that the resilient modulus of SFA mixtures had increased by about 67-89% compared with bituminous concrete. The resilient modulus of SFA mixtures was reduced with increased test temperature, interestingly, more sensitive to temperature than HMA mixtures.

Luo et al. (2020) investigated rutting and low-temperature resistance of SFA mixture by Hamburg wheel tracking tester and three-point beam bending test. The rutting and low-temperature resistance of SFA mixtures with NMAS of 13mm was better or comparable to that of NMAS of 16mm. However, improvement in flexural modulus seemed marginal. The fatigue life in stress-controlled mode was determined using a repeated loading tester. Interestingly, the SFA mixture exhibited lesser fatigue life than the HMA mixtures at all stress ratios, attributed to the stiffer skeleton. Bharath et al. (2020) observed that the resilient modulus of SFA mixtures at 35 °C was seven times higher than the bituminous concrete mix. The resilient modulus reduced with an increase in temperature. However, the temperature susceptibility of HMA mixtures in terms of

resilient modulus was significantly higher than SFA mixtures. The dynamic modulus was significantly higher than HMA mixtures and decreased with increased temperature. The rutting resistance was substantially higher regarding rut depth and flow number than bituminous concrete. The cantabro loss (durability) was higher for the SFA mixture; however, less than 20%.

2.4 MARGINAL AGGREGATES IN SFA MIXTURES

The potential to utilize the marginal aggregates in SFA mixtures was enormous as the OGA skeleton is supported by hardened grout. However, only a few studies reported the potential of SFA mixtures. Ding et al. (2015) used 68% by weight RAP in the OGA skeleton of SFA mixtures and studied the failure mechanism in SFA mixtures under static and dynamic tensile loading. The efficacy of the rejuvenator significantly affected the SFA mixture's cracking resistance. The SFA mixtures exhibited improved tensile strength and cracking resistance with a modified rejuvenator. Based on fracture morphology, major cracks occurred at the interface of asphalt and hardened grout; however, a few minor cracks also passed through the RAP aggregates. The initial crack appeared at the interface of the recovered binder and grout. The natural aggregates crushed the portion of RAP aggregates during the loading. Therefore, the marginal aggregates should be selected and investigated prior.

Thao et al. (2020) observed a decrease in compressive strength by 25-40% when a RAP content of 45-62% was incorporated in the OGA skeleton to investigate the effect on SFA mixtures. It was concluded that the mechanical performance of SFA mixtures with RAP satisfied the requirements of the sub-base layer per the Design Manual for Roads and Bridges for United Kingdom. Afonso et al. (2016) prepared SFA mixtures having a cold mix asphalt skeleton with RAP and altered granite aggregates. The SFA mixtures with altered granite aggregates improved the stiffness and stability, while the SFA with RAP increased the rutting resistance and compressive strength. Zachariah et al. (2020) evaluated the SFA mixtures with natural stone, first-class brick and over-burnt brick aggregates. The SFA with brick aggregates exhibited a 3-24% reduced rut depth and a 118-137% increased

fatigue life compared to the control sample. Since the performance of over-burnt bricks was observed to be better than that of first-class bricks, the use of over-burnt bricks as a replacement for aggregates was recommended.

Kaushik and Siddagangaiah (2022) prepared SFA mixtures with aggregates that did not pertain to the requirements of MoRTH (2013). The marginal aggregates, as earlier stated, can be natural aggregates that do not adhere to a specification or code. The SFA with marginal aggregates exhibited good resistance to high temperature and moisture susceptibility. The tensile strength was comparable with HMA mixtures, while the resilient modulus and indirect tensile stiffness modulus increased by about 60-70% compared to HMA mixtures. The construction cost of the SFA layer was 4% lesser than the conventional asphalt layer. Based on the literature, utilising marginal aggregates in SFA mixtures was feasible and economical without compromising the quality.

2.4.1 Recycled Concrete Aggregates in HMA

Due to the enormous generation of Construction and Demolition (C&D) waste, processing and utilising recycled aggregates in pavement layers, particularly in asphalt layers, was necessary to reduce the disposal problem and depletion of natural resources. The C&D waste should be processed to obtain the Recycled Concrete Aggregate (RCA). The quality of RCA depended on the processing techniques. Mechanical treatment was the most common processing technique among acid soaking, thermal and ultrasonic treatment (Prasad et al. 2022). Evaluating the performance of asphalt mixtures with RCA was complex due to the heterogeneity of materials and sources and processing techniques used to obtain the RCA (Sanchez-Cotte et al. 2020). The volumetrics of HMA mixtures with RCA, such as air void content (V_a), Voids in Mineral Aggregates (VMA) and Voids Filled with Bitumen (VFB), depended on surface voids, adhered mortar and content of RCA (Nwakaire et al. 2020; Sanchez-Cotte et al. 2020). The inclusion of RCA, in general, increased the V_a and VMA, while bulk density and VFB decreased (Mikhailenko et al. 2020; Rafi et al. 2011; Tanty et al. 2018; Zulkati et al. 2013).

However, contradictory results in terms of stability, ITS, moisture resistance, fatigue and rutting resistance were reported in the literature. The Marshall stability increased with RCA content, which may be attributed to the stable or denser aggregate skeleton and increased OBC (Gopalam et al. 2020; Leite et al. 2011; Nwakaire et al. 2020; Pasandín and Pérez 2020; Zulkati et al. 2013). The RCA decreased stability due to insufficiently coated RCA or the presence of old mortar (Kumari et al. 2020; Pasandín and Pérez 2013a; Rafi et al. 2011; Tanty et al. 2018). The ITS was increased with RCA content, attributing to the stable aggregate skeleton and surface texture (Galan et al. 2019; Mikhailenko et al. 2020). Kumari et al. (2020) and Galan et al. (2019) recommended a maximum RCA content of 20% and 60%, respectively. On the contrary, an increase in the RCA content resulted in a decrease in the ITS, which may be attributed to the inferior properties of RCA (Cho et al. 2011; Gopalam et al. 2020; Pasandín and Pérez 2013; Sanchez-Cotte et al. 2020).

The inclusion of RCA increased the rutting resistance, attributing to the stable aggregate skeleton and the increased contact points between the aggregates (Bastidas-Martínez et al. 2022; Mikhailenko et al. 2020; Zulkati et al. 2013). While Kumari et al. (2020), Cho et al. (2011), and Nwakaire et al. (2020) observed a decrease in rutting resistance due to higher binder content and voids, Pasandín and Pérez (2013) observed increased rutting resistance up to 30% RCA only. The fatigue resistance was increased with RCA content, attributed to the increased binder content (Nwakaire et al. 2020; Pasandín and Pérez 2017). Wu et al. (2017) reported the decreased fatigue resistance attributed to reduced stiffness. The HMA with 20% RCA content exhibited similar resistance to HMA (Pasandín and Pérez 2013; Wu et al. 2017). The resilient modulus was increased with RCA content (Sanchez-Cotte et al. 2020; Zulkati et al. 2013). Nwakaire et al. (2020) observed an increase in modulus up to 20% and then decreased, possibly due to increased void content reducing the elasticity. The RCA inclusion decreased the modulus due to lower strength (Gopalam et al. 2020; Kumari et al. 2020; Nwakaire et al. 2020). Sanchez-Cotte et al. (2020) and Nwakaire et al. (2020) recommend an RCA content of 15% and 40%, respectively, based on the modulus and TSR. The RCA inclusion decreased the moisture

resistance due to the high porosity and insufficiently coated RCA (Galan et al. 2019; Gopalam et al. 2020; Kumari et al. 2020; Mikhailenko et al. 2020; Sanchez-Cotte et al. 2020; Zulkati et al. 2013). While Pasandín and Pérez (2020) observed an increased moisture resistance, Nwakaire et al. (2020) reported increased moisture resistance up to 40% RCA content only.

2.4.2 Ferrochrome Slag Aggregates in Concrete

The Ferrochrome Slag aggregates (FCS) exhibited good mechanical and engineering characteristics and can be utilized as coarse aggregates to prepare high-strength concrete mixtures (Das et al. 2023; Panda et al. 2013). The compressive strength improved with FCS content; however, chromium leaching is insignificant or very low in all cement and concrete mixes. Gökalp et al. (2018) stated FCS as an inert material based on leaching studies. Zelić (2005) investigated the utilization of FCS in concrete pavements, which typically demand higher strengths. It was concluded that the FCS mixes have higher abrasion resistance and compressive and flexural strengths than Natural Coarse Aggregates (NCA) and could be used as a partial replacement. Acharya and Patro (2016) also reported similar observations and concluded that 100% NCA could be replaced by FCS. Apart from replacing NCA in concrete mixtures, Das et al. (2023) and Gökalp et al. (2018) recognized the prospect of using FCS in the most flexible pavement layers and regarded FCS as a viable road construction material. Yılmaz and Karaşahin (2010) investigated the mechanical properties of the granular layer (base) having FCS through dry density, resilient modulus and permanent deformations. The FCS mixtures exhibited higher dry density and resilient modulus values than the NCA mixtures. Since the resistance to permanent deformation improved due to increased FCS content, the same was recommended as a granular base material.

Though the utilization of FCS in concrete pavements and the base layer of flexible pavements were examined, no research has been implemented on utilizing FCS in HMA mixtures.

2.5 WARM MIX ASPHALT MIXTURES

The WMA mixtures were produced and placed at lower temperatures compared to conventional HMA. Such a reduction temperature, normally in the range of 10 - 90 °C below that used for HMA, had led to the following temperature-based classification of asphalt mixes: HMA (150 - 190 °C); WMA (100 - 140 °C) (EAPA 2010). The warm mix asphalt technologies could be divided into three categories by use of synthetic or organic additives, which ultimately affect the level of temperature reduction. These methods were based on special additives, binders and technical processes (EAPA 2010; Sheth 2010). You et al. (2018) stated that the additives had not considerably affect the rheological and mechanical properties of asphalt mixtures. Table 2.3 summarised WMA categories, techniques and products (d'Angelo et al. 2008; Rubio et al. 2012).

Table 2.3 Type of additives used in WMA (d'Angelo et al. 2008; Rubio et al. 2012)

Additive Type	Technology	Content (%)
Organic	Ashpaltan B	2-4
	Licomont BS	3
	Sasobit	1.5-4
	Ashpa-Min	0.3
	Ecoflex	-
Chemical	Iterlow T	0.3-0.5
	Cecabase RT	0.2-0.4
	Revix	-
	Evotherm	0.5
	Rediset	1.5-2
	RH-WMA	3
Foaming	WAM-Foam	2-5
	LT Asphalt	0.5-1
	Aspha-Min	0.3
	Double Barrel Green	2
	ECOMAC	-
	LEAB	0.1
	Advera	0.25
	Terex WMA	2

Wang et al. (2018a) used foamed asphalt technology to prepare OGA samples. The preparation of foamed asphalt is an important part. The expansion ratio and half-life time were the two main indexes for evaluating the effect of asphalt foaming that should be satisfied: the expansion ratio was more than 10 times, and the half-life time was more than 8 s. In order to determine the appropriate heating temperature and water injection rate for better effect of asphalt foaming, five temperatures, 145 °C, 150 °C, 155 °C, 160 °C and 165 °C, and five water injection rates, 2%, 2.5%, 3%, 3.5% and 4% (based on the mass of asphalt) were suggested. At the preset temperatures and water injection rates, samples of foamed asphalt were prepared, and their expansion rates and half-life time were measured. However, Wang et al. (2018a) used foamed asphalt WMA technology to prepare the OGA samples but had not studied the effect of foamed asphalt on OGA and SFA samples.

Tan et al. (2021) used warm-mixed RAP materials to prepare the SFA mixtures but studied the effect of warm-mixed additives and RAP on the interfacial weakening effect from a microstructural perspective. It was concluded that the maximum compressive stress of the new and RAP aggregates and cement mortar with the interface was greater than that without the interface. Besides, the maximum compressive strain of the material with the interface was greater than that without the interface and the strain values in the models with an interface at all three positions were greater than those without the interface. Sasobit additive was a widely used additive and the effect on working temperatures was significant (Jamshidi et al. 2013). The effect of Rediset and Zycotherm was not studied on OGA mixtures (Cheraghian et al. 2020).

Other than the earlier mentioned three research works, no study focused on effect of WMA additives on SFA mixtures.

2.6 SUMMARY

The composition of grout strongly influenced the performance of SFA mixtures. The W/C ratios ranging from 0.30 to 0.72 and S/C ratios from 0.15 to 0.67 were adopted to prepare the grout. However, the studies focused on S/C ratio and its effect on selecting the optimal grout were limited. The various superplasticizers were used to reduce the water demand,

i.e., W/C, and achieve higher flowability at a lower W/C ratio and higher strength. The flowability of the grout was determined based on Fluidity. The fluidity ranged from 8 to 110 seconds, with various superplasticizers were observed. The compressive strength of grout observed after 7 days curing was from 3.9 MPa to 90 MPa. The grout selection depended on (i) fluidity (ii) fluidity and compressive strength and (iii) fluidity, compressive and flexural strengths; however, achieving full-depth grouting in OGA mixtures was the primary goal in selecting the grout. The researchers adopted orthogonal arrays, mathematical programming, and response surface methodology to select the optimal grout composition based on the earlier requirements and reduce the number of experiments. Therefore, in the present study, using Taguchi technique in conjunction with Grey Relational Analysis, an optimization technique, was adopted to assess the effect of S/C ratio in selecting the optimal grout.

The grout reinforces the OGA skeleton to improve the performance of SFA mixtures. The OGA mixtures with air voids of 18-36% were prepared to be grouted. The gradations with NMAS ranges from 9 to 19 mm were successfully adopted in preparing the grout; however, the selection of the gradation of the OGA mixture depended on achieving the targeted air voids ranging from 18-36%. The fine aggregate content in OGA mixtures was reduced to provide high air void content. At the same time, they strongly influenced the permeability, i.e., the interconnectivity of voids and the volume of voids. A mere increase in air voids did not necessarily increase the OGA skeleton's grout volume, leading to improved mechanical properties. The OGA mixtures were prepared with various binder types, such as neat bitumen, SBS-modified and epoxy-modified binders. However, the effect of bitumen type on the mechanical properties of SFA mixtures was not investigated. The SFA mixtures exhibited higher Marshall stability, ITS, moisture resistance, fatigue and rutting resistance, and fuel and oil spillage resistance than conventional HMA mixtures.

The potential to utilize the marginal aggregates in SFA mixtures was very effective as the OGA skeleton was supported by hardened grout. However, only a few studies reported the potential of SFA mixtures. The marginal aggregates, such as RAP mixtures,

altered granite aggregates, first-class brick and over-burnt brick aggregates, were utilized in SFA mixtures. It was observed that high percentages of marginal aggregates were possible. Due to the generation of construction and demolition waste, the processing and utilizing the recycled aggregates in pavement layers, particularly in asphalt layers, had been a common practice these days. The quality of recycled aggregates highly depended on the processing technique, but the source variation has been troublesome. On the other hand, the ferrochrome slag aggregate exhibited good mechanical and engineering characteristics, thus encouraging it to be utilized in concrete mixtures. As ferrochrome slag aggregates were the byproduct and massive production of recycled concrete aggregates, utilising these marginal aggregates was necessary in order to protect environment and disposal problems.

The warm mix asphalt technology enabled the construction of the asphalt layers at lower working temperatures and provides a longer time to compact. A few studies reported the use of WMA technology to prepare SFA mixtures. Although foamed WMA technology, redist and zycotherm were used to prepare the OGA mixtures, the studies on effect of WMA additives on the mechanical properties of OGA and SFA mixtures were limited.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1. MATERIALS

The primary materials used in this study are aggregates, asphalt binder, mineral filler, cement, sand, superplasticizer and Warm Mix Asphalt (WMA) additives (Sasobit, Rediset, and Zycotherm). This section briefly explains the adopted materials, tests and methodology adopted for preparing the Open-Graded Asphalt (OGA), grout and Semi-Flexible (SFA) mixtures.

3.1.1 Cement

Cement acts as a binder to hold the coarse or fine aggregates. The Ordinary Portland Cement (OPC) 43 Grade cement of UltraTech company is used to prepare the grout in this study. The IRC SP 125-2019 recommends using OPC 43 grade cement. The basic tests, including specific gravity, initial and final setting times, fineness, soundness, and standard consistency were conducted, and the results are tabulated in Table 3.1.

3.1.2 Sand

As sand is a vital constituent material in resisting load, it is desirable to use good-quality sand. The river sand is used to prepare the grout. The sand size plays a crucial role in facilitating full-depth grouting. Therefore, the sand should be smaller to allow the grout to permeate easily through the air voids in OGA mixes. The IRC: SP: 125-2019 recommends using sand size passing 0.6 mm Indian Standard (IS) sieve. It also recommends using the sand passing 45 μ sieve to achieve better grouting results. However, it is practically challenging to sieve such fine sand. It is necessary to use the coarser sand and still achieve full-depth grout. The sand that passes through a 600 μ sieve and retains on 300 μ was used in the present study.

Table 3.1 Test results of OPC 43 grade cement

Property	Test Method	Obtained values	Specifications as IS 269-2015
Specific Gravity	IS 269:2015	3.16	-
Fineness	IS 4031-Part 1(1988)	8%	< 10%
Initial Setting Time	IS 4031-Part 5(1988)	90 minutes	Minimum 30 min.
Final Setting Time	IS 4031-Part 5(1988)	9 hr	Maximum 10 hr
Standard Consistency	IS 4031-Part 4(1988)	28%	25-35%
Soundness	IS 4031-Part 3(1988)	3 mm	< 10 mm
Compressive strength	IS 4031-Part 6(1988)	45 MPa	Minimum 43 MPa

3.1.3 Superplasticizer

The Superplasticizer (SP) improve workability at lesser water contents and achieve early strength gain. The Master Glenium SKY 8233 is an admixture of a new generation based on modified polycarboxylic ether and primarily developed for high-performance concrete applications. It is free of chloride and low alkali and compatible with all types of cement. MasterGlenium SKY 8233 has a different chemical structure from the traditional superplasticizers. It consists of a carboxylic ether polymer with long side chains. Table 3.2 presents the basic properties of SP provided by the supplier.

Table 3.2 Physical properties of SP (as provided by the supplier)

Property	Result
Aspect	Reddish-brown liquid
Relative Density	1.08 ± 0.02 at 25°C
pH	≥ 6
Chloride ion content	< 0.2%

3.1.4 Aggregates

As the aggregates form the skeleton of OGA or Hot Mix Asphalt (HMA) mixtures, the good quality aggregates are essential to resist the loads. The coarse aggregates should be clean, hard, and durable, with a cubical shape free of dust and soft organic or other harmful

substances. The crushed rock retained on a 2.36 mm sieve is considered coarse aggregates. In this study, the crushed granite rocks collected from a stone crushing plant near Karkala, Udupi district of Karnataka, India, have been used after ensuring their suitability in OGA mixtures based on IRC guidelines. The Recycled Concrete Aggregate (RCA) was obtained by crushing the laboratory-prepared concrete specimens and passing them through the jaw crusher, followed by the ball-milling. Initially, concrete specimens were cast by adopting 1:2:4 nominal concrete mix with 0.45 water-to-cement ratio and medium slump ranging from 50-75mm and cured for 28 days. The specimens left to age for 2 years, following by jaw crushing and ball-milling process.

The Ferrochrome Slag aggregates (FCS) were supplied by M/s Balasore Alloys Limited, Balasore, Odissa, India. The aggregates' physical properties were tested as per the procedures prescribed in IS 2386 and tabulated in Table 3.3. The physical appearance of the aggregates is depicted in Fig. 3.1. The results are compared with the requirements of OGA mixes as per IRC: SP: 125 - 2019. The granite stone dust satisfying the requirements of mineral filler is used as the same.

Table 3.3 Properties of coarse aggregates

Test	Test Method	Granite	RCA	FCS	Specifications as per IRC: SP:125-2019
Grain size analysis	IS:2386 Part 1	0.6%	0.8%	0.5%	< 2% passing 75 μ
Specific Gravity	ASTM C127	2.62	2.38	3.16	-
Combined Flakiness and Elongation index	IS:2386 Part 1	26%	29%	17%	< 35%
Los Angeles abrasion	IS:2386 Part 4	18%	31%	9%	< 30%
Aggregate impact value	IS:2386 Part 4	20%	29%	12%	< 24%
Water absorption	IS:2386 Part 3	0.10%	2.4%	0.80%	< 2%

3.1.5 Bitumen

In this study, two asphalt binders –conventional and modified bitumen were used as binders to prepare the OGA mixtures. The VG 30 bitumen, a commonly used bitumen suited for

most paving applications in India, is the conventional bitumen used in this study. A modified bitumen, PMB 40, was also used for preparing OGA mixtures. The VG 30 was supplied from Mangalore Refineries and Petrochemicals Limited, Mangalore, Karnataka. The PMB 40 binder was procured from Hindustan Colas Ltd., Mangalore, Karnataka.

The physical properties of both binders were tested as per IS 73 (2013, reaffirmed in 2023) and IS 15462 (2019) specifications for conventional and modified bituminous binders, respectively. However, the grading of PMB was as per IS 15462 (2004). The conventional and modified bitumen test results are tabulated in Tables 3.4 and 3.5.



Fig. 3.1 Physical appearance of (a) natural granite aggregate (b) recycled concrete aggregate (c) ferrochrome slag aggregate

Table 3.4 Properties of VG 30

Property	Test Method	Results Obtained	Requirements IS 73 (2013, reaffirmed in 2023)
Penetration at 25°C, 100g, 5 s, 0.1 mm,	IS 1203	52	45 Minimum
Softening point, (R&B), °C	IS 1205	49	47 Minimum
Ductility at 25°C (5 cm /minute pull), cm	IS 1208	98	-
Specific Gravity	IS 1202	1.01	-
Flash point (Cleaveland Open cup), °C	IS 1209	242	220 Minimum
Absolute Viscosity at 60°C, Poises	IS 1206 Part 2	2750	2400 – 3600
Kinematic Viscosity at 135°C, cSt	IS 1206 Part 3	380	350 Minimum

Property	Test Method	Results Obtained	Requirements IS 73 (2013, reaffirmed in 2023)
<i>Test on residue from rolling thin film oven test:</i>			
Viscosity ratio at 60°C	IS 1206 Part 2	3.2	4.0 Maximum
Ductility after thin film oven test at 25°C, cm	IS 1208	48	40 Minimum

Table 3.5 Properties of PMB 40

Property	Test Method	Results Obtained	Requirements IS 15462-2019
Softening point, (R&B), °C	IS 1205	66	60 Minimum
Elastic recovery of half thread in ductilometer at 15°C, percent,	Annex A of IS:15462-2004	78	70 Minimum
Specific Gravity	IS 1202	1.01	-
Flash point (Cleaveland Open cup), °C	IS 1209	246	230 Minimum
Viscosity at 150°C, Pa.s	ASTM D 4402	0.9	1.2 Maximum
Separation, difference in softening point, (R&B), °C	Annex C of IS:15462-2004	1.8	3 Maximum
<i>Test on residue from rolling thin film oven test:</i>			
Loss in Mass, Max	IS 9382	0.52	1 Maximum

3.1.6 WMA additives

The WMA additives, Sasobit, Rediset and Zycotherm, were used in the study and the same are depicted in Fig. 3.2. The WMA additives are classified into organic, chemical, and foaming categories. Rediset and Zycotherm have recently developed chemical additives that improve aggregate coating by reducing surface tension. Much research was carried out using Sasobit, an organic additive; therefore, it will be easier to compare the performance of Rediset and Zycotherm additives. On the other hand, the foaming additives improve the workability and coating due to the evaporation of water in the foamed asphalt binder. Therefore, the foaming additives were not chosen due to the complexity involved in testing the foamed additive-added bitumen and the possible interactions with the grout which has

higher water content. The physical properties of WMA additives are tabulated in Table 3.6 (Kumar and Suresha 2018). Sasobit, Rediset LQ-1200 and Zycotherm, were respectively supplied by M/s KPL International Limited, M/s Azelis (India) Pvt. Ltd. and M/s Zydex Industries Pvt. Ltd. The Sasobit, Rediset and Zycotherm, were added to PMB 40 bitumen in 3%, 0.8% and 1% by weight of the binder, respectively.

Table 3.6 Properties of WMA additives

Property	Sasobit	Rediset	Zycotherm
Physical state	Pastilles, flakes	liquid	Liquid
Colour	Off-white to pale brown	Pale yellow	Pale yellow
Odour	Practically odourless	Aminelike	-
Density (g/cc)	1.03	0.969	0.97
Freeze point	-	5 °C	5 °C
Flash point	Approximately 290 °C	230 °C	>80 °C
Solubility in water	Insoluble	-	Soluble



Fig. 3.2 WMA additives

The PMB 40 binder was modified with WMA additives, such as Sasobit (3% by weight of binder), Rediset (0.8% by weight of binder) and Zycotherm (0.1% by weight of binder). The additives were added to PMB 40 binder at 150 °C employing a mechanical

agitator (Veeraiah and Nagabhushanarao 2020). The sasobit dosage of 3% by weight of binder was recommended as the optimal dosage (Liu et al. 2023; Rochishnu et al. 2020). The sasobit dosage of 3% or more improved the rheological properties, as indicated by the one-grade jump in PG grading (Liu et al. 2023). Therefore, sasobit of 3% by weight of the binder was adopted in the present study. As seen in Table 3.7, it is evident that the sasobit decreased the penetration value and increased the softening point, owing to the crystallization of wax at lower temperatures (Hurley and Prowell 2005). However, the percentage of variation depended on the type of base bitumen and dosage of the additive (Almusawi et al. 2021; Li et al. 2021; Liu et al. 2021; Luo et al. 2021; Rochishnu et al. 2020). The rediset dosage of 0.8% by weight of the binder was adopted in the study as per manufacturer's recommendation. The rediset reduced the penetration value and increased the softening point when compared with the base bitumen, which is evident from Table 3.7. Khairuddin et al. (2019) also reported a similar trend. The optimal zycotherm dosage of 0.15% by weight of binder was recommended and further increase in dosage changed the PG grading (Famarzi et al. 2017; Mansourkhaki and Aghasi 2019). Singh et al. (2021) concluded that the physical properties of binders added with 0.1 and 0.15% zycotherm were comparable; thus, the zycotherm dosage was recommended as 0.1%, and the same was adopted in the present study. Table 3.7 shows that the zycotherm reduced the softening point and increased the penetration value (Famarzi et al. 2017; Gupta and Bellary 2018; Sanij et al. 2019; Singh et al. 2021).

Table 3.7 Physical properties of WMA-modified binders

Modified binder type	Penetration value, 0.1mm	Softening point, °C
PMB 40	30	77
PMB 40 + 3% Sasobit	19	85
PMB 40 + 0.8% Rediset	30	63
PMB 40 + 0.1% Zycotherm	33	61

3.2 METHODOLOGY

The methodology adopted to prepare and test the grout, OGA, and SFA samples is mentioned in the flow chart in Fig. 3.3.

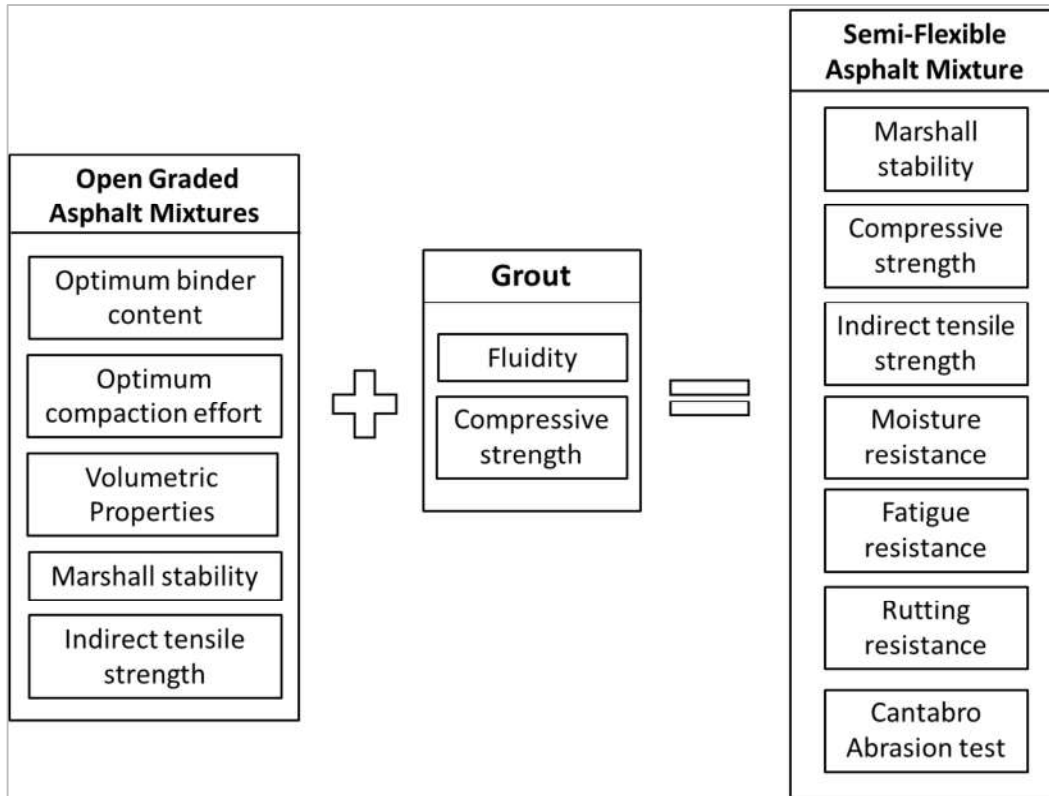


Fig. 3.3 Typical methodology adopted in the study

3.3 MIX DESIGN AND TESTS OF OGA MIXES

The Marshall's mix design method was adopted in the present study as per Asphalt Institute's specifications in Manual Series-2. The OGA mixture requirement specified by IRC: SP: 125-2019 is tabulated in Table 3.8. The loose OGA mixtures were prepared to determine the drain down test, the maximum theoretical specific gravity and stripping behaviour. The drain-down test determines the Optimum Binder Content (OBC) of OGA mixes. The test samples were prepared by adding 2.0, 2.5, 3.0, 3.5, and 4.0% of bitumen to the total weight of the mix. The bitumen content corresponding to the drain-down loss of 0.30% was considered as OBC. The test samples prepared using OBC were compacted in the Automatic Marshall Compactor, as shown in Fig. 3.4. The compaction effort (number of blows on one side) depends on the gradation (IRC SP 125). If a new aggregate gradation is adopted, then the Optimum Compaction Effort (OCE) should be determined by increasing the number of blows from 20 to 70 with an increment of 10 blows. The OCE

was determined based on the bulk density of the compacted mixes where the increase in bulk density and air voids content is insignificant. The cylindrical OGA specimens prepared with OBC and OCE were tested to evaluate the volumetric properties, Marshall stability (MS) and Indirect Tensile Strength (ITS).

