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Performance of Stone Matrix Asphalt Modified with Crumb Rubber and Fibres

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ABSTRACT

This article investigates the impact of Crumb Rubber Modified Bitumen (CRMB) and fibre additives (aramid fibre and basalt fibre) on the performance properties of Stone Matrix Asphalt (SMA) mixtures. Tests were conducted to evaluate mix design, draindown, cantabro loss, moisture sensitivity, rutting resistance and fatigue behavior. The Marshall method, the draindown parameters (ASTM D6390-11) and the cantabro loss characteristics (ASTM D 7064) were used to examine the mix design qualities. The modified Lottman test was used to assess the moisture sensitivity of SMA mixes. The roller compactor cum rut analyzer was used to assess rutting resistance. Findings showed that CRMB and fibre additives effectively controlled binder draindown and minimized abrasion loss in SMA mixtures. SMA-CRMB mixtures had higher draindown, but comparable cantabro loss than SMA-AF and SMA-BF mixtures. Incorporating CRMB and fibre additives enhanced moisture sensitivity, rutting resistance and fatigue behavior. SMA mixtures with 0.3% fibre addition displayed similar performance properties to SMA with CRMB. Further, substituting fibre additions for CRMB in SMA combinations may yield similar performance.

KEYWORDS: Stone matrix asphalt, Crumb rubber-modified bitumen, Fibre additives, Draindown, Cantabro loss, Moisture sensitivity, Rutting resistance, Fatigue behaviour.

INTRODUCTION

The road transport mode occupied a vital position in the overall transportation system of India due to user-friendliness, ease of access, simple operations and door-to-door service. India's road transportation sector is estimated to account for around 80% of passenger travel and 65% of freight transport (Bose et al., 2006; Kumar et al., 2007; Pravakar, 2011; Shiva Kumar et al., 2022). According to an evaluation of the Indian road network by the National Highway Authority of India (NHAI), national highways constitute only around 1.7% of the total road network, although they carry nearly 40% of the traffic. Over the past five years, highway traffic has soared 7% to 10% annually, while the number of automobiles has increased by 10.16% annually (Jain et al., 2004; Kumar et al., 2004; Shiva Kumar et al., 2023). Asphalt mixtures, due to their superior properties, are used in road building, as they preserve the base course

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and the underlying pavement structure from the damaging effects of water and traffic abrasions. As a result of the flexibility of asphalt mixtures, the pavement structure can react to the modest consolidation or deformation generated by wheel loads without compromising performance (Brown et al., 1997, Putman et al., 2004). The presence of water and repetitive application of traffic loads results in fatigue cracks and rutting throughout wheel paths, as well as moisture damage to pavements (Li et al., 2014; Chen et al., 2017; Shiva Kumar & Suresha, 2019). Stone matrix asphalt (SMA) was created in Germany in the mid 1960s to address these issues and has been utilized throughout Europe for more than 30 years (Brown et al., 1997; Putman et al., 2004; Cooley and Hurley, 2004; Kandhal, 2006). SMA is a gap-graded mixture composed of two components: a high-concentration coarse aggregate skeleton and a mortar with a high binder percentage. SMA contains a substantial number of coarse aggregates which give a high density of stability structure through stone-to-stone contact, superior interlock and a mortar with high binder content (Brown et al., 1997; Putman et al., 2004; Cooley and Hurley, 2004). The coarse aggregates in SMA interlock to resist permanent deformation. The mix is held together with sufficient specialized mortar for durability and to prevent draindown of the binder. It provides good friction properties because of its rough surface texture. These mixtures have good aging properties and reduce traffic noise. Fine aggregate, asphalt binder, mineral filler and a stabilizing agent are typical mortar components (Asi, 2006; Abtahi et al., 2010; Al and Tan, 2011). SMA mixtures are stabilized with natural fibre, cellulose fibre, synthetic fibre and polymers to prevent the mastics from draining (Shiva Kumar et al., 2019).

Previous research has shown that SMA mixtures containing natural and cellulose fibre are superior in avoiding draindown and increasing resistance to rutting (Panda et al., 2013; Dang and Cheng, 2013; Gridchin et al., 2014; Shiva Kumar et al., 2019; Shiva Kumar and Ravishankar, 2020). In addition, type and percentage of fibre had a significant effect on the rutting performance of SMA mixtures (Behbahani et al., 2009). Putman et al. (2004) examined the effect of natural and cellulose fibre in SMA mixtures. They detected no difference between SMA mixtures containing natural fibre and cellulose fibre with regard to their resistance to moisture damage and rutting. Oda et al. (2012) compared SMA mixtures with natural fibres (sisal fibre and coconut fibre) to SMA mixtures with cellulose fibre. When compared to SMA mixtures with cellulose fibre, the draindown characteristics of SMA mixtures with sisal and coconut fibres were excellent. The rutting and fatigue behaviour of SMA mixtures with sisal, coconut and cellulose fibres are not significantly different. The usage of these fibres also increases the fatigue resistance of the asphalt mixture (Nejad et al., 2010, Mehrez and Karim, 2010). Both natural and cellulose fibres enhanced resistance to high tensile stresses, stiffness and fatigue life of SMA mixtures (Mohamadzadeh et al., 2014). However, previous studies on SMA mixtures focused on using natural and cellulose fibres, while SMA mixtures with basalt fibre and aramid fibre have not been addressed pertaining to properties related to draindown, cantabro loss, rutting, fatigue and moisture-damage performance.