Table 3.8 OGA mixture requirements as per IRC SP 125 2019

Mix design parameters	Requirement
Va, %	25-35
Optimum Bitumen content, %	Bitumen content corresponding to a maximum drain down of 0.30%
VMA, %	40 maximum
Voids in Coarse Aggregates in mix (VCA _{MIX} , %)	Less than dry rodded Voids in Coarse Aggregates (VCA _{DRC})
Asphalt drain-down, %	0.30 maximum



Fig. 3.4 Automatic Marshall Compactor

The following procedure was adopted for the preparation and compaction of OGA mixtures:

Preparation of uncompact OGA Mixture: The aggregates were proportioned and mixed as per the gradation and heated to a temperature of 150 – 170°C. The binders were heated to the required mixing temperature and then added to the heated aggregates in the required quantity (i.e., OBC). The mix was thoroughly mixed by maintaining the mixing temperature until the aggregates are fully coated with bitumen.

Preparation of compacted OGA specimen: The prepared mixture was placed in a pre-heated Marshall mould of 101.6 mm dia. The mould was placed on a compaction pedestal for compaction as shown in Fig. 3.4. The number of blows was adjusted as per the requirement, and the compaction procedure was started. Once the compaction was completed, the mould was taken out. After the mould cools to room temperature, the specimen was removed from mould using extruder and the diameter, height, and mass of the specimen were determined. The bulk specific gravity (G_{mb}) was determined per ASTM D3203M-22.

3.3.1 Volumetric Properties

Bulk Specific Gravity of Total Aggregate

The bulk specific gravity of aggregate (G_{sb}) was calculated by determining the specific gravities of coarse aggregates, fine aggregates and filler. It was calculated using Eq. 3.1.

$$G_{sb} = \frac{100}{\frac{W_1}{G_1} + \frac{W_2}{G_2} + \frac{W_3}{G_3}} \quad (3.1)$$

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

G_1 = Specific gravity of coarse aggregate

G_2 = Specific gravity of fine aggregate

G_3 = Specific gravity of filler

Theoretical Maximum Specific Gravity

The theoretical maximum specific gravity (G_{mm}) was measured for the uncompacted OGA mixtures to assess the specific gravity of the mixtures with no air voids in the mixture after the bitumen absorption by aggregates. The Asphalt Mixture Density Meter, shown in Fig. 3.5, was used to determine the G_{mm} as per ASTM D 2041, and the procedure is as follows:

1. Oven-dry aggregates were used to prepare the OGA mixtures. The aggregate particles of the mixture were manually separated without fracturing them so that the fine particles of the aggregates were not larger than 6mm. After that, the mixture was allowed to cool to ambient temperature.
2. The mixture was weighed when it was still in the cylindrical container of the asphalt mixture density tester. The net mass of the mixture was referred to as A.
3. After adding adequate water to completely cover the mixture at a temperature of about 25 °C, the container was closed with a lid.
4. The container having the mixture and water was then placed inside the asphalt mixture density meter. Agitation was then immediately started, and the vacuum pressure was gradually increased (using a vacuum pump connected to it) until the residual pressure manometer records 3.7 ± 0.3 kPa, to release any trapped air in the mixture. The necessary vacuum was attained within two minutes, and kept there for 15 ± 2 minutes while the specimen was being stirred.
5. The vacuum pressure was gradually released using the bleeder valve. The mass of the container, mixture, water and lid was determined and designated as E.
6. The bleeder valve was used to release the vacuum pressure gently. The container was weighed with the lid (D). Eq. 3.2 was used to compute the G_{mm} .

$$G_{mm} = \frac{A}{[A+D-E]} \quad (3.2)$$

where:

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

A = weight of the dry sample in air, g,

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

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

Bulk Density of Compacted Specimen

By using Eq. 3.3, the G_{mb} of each compacted specimen was determined

$$G_{mb} = \frac{W_a}{W_{ssd} - W_w} \quad (3.3)$$

where,

W_a = Weight of specimen in air

W_w = Weight of specimen in water

W_{ssd} = Weight of specimen in Saturated Surface Dry (SSD) condition



Fig. 3.5 Asphalt Mixture Density Tester

Air Voids in Total Mix (V_a)

Small pockets of air between coated aggregate particles in the compacted OGA specimen were measured as a proportion of the total volume of the mix and are referred to as “voids in the mix”. The air voids are calculated using Eq. 3.4.

$$V_a = \frac{G_{mm} - G_{mb}}{G_{mm}} \times 100 \% \quad (3.4)$$

Voids in Mineral Aggregates

In the compacted mixture, the void spaces between aggregate particles are referred to as VMA. The VMA includes the air voids and the volume of bitumen not absorbed into the aggregates. The VMA is determined using Eq. 3.5.

$$VMA = 100 - \frac{G_{mb} \times P_s}{G_{sb}} \quad (3.5)$$

where, G_{sb} = Bulk specific gravity of total aggregates used in the mixture
 P_s = Percentage of aggregate by total mixture weight

Voids Filled with Bitumen

To determine VFB, which was the percentage of the volume of the air voids that is filled with bitumen, Eq. 3.6 is used.

$$VFB = \frac{VMA - V_a}{VMA} \times 100 \quad (3.6)$$

Voids in the Coarse Aggregates (VCA)

The ASTM C 29 was used to determine the voids in the coarse aggregates. The coarse aggregates were first washed and dried. The dried coarse aggregates were filled in a cylindrical measure of approximately 10-litre volume in three equal layers by tamping 25 times with the rounded end of a tamping rod. Eq. 3.7 was used to determine the unit weight of coarse aggregates by the dry rodding method (γ_s), taking into account the weight of the measure with the aggregates.

$$\gamma_s = \frac{G - T}{V} \quad (3.7)$$

γ_s = Unit weight of the coarse aggregate in dry rodded condition, kg/m³
 G = Mass of the measure plus aggregate, kg
 T = Mass of the measure, kg

V = Volume of the measure, m^3

Eq. 3.8 was used to determine the dry-rodded VCA of the coarse aggregates.

$$VCA_{DRC} = \frac{G_{ca}\gamma_w - \gamma_s}{G_{ca}\gamma_w} \times 100 \quad (3.8)$$

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

Eq. 3.9 was then used to determine VCA of the mixture (VCA_{MIX})

$$VCA_{MIX} = 100 - \left(\frac{G_{mb}}{G_{ca}} \times P_{ca} \right) \quad (3.9)$$

G_{ca} = Bulk specific gravity of the coarse aggregate fraction
 P_{ca} = Percent coarse aggregate in the total mixture

3.3.2 Aggregate Gradation and Packing Characteristics

The air void content in the compacted bituminous mix will depend to a greater extent on the aggregate gradation, binder content, type of binder, compaction method and effort. The packing characteristics of different gradations can be defined by imparting similar compaction efforts and determining the voids. The VCA_{DRC} and VCA_{MIX} were used to check the suitability and packing characteristics of the gradations for preparing high voids bituminous mixes. The VCA_{DRC} should be greater than the VCA_{MIX} to ensure stone-on-stone contact. The IRC: SP: 125-2019 recommends gradation of 19 mm Nominal Maximum Aggregate Sizes (NMAS) as control mix gradation (Gr-I), and the same was adopted for the present study. “The Semi-Flexible Pavement Construction Manual (SFPCM)” Japan recommends the SFPCM-Gr tabulated in Table 3.9 (Luo et al. 2020). The Trial Gradations (TG) 1 to 10 were considered for initial trials based on SFACM gradation. The OGA mixtures were prepared with trial bitumen content. The VCA_{DRC} values of Gr-I and TG1 to 10 gradations were 40% and 36-38%, respectively. The VCA_{DRC} for any gradations should be less than 44% as per IRC: SP: 125-2019. As the TG9 gradation

provided more than 28% air voids, the same was selected in the present study. The adopted gradations are depicted in Fig. 3.6. Based on the stress-strain curves of SFA mixtures, Ling et al. (2022) recommended the OGA skeleton to have air voids of 25% and 30% for light and heavy traffic, respectively. Taghipoor et al. (2021) concluded that the void content, interconnectivity of voids, permeability and durability were vital in designing the OGA skeleton.

Table 3.9 Aggregate gradations for OGA mixes

IS Sieve (mm)	NMAS 19mm	Gr-I	SFPC M-Gr	TG1	TG2	TG3	TG4	TG5	TG6	TG7	TG8	TG9	TG10
26.5	100	100	-	-	-	-	-	-	-	-	-	-	-
19	85-100	92.5	100	100	100	100	100	100	100	100	100	100	100
13.2	0-40	20	35-70	70	70	70	70	70	70	40	35	25	20
9.5	0-7	3.5	-	45	40	30	25	15	10	10	8	8	8
4.75	-	-	7-30	7	7	7	7	7	7	7	7	7	7
2.36	0-2	1	5-20	5	5	5	5	5	5	5	5	5	5
0.6	-	-	4-15	4	4	4	4	4	4	4	4	4	4
0.3	-	-	3-12	3	3	3	3	3	3	3	3	3	3
0.075	0-1.5	0.75	1-6	1	1	1	1	1	1	1	1	1	1

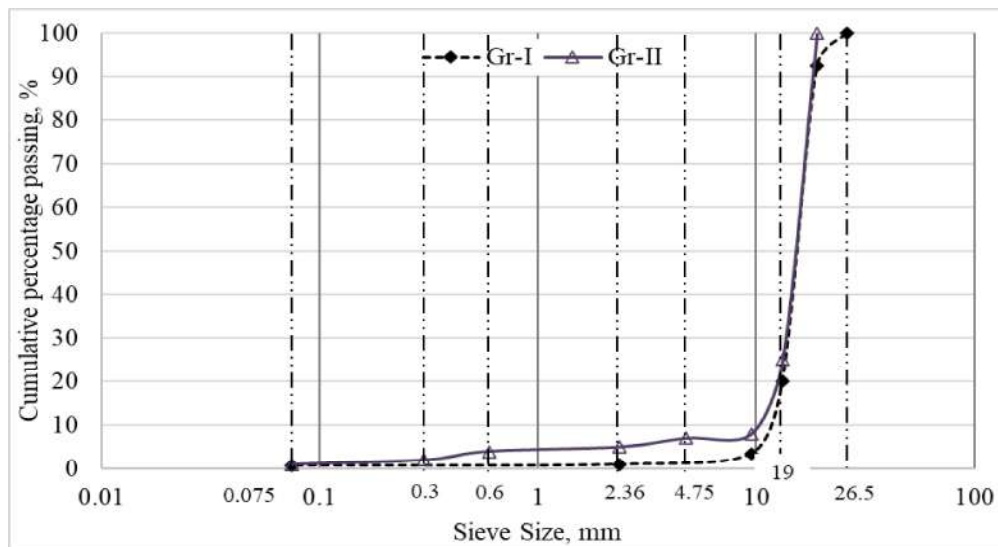


Fig. 3.6 Gr-I and Gr-II gradations

Husain et al. (2014) observed statistically the improved compressive strength and abrasion resistance of SFA mixtures with decreased fine aggregate content in the OGA mixture. The reduced fine aggregate content increased the voids in the OGA mixture, which increased the grouting volume, thus improving the performance of SFA mixtures. However, after thorough investigation in effect of aggregate gradation, Hou et al. (2017) concluded that the higher air voids in OGA mixtures were not necessarily promotes a high degree of grouting and indicated the interconnectivity. These were significantly influenced and improved by coarse aggregate proportion of 10-5mm sieves. Therefore, in this study, the aggregate portions passing through 13.2-9.5mm were varied to understand the variation of air void and interconnectivity of voids. Such gradations are mentioned in Table 3.9. On the other hand, Cai et al. (2020) prepared three SFA mixtures with OGA skeletons having 22%, 25% and 30% air void content and investigated the interlocking characteristics of OGA skeleton and grout. It was concluded that the SFA with OGA skeleton having 25% voids was the most stable gradation.

Therefore, it was understood that the higher air voids were not only a way for improved performance of SFA mixtures. Though, air voids of OGA mixture prepared using new gradation were reduced, it was considered for further study.

3.3.3 Drain-down Test

The drain-down test of uncompacted OGA mixtures was conducted as per ASTM D 6390. The test was performed at the mixing temperature of OGA mixtures and 10 °C higher than mixing temperature and meets the maximum drain-down loss of 0.30 %. If the mixture fails to meet this requirement, then fibres will be added to reduce the drain down to an acceptable level. Sufficient bitumen is required to maintain the SFA's flexibility and hold the coarse aggregate skeleton.

The open and gap-graded mixes were to be tested for drain-down loss. Since the OGA mixes have lesser fine aggregate content (passing through a 2.36 mm sieve) and filler material, the aggregates get coated with bitumen easily. However, forming the aggregate skeleton and holding the aggregates in place is difficult. The aggregates may be coated

easily at high bitumen contents but have more drain-down loss due to excessive bitumen. The higher V_a of OGA mixtures makes the mixes more prone to drain-down loss. The mixes prepared with lower bitumen contents may not have the drain-down loss, but it makes the mixtures brittle. Therefore, the bitumen content of OGA mixtures should be sufficient to withhold the aggregates in place and provide stability without causing a drain down.

A catch plate was placed beneath the wire basket to catch the drained material after about 1000g of OGA mixture was prepared and placed in the basket. The wire basket was then suspended in a temperature-controlled oven that is kept at a pre-determined temperature, as shown in Fig. 3.7. The test was conducted for a period of one hour. After the test period of an hour, the ratio of the weight of material separated from the mixture to the weight of the mixture taken for the test, expressed in percentage, was the drain-down. To account for the variation in the plant production temperature, the test was also conducted at a temperature of 10 °C higher than the production temperature. Eq 3.10 was used to calculate the drain down.

$$\text{Drain Down (\%)} = \left[\frac{(D - C)}{(B - A)} \right] \times 100 \quad (3.10)$$

Where, A = mass of the empty wire basket, g

B = mass of the wire basket plus sample, g

C = mass of the empty catch plate, g

D = mass of the catch plate plus drained material, g

3.3.5 Permeability Test

Permeability is an essential feature of OGA mixtures to facilitate the grout permeation. The permeability of OGA mixtures was determined by a constant head permeability test as per EN 12697–19. In the first step, the compacted specimen was not demoulded and then attached to the graduated pipe with duct tape tightly, as depicted in Fig. 3.8., thus, forcing the water to permeate through the OGA specimen. Before pouring water through the top of the pipe, the rubber glove (hand glove) was placed between the Marshall mould and

stand to maintain the constant head by preventing water leakage. The time required for the water level to reach from a height of h_1 to h_2 was measured, and permeability was then determined using Eq. 3.12.

$$K = \frac{aL}{At} \times \ln \frac{h_1}{h_2} \tag{3.12}$$

- Where k = permeability cm/s
- a = the area of the top standpipe in cm^2
- L = the height of the sample in cm
- A = the cross-sectional area of the sample in cm^2
- h_1 and h_2 = the initial and final water head in cm, respectively



Fig. 3.7 Wire Basket Assembly for Drain down Test



Fig. 3.8 Permeability test set-up

3.3.6 Marshall Stability

The Marshall test evaluates the resistance of OGA and SFA mixtures to plastic flow as per ASTM D 6927-22. The Marshall specimens were kept at a constant temperature of 60 ± 1 °C in the water bath for 30 to 40 minutes. These were then removed from the water bath, and placed in the lower segment of the breaking head. The upper segment of the breaking head of the sample was placed in position, and the complete assembly was placed in position on the testing machine, as shown in Fig. 3.9. Load was applied at a 51 mm/minute rate until the maximum load reading was obtained. The maximum load reading in kilo Newton (kN) was observed.



Fig. 3.9 Marshall Stability Testing Machine

3.3.7 Indirect Tensile Strength

The ITS of OGA and SFA specimens were tested as per ASTM D 6931 to assess the fatigue resistance. The load was applied diametrically on a cylindrical specimen of 101mm diameter. Before testing, the specimens were kept in a water bath maintained at the required temperature 25-45 °C for one hour. After conditioning, the specimen was placed in ITS setup, as shown in Fig. 3.10. The maximum load required for the failure of the specimen was recorded. Eq. 3.14 was used to calculate the ITS of OGA and SFA mixtures.

$$ITS = \frac{2P}{\pi Dt} \quad (3.14)$$

- Where, ITS = Tensile strength (N/mm²)
P = Failure load (N)
D = Diameter of specimen (mm)
t = Thickness of specimen (mm)

3.3.8 Percentage Coating

The percentage of coating in bituminous mixtures was determined as per ASTM D 2489M-24. The uncompacted bituminous mixtures were prepared by adding the specified bitumen content to the heated aggregates and followed by mixing. The total weight of asphalt mixtures should be selected so that at least 200-500 coarse aggregates retain on a 9.5mm sieve. In this test, the uncompacted asphalt mixture was sieved immediately through the 9.5mm sieve without losing the temperature. The percentage coating was determined as the ratio of completely coated aggregates to the total aggregates retained on 9.5mm. IRC SP 101 recommends at least 95% coating for WMA mixtures. With careful visual observation, an aggregate with a tiny speck of uncoated part should be considered as uncoated aggregate. Generally, this method determines the minimum mixing time required at the mixing plant for a given set of conditions. Eq. 3.15 was used to determine the percentage coating.

$$\text{percentage coating} = \frac{\text{number of completely coated particles}}{\text{Total number of aggregates}} \quad (3.15)$$



Fig. 3.10 ITS setup

3.3.9 Stripping

The bitumen should have a strong and lasting adherence to the aggregate surface in order to ensure good performance and durability of flexible pavements. The stripping resistance of OGA mixtures was assessed by conducting the boiling test as per ASTM D 3625. The uncompacted OGA mixtures were prepared for the test and allowed to cool at a temperature of 85 to 100°C. The distilled water in a clean beaker was boiled on a heating device.

The prepared mixture in its loose form was placed in the beaker with boiling water. The boiling was continued for about 10 minutes. In order to avoid recoating, the container was then removed, and the free bitumen on the surface of the water was skimmed off. The water and the mixture were allowed to cool to room temperature. After cooling, the water was removed, and the mixture was placed on a white paper towel for visual inspection of bitumen stripping. The amount of stripping and the area stripped, if any, were calculated based on visual observation. This test is qualitative, and the assessment of stripping was subject to individuals.

3.4 TESTS ON SFA MIXTURES

The SFA is a composite material in which the OGA samples are grouted, with the grouts having high flowability. The OGA samples should have around 25-35% V_a to achieve full-depth grouting. The SFA specimens were cured for 3, 7, and 28 days depending on the requirement. The mechanical properties of cured SFA specimens were evaluated through Marshall stability, compressive strength, ITS, repeated load testing (fatigue resistance), wheel rut tester (rutting resistance), moisture resistance and cantabro abrasion test.

3.4.1 Compressive Strength

The Compressive Strength (CS) of SFA mixtures was determined as per ASTM C39 on the specimens, having a length of 200mm and diameter of 100 mm, prepared ASTM D6927. The CS was calculated using Eq. 3.16.

$$CS = \frac{4000 \times P_{\max}}{\pi D^2} \quad (3.16)$$

where, CS = compressive strength, MPa

P_{\max} = maximum load, kN

D = average measured diameter, mm

3.4.2 Fatigue Resistance

The pavements were subjected to repeated wheel loads during service life, causing cracking in wearing or asphalt layers. Therefore, to investigate the fatigue resistance of SFA mixtures, the Repeated Load Testing (RLT) system was used as shown in Fig. 3.11. The dynamic load was applied diametrically on a cylindrical specimen using a movable shaft of a hydraulic loading system. The specimen was placed in a setup similar to the ITS test, as shown in Fig. 3.12. The deformation was measured by the two horizontal and two vertical LVDTs, placed on the specimen. Using 'The Fatigue 4.0' software, the applying load and frequency can be adjusted. The constant loading frequency of 1 Hz and loading and rest periods of 0.1 seconds and 0.9 seconds, respectively, were used in the study (Chinnabhandar et al. 2022). The load will be applied in a haversine form. The Fatigue Life (FL) was defined as the total number of load repetitions required to cause the specimen to fail. For the fatigue test, the deformation of 5mm was considered as the failure criterion (Priyanka et al. 2019; Sarang et al. 2015, 2016). The load values of 15%, 33% and 50% of the lowest ITS failure load were applied on SFA mixtures and the FL was determined. The FL was used to evaluate the fatigue resistance of mixtures relatively.

3.4.3 Rutting Resistance

The unrecoverable depression in the longitudinal direction of repeated vehicular paths is called rutting. The movement of heavy vehicles and the continuous vehicular loads at high temperatures causes rutting. In this investigation, the Wheel Rut Tester (WRT), as depicted in Fig. 3.13, was used to evaluate the rutting resistance of SFA mixtures by repeated wheel loading over slab specimens. The OGA specimen with dimensions (300X300X50 mm) was cast using the Wheel Rut shaper, as depicted in Fig. 3.14 (Hou et al. 2017). The OGA specimen was grouted, cured for 28 days, and tested using the WRT.



Fig. 3.11 Repeated Load Testing device



Fig. 3.12 Specimen arrangement in RLT device

In the WRT, a wheel of 200 mm diameter and 50 mm thick rubber applies the standard load of 150 N. The specimen in a tightly restrained mould was placed on the platform as depicted in Fig. 3.13. The wheel was placed on the specimen, and then the platform carrying the specimen and mould was made to move back and forth for a distance of 230 mm due to a motor. The wheel will be in a static position above the specimen. An

LVDT placed on the side of the wheel measures the depth of deformation due to the movement of the platform. The computer connected to the WRT shows real-time data and a graph showing the total permanent deformation in relation to the number of passes. A total of 10,000 cycles (including back and forth) were made over the slab. The total permanent deformation along the wheel path was recorded. The Dynamic Stability (DS) of the corresponding mixtures was determined using Eq. 3.17 (Alae et al. 2022; Zhang et al. 2022). The DS was the indicator of rutting resistance. Higher DS indicates a higher rutting resistance.

$$DS = \frac{15 \times 42}{d_{60} - d_{45}} \quad (3.17)$$

where, DS = Dynamic stability (cycles/mm)

d_{60} = rut depth at 60 min

d_{45} = rut depth at 45 min

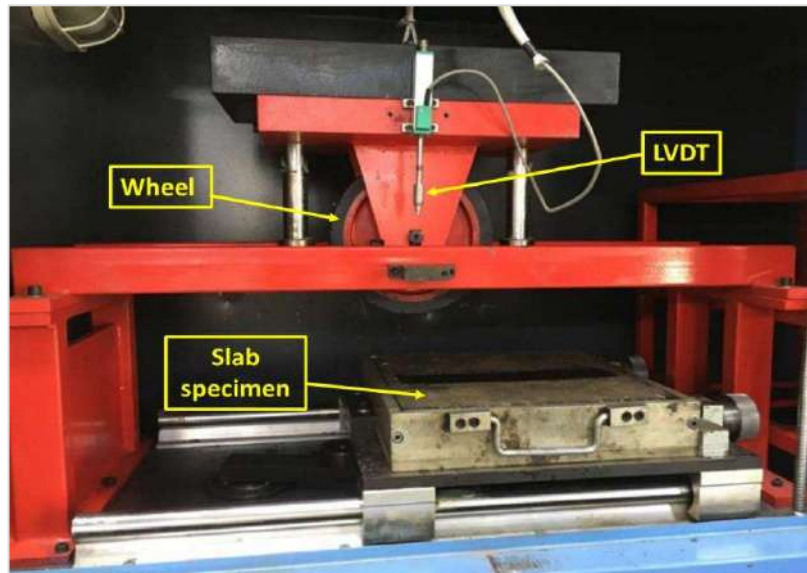


Fig. 3.13 Wheel Rut Tester



Fig. 3.14 Wheel rut shaper

3.4.4 Moisture Susceptibility Tests

The moisture susceptibility of asphalt mixtures is one of the primary causes or the acceleration of various distress in flexible pavements. The loss of stability, stripping, ravelling and permanent damage are the few distress caused by moisture. The degradation of the mechanical characteristics of the asphalt mixtures is caused by the presence of moisture at microlevel. In the present study, Retained Marshall Stability, Tensile Strength Ratio and Stripping test are used to evaluate the moisture susceptibility of SFA mixtures.

Retained Marshall Stability

The Retained Marshall Stability (RMS) test evaluates the effect of moisture on the Marshall stability of SFA mixtures. To accelerate the effect of moisture on Marshall stability, the SFA specimens were conditioned by keeping them in the water bath for 24 hrs at a temperature of 60°C. The values determined per ASTM D 6927 were taken as the unconditioned Marshall stability, whereas the other set of specimens is conditioned by immersing in a water bath maintained at 60°C for 24 hours. The Marshall stability of SFA specimens without conditioning was also determined. The RMS was determined as the ratio of stability values of conditioned and unconditioned specimens. The RMS indicates

the variation of MS of SFA mixtures to the conditioning process of water intrusion for 24 hrs.

Tensile Strength Ratio

The method includes the preparation of SFA mixtures and measuring the change in tensile strength caused by water saturation and the freeze-thaw cycle as per AASHTO T 283. Six specimens were prepared and divided into two equal subsets. One subset was tested for ITS in dry conditions (unconditioned specimens). The other subgroup was subjected to vacuum saturation and a freeze-thaw cycle (conditioned samples). The unconditioned samples were brought to a temperature of $25\pm 1^{\circ}\text{C}$ by immersing them in a water bath maintained at test temperature for 2 hours. The specimen was placed over the lower loading strip of the ITS mould. The top-loading strip was gradually lowered to make light contact with the specimen (Fig. 3.15) and ensured that the loading strips were parallel and centred on the vertical diametric plane. The mould was placed in the Marshall stability testing equipment at a strain rate of 50mm/minute until failure. The load at failure was recorded.



Fig. 3.15 ITS testing on unconditioned samples

The conditioned specimens were placed in an Asphalt mixture density meter and submerged in a vacuum container filled with water at room temperature for 30 minutes. The specimens were then placed in plastic bags containing 10 ml of water, sealed, and kept in the freezer at $-18\pm 3^{\circ}\text{C}$ for 16 hours. The specimens were kept in a water bath for 24 ± 1 hours, maintaining a 60°C temperature. This entire process is known as the freeze and thaw cycle. After a freeze-thaw cycle, the specimens were brought to a temperature of $25\pm 1^{\circ}\text{C}$ by immersing them in a water bath kept at test temperature for 2 hours. These conditioned specimens were tested for ITS. The load at failure was measured. The ITS for both conditioned and unconditioned specimens of the SFA mixture was calculated using Eq. 3.14. The Tensile Strength Ratio (TSR) was calculated using Eq. 3.18.

$$\text{TSR} = \frac{\text{ITS}_c}{\text{ITS}_{un}} \quad (3.18)$$

Where ITS_c = ITS of conditioned subset, MPa

ITS_{un} = ITS of unconditioned subset, MPa

3.4.5 Cantabro Test

The durability characteristics of SFA mixtures must be investigated to ensure long-term performance. The OGA mixtures were grouted, contributing to enhanced load-bearing capacity. ASTM C 131 guidelines were followed to conduct the cantabro test in the Los Angeles abrasion machine. The specimen was conditioned at 25°C for 48 hr and then placed in an abrasion machine without steel balls for 300 rounds at a speed of 30-33 rpm. The weight of the specimen was noted before and after the test. The abrasion loss of SFA mixtures is determined using Eq. 3.19.

$$P = 100 \times \frac{P_1 - P_2}{P_1} \quad (3.19)$$

Where P = abrasion loss percentage (%)

P_1 = initial specimen mass (g)

P_2 = final specimen mass after the test (g)

3.5 TESTS ON GROUT

The grout comprises OPC Grade 43, Sand, and SP. The cement, sand and SP were proportioned and mixed thoroughly by adding a certain quantity of water based on the water-cement ratio. The prepared grout mix was subjected to fluidity and CS tests to measure flowability and strength.

3.5.1 Fluidity

The fluidity indicates the resistance of grout to flow. The main requirement of grout was to fill the voids in the OGA skeleton and enhance its strength and durability. Fluidity plays a significant role in selecting the grout. The Marsh Flow cone test was used to measure the fluidity of the grout as per ASTM C939M-22. The standard volume of the cone was 1725 ml, and the diameter varied accordingly up to 75 mm height, i.e., the level controller height and diameter was 178 mm. From there onwards, gradually, it decreased to 12.7 mm at 265 mm from the top. Then it maintained the same diameter throughout the remaining length. The geometry of the Marsh flow cone is depicted in Fig. 3.16. The following procedure stepwise was adopted to determine the flow time and compressive strength of the grout mix:

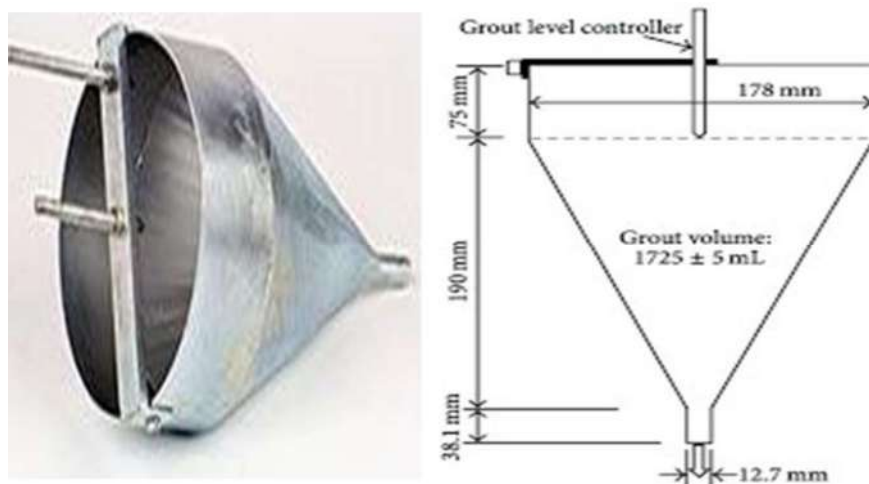


Fig. 3.16 Geometry of the Marsh flow Cone

The proportions of the ingredients of the grout mix were determined via the trial-and-error method. The weighed materials were then mixed thoroughly to avoid the formation of lumps. The paste was poured through the flow cone within 1 minute of mixing to ensure that the grout did not set. Flow time was noted to effluent the 1725 ml grout using the stopwatch. Before pouring the grout, the flow cone was calibrated with water, and the fluidity was determined based on three trials. The fluidity should be 8 sec, and only then grout should be tested for fluidity.

3.5.2 Compressive Strength of Grout

The compressive strength of grout influences the strength and durability of SFA samples. The higher CS of grout indicates the higher CS of SFA samples. To cast the cubes of grout, the grout mix used for fluidity was transferred to moulds of size 7.05 cm. For each trial mix, three cubes were cast to determine the average compressive strength as per ASTM C39M. The cubes were demoulded after 24 hours and kept in water for 7 days for curing at room temperature. The failure load was recorded using the compression testing machine, as shown in Fig. 3.17, to determine the CS.



Fig. 3.17 Compressive strength test setup

3.6 SUMMARY

In this chapter, the various materials used in the present study are discussed, along with their sources. The OPC of 43 grade, sand passing through 600 μ and retained on 300 μ and the modified polycarboxylic ether-based superplasticizer were used to prepare the grout. The natural granite aggregates were procured from a stone-crushing plant near Karkala, Udupi district of Karnataka, India. The RCA was obtained by crushing the laboratory-prepared concrete specimens and passing them through the jaw crusher, followed by the ball-milling. The FCS aggregates were supplied by M/s Balasore Alloys Limited, Balasore, Odissa, India. Two types of bitumen (VG 30 and PMB 40) are used in the present study. VG 30 bitumen was procured from M/s. Mangalore Refineries and Petrochemicals Ltd. and PMB 40 was procured from M/s HINCOL, Mangalore. The WMA additives, such as Sasobit, Rediset and Zycotherm, were added to PMB 40 bitumen in 3%, 0.8% and 1% by weight of binder, respectively. All the materials were tested according to relevant standards and were found to satisfy the requirements of relevant codes. The chapter also discussed the methodology for preparing the Open Graded Asphalt mixture, grout and Semi-Flexible Asphalt mixtures.

CHAPTER 4

EFFECT OF SAND/CEMENT RATIO IN THE SELECTION OF OPTIMAL GROUT MIX

4.1 GENERAL

The mix design aimed to achieve full-depth grouting in Semi-Flexible Asphalt (SFA) samples with stability. The grout mixes were selected based on Fluidity and Compressive Strength (CS) tests. The flow cone was calibrated using water before testing the grout. After testing the grout for fluidity, the same grout was poured into the cubical mould of size 7.05 cm. For each grout mix, three cubes were cast. The specimens were de-moulded after curing for 7 days, and the CS test was conducted. The investigation of the effect of Sand-to-Cement (S/C) ratio in selecting the optimal grout mix was discussed in detail in this chapter.

4.2 TAGUCHI METHODOLOGY

The Taguchi methodology is a statistical technique that helps design the experiments and forms a framework to identify the most influencing input factors (Mason et al. 2003). Taguchi technique reduces the number of experiments to be conducted without compromising the efficacy of the results (Priyanga and Muthadhi 2023). It provides the optimal input conditions to achieve the optimal output parameter. The Signal-to-Noise (S/N) ratios are used to identify the optimal input conditions and most influencing factors. The S/N ratio measures the quality of the output factor, i.e., signal, considering the variability of the input factors, i.e., noise (Vijayakumar and Pannirselvam 2022). Therefore, the S/N ratio should be maximum to achieve better quality output. The S/N ratio values were calculated for each input parameter at all levels using Eqs. 4.1 and 4.2 to understand the influence on response parameters (Slebi-Acevedo et al. 2020). In the Taguchi technique, the number of input parameters and their levels should be selected as a first step, followed by the suitable orthogonal array. In the present study, based on the initial trials and literature, the input parameters (S/C ratio, W/C ratio, and SP content) at

four levels were considered for the study, as indicated in Table 4.1. Therefore, the L16 (Levels^{Factors} = 4³) orthogonal array was selected from Taguchi designs. The Taguchi method was adopted to get the optimum mix and to reduce the number of experiments. The fluidity and CS tests were conducted for the combinations (Test No. 1-16) given by Taguchi technique and the same were mentioned in Table 4.2. The results of fluidity and CS tests are tabulated in Tables 4.2 – 4.4. For example, the test no. 1; the grout was prepared using sand-to-cement ratio of 0.3, water-to-cement ratio of 0.4 and superplasticizer content of 0%. Firstly, the fluidity of grout was measured three times, and the average value was reported as the fluidity value, i.e., 95 seconds. The same grout was poured into three cube moulds having 7.05 cm on each side. After 24 hours, the cubes were demoulded and kept in water for a 7-day curing period. The three replicates were tested and the average value was reported as 33MPa.

Table 4.1 Input parameters and levels for Taguchi methodology

Variables	Levels			
S/C ratio	0.30	0.40	0.50	0.60
W/C ratio	0.40	0.45	0.50	0.55
Superplasticizer (SP) content, % by weight of cement	0.00	0.50	0.75	1.00

For fluidity: Smaller-the-better criterion,

$$S/N \text{ ratio} = -10 * \log \left(\frac{1}{n} * (\sum y^2) \right) \quad (4.1)$$

For CS: Larger-the-better criterion,

$$S/N \text{ ratio} = -10 * \log \left(\frac{1}{n} * \left(\sum \frac{1}{y^2} \right) \right) \quad (4.2)$$

Where y = responses for the given factor level combination; n = number of responses in the factor level combination.

Fig. 4.1 indicates that the fluidity decreases with an increase in W/C ratio and SP content. The slope of the fluidity at lower SP contents ranging from 0 to 0.75% is higher and then reduced relatively after 0.75% SP content, demonstrating the marginal effect of higher SP dosages. However, the S/C ratio is the least influencing factor of fluidity compared to the W/C ratio and SP content.

Table 4.2 Design of experiments from Taguchi methodology

Test No.	S/C	W/C	SP	Fluidity (seconds)	CS (MPa)	S/N ratio	
						Fluidity	CS
1	0.3	0.4	0	95	33	-39.554	30.370
2	0.3	0.45	0.5	30	32	-29.542	30.103
3	0.3	0.5	0.75	11	27	-20.828	28.627
4	0.3	0.55	1	11	23	-20.828	27.235
5	0.4	0.4	0.5	55	42	-34.807	32.465
6	0.4	0.45	0	82	38	-38.276	31.596
7	0.4	0.5	1	12	31	-21.584	29.827
8	0.4	0.55	0.75	13	22	-22.279	26.848
9	0.5	0.4	0.75	28	45	-28.943	33.064
10	0.5	0.45	1	20	36	-26.021	31.126
11	0.5	0.5	0	35	29	-30.881	29.248
12	0.5	0.55	0.5	16	28	-24.082	28.943
13	0.6	0.4	1	31	45	-29.827	33.064
14	0.6	0.45	0.75	24	46	-27.604	33.255
15	0.6	0.5	0.5	29	32	-29.248	30.103
16	0.6	0.55	0	23	29	-27.235	29.248

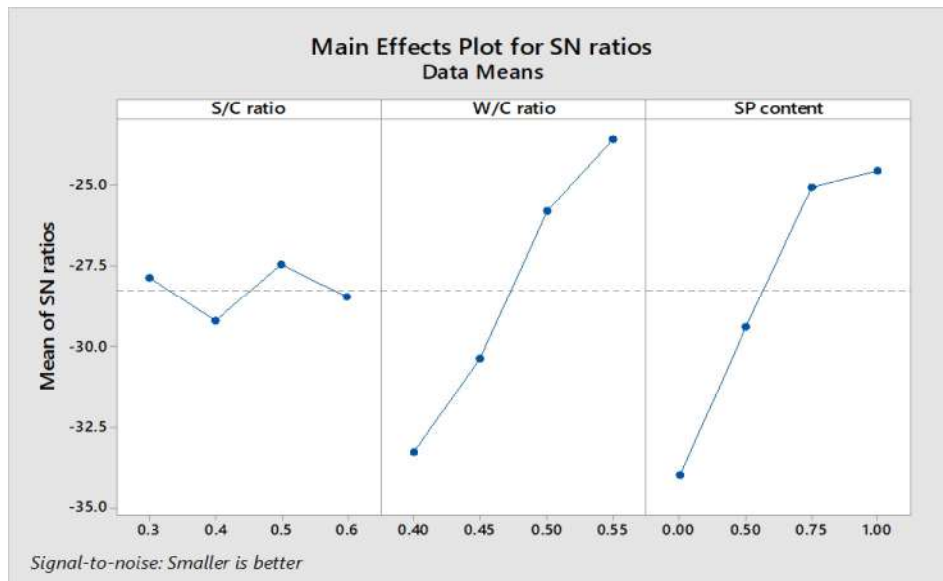


Fig. 4.1 Main effects plot for S/N ratios of fluidity

The response tables (Tables 4.3 and 4.4) contain the means of the S/N ratio and mean at various input levels. While the means of S/N ratio indicate the fluidity or CS values considering the noise, i.e., variability in the results, the means of mean indicates the average

of the experimental results at the corresponding input level. Therefore, the delta values of the S/N ratio are used to identify the influencing factors. The delta value in Table 4.3 is the absolute difference between the maximum and minimum fluidity values in the corresponding column, i.e., the input parameter, and helps determine the order of influencing factors. A higher delta value implies the most significant factor. The delta values of the W/C ratio and SP content are higher than the delta value of the S/C ratio, demonstrating the more significant influence of the W/C ratio and SP content on fluidity than the S/C ratio. The same is evident from the assigned ranks in Table 4.3. Therefore, the most to least influencing factors on the fluidity, in order, are the W/C ratio, SP content, and S/C ratio.

Based on the response table, for fluidity (Table 4.3), the optimal combination is the level 3 of S/C ratio, level 4 of W/C ratio, and level 4 of SP content which are 0.5, 0.55, and 1.0%, respectively (i.e., S/C=0.5, W/C=0.55, and SP content=1.0%). However, the aforementioned optimal combination is to achieve the lowest fluidity value.

Table 4.3 Taguchi response table for S/N ratios and mean of fluidity

Level	S/N ratio			Mean		
	S/C ratio	W/C ratio	SP content	S/C ratio	W/C ratio	SP content
1	-27.69	-33.28	-33.99	36.75	52.25	58.75
2	-29.24	-30.36	-29.42	40.5	39	32.5
3	-27.48	-25.64	-24.91	24.75	21.75	19.25
4	-28.48	-23.61	-24.56	26.75	15.75	18.5
Delta	1.76	9.67	9.43	15.75	36.5	40.25
Rank	3	1	2	3	2	1

The data presented in Fig. 4.2 illustrates a positive correlation between the S/C ratio and the CS of the grout, as well as an inverse relationship between the W/C ratio and the CS. It is crucial to carefully govern the proportion of sand content in the grout, as excessive amounts can negatively impact the fluidity while concomitantly increasing its CS. This phenomenon can be attributed to the capacity of sand to fill voids between cement particles and to facilitate the formation of a network for the hydration products, thereby augmenting the CS (Neville 1996). A similar trend has been observed by Zhang et al. (2016). The

decline in CS observed with an increase in the W/C ratio can be attributed to the presence of an excess of free water, which impairs the hydration process. Additionally, as the SP content increases from 0 to 0.75%, the CS initially increases before decreasing as the SP content continues to rise. This suggests that while higher dosages of SP may enhance workability, but also hinder the attainment of optimal strength. Based on the delta values presented in Table 10, the factors that exert the greatest influence on the CS, in descending order, are the W/C ratio, S/C ratio, and SP content. However, the impact of SP content on the CS appears to be less pronounced than that of the W/C and S/C ratios. The optimal combination of factors for achieving a high CS, as determined by the response table in Table 4.4, is an S/C ratio of 0.6, a W/C ratio of 0.4, and an SP content of 0.75%.

Table 4.4 Taguchi response table for S/N ratios and mean of CS

Level	S/N ratio			Mean		
	S/C ratio	W/C ratio	SP content	S/C ratio	W/C ratio	SP content
1	29.08	32.24	30.12	28.75	41.25	32.25
2	30.18	31.52	30.40	33.25	38	33.5
3	30.6	29.45	30.45	34.5	29.75	35
4	31.42	28.07	30.31	38	25.5	33.75
Delta	2.33	4.17	0.33	9.25	15.75	2.75
Rank	2	1	3	2	1	3

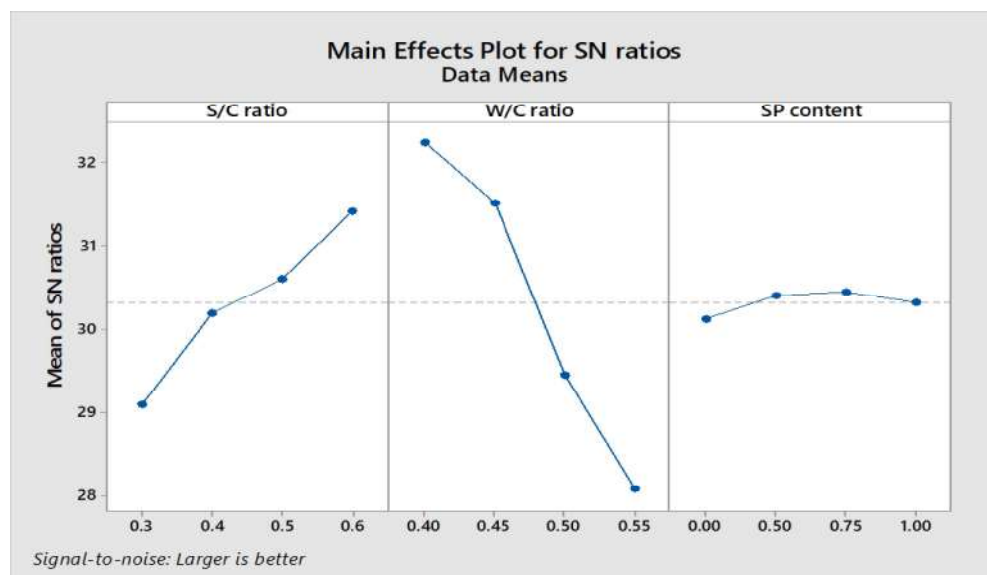


Fig. 4.2 Main effects plot for S/N ratios of CS

As the optimal combinations for minimum fluidity and maximum CS, the two grout mixes with the proportions of S/C ratio = 0.5, W/C ratio = 0.55, SP content = 1.0%, and S/C ratio = 0.6, W/C ratio = 0.4, are identified. However, these two grout proportions have minimum fluidity and maximum CS discretely.

4.3 GREY RELATIONAL ANALYSIS

Taguchi Method can obtain the optimal input parameters for a single response, i.e., fluidity or CS. Therefore, Multi-Criteria Decision Making (MCDM) methods are used when the multiple responses have different criteria to optimize. The present work uses the MCDM method to obtain an optimal grout proportion with minimum fluidity, maximum CS, and the most influencing input parameters. The Grey Relational Analysis (GRA), an MCDM method, combined with Taguchi methods, is used to optimize the multiple parameters simultaneously (Cui et al. 2017). In GRA, the multiple responses are converted into a single response which helps to select the optimal input parameters for optimizing multiple output parameters. The S/N ratios of input parameters obtained in the Taguchi technique from Table 4.2 are normalized using Eqs. 4.3 and 4.4, respectively, while the deviation values are determined using Eq. 4.5.

- (1) To minimize the response – smaller-the-better criterion

$$x_k^* = \frac{|\max x_i^o(k) - x_i^o(k)|}{\max x_i^o(k) - \min x_i^o(k)} \quad (4.3)$$

- (2) To maximize the response – larger-the-better criterion

$$x_k^* = \frac{|x_i^o(k) - \min x_i^o(k)|}{\max x_i^o(k) - \min x_i^o(k)} \quad (4.4)$$

Where, x_k^* represents the normalized value of a response, $x_i^o(k)$ are the S/N ratios of a response. The $\max x_i^o(k)$ and $\min x_i^o(k)$ represent the maximum and minimum values of $x_i^o(k)$. i and k represent the number of experiments and responses.

$$\Delta_{oi}(k) = \|x_o^*(k) - x_i^*(k)\| \quad (4.5)$$

Where, Δ_{oi} are the deviation values. The Grey Relational Coefficient (GRC) (ξ_i) is determined using Eqs. 4.6 – 4.8 which expresses the correlation between the desired and actual normalized values.

$$\xi_i(k) = \frac{\Delta_{min} + \varphi\Delta_{max}}{\Delta_{oi}(k) + \varphi\Delta_{max}} \quad (4.6)$$

$$\Delta_{max} = \max_{j \in i} \max_k \|y_o(k) - y_i(k)\| \quad (4.7)$$

$$\Delta_{min} = \min_{j \in i} \min_k \|y_o(k) - y_i(k)\| \quad (4.8)$$

$y_o(k)$ and $y_i(k)$ are the referential and comparative sequences, respectively. Δ_{max} and Δ_{min} are the maximum and minimum values of $\Delta_{oi}(k)$, respectively. φ is the identification coefficient or distinguishing factor, generally considered 0.5 (Cui et al. 2017). The Grey Relation Grade (GRG) was the average of the GRCs, ranging from 0 and 1. In GRG, the criteria of multiple responses are converted into a single response. Grey Relational Order (GRO) or ranks are assigned based on GRG values. Higher GRG values are preferred.

In the present investigation, Eqs. 4.3 and 4.4 are used to normalize the S/N ratios of fluidity and CS, respectively, based on the larger or smaller-the-better criteria, and the deviation values are determined using Eq. 4.5. The GRC, GRG, and GRO are determined and tabulated in Table 4.5.

The GRG values are given as an input parameter to the Taguchi technique to obtain the optimal grout proportion considering the fluidity and CS collectively. The responses for GRG values are tabulated in Table 4.6. It concluded that the optimal grout proportions, considering both the fluidity and CS, were an S/C ratio of 0.60, a W/C ratio of 0.40, and an SP content of 0.75%. The optimal grout mix achieved a fluidity of 27 sec and CS of 66 MPa after a 28-day curing period.

Table 4.5 Normalization and deviation sequence for fluidity and CS responses

Test No.	S/N ratio		Normalization values		Deviation values		GRC		GRG	GRO
	fluidity	CS	fluidity	CS	fluidity	CS	fluidity	CS		
1	-39.554	30.370	1.000	0.550	1.000	0.450	0.333	0.526	0.430	16
2	-29.542	30.103	0.465	0.508	0.465	0.492	0.518	0.504	0.511	13
3	-20.828	28.627	0.000	0.278	0.000	0.722	1.000	0.409	0.705	4
4	-20.828	27.235	0.000	0.060	0.000	0.940	1.000	0.347	0.674	6
5	-34.807	32.465	0.747	0.877	0.747	0.123	0.401	0.802	0.602	8
6	-38.276	31.596	0.932	0.741	0.932	0.259	0.349	0.659	0.504	14
7	-21.584	29.827	0.040	0.465	0.040	0.535	0.925	0.483	0.704	5
8	-22.279	26.848	0.078	0.000	0.078	1.000	0.866	0.333	0.600	9
9	-28.943	33.064	0.433	0.970	0.433	0.030	0.536	0.944	0.740	2
10	-26.021	31.126	0.277	0.668	0.277	0.332	0.643	0.601	0.622	7
11	-30.881	29.248	0.537	0.375	0.537	0.626	0.482	0.444	0.463	15
12	-24.082	28.943	0.174	0.327	0.174	0.673	0.742	0.426	0.584	10
13	-29.827	33.064	0.481	0.970	0.481	0.030	0.510	0.944	0.727	3
14	-27.604	33.255	0.362	1.000	0.362	0.000	0.580	1.000	0.790	1
15	-29.248	30.103	0.450	0.508	0.450	0.492	0.527	0.504	0.515	12
16	-27.235	29.248	0.342	0.375	0.342	0.626	0.594	0.444	0.519	11

Table 4.6 indicates that the fluidity and CS are significantly affected by SP content, followed by the S/C ratio and W/C ratio. In Fig. 4.3, the GRG value decreased with an increase in SP content from 0.75 % to 1%, indicating that higher SP content has a negative effect on fluidity and CS. It is evident that the effect of the S/C ratio is more significant than the W/C ratio and should be considered while selecting the optimal grout.

Table 4.6 Response table for GRG

Level	S/C ratio	W/C ratio	SP content
1	0.580	0.624	0.479
2	0.602	0.607	0.553
3	0.602	0.597	0.708
4	0.638	0.594	0.682
Delta	0.058	0.030	0.229
Rank	2	3	1

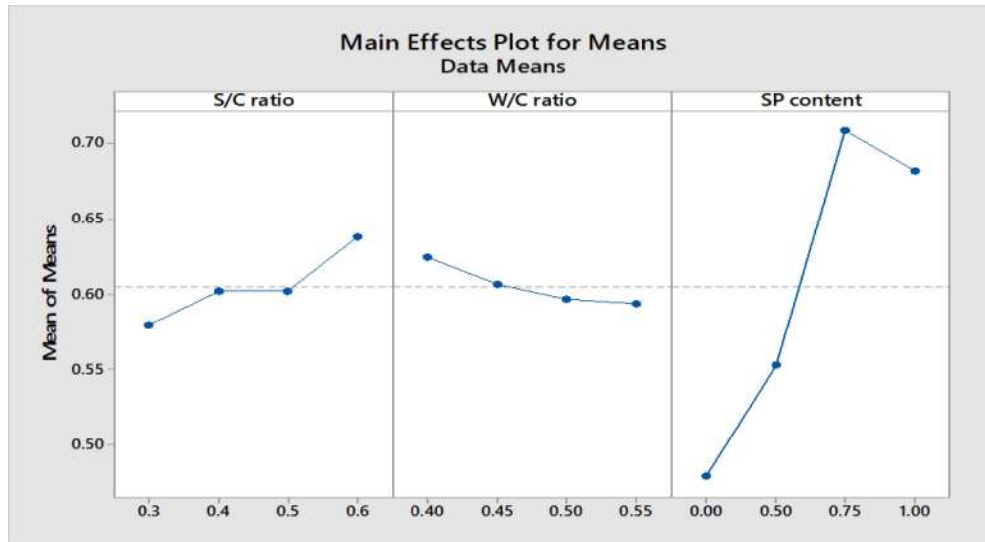


Fig. 4.3 Main effects plot for GRG value

4.4 SUMMARY

In this chapter, the grout mixes were prepared and tested for fluidity and CS at seven days curing period. The four levels of each parameter, S/C ratio, W/C ratio and SP contents, were varied to prepare the grout mixtures as recommended in Taguchi methodology. It was observed that for fluidity, the optimal combination is the level 3 of S/C ratio, level 4 of W/C ratio, and level 4 of SP content which are 0.5, 0.55, and 1.0%, respectively (i.e., S/C=0.5, W/C=0.55, and SP content=1.0%). However, the aforementioned optimal combination of these input parameters was to achieve the lowest fluidity value. The most to least influencing factors on fluidity are the W/C ratio, SP content, and S/C ratio. Similarly, to achieve the highest CS, the optimal grout combination is an S/C ratio of 0.6, a W/C ratio of 0.4, and an SP content of 0.75%. In descending order, the factors that exert the greatest influence on the CS are the W/C ratio, S/C ratio, and SP content. However, the impact of SP content on the CS appears to be less pronounced than that of the W/C and S/C ratios.

The GRA was adopted to obtain an optimal grout proportion with minimum fluidity and maximum CS simultaneously. The GRC, GRG, and GRO are determined and the GRG values are given as output parameters to Taguchi methodology for the recommended

mixture combinations. The optimal grout proportions, considering both the fluidity and CS, were an S/C ratio of 0.60, a W/C ratio of 0.40, and an SP content of 0.75%. The fluidity and CS are significantly affected by SP content, followed by the S/C ratio and W/C ratio. GRG value decreased with an increase in SP content from 0.75 % to 1%, indicating that the higher SP content has a negative effect on fluidity and CS. The optimal grout mix achieved a fluidity of 27 seconds and CS of 66 MPa after a 28-day curing period.

CHAPTER 5

EFFECT OF AGGREGATE GRADATION AND BITUMEN TYPE ON MECHANICAL PROPERTIES OF SEMI-FLEXIBLE ASPHALT MIXTURES

5.1 GENERAL

The first part of this chapter deals with preparing the Open-Graded Asphalt (OGA) mixture to be grouted, thus forming the Semi-Flexible Asphalt (SFA) mixtures. The later part discusses the effect of aggregate gradation and bitumen type on the mechanical properties of SFA mixtures. The present study adopted two aggregate gradations, IRC SP 125 recommended (Gr-I), and a new gradation (Gr-II), to assess the gradation effect. The two binders, VG 30 and PMB 40, were used to prepare the OGA mixtures, thus, evaluating the effect of binder type on the mechanical properties of SFA mixtures. The SFA mixtures were tested for Marshall Stability (MS), Compressive Strength (CS), Indirect Tensile Strength (ITS), Cantabro loss, fatigue resistance, rutting resistance, moisture and Oil spillage resistance tests were conducted.

5.2 PREPARATION OF OGA MIXTURE

The mix design and preparation of OGA mixtures were aimed at preparing the OGA mixtures with targeted air voids content. The air voids in the 25-35% range were recommended by IRC SP 125-2019. EuroDensit (2000) and Mayer and Thau (2001) recommended a maximum air void of 30% to maintain the flexibility provided by OGA mixtures. Therefore, the present study considered $30 \pm 0.5\%$ air voids. The Voids in the Coarse Aggregates in the dry-rodded condition (VCA_{DRC}) was the preliminary criterion for selecting any gradations and determined as per ASTM C29. However, the maximum value of 44% was suggested by IRC SP 125 2019. The new aggregate gradation (Gr-II) was selected to provide 25-30% air voids and a higher fine aggregate proportion, which was based on the Construction Manual for Semi-Flexible Pavement (SFPCM) of Japan for Nominal Maximum Aggregate Sizes (NMAS) of 16 mm with air voids of 30%. The fine

aggregate content in Gr-II is relatively different than in Gr-I, which is evident from Fig. 3.6.

The VCA_{DRC} of Gr-I and GR-II gradations were determined to ensure good aggregate packing, as 40% and 38%, respectively. The control mix (OGA) was prepared using Gr-I gradation and VG 30 bitumen. To examine the effect of bitumen type, the OGA mixtures with Gr-II gradation were prepared using VG 30 and PMB 40 binders.

5.2.1 Determination of Optimum Binder Content

The Optimum Binder Content (OBC) was determined based on the drain-down test (Bharath et al. 2020; Gupta and Kumar 2021; Saboo et al. 2019b; Shukla et al. 2021). The bitumen content corresponding to a maximum drain-down loss of 0.3% was considered as the OBC (EucoDensit 2000). The test on uncompacted OGA mixtures was conducted as per ASTM D6390 for three OGA mixtures: i) Gr-I gradation with VG 30, ii) Gr-II gradation with VG 30, iii) Gr-II gradation with PMB 40, and the OBCs were determined as 2.5%, 3.5%, and 3.75%, respectively. The test temperatures were 180 °C and 160 °C for PMB 40, and VG 30 binders, respectively. The mixing temperatures were the temperatures corresponding to viscosity of 0.17 ± 0.0 Pa.S. The temperatures were adopted from Kumar et al. (2017). The results are presented in Fig. 5.1.

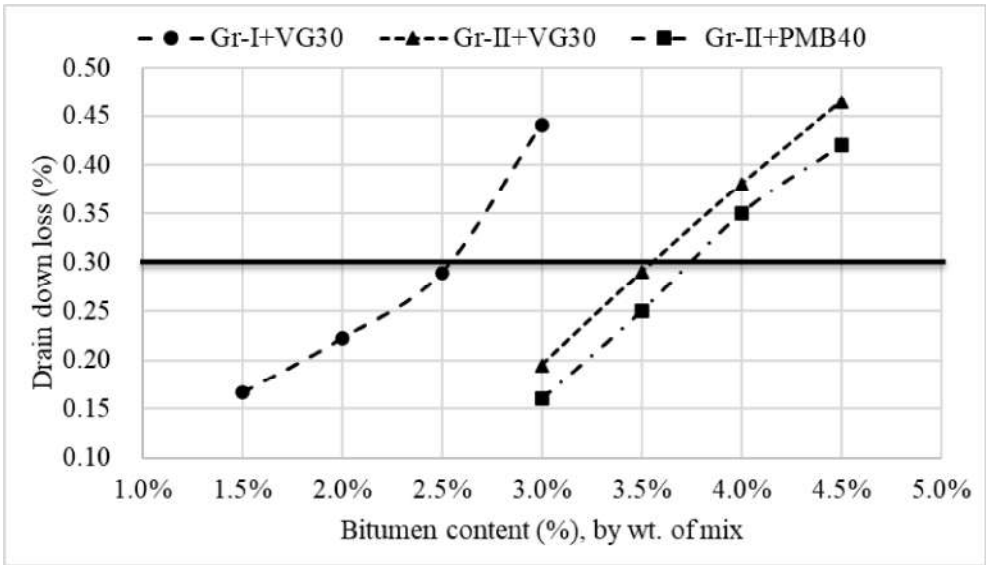


Fig. 5.1 Drain down test results of OGA mixtures

5.2.2 Determination of Optimum Compaction Effort

Generally, the OGA specimens were prepared as per Manual Series-2 (7th Edition) and compacted using a Marshall compactor and Superpave gyratory compactor (Cai et al. 2020c; Oliveira 2006). Many researchers used the Marshall compactor since one can get uniform compaction, density and easy to handle (Bharath et al. 2020; Gupta and Kumar 2021; Saboo et al. 2019b; Shukla et al. 2021). It was necessary to determine the Optimum Compactor Effort (OCE) for any new gradation as the over-compaction leads to the breakage of aggregates. At the same time, the under-compaction leads to a change in the densities of the field specimens, which ultimately changes the air voids and grouting volume. Therefore, the OCE needs to be determined for the new aggregate gradation, i.e., Gr-II. Using the trial-and-error method, the OCE was determined by varying the number of Marshall blows per one or both sides. Some researchers tried 50 and 75 blows on one side (Du 2014; Hou et al. 2016, 2017; Zhang et al. 2019). Al-Qadi et al. (1994) applied 10-20 blows per one or each side and selected the 10 blows to each side of the OGA sample as optimum based on the air void content. Shukla et al. (Shukla et al. 2021) varied the compaction effort of 20-60 blows on one side and determined the OCE for each gradation based on the air void content, and the same methodology was adopted in the present work for Gr-II gradation.

The recommended compaction effort for OGA mixtures prepared with Gr-I gradation was 40 Marshall blows on one side (IRC: SP: 125 2019). The OCE for OGA mixtures, prepared with Gr-II gradation and VG 30 bitumen, was determined based on V_a and G_{mb} . The compaction effort varied from 30 to 80 blows with an increment of 10. Three specimens were cast at each compaction effort and their V_a and G_{mb} were determined. The variation in V_a and G_{mb} was marginal from 60 to 80 blows and it is evident from Fig. 5.2. Therefore, the OCE for Gr-II gradation was recommended as 60 blows. The OGA mixtures made with Gr-II gradation and PMB 40 bitumen were also compacted using 60 blows. From Table 5.1 it is evident that all mixtures achieved V_a of 28.9 - 30.7 %. Due to the fact that the gradation needed to be changed for every mix to obtain the V_a of 30%, the variation of V_a is acceptable.

The permeability test was carried out following EN 12697-19. The results showed that both gradations could endure 360-380 m/day, demonstrating a high degree of interconnectivity and volume of air voids. Hassani et al. (2020) and Saboo et al. (2019b) suggested a minimum of 100 m/day for OGA mixtures to prepare the SFA mixtures.

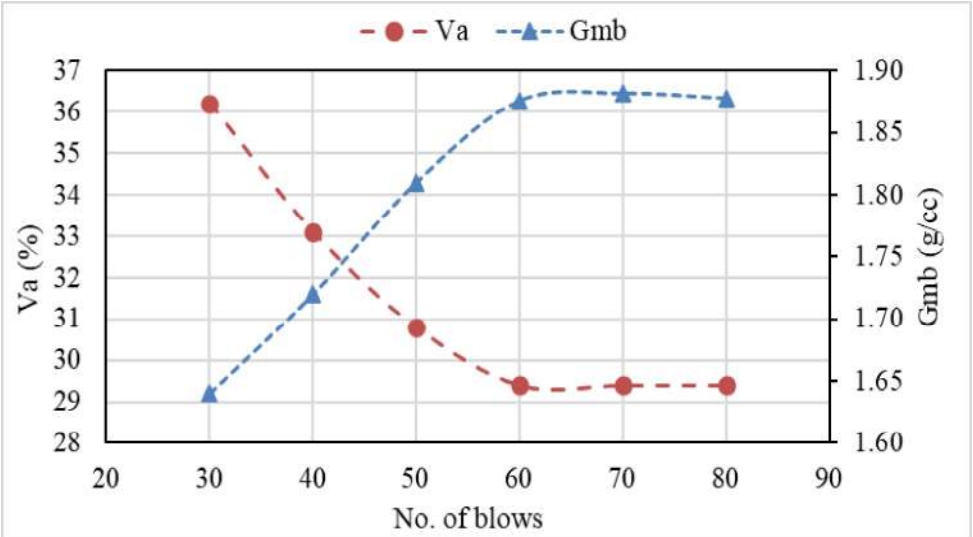


Fig. 5.2 Variation of Va and G_{mb} with compaction effort

Table 5.1 Volumetric properties of OGA mixtures

Type of Gradation	Bitumen type	OBC (%)	G _{mm} (g/cc)	G _{mb} (g/cc)	V _a (%)	VMA (%)	VFB (%)	OCE (blows on one side)	ITS (kPa)
Gr-I	VG 30	2.5	2.681	1.859	30.7	34.11	10.1	40	303
Gr-II	VG 30	3.5	2.663	1.879	29.4	34.18	13.9	60	337
	PMB 40	3.75	2.659	1.890	28.9	33.97	14.9		385

5.3 PREPARATION OF SFA MIXTURES

The compacted OGA mixtures were extracted, wrapped with cellophane tape, and grouted with the optimal mix (as determined in Chapter 4). This process is as depicted in Fig. 5.3. Before testing, the grouted SFA specimens were cured at 34 °C (the average annual temperature for most south Karnataka regions) for 3, 7, and 28 days using wet gunny bags. The notations of SFA mixtures are tabulated in Table 5.2.

Table 5.2 Notations of SFA mixtures

OGA Mixture Constituents	Notation of corresponding SFA mixtures *
Gr-I gradation + VG 30 bitumen + OBC of 2.5% + OCE of 40 blows	SV-I
Gr-II gradation + VG 30 bitumen + OBC of 3.5% + OCE of 60 blows	SV-II
Gr-II gradation + PMB 40 bitumen + OBC of 3.75% + OCE 60 blows	SP-II

*Note: The first letter of the acronym 'S' indicates the grouted OGA specimen, i.e., SFA specimen. The second letter indicates the bitumen type, while the roman number indicates the gradation used.



Fig. 5.3 (a) Grout (b) OGA specimens before grouting (c) SFA specimens: partially grouted specimens (on left) and full-depth grouted (on right) (d) Full-depth grouted SFA specimens (e) Visual inspection of full-depth grouting by cutting SFA specimens into halves

5.4 RESULTS AND DISCUSSION

5.4.1 Marshall Stability

The three specimens were prepared for MS, ITS, CS, Retained Marshall Stability (RMS), Tensile Strength Ratio (TSR) and Cantabro tests and the average value is presented in study. The MS test was conducted on SV-I, SV-II, and SP-II mixes at 60°C. The test results for 3, 7, and 28 days cured specimens are depicted in Fig. 5.4. For all the mixes, the MS value increases with the curing period and follows the general concrete trend due to the hydration of cement. The hydrated products in fibrous structure will be formed at the interface of grout and bitumen over the initial curing period (Hou et al. 2017). As the curing period increases, the hydration products form the spatial network structure at the interface of the hardened cement paste and bitumen, providing extra stability (Hou et al. 2016). Therefore, the strength gained over the curing period improved the stability of SFA mixtures.

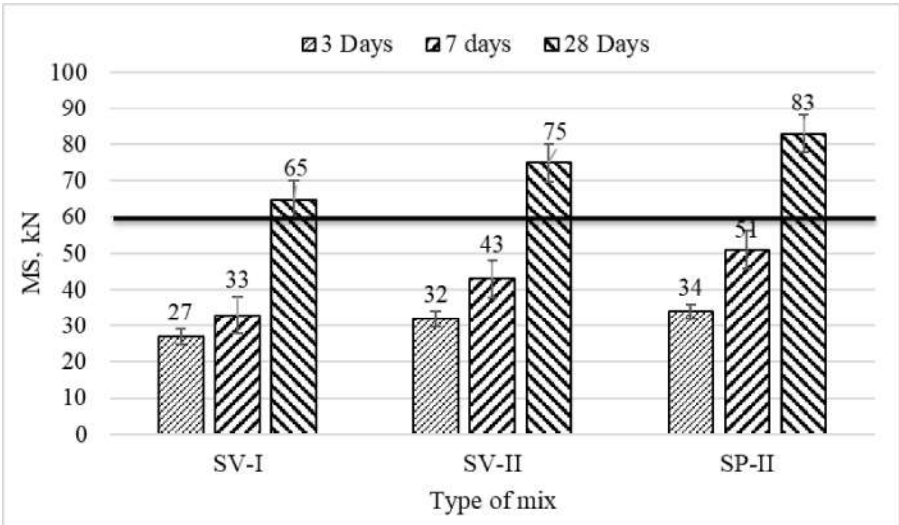


Fig. 5.4 Variation of MS for different SFA mixtures

The 28 days cured samples of SP-II mixes exhibited MS values 1.4 times that of 3-day cured samples, while SV-I samples have the lower MS values, irrespective of the curing period. Three SFA mixtures met the MS value of 60 kN at 28-days curing as per IRC SP 125-2019. The SV-II mixtures exhibited a 15% higher stability value after 28-days curing than SV-I mixtures. This may be due to the good aggregate packing characteristics of Gr-II gradation compared with Gr-I gradation and the flexibility provided by more fine

aggregate content. The SP-II mixtures have about 10% higher MS values after 28-day curing than SV-II mixtures, and this may be due to the higher performance of PMB 40 than VG 30 binder. It is evident from the above tests that the binder characteristics significantly affect MS values. The SP-II mixtures have better stability than other SFA mixtures. The earlier researchers Gupta and Kumar (2021) reported a stability of about 68-88 kN, and Mukherjee and Sahoo (2019) reported a stability of 48 kN for 28 days cured specimens.

5.4.2 Compressive Strength

The CS test was conducted on cylindrical specimens of 100 mm diameter and 63.5 mm height, and the results are depicted in Fig. 5.5. The CS of all mixes having more than 5 MPa after 28-day curing satisfies the IRC's recommendation. The CS values of SV-I mixes are low, whereas the SP-II mixes exhibited higher CS. The CS of the SP-II mix is 21% and 41% higher than SV-II and SV-I mixes, respectively. The OGA mixtures with PMB 40 exhibited higher CS values, indicating an effect of the type of binder on SFA mixtures. The CS of 3-day cured SFA mixtures was found to be 48-51% of 28-day cured samples, attributed to the early strength of grout due to the superplasticizer. Setyawan (2013) observed a similar trend of results. Bharath et al. (2020) observed the CS of 6 kN for 28 days cured specimens.

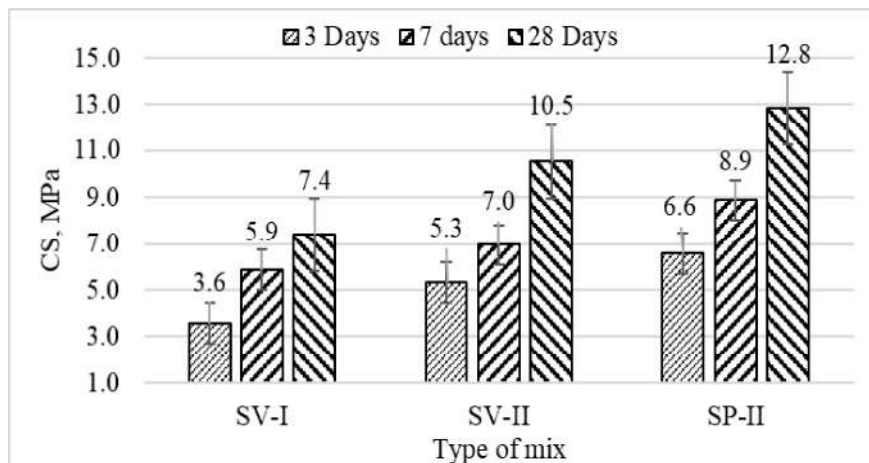


Fig. 5.5 Variation of CS for different SFA mixtures

5.4.3 Indirect Tensile Strength

The ITS was conducted at 35 °C and 25°C as per ASTM D6931 to assess the permanent deformation of SFA mixes, and the results are depicted in Figs. 5.6 and 5.7. The ITS values increased with the curing period for all mixes which may be attributed to the strength gained due to the hydration process. Kaushik and Siddagangaiah (2022) also observed similar results. The ITS values at 35°C of all SFA mixtures cured for 28 days have met the minimum requirement of 1 MPa specified by IRC SP 125-2019. The SP-II mixtures exhibited a higher ITS value of 2.4 MPa, which is 26% higher than the SV-II mix. The strength gain is attributed to the higher tensile strength exhibited by PMB 40 than VG 30 binder, as tabulated in Table 13.

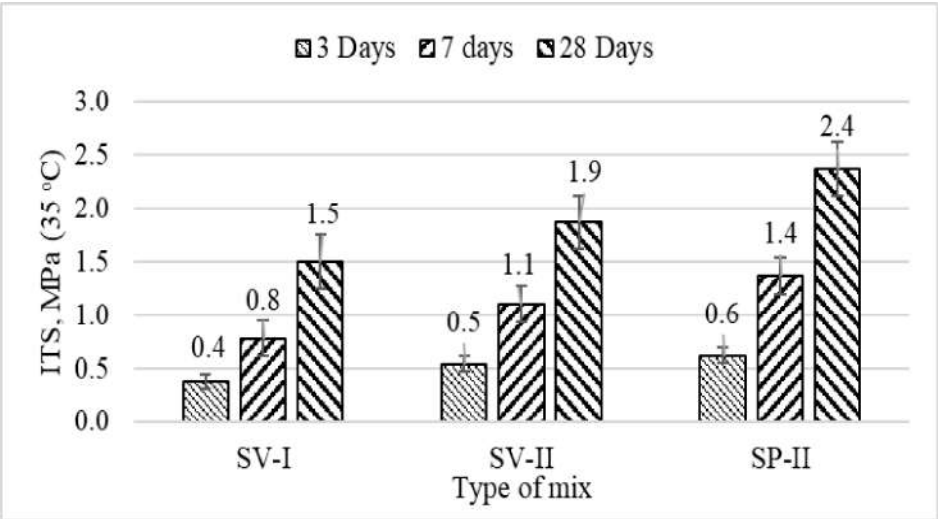


Fig. 5.6 Variation of ITS at 35 °C for different SFA mixtures

The SV-II mixtures exhibited 26% higher ITS values than the SV-I mixtures. The strength gain is attributed to a higher tensile strength, finer aggregate proportion and bitumen content of the SV-II mixture than the SV-I mixture. Similar observations were made in ITS values at 25 °C based on the tensile strength, aggregate gradation and binder type. Figs. 5.6 and 5.7 show that ITS at 25 °C values are higher than the corresponding ITS at 35 °C, indicating the temperature susceptibility of SFA mixtures. It may be attributed to the loss of bond between aggregates due to the softening of coated bitumen (Gupta and Kumar

2021). Bharath et al. (2020) reported ITS of 2.3 MPa for 28 days cured specimens, and Kaushik and Siddagangaiah (2022) observed a decrease in ITS with increased temperature.

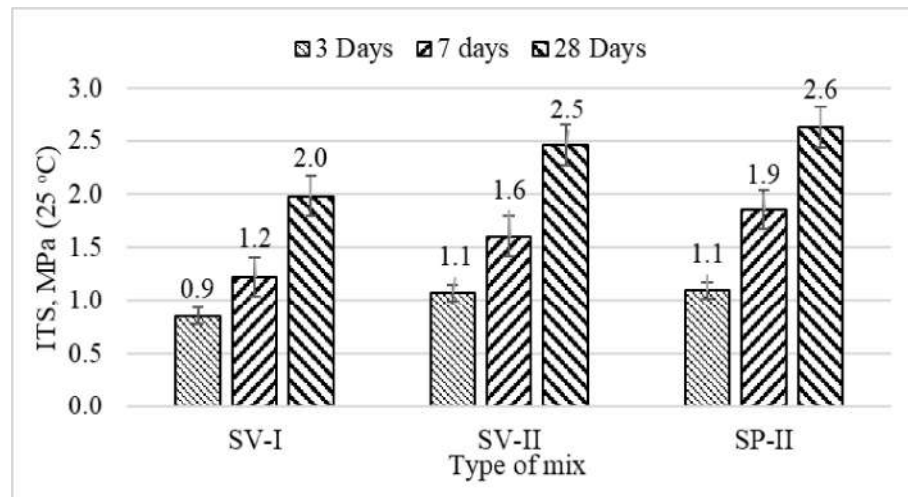


Fig. 5.7 Variation of ITS at 25 °C for different SFA mixtures

5.4.4 Moisture Susceptibility and Oil Spillage Resistance

Moisture susceptibility of SFA mixtures was studied in terms of RMS and TSR tests. From Fig. 5.8, it is evident that all mixes showed good resistance to moisture damage with RMS values of at least 93%. All SFA mixtures exhibited an RMS of 100% after 28 days of curing, and it may be inferred that the moisture intrusion has an insignificant effect on the stability of SFA mixtures. The ITS test was conducted on conditioned and unconditioned samples to determine TSR. From Fig. 5.9, it is evident that the TSR of all SFA mixtures cured for 28 days could achieve 97% as recommended by IRC SP 125-2019. However, the SP-II mixtures exhibited higher TSR values of 97-100% for a curing period of 3-28 days compared to the other mixes. Overall, SP-II mixes exhibited better moisture resistance than SV-II and SV-I mixes. Gupta and Kumar (2021) reported TSR values of about 92-94%, while Bharath et al. (2020) observed 96% TSR.

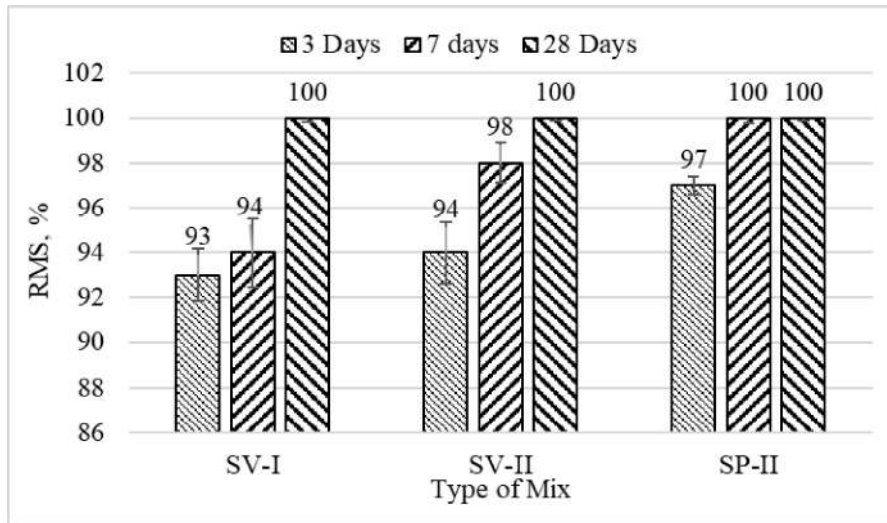


Fig. 5.8 Variation of RMS with different SFA mixes

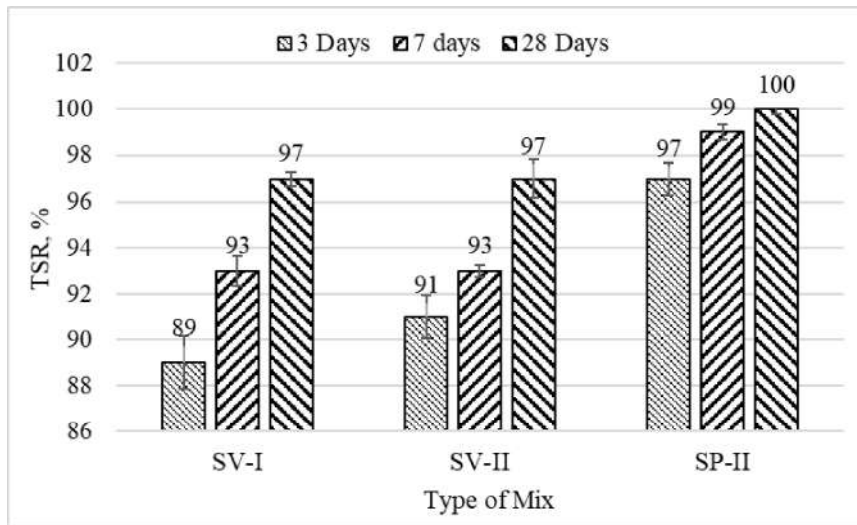


Fig. 5.9 Variation of TSR with the type of mix and curing period

The SFA pavements offer higher oil spillage resistance from the grout; therefore, the SFA mixtures become the best solution in industrial areas than Hot Mix Asphalt (HMA) mixtures. However, there is no specific test procedure mentioned in IRC SP 125 to determine the oil spillage resistance of SFA mixtures. However, to have comparative study, Bharath et al. (2020) adopted a method of soaking the specimens in a diesel bath for 24 hr and testing for conditioned ITS value. The ratio of ITS of conditioned and unconditioned samples was used as a relative parameter, similar to TSR. The TSR ratios obtained for SV-

I, SV-II, and SP-II mixes cured for 28 days were about 92-94%, attributed to the resistance offered by grout. Gupta and Kumar (2021) observed oil spillage resistance in terms of TSR at about 86-91%, while Bharath et al. (2020) reported 92%.

5.4.5 Fatigue Characteristics

The fatigue characteristics were investigated by applying repeated loading on SFA mixtures in the RLT system. Due to the variability of the fatigue results, the five specimens were tested for each mix and the average Fatigue Life (FL) is reported in the study. The FL was defined as the total number of load repetitions required to cause the failure i.e., the deformation of 5mm (Chinnabhandar et al. 2022). The SFA mixtures were divided into three groups based on the curing period. The applied load is 15, 33, and 50% of ITS failure load on specimens cured for 3, 7, and 28 days, respectively. The lowest failure loads of 3, 7, and 28 days are 8.5kN, 12.16kN, and 19.74 kN, respectively, and the same was considered for testing. From Table 5.3, it is evident that the FL of SV-I mixtures is lower than SV-II and SP-II mixtures. The FL increases with the curing period for all SFA mixes due to the strength gain of grout over the curing period. The SP-II mixes exhibited a higher FL at all stress levels and curing periods, and this may be due to the good fatigue resistance offered by PMB 40 binder and higher binder content in the mix, and a similar trend was observed by Oliveira (2006).

Table 5.3 The fatigue life of SFA mixtures

Curing period	Failure load for ITS (kN)	Applied Load percentage	Fatigue life (Number of cycles)		
			SV-I	SV-II	SP-II
3 Days	8.5	0.15	9913	12051	14723
		0.33	9861	11745	13128
		0.50	7442	9753	11754
7 days	12.16	0.15	18612	20158	23715
		0.33	16487	18632	21053
		0.50	11428	13972	15319
28 Days	19.74	0.15	71912	91251	110512
		0.33	34298	53691	79142
		0.50	17621	23514	26793

5.4.6 Rutting Characteristics

The Wheel Rut Tester (WRT) was used to determine the permanent deformation of SFA mixtures and the results are presented in Fig. 5.10. All SFA mixtures exhibited lower rut depth and highest Dynamic Stability (DS), indicating higher rutting resistance. However, the SP-II mixtures exhibited lower the rut depth of 0.56 mm and higher DS of 28154 cycles/mm, attributed to the good aggregate packing characteristics of Gr-II compared with Gr-I. However, the effect of aggregate gradation on rutting resistance was more significant than the binder type.

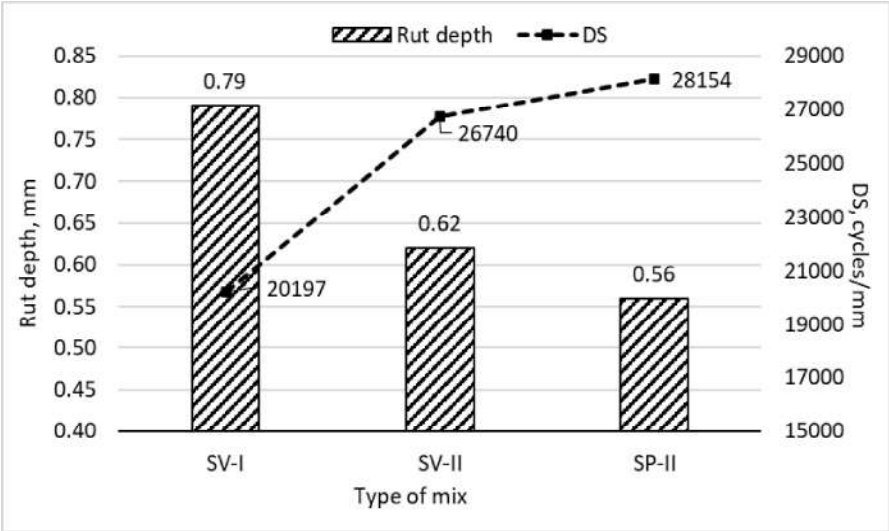


Fig. 5.10 Variation of rutting characteristics with type of mix

5.4.7 Cantabro Abrasion test

The Los Angeles Abrasion machine without surcharge was used to evaluate the durability of the SFA mixtures to the ravelling and traffic abrasion. Kaushik and Siddagangaiah (2022) considered the abrasion loss of 50% as a failure criterion since the presence of grout increases the disintegration in SFA specimens. However, Hassani et al. (2020) considered a maximum weight loss of 20%, which is adopted in the present study. The test results are presented in Fig. 5.11. The weight loss decreased with the curing period, attributing to the strength gain of grout over the period indicating high durability. The spatial network formed at the interface of hardened grout and binder improved the bonding strength, thereby improving durability (Hou et al. 2017). The SP-II mixtures exhibited lesser weight

loss than the other SFA mixtures, implying higher durability. From Figure 14, it is evident that the aggregate gradation and bitumen type significantly affected the durability of SFA mixtures. Bharath et al. (2020) observed the cantabro loss of 16%.

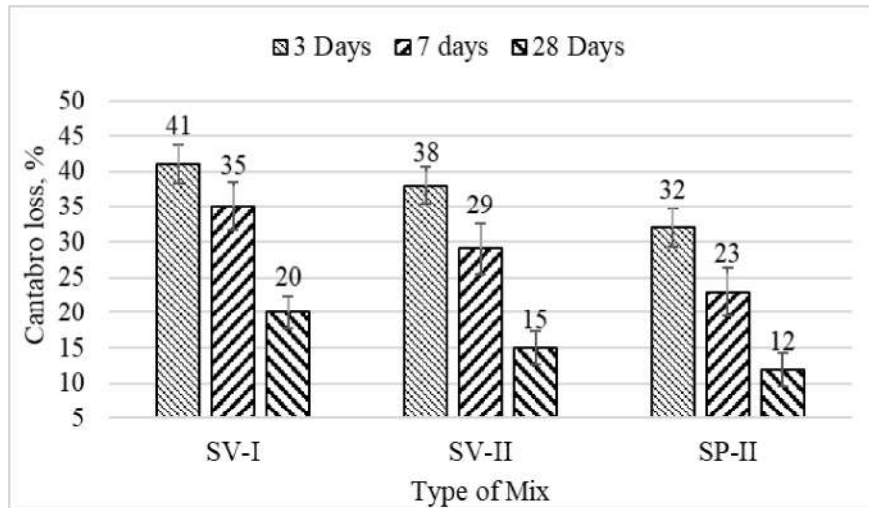


Fig. 5.11 Variation of cantabro loss with the SFA mixtures

5.4.8 Scanning Electron Microscope

The Scanning Electron Microscope (SEM) analysis was used to study the microstructure of SFA mixtures, focusing specifically on SV-II mixtures and the SEM images of the same are presented in Figs. 5.12(a-c). Fig. 5.12(a) showed that the grout effectively coated the bitumen-covered aggregates. This coating of the bitumen by the grout was crucial because it ensured a strong connection between the bitumen and the surrounding materials, contributing to the structural integrity of the mixture. The grout served as a binding agent that not only covered the bitumen-coated aggregate but also interlocked with it, providing a continuous phase that enhanced the mixture's mechanical performance. The formation of fibrous hydration products, as depicted in Fig. 5.12(b), played a significant role to provide such a continuous phase, thus improving the interfacial bond. Fig. 5.12(c) depicted the complete formation of crystallized structures within the bitumen and hardened grout matrix. This phase transformation indicated that the grout had undergone full hydration, leading to the development of a rigid, interconnected crystalline network. The crystallized phase was not susceptible to temperature changes and formed a durable matrix that could

withstand harsh environmental condition and repeating loading (Hou et al. 2016). The enhanced mechanical properties of the SFA mixtures were thus directly related to the thorough crystallization and bonding observed at the microstructural level (Hou et al., 2016).

Overall, the SEM analysis highlighted the importance of grout-bitumen interactions in the SFA mixtures. The coating of bitumen-coated aggregates, the formation of fibrous hydration products, and the development of a crystallized phase collectively contributed to the improved performance of the SFA mixtures.

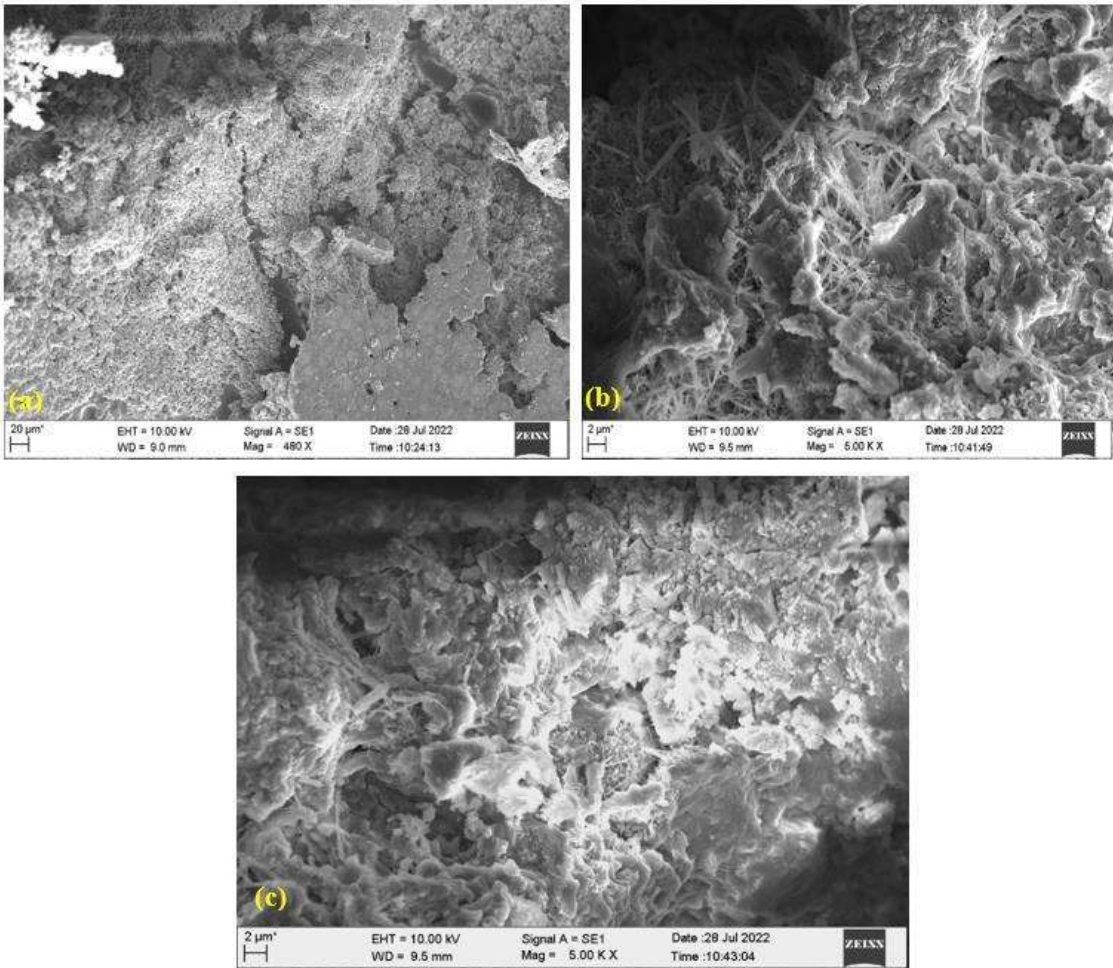


Fig. 5.12 SEM image of (a) SV-II mixture (b) SV-II mixture cured for 7 days (c) Hardened grout and bitumen phase

5.5 STATISTICAL ANALYSIS

Statistical analysis was conducted to identify the significant change between the groups. In this study, the one-way ANOVA was performed to determine the effect of gradation and bitumen type on the mechanical properties of three SFA mixtures. The significance level of 5% was adopted for the analysis, and the results are tabulated in Table 5.4. The null hypothesis is that there is no significant difference between the groups. The alternate hypothesis is that there is significant difference between the groups. If the F is more than F_{crit} , the null hypothesis should be rejected, implying that there was difference between the groups. From Table 5.4, it is evident that the F values were more than F_{crit} value for all test parameter and the p -values are less than 0.05. Hence, the null hypothesis should be rejected, implying the significant difference in properties tested between the groups. Therefore, it was concluded that the gradation and bitumen type had a statistically significant effect on mechanical properties of SFA mixtures. However, no change is observed statistically in the RMS of mixtures cured at 28 days since the RMS of all the mixtures is 100%. Therefore, RMS of SFA mixtures might not be affected due to moisture.

Table 5.4 Statistical analysis of results

Test Parameter	p-value	Sig.	F	F_{crit}
MS	0.000	Yes	39	5.14
CS	0.000	Yes	285	5.14
ITS at 35 °C	0.000	Yes	21	5.14
Cantabro	0.002	Yes	19	5.14
TSR at 28 days curing	0.021	Yes	7.5	5.14

5.6 SUMMARY

The SFA is a composite pavement material consisting of an OGA sample with a higher V_a of 30% filled with grout of high flowability and CS. The OGA mixtures were prepared with 19 mm and 16 mm NMAS aggregate gradations (Gr-I and Gr-II gradations) using PMB 40 and VG 30 binders. The OBC values were 2.5, 3.5 and 3.75% for SV-I, SV-II and SP-II mixtures. The higher OBC of SV-II and SP-II is attributed to the higher fine aggregate content and higher adhesive property of PMB 40.

The SP-II mixtures have the highest MS of 83 kN, while the SV-I and SV-II mixtures have 65 and 75 kN, respectively. The SP-II mixtures have the higher MS, CS, and ITS values of 83 kN, 12.8 MPa, and 2.4 MPa, respectively, among the other mixtures. The mechanical properties of all SFA mixtures improved with the curing period. The SP-II mixtures exhibited the highest FL, followed by SV-II and SV-I mixtures. The FL increased with the curing period. All SFA mixes exhibited 100% RMS at a 28-day curing period attributed to the grout coated around the aggregates absorbing the moisture resulting in higher strength, thus exhibiting no decrease in MS after conditioning. The SP-II mixtures showed better moisture resistance with a 97-100% TSR for all curing periods. It can be attributed to the good moisture resistance offered by PMB 40 binder. The oil spillage resistance of all SFA mixtures was about 92-94% of TSR, indicating good oil spillage resistance. The one-way ANOVA statistical analysis indicated that the aggregate gradation and bitumen type significantly affected the mechanical properties of SFA mixtures.

CHAPTER 6

EFFECT OF MARGINAL AGGREGATES ON MECHANICAL PROPERTIES OF SEMI-FLEXIBLE ASPHALT MIXTURES

6.1 PREPARATION OF OPEN-GRADED ASPHALT MIXTURES

The Semi-Flexible Asphalt (SFA) mixtures were prepared by replacing Natural Coarse Aggregates (NCA) with Recycled Concrete Aggregate (RCA) and Ferrochrome Slag aggregate (FCS). The Open-Graded Asphalt (OGA) mixtures were prepared with marginal materials that satisfied Grade II and PMB 40, with a compaction effort of 60 blows on one side. The NCA was replaced by 50% and 100% RCA by weight, and FCS by 100% by weight. The mixing and compaction temperatures of 175 °C and 163 °C were maintained (Saboo et al. 2023). The Optimum Binder Content (OBC)s of OGA mixtures with 50%RCA, 100%RCA and 100% FCS were obtained as 3.95%, 4.19%, and 3.5%, respectively, based on the maximum permissible drain-down of 0.30%. The drain-down test temperature was conducted at 180 °C. The OBC increased with RCA content, attributed to the higher absorption and porous nature of RCA (Pasandín and Pérez 2020; Sanchez-Cotte et al. 2020; Tanty et al. 2018). The presence of mortar attached to RCA increases the absorption of the binder, thus increasing the OBC (Pasandín and Pérez 2020).

From Table 6.1, it is evident that the air voids of OGA mixtures varied for each mix. The variation was attributed to OBC and aggregate packing characteristics. In order to achieve 30% air voids, the gradation must be adjusted and, thereby, OBC changes. Therefore, the variation in V_a was not considered while comparing the performance of mixtures. It was observed that the OGA mixtures with FCS exhibited higher Marshall Stability (MS) and Indirect Tensile Strength (ITS) compared to those with RCA, attributed to the stronger skeleton of aggregates having lesser aggregate impact value. Sanchez-Cotte et al. (2020), Pasandín and Pérez (2013) and Tanty et al. (2018) reported a similar trend of results. The compacted OGA specimens were grouted after cooling to room temperature, cured for 28 days, and then the mechanical properties were evaluated.

Table 6.1 Volumetrics of OGA mixtures with marginal aggregates

Type of mixture	OGA	OBC (%)	G _{mm}	G _{mb}	V _a (%)	VMA	MS (kN)	ITS (kPa)
50%RCA		3.95	2.581	1.842	28.6	30.9	7.7	356
100%RCA		4.19	2.416	1.760	27.2	29.4	6.5	308
100%FCS		3.50	2.933	2.067	29.5	36.6	9.4	432

6.2 RESULTS AND DISCUSSIONS

6.2.1 Marshall Stability

The MS test results on SFA mixtures with marginal aggregates are depicted in Fig. 6.1. The SFA with 100% RCA obtained an MS of 68 kN, which is the lowest compared with other mixtures. The MS of SFA with 50% RCA was 13% higher than those of 100% RCA due to the reduced RCA content. The mortar attached to RCA breaks faster while loading, and hence, the MS value reduces. In the present study, SFA with 100% RCA exhibited lower MS. On the other hand, SFA with 100% FCS exhibited higher MS among all the mixtures due to strong aggregates in terms of impact and stable aggregate skeleton. The SFA with 100%FCS exhibited 15% higher MS than the control mix SP-II, whereas the SFA with RCA exhibited lower MS. All mixtures satisfy the minimum requirement of 60 kN as per IRC SP 125 2019. Zachariah et al. (2020) utilized brick aggregates to prepare SFA mixtures and observed that the SFA with brick aggregates exhibited reduced MS than those with natural stone aggregates. A similar trend of results is observed for SFA mixtures with RCA, where the trend is different due to strong FCS aggregates.

6.2.2 Compressive Strength

The CS results of SFA prepared with marginal aggregates are depicted in Fig. 6.2. The SFA with 100% RCA exhibited CS of 10 MPa, 11 MPa for 50% RCA and 15.3 MPa for 100%FCS. As the RCA percentage increases, the CS values are reduced due to the increase in the attached mortar to RCA, reducing the load resistance of mixtures. On the contrary, the SFA mixtures with FCS exhibited the highest CS compared to other mixes. It is evident that the SFA with 100% FCS exhibited 53% higher CS than RCA with 100%. Similarly, the SFA with 100%FCS exhibited 19% higher CS than the SP-II mixture, whereas the SFA

with RCA exhibited lower MS than SP-II mixtures. However, all the mixtures satisfy the minimum strength requirement of 5 MPa per IRC SP 125. Zachariah et al. (2020) observed the same trend with other marginal aggregates.

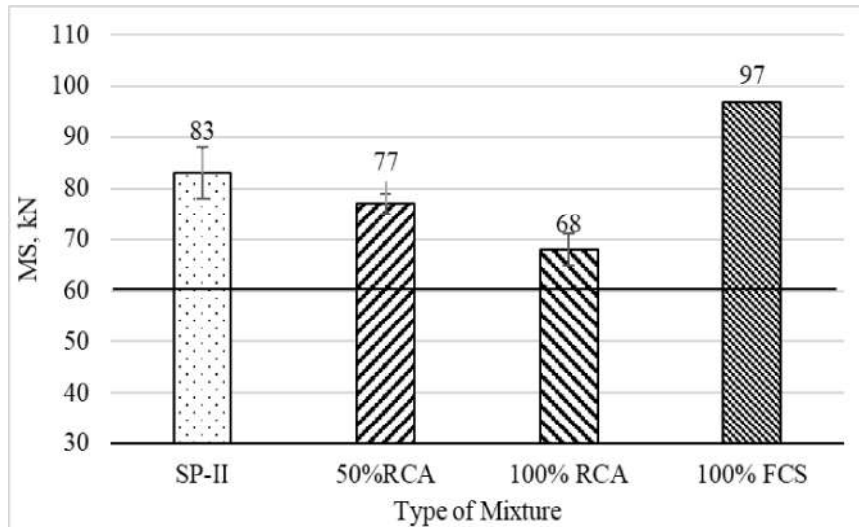


Fig. 6.1 MS of SFA mixtures with marginal aggregate

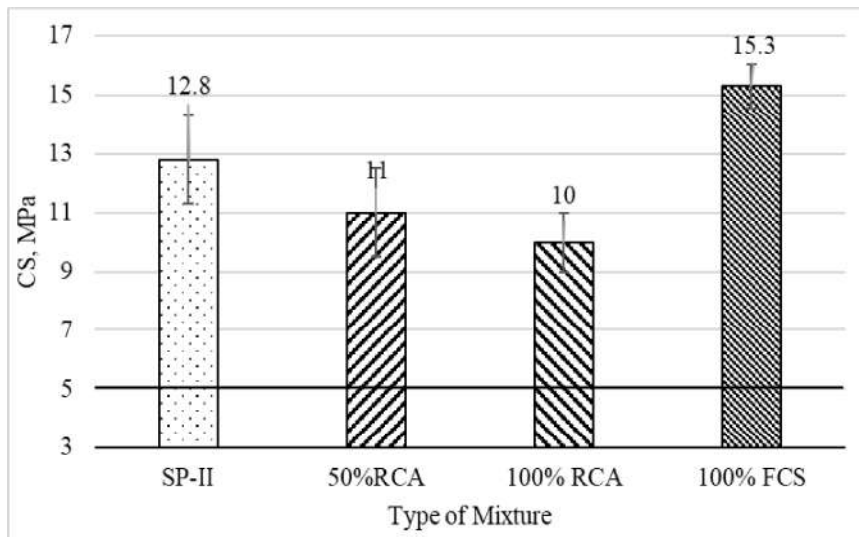


Fig. 6.2 CS of SFA mixtures with marginal aggregate

6.2.3 Indirect Tensile Strength

The ITS test was conducted at 25 °C, 35 °C and 45 °C to evaluate the temperature susceptibility of SFA mixtures having marginal aggregates. The results are depicted in Fig.

6.3. It was observed that the SFA with 100% RCA had the lowest ITS at all temperatures. For 25-45 °C temperatures, SFA with 50% RCA exhibited higher ITS values by about 3-21% than those with 100% RCA. The breakage of RCA was evident from Fig. 6.4, whereas the breakage of grout for FCS was evident. Pasandín and Pérez (2020) reported a similar trend for Hot Mix Asphalt (HMA) mixtures with RCA. The SFA with 100%FCS at temperatures of 25 °C, 35 °C and 45 °C exhibited ITS values of 2.8, 2.5, and 2.15 MPa, respectively. Similarly, with 100%RCA, the ITS values were 1.91 MPa, 1.39 MPa and 1.2MPa, and with 50%RCA, it was 1.98 MPa, 1.62 MPa, and 1.46 MPa, respectively. From the above comparison, the FCS exhibited better ITS values with 100% and 50% RCA. However, the SP-II mixtures at similar temperatures exhibited 2.6 MPa, 2.4 MPa, and 2.2 MPa, respectively. From the above comparison, the SFA with 100%FCS performs much better when compared to SP-II, SFA with 50%RCA and 100%RCA. However, all the mixtures satisfy the ITS of 1MPa as per IRC SP 125.

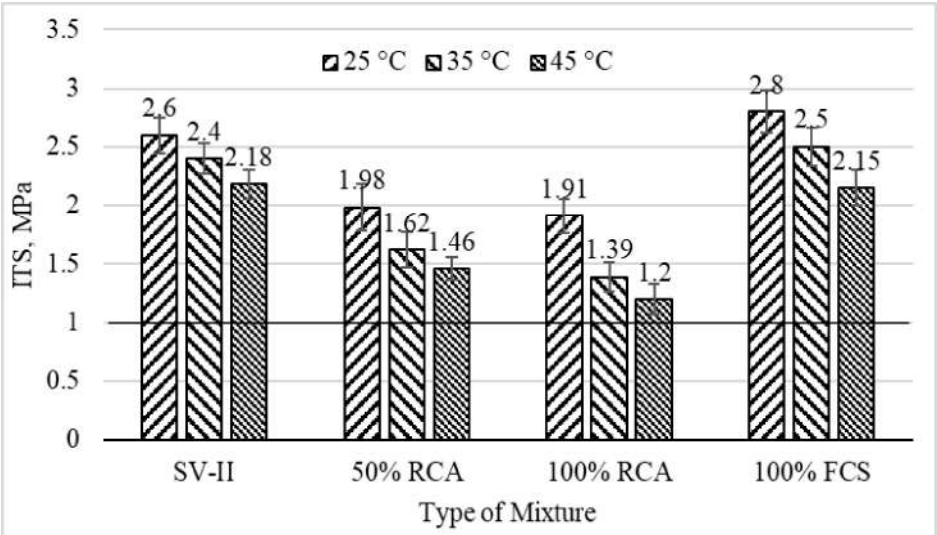


Fig. 6.3 ITS of SFA mixtures with different aggregate types

The variation in ITS was not uniform for SFA mixtures with 100%RCA. Pasandín and Pérez (2013) reported higher temperature susceptibility of HMA mixtures with RCA. However, all SFA mixtures satisfied the minimum ITS requirement of 1 MPa at 35 °C as per IRC SP 125. Zachariah et al. (2020) also reported a similar trend of reduced ITS values of SFA with marginal aggregates due to the lower strength and highly porous nature of

marginal aggregates. Though Tensile Strength Ratio (TSR) values among the mixtures were comparable, the variation depended on the aggregate type and quality.

6.2.4 Fatigue Characteristics

The Fatigue Life (FL) is determined as the number of load repetitions to a maximum deformation of 5 mm or failure of the specimen. The loads applied for determining the FL were 15, 33.3, and 50% of the lowest ITS failure load obtained for three SFA mixtures. The lowest failure was 14 kN for SFA with 100% RCA. The results are depicted in Fig. 6.5. The SFA mixtures with FCS exhibited the maximum FL, while the SFA with 100% RCA exhibited the lowest FL, irrespective of the percentage of the applied load.

As the applied load increased from 15% to 50%, the number of failure cycles decreased for all mixtures, indicating the higher loading percentages accelerate the fatigue failure, thus reducing the lifespan of the mixtures. At lower applied loads (15%-30%), the difference in failure cycles among the mixtures were more pronounced, with the SFA containing 100%FCS exhibiting significantly higher FL. As the applied loads increased to 50%, the difference in the FL among the mixtures became narrow.

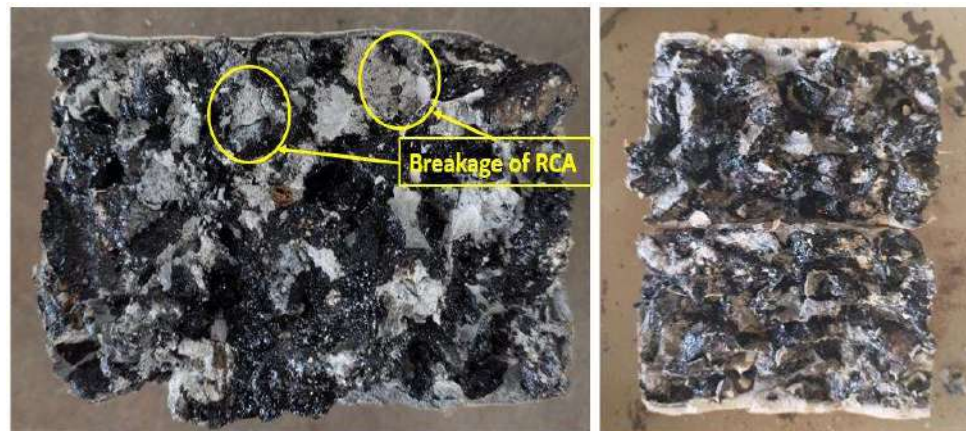


Fig. 6.4 Failure surface morphology of SFA mixtures with (a) RCA (b) FCS

Similar observations were made by Pasandín and Pérez (2013) for HMA mixtures. Wu et al. (2017) reported reduced FL with increased RCA content for HMA mixes. The FL of SFA mixtures aligned with the tensile strength of corresponding OGA mixtures; the higher ITS implied a higher FL. Therefore, the aggregate type and replacement

significantly influenced the fatigue resistance of SFA mixtures. Zachariah et al. (2020) also concluded that the FL of SFA with marginal aggregates was lesser than those with natural aggregates; however, they performed better than the control mixtures (Bituminous concrete- Gradation-II mixture).

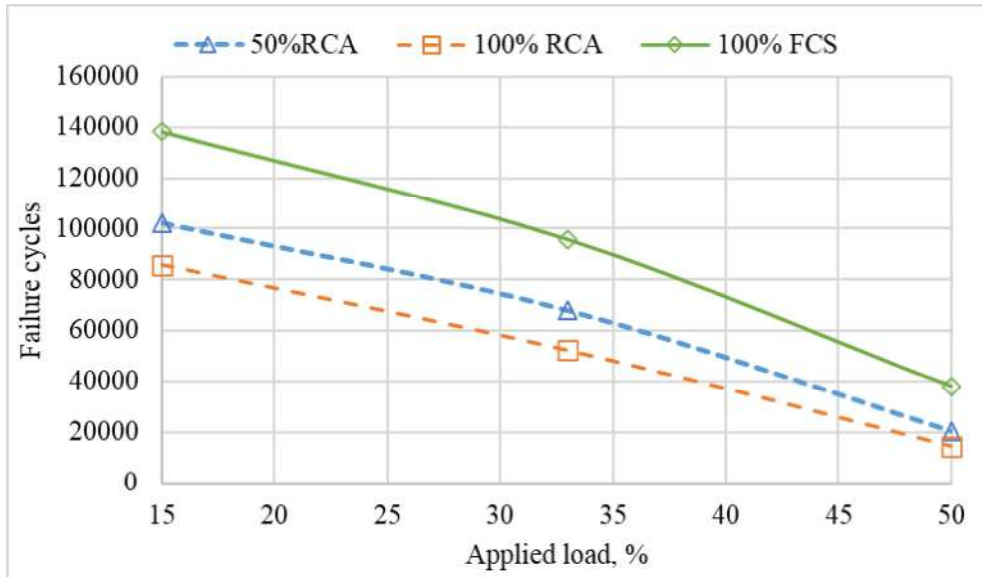


Fig. 6.5 Failure cycles of SFA mixtures with marginal aggregates

6.2.5 Rutting Characteristics

The rutting results of SFA mixtures are depicted in Fig. 6.6. All SFA mixtures exhibited a rut depth of less than 1.24 mm and higher Dynamic Stability (DS), indicating higher rutting resistance. However, the SFA with 100%FCS exhibited the lowest rut depth of 0.51 mm and highest DS of 29741 cycles/mm, attributed to the good aggregate packing characteristics forming a more robust skeleton and the higher strength of FCS aggregates. The rut depth and DS of SFA with FCS are almost on par or marginally higher than SP-II mixtures.

The SFA with 100% RCA exhibited 23% higher rut depth than those with 50% RCA. It was due to cement mortar adhering to RCA. Pasandín and Pérez (2013) reported a similar trend in the case of HMA mixes. Gul and Guler (2014) also concluded that the rutting resistance depended more on aggregate gradation than RCA content.

Therefore, all the SFA mixtures were highly rut resistance mixtures. Zachariah et al. (2020) reported that the SFA mixtures with brick aggregates (marginal aggregates) reduced DS and increased rut depth, indicating weak aggregates replacing strong aggregates. The variation in rutting resistance depended on the type of marginal aggregates, volume and strength of grout.

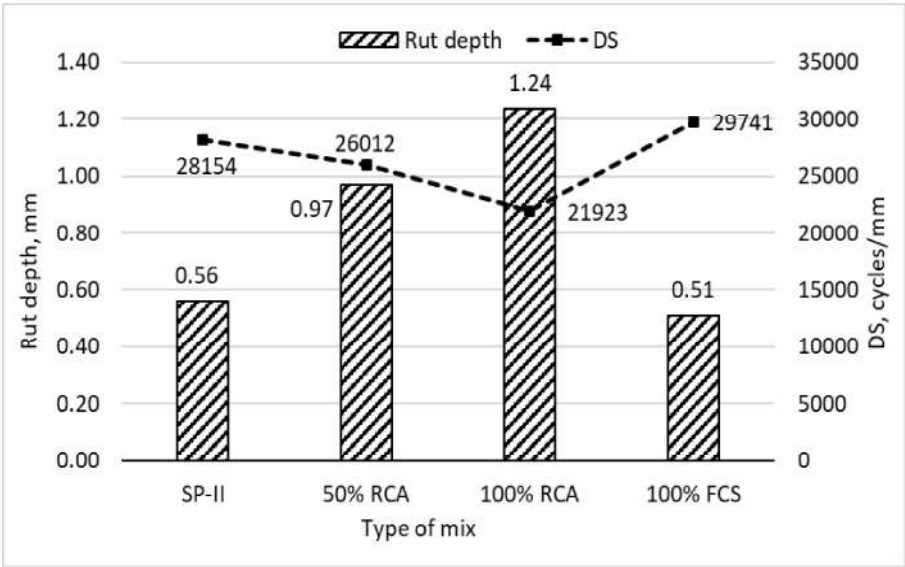


Fig. 6.6 Rutting characteristics of SFA with marginal aggregates

6.2.6 Moisture Susceptibility Tests

The Retained Marshall Stability (RMS) and TSR tests are used to determine the moisture resistance of SFA mixtures. The RMS of all SFA mixtures were above 97%, indicating good moisture resistance, and it is evident from Fig. 6.7. However, the SFA mixtures with 100% FCS and 50% RCA performed better than SFA with 100%RCA, due to the lower water absorption of FCS and lesser RCA content, respectively. The lower RCA content implies the lower quantities of attached mortar to RCA.

The TSR of SFA mixtures were aligned with the RMS of corresponding mixtures. The SFA with FCS and SP-II mixtures showed 100% TSR, indicating the insignificant effect of moisture on tensile strength. It is evident from Fig. 6.8 that the SFA with 100% RCA had a TSR of 98% and lesser than those with 50% RCA, attributed to the increased quantity of attached mortar to RCA. As RCA content increases, the attached mortar to RCA

increases, thus increasing moisture susceptibility. Though the RCA was coated with bitumen, there was a slight reduction in TSR and RMS; however, the results were comparable. All SFA mixtures satisfied the minimum requirement of 97% TSR recommended by IRC: SP-125. Zachariah et al. (2020) also reported reduced TSR values of the SFA mixture with marginal aggregates of porous nature compared with those of natural stone aggregates; however, all the mixtures met the requirement of 80%.

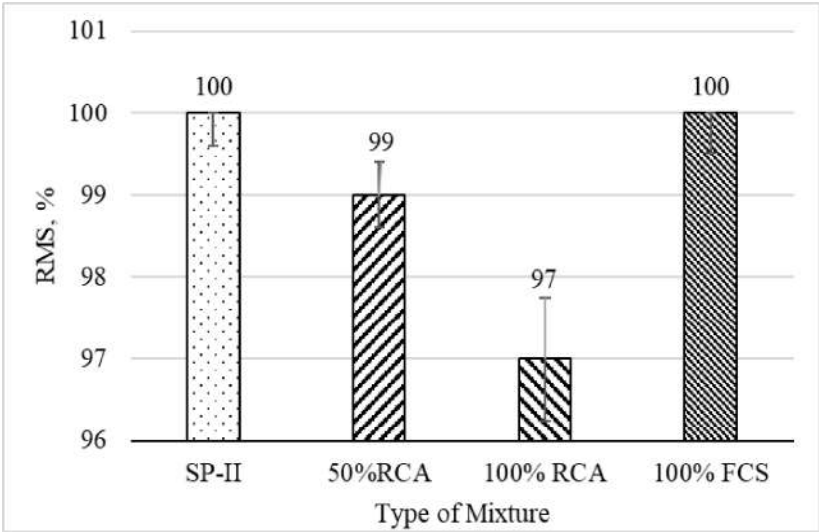


Fig. 6.7 RMS of SFA mixtures with marginal aggregate

6.2.7 Cantabro Test

The cantabro test was conducted to evaluate the durability of the SFA mixture. It is evident from Fig. 6.9 that the weight loss was high for SFA with 100 % RCA among the mixtures. The cantabro loss of SP-II and SFC with 100%FCS mixtures are 12 and 13%, respectively, with a marginal difference of 1%. In the case of SFA with 100%RCA and 50%RCA, the variation is around 3%. However, all the mixtures are within the permissible limits of 20%.

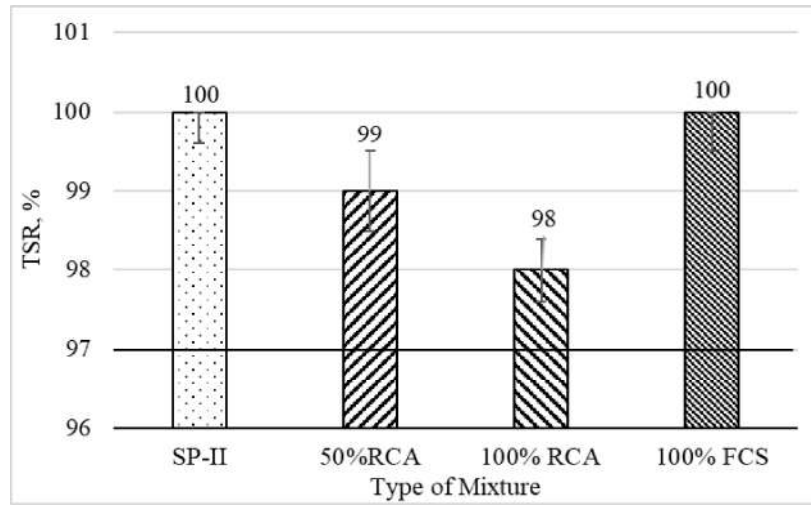


Fig. 6.8 TSR of SFA mixtures with marginal aggregate

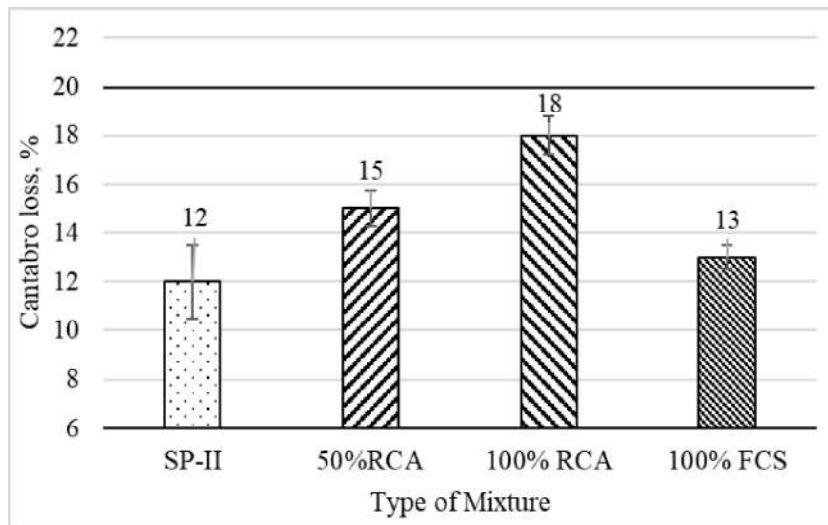


Fig. 6.9 Cantabro loss of SFA mixtures with marginal aggregate

6.2.8 Scanning Electron Microscope

The SEM image of RCA depicted the adhered mortar attached to the virgin aggregate (Fig. 6.9). Typically, the crack would be initiated at the interface of adhered mortar and aggregate upon loading to pre-existing cracks, therefore considered as weak zone. However, in SFA mixtures, the RCA could be coated with bitumen, but that bitumen could not be absorbed at the interface, therefore, the interface remained as a weak zone. Consequently, the performance of SFA mixtures with RCA was comparably lower than

that of FCS mixtures. However, in SFA mixtures, the bitumen coated-RCA would be reinforced by the grout. In case of SFA mixture with FCS, no such weaker interfaces or zones existed, thus, improved the mechanical properties over the RCA mixtures was observed.

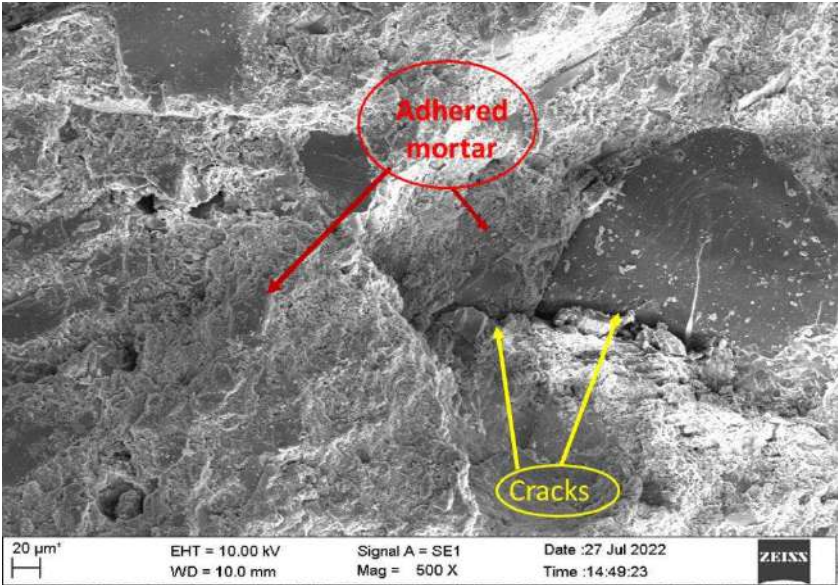


Fig. 6.10 SEM image of recycled concrete aggregate

6.3 SUMMARY AND CONCLUSIONS

In this chapter, the replacement of NCA with marginal aggregates in SFA mixtures was investigated in detail. The SFA mixtures were prepared by replacing NCA with 50% RCA, 100% RCA, and 100% FCS by weight of aggregates, and the mechanical properties were evaluated. The OBC was increased with RCA content, owing to higher binder absorption of RCA. The MS and ITS of OGA mixtures were reduced with the inclusion of RCA. In contrast, the trend is reversed with the inclusion of strong FCS aggregates. It was observed that the MS, CS and ITS of SFA mixtures reduced with the increase of RCA and increased with FCS. The RMS and TSR of SFA with RCA were comparable for different RCA percentages. However, all the mixtures satisfied the minimum requirement of 97% (TSR), while the moisture had an insignificant effect on FCS mixtures. The FL of SFA with FCS was maximum irrespective of applied load, followed by SFA with 50%RCA and 100%

RCA, respectively. The rutting resistance of all SFA mixtures with marginal aggregates was higher, as indicated by the higher DS and lower rutting depths. The cantabro loss was high for the mixtures with 100%RCA, followed by 50% RCA, indicating lesser durability. However, all SFA mixtures satisfied the maximum loss of 20%. The performance of SFA mixtures with FCS was better than that of the other mixtures.

Based on this experimental investigation, the following conclusions are drawn:

1. The SFA with 100% FCS and 50% RCA exhibited higher MS and CS values compared to SFA with 100% RCA, attributed to the higher impact value of FCS and lower attached mortar to RCA.
2. The SFA with 100% FCS exhibited higher ITS among all mixtures. The variation in ITS of SFA with 100% FCS concerning temperature was lower than other mixtures, implying lower temperature susceptibility.
3. The RMS and TSR of SFA with marginal aggregates were higher than 97% and 98%, respectively. However, the SFA with 100% FCS showed the highest value of 100% RMS and TSR, indicating the insignificant effect of moisture intrusion.
4. The FL of SFA with 100% FCS was higher than other mixtures and aligned with the ITS of corresponding SFA mixtures. The SFA with FCS exhibited the lowest cantabro weight loss of 13%, implying the higher durability of SFA mixtures.
5. The SFA mixtures with 100% FCS performed better than those with 50% RCA and 100% RCA.

CHAPTER 7

EFFECT OF WARM MIX ASPHALT ADDITIVES ON MECHANICAL PROPERTIES OF SEMI-FLEXIBLE ASPHALT MIXTURES

7.1 PREPARATION OF OPEN-GRADED ASPHALT MIXTURES

The Semi-Flexible Asphalt (SFA) mixtures were prepared by modifying PMB 40 binder using Warm Mix Asphalt (WMA) additives, such as Sasobit (3% by weight of binder), Rediset (0.8% by weight of binder) and Zycotherm (0.1% by weight of binder). The additives were added to PMB 40 binder at 150 °C employing a mechanical agitator (Veeraiah and Nagabhushanarao 2020).

Determination of Mixing and Compaction Temperatures:

For WMA mixtures, the Mixing Temperature (MT) and Compaction Temperature (CT) determined based on the equi-viscous method for WMA-modified binders would be overestimated, leading to higher MTs (Chen et al. 2021; Sukhija et al. 2021). The methods such as Equi-viscous, simplified zero shear viscosity approach, high shear rate-original method, high shear evolution approach, and steady shear flow overestimated the mixing and compaction temperatures for the WMA-modified VG 30 binder (Sukhija et al. 2021). Therefore, researchers determined the MT and CTs based on the workability method. In this approach, the WMA mixtures were prepared at various MT and CTs and the bulk densities or air voids were determined. The temperature at which the bulk density of WMA mixtures was the same or similar to that of Hot Mix Asphalt (HMA) mixtures was considered as CT or MTs (Chen et al. 2021; Li et al. 2016; Silva et al. 2010; Zaumanis 2014; Zhang et al. 2021). However, the bitumen content and compaction effort should be identical for HMA and WMA mixtures except for the MT and CTs. Zaumanis (2014) adopted the procedure depicted in Fig. 7.1. It was observed that the air voids reduced with an increase in MT and CTs; in other words, the densities increased, as evident from Fig. 7.1. The increase in temperature facilitated and improved the compaction of the mixture, binder absorption and coating, thus increasing the bulk density of mixtures. This approach

yielded satisfactory results in dense-graded or gap-graded asphalt mixtures. In the present study, the same approach was adopted to prepare the Open-Graded Asphalt (OGA) mixtures having higher air voids of 25-30% to facilitate the grout's permeation.

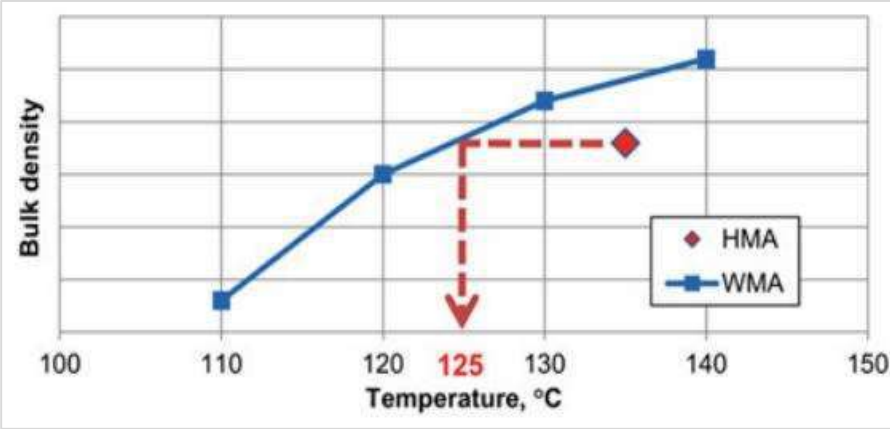


Fig. 7.1 Procedure adopted to determine the CT based on bulk density (Zaumanis 2014)

At the mixing and compaction temperatures ranging from 125 °C to 145 °C, the WMA-modified OGA (WOGA) mixtures were prepared using the same bitumen content corresponding to HMA mixtures. The CT was considered at 10 °C less than MT (Li et al. 2016, 2017). Due to the improved wettability of aggregates and lubricity of bitumen, the lower bitumen contents may satisfy the mix design requirements, thus suggesting reducing bitumen content. Almusawi et al. (2021) reported that the WMA mixtures reduced the Optimum Binder Content (OBC) compared to base bituminous mixtures. However, Zaumanis (2014) recommended using the same OBC of HMA mixtures to avoid stiff mixtures. The variation in OBC was marginal when WMA additives were added (Hamzah et al. 2013; Khairuddin et al. 2019; Wang et al. 2013; Zaumanis 2014). Therefore, the same bitumen content of HMA mixtures was used to prepare the WMA mixtures. It was observed that the variation in G_{mb} was insignificant, and it is evident from Table 7.1; thus, the applicability of the density-based approach was inappropriate.

On the other hand, it was observed that the coating of aggregates was less than 95% at the lower mixing temperatures of 125 °C - 130 °C and improved as temperature increased. Fig. 7.2 depicts the typical coated and uncoated aggregates. The degree of

coating in asphalt mixtures was determined as per ASTM D 2489M-24. As per IRC SP 101, the coating percentage should be more than 95%. Therefore, it would be reasonable to consider the temperature corresponding to more than 95% of the coating as the MT of WMA-modified mixtures. The typical methodology adopted is presented in Fig. 7.3. The results are tabulated in Table 7.1.

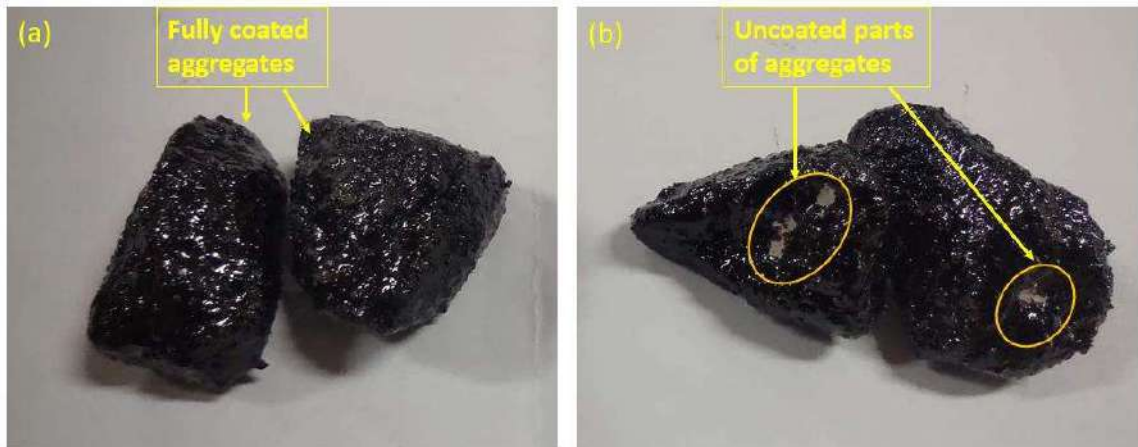


Fig. 7.2 (a) Fully coated aggregates (b) uncoated aggregates

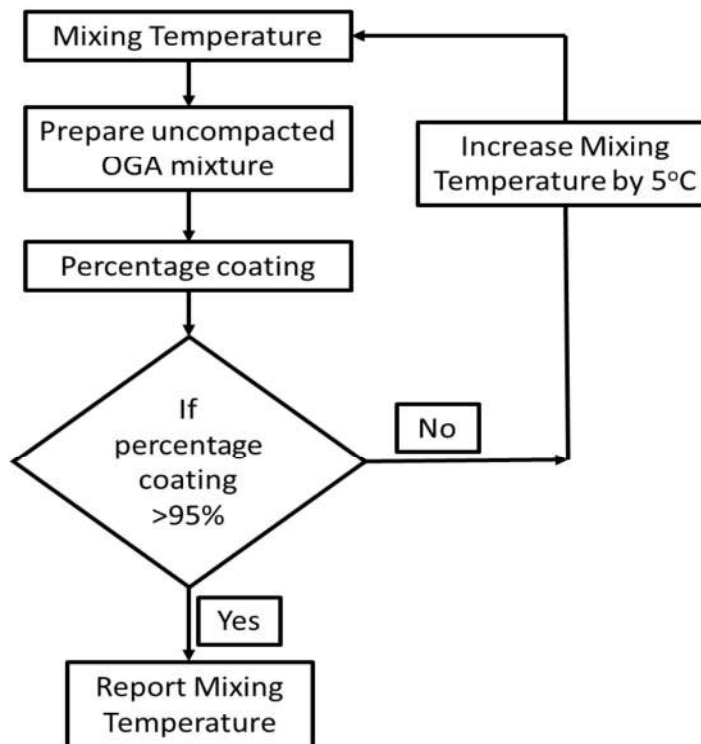


Fig. 7.3 Methodology to determine mixing temperature

Table 7.1 Volumetrics and percentage coating of WMA-modified OGA mixtures

WMA additive	OBC (%)	G _{mb}	V _a (%)	VMA (%)	MS (kN)	ITS (kPa)	MT (°C)	CT (°C)	Percentage Coating (%)
PMB 40	3.75	1.890	28.90	34.0	7.8	385	175	163	100
Sasobit	3.75	1.886	29.07	34.1	7.0	326	135	125	98
	3.75	1.884	29.00	34.0			140	130	100
Rediset	3.75	1.892	28.85	33.9	4.5	264	140	130	99
	3.75	1.889	28.96	34.0			145	135	98
Zycotherm	3.75	1.893	28.81	33.9	5.7	296	140	130	96
	3.75	1.899	28.96	34.0			145	135	99

The mixing and compaction temperatures for OGA mixtures with sasobit, rediset, and zycotherm were determined as 140 °C, 145 °C and 145 °C, and 130 °C, 135 °C and 135 °C, respectively. However, the same percentage of coating is achieved when mixed at 135 °C, 140 °C and 140 °C. From Table 7.1, the sasobit, rediset and zycotherm additives reduced the mixing temperatures by 35 °C, 30 °C, and 30°C, respectively, while the compaction temperatures were reduced by 33 °C, 28 °C and 28°C, respectively. The compaction effort of 60 blows on one side of the specimen was adopted to compact WOGA specimens and grouted them after cooling to room temperature. The grouted specimens were cured for 28 days and tested for mechanical properties. The following sections discussed the mechanical properties of SFA with WMA additives. From Table 7.1, it is evident that the WMA additives reduced the Marshall Stability (MS) and Indirect Tensile Strength (ITS). The rediset mixtures exhibited lower MS and ITS, while the sasobit mixtures performed relatively better. The MS and ITS of WMA mixtures were reduced with the inclusion of sasobit and rediset.

7.2 RESULTS AND DISCUSSIONS

7.2.1 Marshall Stability

The MS test was conducted on SFA mixtures with WMA additives, and the results are depicted in Fig. 7.4. The SP-II mixture was considered as the control mix to evaluate the effect of WMA additives on the mechanical properties of SFA mixtures. The SFA with rediset exhibited the lowest value of 62 kN, whereas, with Sasobit and zycotherm, the

values were 76 kN and 69 kN, respectively. At the same time, all the mixtures with WMA additives satisfy the minimum values of 60 kN. However, the SFA with Sasobit performed better than the rediset and zycotherm mixtures. The MS of SFA mixtures with WMA additives were aligned with WOGA mixtures, indicating the significant influence of OGA mixtures. The SFA with WMA additives exhibited lesser MS values than the SFA mixture with PMB 40 (SP-II). The SFA with sasobit exhibited the highest MS among the other mixtures due to the improved bond strength between the aggregates and binder (Liu et al. 2023).

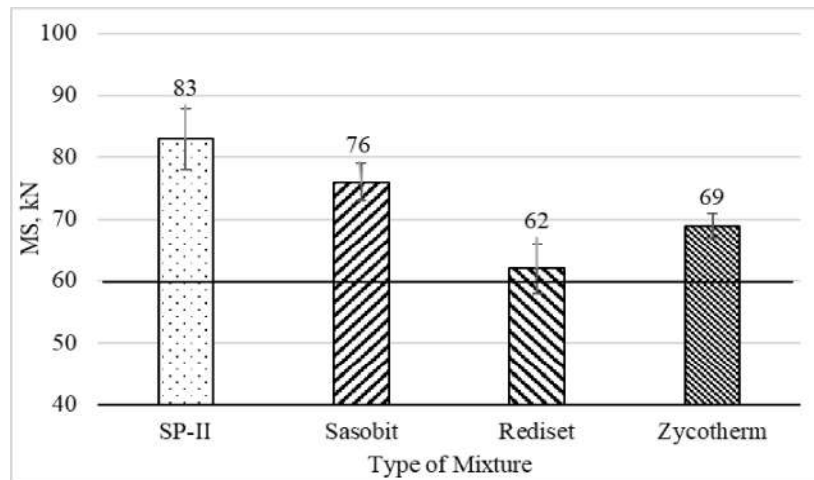


Fig. 7.4 MS of SFA mixtures with different WMA additives

7.2.2 Compressive Strength

The Compressive Strength (CS) results of SFA prepared with WMA additives are presented in Fig. 7.5. The CS of the SFA mixture with rediset was 8.3 MPa, the lowest among the mixtures. The SFA with WMAs satisfied the minimum requirement of 5 MPa as recommended by IRC: SP 125. The CS of SFA with Sasobit, rediset, and zycotherm additives were 10.2 MPa, 8.3 MPa, and 8.7 MPa, respectively. However, the SFA with Sasobit exhibited higher CS among the other additives. The SP-II mixture without WMA additives exhibited higher strength of 12.8 MPa.

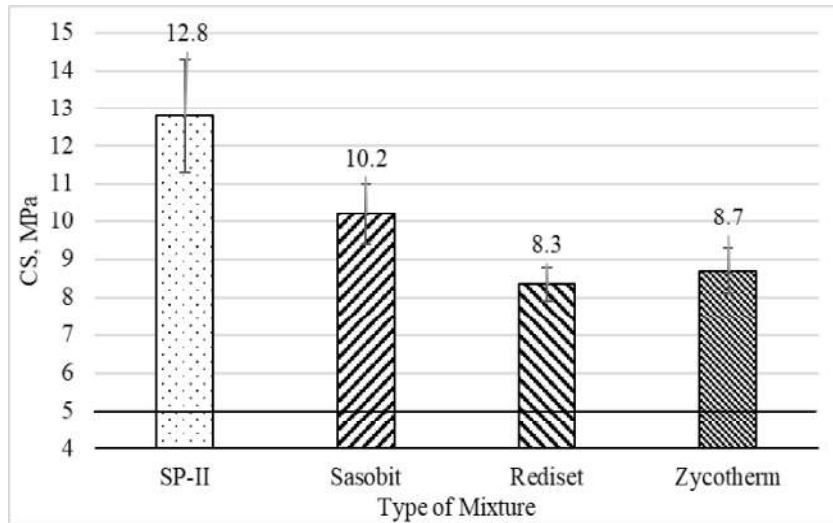


Fig. 7.5 CS of SFA mixtures with different WMA additives

7.2.3 Indirect Tensile Strength

The ITS tests were conducted at 25 °C, 35 °C and 45 °C to evaluate the temperature susceptibility of SFA mixtures prepared with WMA additives. At any given temperature, the SFA with sasobit showed higher ITS, followed by the SFA with zycotherm, as depicted in Fig. 7.6. The SFA with rediset exhibited the lowest ITS values at all temperatures. The ITS of SFA with Sasobit at 25 °C, 35 °C and 45 °C were 1.96 MPa, 1.8 MPa, and 1.57 MPa with rediset were 1.67 MPa, 1.21 MPa and 1.13 MPa, respectively. The variation in ITS was not uniform for SFA mixtures with rediset.

7.2.4 Repeated Load Testing

The repeated load testing was used to determine the Fatigue Life (FL), defined as the number of load repetitions to obtain the maximum deformation of 5 mm. The loads applied for determining the FL are 15, 33.3, and 50% of the lowest ITS failure load obtained for three SFA mixtures. The lowest failure load was 12.18 kN for SFA with rediset. The fatigue results are depicted in Fig. 7.7. The SFA mixtures with sasobit exhibited a higher FL than those with zycotherm and rediset additives. The SFA with rediset additive showed the lowest among the other mixtures at all applied loads. The general trend of reduced FL with increasing applied load was observed. However, the FL of SFA mixtures were aligned with

the ITS of OGA and SFA mixtures. Higher ITS values of SFA mixtures implied an improved FL.

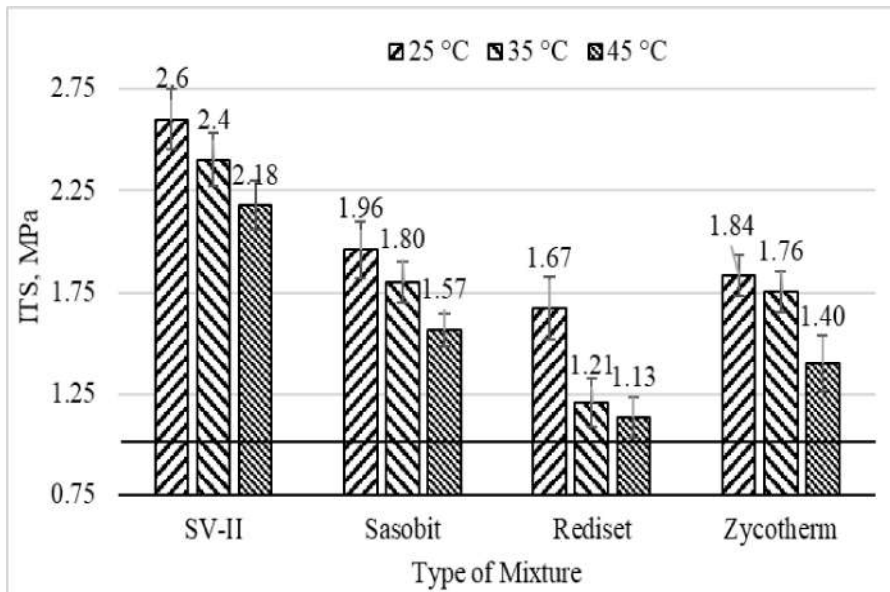


Fig. 7.6 ITS of SFA mixtures with different WMA additives

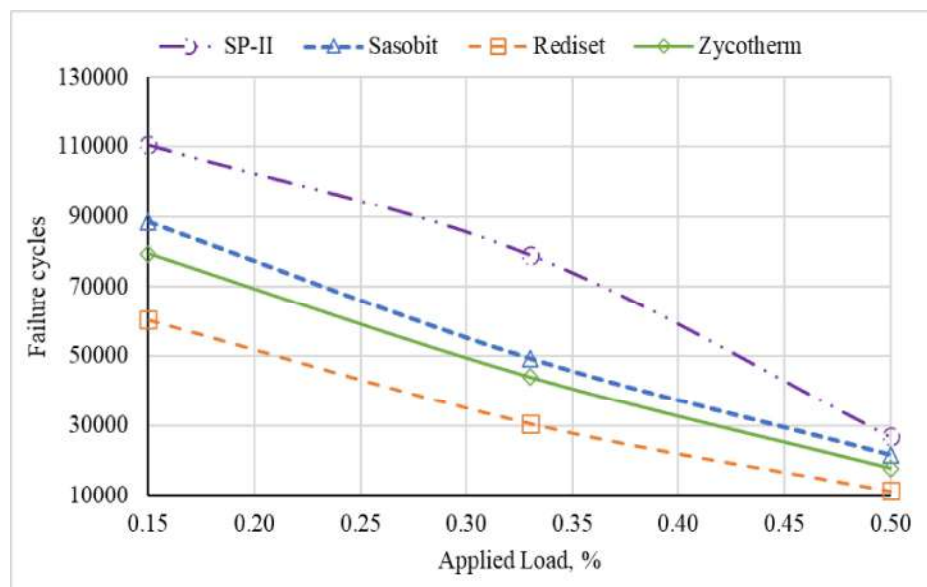


Fig. 7.7 Failure cycles of SFA mixtures with different WMA additives

Benta et al. (2015) determined the fatigue life by applying repeated loading on the asphalt beam and concluded that the rediset reduced the fatigue life of asphalt mixtures. Ameli et al. (2020) prepared WMA mixtures with sasobit and zycotherm, conducted the four-point bending beam test, and found that sasobit mixtures exhibited better fatigue resistance than zycotherm mixtures. A similar trend of results is observed in Fig. 7.7 for SFA mixtures.

7.2.5 Rutting Characteristics

The rutting results of the SFA mixture are depicted in Fig. 7.8. All SFA mixtures exhibited a rut depth of less than 0.63 mm and higher Dynamic Stability (DS), indicating higher rutting resistance. The SFA mixtures with sasobit exhibited the lowest rut depth of 0.59 mm and the highest DS of 27224 cycles/mm, attributed to the higher MS and ITS of corresponding OGA mixtures. However, the rutting resistance of all SFA with WMA additives was comparable with marginal variations. The SFA mixtures with WMA additives exhibited lesser rutting resistance than SP-II mixtures, attributed to the higher rutting resistance offered by PMB 40. However, all the SFA mixtures with WMA additives exhibited excellent rutting resistance, owing to the OGA skeleton being reinforced with grout and holding the aggregates in place. Benta et al. (2015) reported increased rut depth for WMA mixtures with rediset. Ameli et al. (2020) prepared the asphalt mixtures with sasobit and zycotherm additives and conducted the rutting test. The sasobit mixtures exhibited better rutting characteristics than the rediset mixtures. In the present study, a similar trend of results is observed in SFA mixtures with WMA additives.

7.2.6 Moisture Susceptibility Tests

The moisture resistance of SFA mixtures with WMA additives in terms of Retained Marshall Stability (RMS) and Tensile Strength Ratio (TSR) are presented in Figs. 7.9 and 7.10. The RMS of all SFA mixtures with WMA additives were higher than 97%, indicating good moisture resistance. However, the SFA mixtures with zycotherm exhibited 100% RMS, indicating the insignificant effect of moisture on the stability of mixtures.

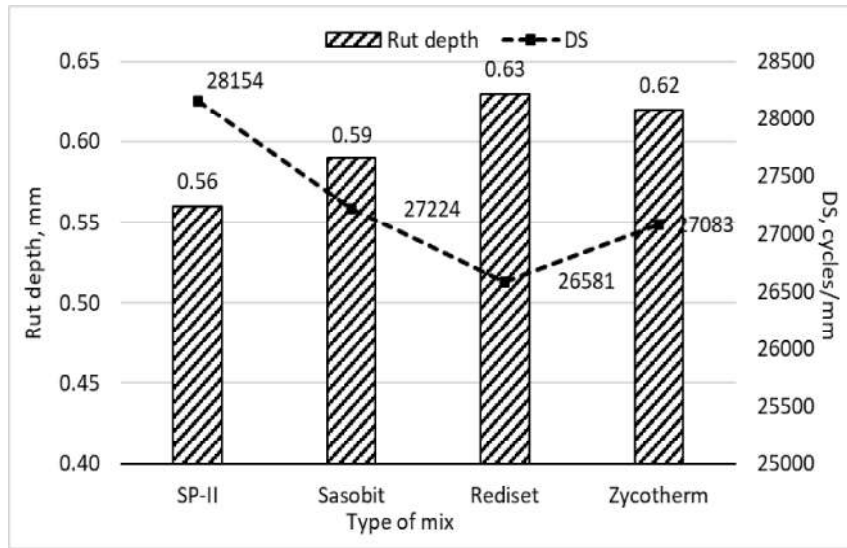


Fig. 7.8 Rutting characteristics of SFA mixtures with different WMA additives

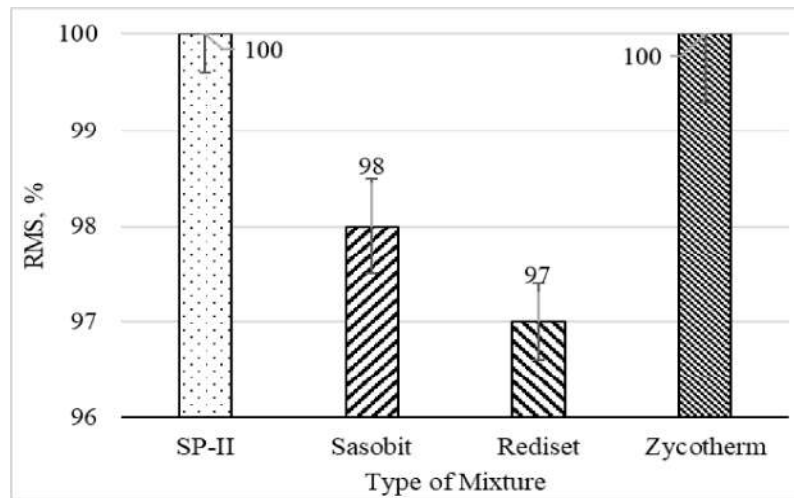


Fig. 7.9 RMS of SFA mixtures with different WMA additives

The SFA mixtures with sasobit and rediset exhibited lesser RMS, which may be attributed to the reduced adhesion between the aggregates and binder (Sukhija et al. 2023). It was worth mentioning that the RMS and TSR of SFA mixtures with WMA additives, except rediset, were in a similar range or comparable without any significant variation. All SFA mixture's TSR values are more than 97%, as shown in Fig. 7.10. However, the SFA with zycotherm and sasobit had comparable TSR values, indicating similar moisture resistance. It was attributed to the function of zycotherm as an anti-stripping additive which

enhanced the bonding between the aggregates and binder, and the grout inhibits moisture intrusion (Ameli et al. 2020). While Rochishnu et al. (2020) and Liu et al. (2023) reported that sasobit improved the TSR of WMA mixtures, Benta et al. (2015) reported reduced TSR of WMA with rediset. Sukhija et al. (2023) concluded that the chemical additives (zycotherm and rediset) were better at improving moisture resistance than the organic additives (sasobit). Sasobit had a marginal effect on the moisture resistance of WMA mixtures for which PMB 40 was a base binder, attributed to the polymer network being more significant than the crystallization of sasobit (Wang et al. 2013). It was worth mentioning that the effect of sasobit on moisture resistance depended on the base binder. However, all SFA mixtures exhibited a TSR of more than 97%, as recommended by IRC SP 125.

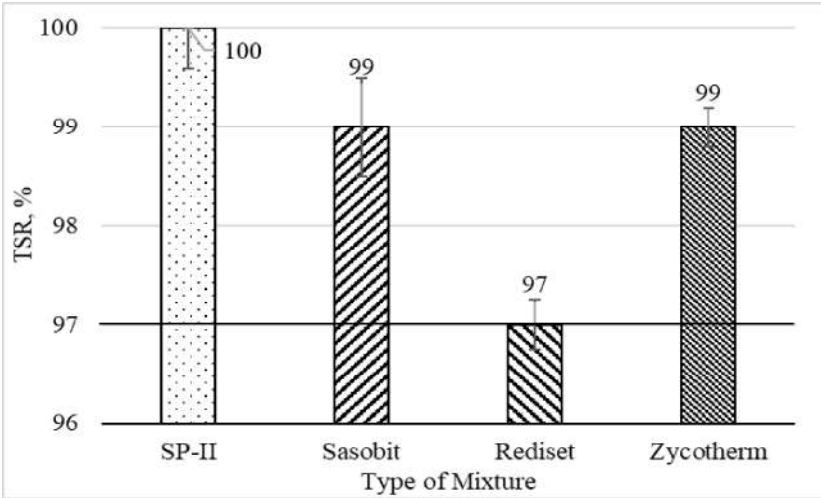


Fig. 7.10 TSR of SFA mixtures with different WMA additives

7.2.7 Cantabro Test

The cantabro test results of SFA with WMA additives are presented in Fig. 7.11. The SFA with zycotherm and rediset additives exhibited 20% weight loss and was 15% higher than SFA with sasobit. Though all the SFA mixtures satisfied the maximum weight loss of 20%, the SFA mixtures with zycotherm and rediset additives marginally satisfied the weight loss criterion. All SFA with WMA additives exhibited higher weight loss compared with SP-II mixtures, indicating reduced durability with WMA additives.

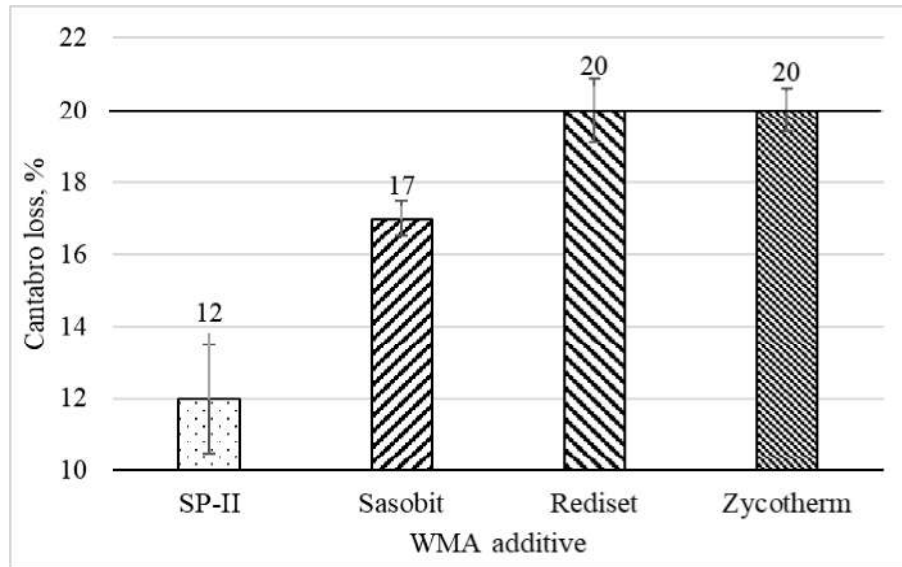


Fig. 7.11 Cantabro loss of SFA mixtures with different WMA additives

7.3 SUMMARY AND CONCLUSIONS

In this chapter, the effect of WMA additives on the mechanical properties of SFA mixtures was investigated in detail. The sasobit (3% by weight of binder), rediset (0.8% by weight of binder) and zycotherm (0.1% by weight of binder) were added to PMB 40 binder and mixed by means of mechanical agitation. Sasobit and rediset additives reduced the penetration values while increasing the softening point of the base binder (PMB 40), attributed to the crystallization of wax at lower temperatures (Hurley and Prowell 2005). On the other hand, zycotherm increased the penetration value and reduced the softening point compared with PMB 40 binder.

The OBC of WOGA mixtures were considered the same as 3.75% by weight of the mixture, which is of OGA mixtures (HMA) to avoid the stiff mixtures. For WMA mixtures, the workability method was adopted to determine the MT and CT, in which the WMA specimens were prepared at various MT and CTs. The density corresponding to HMA specimen was used to determine the MT and CT. Interestingly, it was observed that the variation in bulk specific gravity was insignificant or marginal, thus nullifying the applicability of the density-based approach. Therefore, the coating percentage was considered a parameter to select the MT and CTs. The MTs for OGA mixtures with sasobit,

rediset and zycotherm were determined as 140 °C, 145 °C and 145 °C, respectively; similarly, CTs were 130 °C, 135 °C and 135 °C, respectively.

The MS, CS, and ITS of SFA mixtures were reduced with the inclusion of WMA additives. Among WMA-modified SFA mixtures, the SFA with sasobit exhibited higher MS, CS, and ITS values. Based on the ITS of SFA at different temperatures, it was observed that the SFA with sasobit has lesser temperature susceptibility than those with zycotherm and rediset. The FL of SFA with sasobit mixtures was higher at all applied loads than those with zycotherm and rediset additives. The fatigue resistance of SFA with WMA additives was aligned with the ITS of corresponding OGA mixtures. All SFA mixtures with WMA additives exhibited a rutting depth lesser than 0.63 mm and a minimum DS of 26581 cycles/mm, indicating good rutting resistance, irrespective of the type of WMA additives. The moisture resistance determined in terms of RMS and TSR indicated that all SFA mixtures with WMA additives have good moisture resistance. However, the SFA with rediset exhibited lesser moisture resistance than other WMA mixtures. The cantabro weight loss of SFA with sasobit was lesser than those with rediset and zycotherm, indicating higher durability. Though SFA mixtures with rediset and zycotherm satisfied the maximum weight loss criterion of 20%, further improvement in durability is needed by adopting high-performing grout. All the SFA mixtures with WMA additives satisfied the requirements of IRC SP 125 and exhibited lower mechanical properties than SP-II mixtures.

Based on the experimental investigation, the following conclusions are drawn:

1. Sasobit, rediset and zycotherm additives reduced the mixing temperatures by 35 °C, 30 °C, and 30°C, respectively, while the compaction temperatures were reduced by 33 °C, 28 °C and 28°C, respectively.
2. The SFA mixtures with sasobit exhibited MS and CS of 7.6 kN and 10.2 MPa, respectively, higher than those with zycotherm and rediset additives.
3. The SFA with sasobit exhibited higher ITS among all mixtures.

4. The RMS and TSR of SFA with WMA additives were higher than 97%. However, the SFA with zycotherm showed the RMS and TSR values of 100% and 99%, respectively, indicating the insignificant effect of moisture.
5. The FL of SFA with sasobit was higher than other mixtures and aligned with the ITS of corresponding SFA mixtures. The SFA with WMA additives exhibited a high rutting resistance, with the highest rut depth of 0.63 mm and the lowest DS of 26581 cycles/mm.
6. The SFA with sasobit exhibited the lowest cantabro weight loss of 17%, implying the higher durability of SFA mixtures. However, the SFA with zycotherm and rediset additives exhibited cantabro loss of 20%.
7. The SFA mixtures with sasobit performed very well compared with zycotherm and rediset.

CHAPTER 8

EFFECT OF WARM MIX ASPHALT ADDITIVES AND MARGINAL AGGREGATES ON MECHANICAL PROPERTIES OF SEMI-FLEXIBLE ASPHALT MIXTURES

8.1 PREPARATION OF OPEN-GRADED ASPHALT MIXTURES

The Semi-Flexible Asphalt (SFA) mixtures were prepared using the Warm Mix Asphalt (WMA)-modified binders and marginal aggregates. The preparation of modified binders is the same as in section 7.1, where the WMA additives were added to PMB 40 binder. The dosages of sasobit, rediset and zycotherm are 3%, 0.8 and 0.1% by weight of the binder, respectively. The marginal aggregates, Recycled Concrete Aggregate (RCA) and Ferrochrome Slag aggregate (FCS), were used to prepare the SFA mixtures. The Natural Coarse Aggregate (NCA) was replaced by 50% and 100% RCA by weight, and FCS by 100% by weight. The same Optimum Binder Content (OBC) of Open-Graded Asphalt (OGA) mixtures with marginal aggregates was adopted to prepare OGA mixtures irrespective of WMA additives. As Zaumanis (2014) recommended using the same OBC of HMA mixtures to avoid stiff mixtures and the variation in OBC was marginal with adding WMA additives, the same OBC of OGA mixtures with marginal aggregates was adopted (Hamzah et al. 2013; Khairuddin et al. 2019; Wang et al. 2013; Zaumanis 2014). The corresponding OBCs of OGA mixtures and the notations of corresponding SFA mixtures are presented in Table 8.1.

Table 8.1 presents the details of the constituents of OGA mixtures and their notations of grouted mixtures. Since the Gr-II gradation was used to prepare the OGA mixtures, the Optimum Compaction Effort (OCE) of 60 blows on one side of the specimen was given. The MT and CTs were determined based on the percentage coating of aggregates. A 5 °C higher than the temperature at which the percentage coating is more than 95% is considered as the MT. The CT was 10 °C less than the MT (Li et al. 2016,

2017). The same methodology was adopted in Chapter 7 to determine the OBC, MT and CTs.

Table 8.1 Volumetrics and percentage coating of OGA mixtures

SFA Mixture Notation	Aggregate type and % replacement	WMA additive	OBC (%)	G _{mb}	V _a (%)	VMA (%)	MT (°C)	CT (°C)	MS (kN)	ITS (kPa)
50RCA-S	50% RCA	Sasobit	3.95	1.84	28.4	30.9	140	130	7.1	314
50RCA-R		Rediset	3.95	1.84	28.6	30.9	145	135	6.0	268
50RCA-Z		Zycotherm	3.95	1.84	28.6	30.9	145	135	4.3	291
100RCA-S	100% RCA	Sasobit	4.19	1.76	27.2	29.4	140	130	5.8	283
100RCA-R		Rediset	4.19	1.76	27.2	29.4	150	140	3.7	201
100RCA-Z		Zycotherm	4.19	1.76	27.1	29.4	150	140	4.1	244
100FCS-S	100% FCS	Sasobit	3.50	2.07	29.5	36.5	140	130	8.1	405
100FCS-R		Rediset	3.50	2.07	29.4	36.4	145	135	7.6	351
100FCS-Z		Zycotherm	3.50	2.07	29.6	36.6	145	135	7.9	378

From Table 8.1, the WMA additives reduced the mixing temperatures by 35-30 °C, 35-25 °C and 35-30 °C, for SFA mixtures with 50%RCA, 100%RCA and 100%FCS, respectively. The WMA additives reduced the compaction temperatures by 33-28 °C, 33-28 °C, and 33-28 °C for SFA mixtures with 50%RCA, 100%RCA and 100%FCS, respectively. The OGA with 100%FCS exhibited the maximum Marshall Stability (MS) and Indirect Tensile Strength (ITS) for all WMA additives, followed by OGA with 50%RCA. The OGA with 100%RCA exhibited lower strength compared with other mixtures. The OGA with Sasobit exhibited higher MS and ITS for all marginal aggregates, followed by OGA with Zycotherm. The OGA with Rediset and 100% RCA exhibited the lowest MS and ITS among all OGA mixtures, as presented in Table 8.1.

8.2 RESULTS AND DISCUSSIONS

8.2.1 Marshall Stability

The MS test was conducted on SFA mixtures prepared with WMA additives and marginal aggregates. The results are presented in Fig. 8.1. The MS of SFA mixtures with WMA additives and marginal aggregates were aligned with the MS of corresponding OGA mixtures. For sasobit-modified mixtures, the SFA mixtures with FCS exhibited a higher MS of 91 kN, which is 33% and 49% higher than those with 50%RCA and 100%RCA

mixtures, respectively. However, the SFA mixtures with sasobit and marginal aggregates satisfied the minimum requirement of 60 kN, while the 100RCA-S mixture exhibited MS of 61 kN. For rediset-modified mixtures, the SFA mixtures with FCS exhibited MS of 75 kN; however, the SFA with 50%RCA and 100%RCA exhibited MS of less than the minimum MS of 60 kN. For Zycotherm-modified mixtures, the SFA mixtures with FCS exhibited an MS of 82 kN, followed by those with 50% RCA and 100% RCA, respectively. Nevertheless, the 100RCA-Z mixture has not met the minimum requirement of IRC. The SFA mixtures with FCS exhibited higher MS of 75-91 kN, irrespective of the type of WMA-modified binders. The SFA mixtures with rediset exhibited the lowest MS for all marginal aggregates.

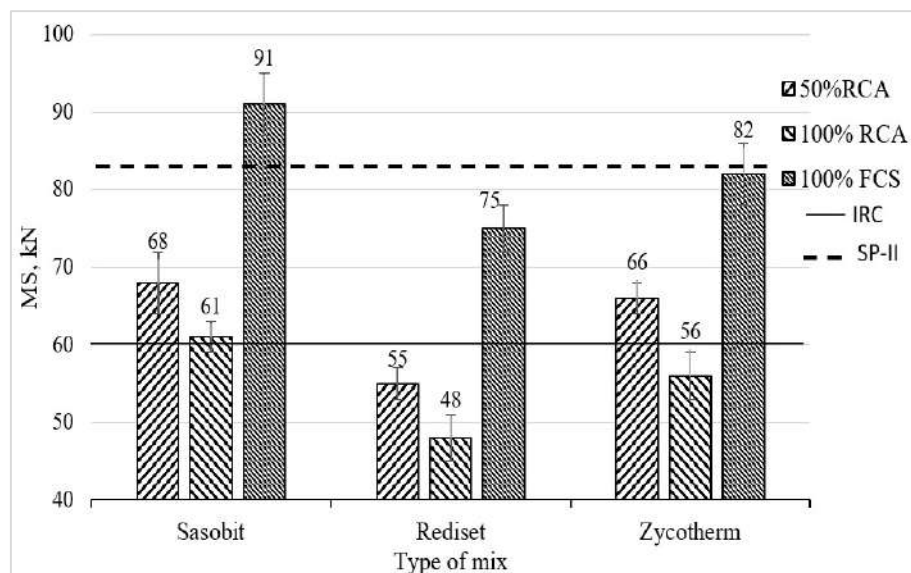


Fig. 8.1 Variation of MS with the type of SFA mixture

8.2.2 Compressive Strength

The Compressive Strength (CS) results of SFA prepared with WMA additives and marginal aggregates are presented in Fig. 8.2. For sasobit-modified mixtures, the SFA with FCS exhibited higher CS of 12.7 MPa, which is 44% and 54% higher than those with 50% and 100% RCA. A similar trend of SFA mixtures with FCS exhibiting higher CS was observed for rediset and zycotherm-modified mixtures. The SFA mixtures prepared with sasobit exhibited a higher CS for all marginal aggregates, followed by zycotherm and

rediset. The 100FCS-S exhibited the higher CS of 12.7 MPa, while the 100%RCA-R exhibited the lowest CS of 6.2 MPa. However, all SFA mixtures with WMA additives and marginal aggregates satisfied the minimum requirement of 5 MPa.

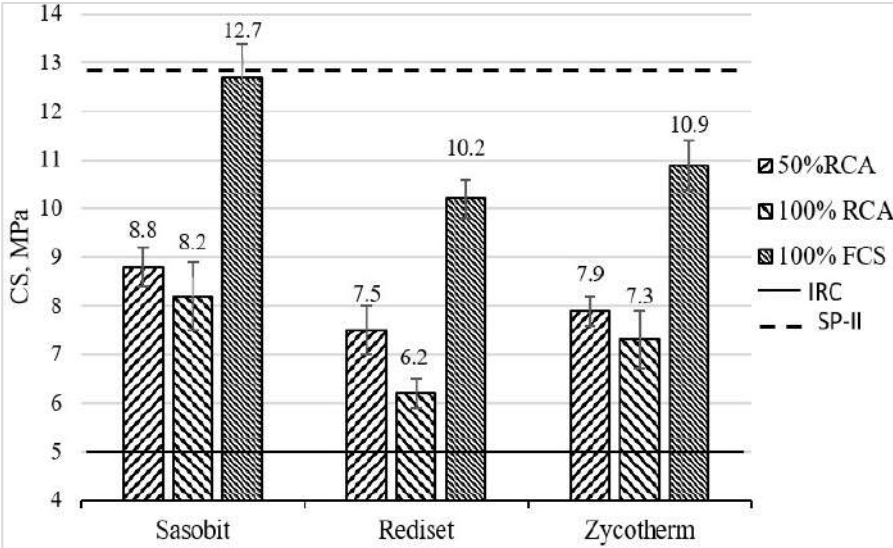


Fig. 8.2 Variation of CS with the type of SFA mixture

8.2.3 Indirect Tensile Strength

The ITS was conducted on the SFA with WMA additives and marginal aggregates and the results are depicted in Fig. 8.3. The Sasobit-modified mixtures, the SFA mixtures with FCS exhibited the higher ITS of 2.08 MPa, which is 56-85% higher than those with RCA mixtures. For rediset-modified mixtures, the SFA mixtures with FCS exhibited higher ITS of 1.68 MPa. The 100RCA-R mixture has not satisfied the minimum requirement of 1MPa, while the 50RCA-R has marginally satisfied the IRC requirement. For Zycotherm-modified mixtures, the SFA with FCS exhibited higher ITS of 1.95 MPa, while the 100RCA-Z exhibited lower ITS of 1.08 MPa. It was worth mentioning that the ITS of SFA mixtures were aligned with the ITS of corresponding OGA mixtures. However, all SFA mixtures with WMA additives and marginal aggregates satisfied the minimum requirement of 1 MPa, except the 100RCA-R mixture. The 50RCA-R and 100RCA-Z satisfied the requirement marginally.

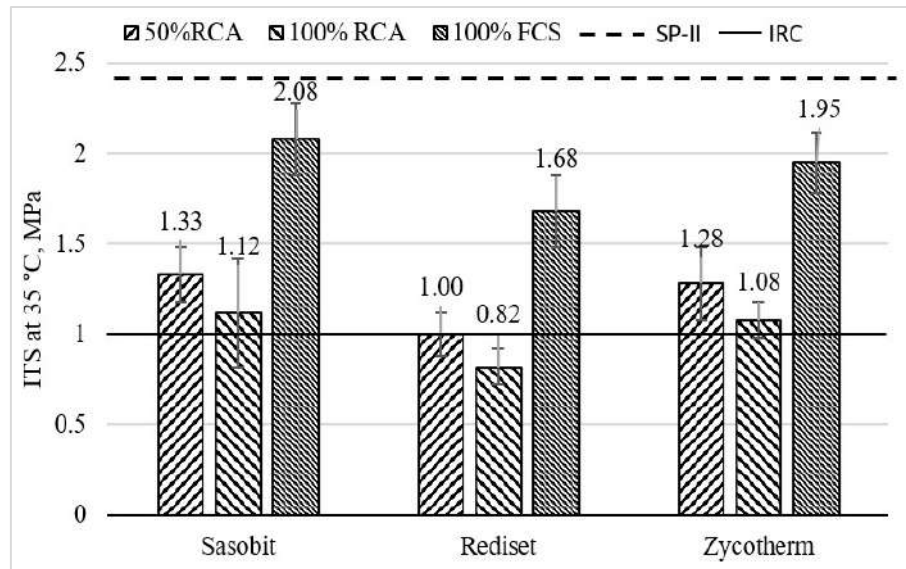


Fig. 8.3 Variation of ITS with the type of SFA mixture

8.2.4 Moisture Susceptibility Tests

The moisture resistance of SFA with WMA additives and marginal aggregates was determined in terms of Retained Marshall Stability (RMS) and Tensile Strength Ratio (TSR). It was evident from Figs. 8.4 and 8.5 that all SFA mixtures exhibited good moisture resistance irrespective of the type of aggregates and WMA additives. However, the SFA with zycotherm exhibited better moisture resistance in terms of RMS and TSR than the other mixtures with WMA additives and marginal aggregates. The 100RCA-R mixture exhibited a lower TSR of 97%; however, it marginally satisfied the minimum requirement.

8.2.5 Cantabro Test

The durability of SFA with WMA additives and marginal aggregates was evaluated by conducting cantabro test without steel balls. From Fig. 8.6, the cantabro loss of 50%RCA and 100%FCS mixtures with the addition of Sasobit is within the permissible limits of 20%, whereas 100%RCA with sasobit could not withstand the abrasion. The cantabro loss of 50RCA-R and 100RCA-R were above the maximum limit of 20%, while the 100FCS-R had a cantabro loss of 20%. The cantabro loss of 100FCS-Z is 18%, within the permissible limit of 20%. However, the 100%RCA-Z could not withstand the abrasion, while 50RCA-Z marginally satisfied the requirement of 20%. The 100%RCA mixtures

with WMA additives exhibited the higher cantabro loss of more than 20%, indicating the lowest durability. The cantabro loss of 100%FCS mixtures with WMA additives was within the permissible limit.

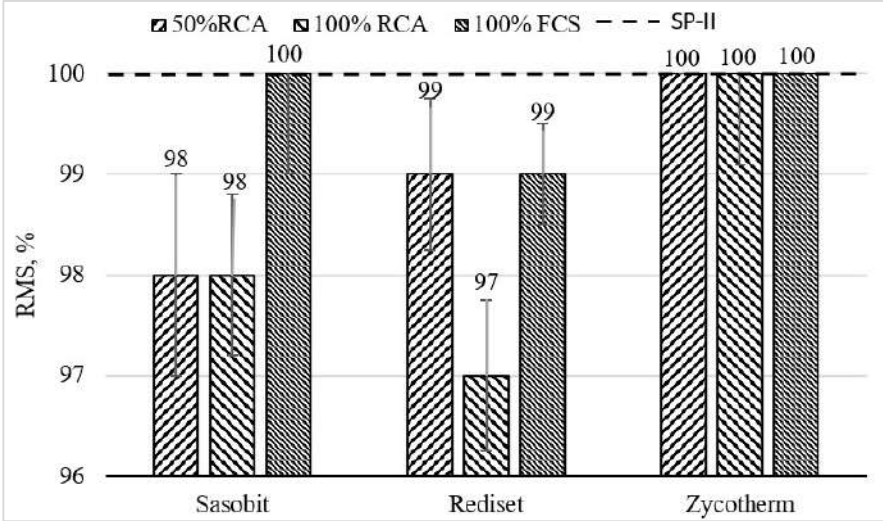


Fig. 8.4 Variation of RMS with the type of SFA mixture

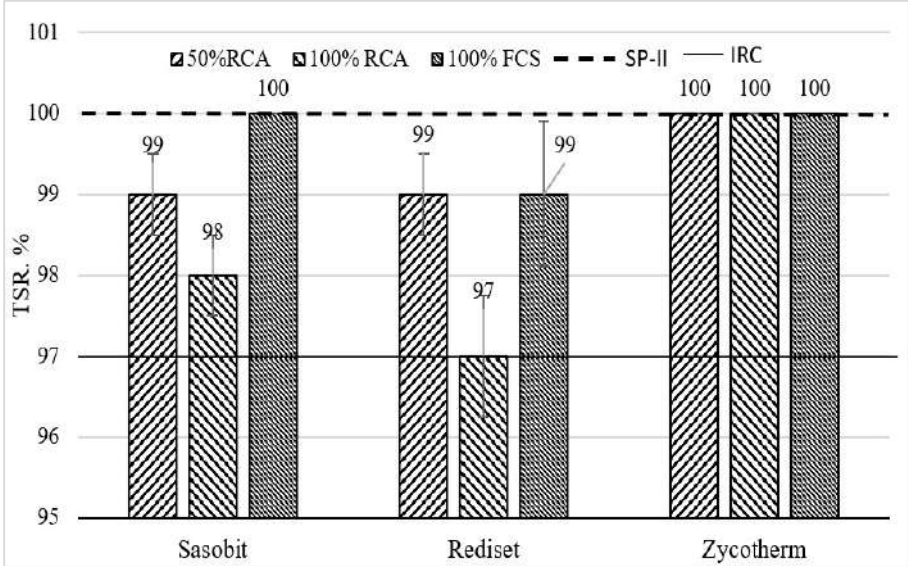


Fig. 8.5 Variation of TSR with the type of SFA mixture

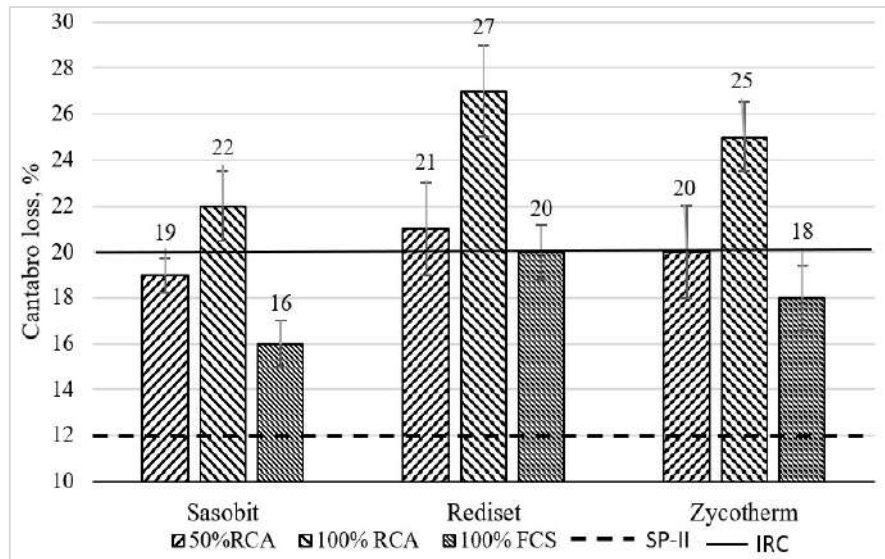


Fig. 8.6 Variation of cantabro weight loss with the type of SFA mixture

8.2.6 Repeated Load Testing

The SFA mixtures might meet the strength requirements; however, durability might be an issue. Therefore, in the present work, the status of SFA mixtures meeting the strength and durability requirements are presented in Table 8.2. The SFA mixtures with WMA additives and marginal aggregates that satisfied the requirements of IRC were considered for further study. Therefore, the fatigue and rutting tests were conducted for the 50RCA-S, 50%RCA-Z, 100FCS-S, 100FCS-R, and 100FCS-Z mixtures. The FL is the number of load repetitions that cause 5mm deformation or failure of the specimen. The loads applied for determining the FL are 15, 33.3, and 50% of the lowest ITS failure load obtained for five SFA mixtures.

The lowest failure load was 12.9 kN for the 50RCA-S mixture. From Fig. 8.7, it is evident that there was a marginal variation in FL of 100FCS-S and 100FCS-Z mixtures. Similarly, the 50RCA-Z and 50RCA-S exhibited comparable FL. However, the 100FCS-S exhibited higher FL, while the 50RCA-Z had a lower FL, attributed to the strength of the OGA skeleton and the presence of RCA.

Table 8.2 Summary of SFA mixtures with WMA additives and marginal aggregates

Mix Code	MS	CS	ITS	RMS	TSR	Cantabro weight loss	Mixtures considered
50RCA-S	Y	Y	Y	Y	Y	Y	Y
50RCA-R	N	Y	Y	Y	Y	N	-
50RCA-Z	Y	Y	Y	Y	Y	Y	Y
100RCA-S	Y	Y	Y	Y	Y	N	-
100RCA-R	N	Y	N	Y	Y	N	-
100RCA-Z	N	Y	Y	Y	Y	N	-
100FCS-S	Y	Y	Y	Y	Y	Y	Y
100FCS-R	Y	Y	Y	Y	Y	Y	Y
100FCS-Z	Y	Y	Y	Y	Y	Y	Y

Y, Mixtures satisfied the requirement; N, Mixtures not satisfied the requirement;

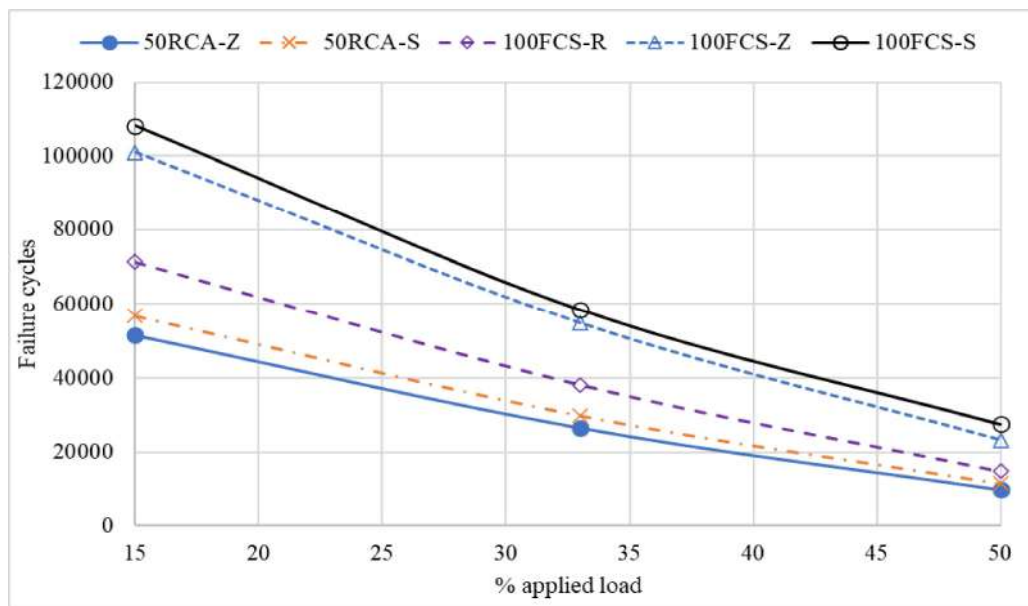


Fig. 8.7 Failure cycles of SFA mixtures with WMA additives and marginal aggregates

8.2.7 Rutting Characteristics

The rutting resistance was evaluated for the 50RCA-S, 50RCA-Z, 100FCS-S, 100FCS-R, and 100FCS-Z mixtures. The results are presented in Fig. 8.8. All mixtures exhibited good rutting resistance with a maximum rut depth of 1.12mm and lower Dynamic Stability (DS) of 23712 cycles/mm. The SFA mixtures with FCS exhibited comparable rut depth and DS, attributed to similar aggregate packing characteristics. At the same time, the SFA

with RCA also exhibited a similar rutting resistance. However, the SFA mixtures with FCS, irrespective of binder type, exhibited higher rutting resistance.

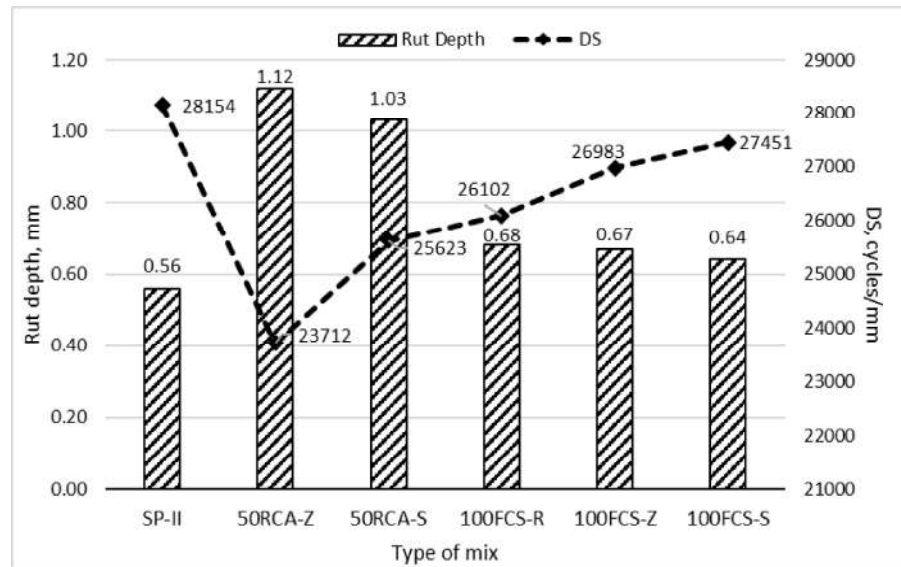


Fig. 8.8 Rutting characteristics of SFA mixtures with WMA additives and marginal aggregates

8.3 SUMMARY AND CONCLUSIONS

In this chapter, the effect of WMA additives and marginal aggregates on the mechanical properties of SFA mixtures was investigated in detail. The sasobit (3% by weight of binder), rediset (0.8% by weight of binder) and zycotherm (0.1% by weight of binder) were added to PMB 40 binder at 150 °C and mixed utilizing mechanical agitator. The NCA were replaced with 50% RCA, 100% RCA, and 100% FCS by weight of aggregates. With combinations of WMA additives and marginal aggregates, a total of nine SFA mixtures were investigated.

The mixing and compaction temperatures were determined for all the mixtures, based on the percentage coating, as 140-150 °C and 130-140 °C, respectively. The OGA with FCS exhibited a higher MS and ITS of 7.6-8.1 kN and 351-405 kPa, respectively. The OGA mixtures with 50%RCA exhibited the lower MS and ITS of 3.7-5.8 kN and 201-283 kPa, respectively. The SFA mixtures with FCS exhibited the higher MS, CS, and ITS of 75-91kN, 10.2-12.7 MPa, and 1.68-2.08 MPa, respectively, for all WMA additives. The

SFA mixtures with Rediest exhibited lower MS, CS, and ITS than those with Sasobit and Zycotherm. The RMS and TSR of SFA mixtures were more than 97%, indicating good moisture resistance. Though the SFA mixtures may satisfy the strength requirement, durability has been an issue. Therefore, the cantabro weight loss test was conducted to evaluate the durability. It was observed that the SFA mixtures with 100%RCA exhibited a higher weight loss, indicating lower durability, while the SFA with FCS exhibited better durability, indicating the lowest weight loss. The mixtures that satisfied the durability criterion of a maximum 20% weight loss were considered for further study, and the mixtures were 50RCA-S, 50%RCA-Z, 100FCS-S, 100FCS-R, and 100FCS-Z. The 100FCS-S and 100FCS-Z mixtures exhibited marginal variation in FL. A similar trend is observed for the 50RCA-Z and 50RCA-S mixtures. However, the 100FCS-S exhibited maximum FL at all stress levels. The rut depth and DS of SFA with FCS exhibited similar values, indicating a strong influence on the quality or type of aggregates. However, all five SFA mixtures have good rutting resistance.

Based on the experimental investigation, the following conclusions are drawn:

1. The WMA additives reduced the mixing temperatures by 35-30 °C, 35-25 °C, and 35-30 °C, for SFA mixtures with 50%RCA, 100%RCA and 100%FCS, respectively. The WMA additives reduced the compaction temperatures by 33-28 °C, 33-28 °C, and 33-28 °C for SFA mixtures with 50%RCA, 100%RCA and 100%FCS, respectively.
2. The SFA mixtures with FCS exhibited higher MS and CS among all other mixtures, irrespective of the WMA additives used. The 50RCA-R and 100RCA-R satisfied the minimum MS requirement of 60 kN.
3. All SFA mixtures with marginal aggregates and WMA additives exhibited the ITS at 35 °C more than 1 MPa, except the 100RCA-R mixture. The SFA mixtures with FCS performed better in ITS than other mixtures, irrespective of the WMA additives used.

4. The RMS and TSR of all SFA mixtures were maximum of 97%. However, the SFA with Zycotherm showed RMS and TSR values of 100% and 100%, indicating the insignificant effect of moisture.
5. The cantabro weight loss of SFA mixtures with 100%RCA was higher than 20% for all WMA additives, indicating the lowest durability to traffic abrasion and ravelling. The SFA mixture with Rediset has inferior durability than those with Zycotherm and Sasobit for all marginal aggregates. The 50RCA-S, 50%RCA-Z, 100FCS-S, 100FCS-R, and 100FCS-Z mixtures only satisfied the maximum requirement of 20% cantabro loss.
6. The FL of SFA mixtures with FCS exhibited better FL than those with 50%RCA for all WMA additives. The SFA with Sasobit exhibited better fatigue resistance than those with Zycotherm. The rut depth of SFA with FCS was less than 0.68 mm, indicating a higher rutting resistance, while the SFA with 50%RCA exhibited a rut depth of 1.12 mm. The quality of aggregates to prepare SFA mixtures was more pronounced in rutting resistance than the binder type.
7. The 50RCA-S, 50%RCA-Z, 100FCS-S, 100FCS-R, and 100FCS-Z mixtures only satisfied the IRC requirements. The SFA mixtures with FCS performed much better than the other mixtures.

CHAPTER 9

CONCLUSIONS

9.1 GENERAL

The effect of the Sand-to-Cement (S/C) ratio, along with the water-to-cement (W/C) ratio and Superplasticizer (SP) content, was investigated in the selection of optimal grout based on fluidity and CS. The Taguchi methodology, in conjunction with Grey Relational Analysis, was adopted to obtain the optimal grout proportions. The open-graded asphalt (OGA) mixtures were grouted using the obtained optimal grout mix. The OGA mixtures were prepared using two aggregate gradations. One is IRC SP 125 (2019) recommended gradation (Gr-I), while the other is a new gradation developed. Two types of bitumen, VG 30 and PMB 40, were used to prepare OGA mixtures. Three types of Semi-Flexible Asphalt (SFA) mixtures using two gradations and two binders were prepared to determine the effect of aggregate gradation and binder type on the mechanical properties of SFA mixtures. The Marshall Stability (MS), Indirect Tensile Strength (ITS), Compressive Strength (CS), Retained Marshall Stability (RMS), Tensile Strength Ratio (TSR), wheel rut tester, repeated load testing, and cantabro tests were conducted to evaluate the mechanical properties of SFA mixtures. In the next phase, the natural coarse aggregates were replaced with 50% recycled concrete aggregate, 100% recycled concrete aggregates and 100% ferrochrome slag aggregates to prepare OGA mixtures. The OGA with marginal aggregates were grouted, cured, and mechanical properties were evaluated. To assess the effect of warm mix asphalt (WMA) additives on the mechanical properties of SFA mixtures, three WMA additives, sasobit, rediset and zycotherm, were used to modify the PMB 40 binder and the OGA mixtures were prepared. The mixing temperatures of OGA mixtures were determined based on the percentage coating test. The SFA mixtures were prepared with WMA additives and Gr-II gradation, and the mechanical properties were evaluated. In the next phase, the OGA mixtures were prepared using the WMA additives and marginal aggregates. The prepared OGA mixtures were grouted, cured and grouted OGA mixtures were tested for mechanical properties.

9.2 EFFECT OF SAND/CEMENT RATIO IN THE SELECTION OF OPTIMAL GROUT MIX

- The SP content is the most influencing factor considering the fluidity and compressive strength collectively, followed by S/C ratio and W/C ratio. The S/C ratio, as the second most influential factor, should be considered while selecting the optimal grout proportion.
- Based on the Taguchi method in conjunction with Grey Relational Analysis, the optimal grout was achieved with the S/C ratio of 0.6. W/C ratio of 0.4, and SP content of 0.75% by weight of cement.

9.3 EFFECT OF AGGREGATE GRADATION AND BITUMEN TYPE ON MECHANICAL PROPERTIES OF SEMI-FLEXIBLE ASPHALT MIXTURES

- The new aggregate gradation, Gr-II can effectively be used to prepare OGA mixtures suitable for SFA mixtures. The optimum compaction effort for Gr-II gradation is 60 Marshall blows on one side of the specimen.
- The SV-II mixtures have better mechanical properties than SV-I mixtures, attributed to the good packing characteristics and increased finer aggregate content.
- The SFA mixtures with PMB 40 exhibited better mechanical properties and moisture resistance than those with VG 30 bitumen, implying the significance of bitumen type.
- The SFA mixtures have a 92-94% TSR due to oil spillage. The mechanical properties and fatigue life of all SFA mixtures increased with the curing period; however, heavy traffic can be allowed after 28 days.

9.4 SFA MIXTURES WITH MARGINAL AGGREGATES

- The SFA mixtures with 100% Ferrrochrome Slag (FCS) aggregate exhibited higher MS, CS and ITS than the SFA mixtures with Recycled Concrete Aggregates (RCA), attributed to the higher strength of FCS aggregates.

- The SFA mixtures with 100% FCS exhibited higher moisture resistance than SFA mixtures with RCA.
- The SFA mixtures with FCS exhibited higher fatigue life, lower rut depth, and lower cantabro loss, indicating better abrasion resistance, fatigue and rutting resistance than SFA mixtures with RCA.
- The SFA with FCS performed better in mechanical properties, followed by SFA with 50% RCA and 100% RCA, respectively. However, all SFA mixtures with marginal aggregates satisfied the minimum requirements of IRC.

9.5 SFA MIXTURES WITH WARM MIX ASPHALT ADDITIVES

- The sasobit, rediset and zycotherm additives reduced the mixing temperatures by 35 °C, 30 °C, and 30°C, respectively, while the compaction temperatures were reduced by 33 °C, 28 °C and 28°C, respectively.
- The SFA with sasobit exhibited higher MS, CS and ITS than SFA mixtures with rediset and zycotherm additives.
- The SFA with zycotherm exhibited better moisture resistance than those with Sasobit and rediset.
- The SFA with sasobit exhibited higher fatigue life, lower rut depth, and lower cantabro loss, indicating better abrasion, fatigue and rutting resistance. The SFA with rediset and zycotherm additives satisfied the requirement of cantabro loss marginally.
- Overall, the SFA with sasobit exhibited better mechanical properties, followed by SFA with zycotherm and rediset, respectively. However, all SFA mixtures with WMA additives satisfied the minimum requirements of IRC.

9.6 SFA MIXTURES WITH WARM MIX ASPHALT ADDITIVES AND MARGINAL AGGREGATES

- The WMA additives reduced the mixing temperatures by 35-30 °C, 35-25 °C, and 35-30 °C, for SFA mixtures with 50% RCA, 100% RCA and 100% FCS, respectively. The WMA additives reduced the compaction temperatures by 33-28

°C, 33-28 °C, and 33-28 °C for SFA mixtures with 50%RCA, 100%RCA and 100%FCS, respectively.

- The SFA mixtures with FCS exhibited higher MS and CS among all other mixtures, irrespective of the WMA additives used. The 50RCA-R and 100RCA-R satisfied the minimum MS requirement of 60 kN.
- All SFA mixtures with marginal aggregates and WMA additives exhibited the ITS at 35 °C more than 1 MPa, except the 100RCA-R mixture. The SFA mixtures with FCS performed better in terms of ITS than other mixtures, irrespective of the WMA additives used.
- The 50RCA-S, 50%RCA-Z, 100FCS-S, 100FCS-R, and 100FCS-Z mixtures only satisfied the maximum requirement of 20% cantabro loss, hence, considered for fatigue and rutting studies.
- The SFA mixtures with FCS exhibited a higher FL and rutting resistance than those with 50%RCA for all WMA additives. The quality of aggregates to prepare SFA mixtures was more pronounced in rutting resistance than the binder type.
- The 50RCA-S, 50%RCA-Z, 100FCS-S, 100FCS-R, and 100FCS-Z mixtures only satisfied the requirements. The SFA mixtures with FCS performed well for all WMA additives due to strong aggregates.

9.7 RECOMMENDATIONS

- The optimal combination of the S/C ratio of 0.6. W/C ratio of 0.4, and SP content of 0.75% by weight of cement can be used to prepare the grout for semi-flexible asphalt mixtures.
- The 100% of natural coarse aggregates in semi-flexible asphalt mixtures can be replaced with recycled concrete and ferrochrome slag aggregates.

9.8 LESSONS LEARNED

- The sand content in grout has significant effect on grout performance and therefore should be considered while selecting optimal grout.

- Increasing the air voids in OGA mixtures is not the only approach to enhance the performance of SFA mixtures; achieving a stable OGA gradation can also contribute to performance improvement.
- The binder type plays a crucial role in influencing the performance of SFA mixtures. The polymer modified bitumen demonstrated a significant improvement in performance of SFA mixtures compared to the unmodified binder.
- In semi-flexible asphalt mixtures, the natural coarse aggregates can be fully replaced with recycled concrete aggregates and ferrochrome slag aggregates.
- The Sasobit, rediset and zycotherm additives reduced the mixing temperatures by 30-35 °C, similarly compaction temperatures by 28-33 °C. The SFA mixtures with WMA additives met the IRC specifications, therefore, can be recommended for further study by constructing trial section.

9.9 PRACTICAL APPLICATIONS

The semi-flexible asphalt mixtures with natural coarse aggregates, recycled concrete aggregates and ferrochrome slag aggregates can be recommended for constructing trial sections for further study. The semi-flexible asphalt mixtures would be an advantageous wearing course particularly at intersections, bus stops, industrial areas and parking places, where there was chance of oil spillage and heavy vehicular movements.

9.10 LIMITATIONS

- The optimal grout mix was optimized based on fluidity and CS at seven day curing period. The grout can be optimized based on CS at 28 days, drying shrinkage, and flexural strength.
- Only two types of binders, VG 30 and PMB 40, were used to determine the effect of bitumen type on the mechanical properties of SFA mixtures. The crumb rubber-modified binder can also be used.
- The properties of RCA vary depending on the source. Therefore, the percentage of utilization of RCA varies with the source.

- The WMA-modified binders were characterized using only physical properties. The rheological properties of the binders should be studied.
- The SFA with WMA additives were analyzed at mixture level.

9.11 FUTURE SCOPE

- Various supplementary cementitious materials can be used to prepare the grout mix.
- The SFA mixtures grouted with geopolymer-based grout can be prepared to achieve improved mechanical properties and higher early strength.
- The high-performing grouts (having high strength) can be used to improve the durability of SFA mixtures with RCA.
- Various marginal aggregates and by-products, such as steel slag, can be utilized.
- The interactions between the WMA-modified binders and aggregates should be analyzed to assess the performance of SFA mixtures.

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LIST OF PUBLICATIONS

Journal:

- **Kumar, D. H.** Chinnabhandar, R. K., Chiranjeevi, K., and Shankar, A. U. R. (2023). “Effect of Aggregate Gradation and Bitumen Type on Mechanical Properties of Semi-Flexible Asphalt Mixtures.” *Case Stud. Constr. Mater.*, e02025. DOI: 10.1016/j.cscm.2023.e02025

Book Chapter:

- **Doma, H. K.** and Ravi Shankar, A. U. (2023). “State-of-the-Art of Grouting in Semi-flexible Pavement: Materials and Design.” *Recent Trends Constr. Technol. Manag.*, Springer, 135–148.

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Ph.D	National Institute of Technology Karnataka, Surathkal	NITK	-	2017-2024
M.Tech	National Institute of Technology Karnataka, Surathkal	NITK	8.23	2015-2017
B.Tech	Rajiv Gandhi University of Knowledge Technologies, Nuzvid, A.P.	RGUKT	7.70	2010-2014
P.U.C (M.Bi.P.C)	Rajiv Gandhi University of Knowledge Technologies, Nuzvid, A.P.	RGUKT	8.73	2008-2010

Projects:

Ph.D Effect of Warm Mix Asphalt Additives and Marginal Aggregates on Mechanical Properties of Semi-Flexible Asphalt Mixtures

M.Tech Laboratory Investigation of Superpave Mixtures with Neat and Modified Binders

B.Tech Design and Analysis of Earthquake Resistance of G+4 Building

Courses Studied during M.Tech:

- Pavement Design
- Pavement Materials
- Highway and Airport Geometric Design
- Urban Transport Planning
- Probability and Statistical Methods
- Traffic Engineering Management
- Traffic Flow Theory
- Traffic Simulation
- Operational Research

Publications:

Journals

1. **Kumar, D. H.**, Chinnabhandar, R. K., Chiranjeevi, K., and Shankar, A. U. R. (2023). "Effect of Aggregate Gradation and Bitumen Type on Mechanical Properties of Semi-Flexible Asphalt Mixtures." *Case Stud. Constr. Mater.*, e02025. DOI: 10.1016/j.cscm.2023.e02025
2. Chiranjeevi, K., **Kumar, D. H.**, Yathish, R. G., and Shankar, A. U. R. (2023). "Laboratory investigation on cement-treated recycled concrete aggregate bases for flexible pavements." *Mater. Today Proc.* DOI: 10.1016/j.matpr.2023.03.509
3. Chiranjeevi, K., **Kumar, D. H.**, Srinivasa, A. S., and Ravi Shankar, A. U. (2023). "Optimisation of recycled concrete aggregates for cement-treated bases by response surface method." *Int. J. Pavement Eng.*, 24(1), 2179051. DOI: 10.1080/10298436.2023.2179051
4. Chinnabhandar, R. K., **Kumar, D. H.**, Yatish, R. G. and Ravi Shankar, A. U. (2022). "Laboratory evaluation of use of areca fibres in SMA mixes." *Int. J. Pavement Eng.*, 1–10. DOI: 10.1080/10298436.2022.2076090

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1. **Doma, H. K.**, and Ravi Shankar, A. U. (2023). "State-of-the-Art of Grouting in Semi-flexible Pavement: Materials and Design." *Recent Trends Constr. Technol. Manag.*, Springer, 135–148.
2. Chethan, B. A., Shankar, A. U., Chinnabhandar, R. K. and **Kumar, D. H.** (2023).

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Conferences

1. **Doma, H. K.**, and Ravi Shankar, A. U. (2021). “State-of-the-Art of Grouting in Semi-flexible Pavement: Materials and Design.” *International Conference on Advances in Construction Technology and Management (ACTM)*, College of Engineering Pune (COEP), Pune, India, March 11-12.
2. Chethan, B. A., Shankar, A. U., Chinnabhandar, R. K., and **Kumar, D. H.** (2021). “Alkali Activated Black Cotton Soil with Partial Replacement of Class F Fly Ash and Areca Nut Fiber Reinforcement.” *International Conference on Advances in Construction Technology and Management (ACTM)*, College of Engineering Pune (COEP), Pune, India, March 11-12.
3. Chiranjeevi, Kondeti., Jaya, K. R., **Kumar, D. H.** and Ravi Shankar, A. U. (2021). “Laboratory Investigation of Cement-Treated Sub-base and Base Courses for Flexible Pavement.” *8th International Conference on Transportation Systems Engineering and Management (CTSEM)*, National Institute of Technology, Calicut, India, August 26-27.
4. Chiranjeevi, Kondeti., **Kumar, D. H.**, Yatish, R. G. and Ravi Shankar, A. U. (2022). “Laboratory Investigations on Cement-Treated Recycled Concrete Aggregate Bases for Flexible Pavements.” *2nd International Conference on Construction Materials and Structures (ICCMS)*, National Institute of Technology, Calicut, India, December 14-18.
5. Soumya, Otageri., **Kumar, D. H.**, Ravi Shankar, A. U. and Raviraj, Mulangi. (2023). “Experimental Investigation of Superpave Mixtures for Optimum and Rich Mixes.” *2nd International Conference on Sustainable Materials and Practices for Built Environment (SMPBE)*, Manipal University, Jaipur, India, January 19-20.
6. Chiranjeevi, Kondeti, **Kumar, D. H.**, Jeevan, K. A., Thapas, N. D. S. and Ravi Shankar, A. U. (2023). “Utilization of Recycled Concrete Aggregates Processed using Ball Milling Method in Cement-Treated Bases for Pavements” *1st International Conference on Sustainable Infrastructure: Innovation, Opportunities and Challenges (SIIOC)*, NITK, Mangalore, India, April 20-21.
7. Soumya, Otageri., **Kumar, D. H.**, Ravi Shankar, A. U. and Raviraj, Mulangi. (2023). “Comparison of Volumetric Properties and Stability of Asphalt Mixes with Shredded Waste Plastic and Rich Mixes.” *1st International Conference on Sustainable Infrastructure: Innovation, Opportunities and Challenges (SIIOC)*, NITK, Mangalore, India, April 20-21.

Seminars:

- Simulation of Traffic regulations at Pump well junction in Mangalore using VISSIM (Student Version).
- Construction of Grade Separators at the Intersection of Ring Road and Aurobindo Marg, New Delhi.

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Achievements and Extracurricular Activities:

- Organizer for Badminton in Research Premier League (RPL), 2022 at NITK.
- Cracked GATE-2015 with score 365.
- Coordinator for Student Internship Committee for Department of Civil Engineering in RGUKT, 2013.
- Selected in merit category (state wide) for Integrated program of RGUKT to pursue PUC and Engineering, based on S.S.C marks.
- Organizer for technical and cultural fests in the Department of Civil Engineering, RGUKT, 2014.
- Cadet of NCC 'C' and 'B' certificates, 17AN Battalion.
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