Recycling End-of-Life (ELT) tires grows yearly with the number of new tires produced (+1.4 billion/year) and with the increase of the multi-disciplinary focus on sustainability (Bressi et al., 2019). It's well known that the use of ELT in asphalt mixtures comprises two main processes, the wet process and the dry process. In the first one, rubber is blended with the binder (15% to 20% weight concentration) to improve its properties (Crumb Rubber Modified Binder - CRMB). In the second process, rubber is included in asphalt mixtures as solid particles (i.e., 2-4% weight concentration) (Bressi et al., 2019). The use of alternative modifiers such as polymers and crumb rubber in SMA mixtures is gaining popularity and has been effectively implemented by transportation agencies. Mashaan et al. (2013) investigated the influence of crumb-rubber modifiers on volumetric, mechanical and stiffness properties of SMA mixtures. The appropriate amount of the added crumb-rubber modifiers was found to be 12% by weight of bitumen. This percentage results in the maximum level of stability and a higher resilient modulus. Shiva Kumar et al. (2019) discovered that polymers in SMA mixtures were more resistant to rutting, fatigue and moisture sensitivity than SMA mixtures with natural and cellulose fibre. However, studies on SMA mixtures with CRMB are limited. As a result, it is necessary to evaluate the effect of CRMB, aramid fibre and basalt fibre on mix design, draindown, cantabro loss and mechanical characteristics of SMA mixtures, including rutting, fatigue behaviour and moisture sensitivity.

Scope and Aims of the Study

Understanding the impact of CRMB, aramid fibre and basalt fibre on mix design, draindown, cantabro loss and mechanical characteristics of SMA mixes, such as rutting, fatigue behaviour and moisture sensitivity, was the primary goal of this study. Studies have shown that SMA blends containing stabilizing additives including polymers and natural fibres have exceptional resistance to rutting, fatigue, draindown and moisture-induced damage. The effects of adding different amounts of aramid and basalt fibres on the mechanical characteristics of SMA mixes have not been studied or compared to already used crumb rubber-modified bitumen. Therefore, research is required to determine the effects of aramid and basalt fibre dosages on the mix design, draindown, workability and mechanical characteristics of SMA mixes, as well as to compare the results to SMA that uses crumb rubber-modified bitumen.

MATERIALS AND METHODOLOGY

Materials

Binder

Penetration grade 60-70 (VG-30) plain paving grade bitumen, which complies with ASTM D 946 and crumb rubber-modified bitumen (ASTM D6114) were used as binders for the SMA mixtures. The plain paving grade was used as the binder for the aramid -and basalt- fibre modification and CRMB was used as it is for the objectives of this study.

Aggregates and Filler

One type of aggregate of the granite variety was employed throughout the investigation for both the finer (ASTM D1073-06) and coarser (ASTM D692-00) materials, all of which conforming to the ASTM standards. Quarry dust and cement were used as fillers.

Additives

In this study, basalt and aramid fibres were adopted and the dosage rates were 0.1%, 0.3% and 0.5% by weight of the mixture. Basalt fibre is a material created from basalt that is exceedingly fine and made up of minerals, such as plagioclase, pyroxene and olivine (Fig. 1a). The length, diameter and density of the basalt fibre were 24 mm, 13–20 mm and 2.80g/cm^3, respectively. Aramid fibre is a polymer (aromatic polyamide) chemically manufactured by spinning a solid fibre from a liquid chemical combination (Fig. 2a). The length, diameter and density of the aramid fibre were 5-30 mm, 12-45 mm and 1.39g/cm^3, respectively. The morphology and chemical composition of the basalt fibre (Fig. 1b & c) and of the aramid fibre (Fig. 2 b & c) were also investigated using scanning electron microscopy (SEM) and Energy Dispersive X-Ray Analysis (EDS). Basalt fibres are highly homogeneous with a smooth surface and small particles with irregularities on the surface. An aramid fibre is a longitudinal fibril structure, indicating that the fibre molecules align along the longitudinal direction.

Table 1. Binder properties

Properties	VG-30		Crumb Rubber-modified Bitumen-55	
	Requirement[a]	Result	Requirement[b]	Result
Penetration at 25 °C , 100 g, 5 s, 0.1 mm	60-70	65	<60	52
Ductility test at 25°C , 5 cm/min, cm	≥ 100	105	--	--
Softening point, °C	≥ 46	54	≥ 55	65
Flash point, °C	≥ 230	320	≥ 220	280
Retained penetration after thin-film oven test, %	>52	58	<40	33
Ductility test at 25°C, 5 cm/min, cm after thin-film oven test	≥ 50	70	≥ 35	50

[a] IS 73 (IS 2006); [b]IS 15462 (IS 2004).

Table 2. Aggregate properties

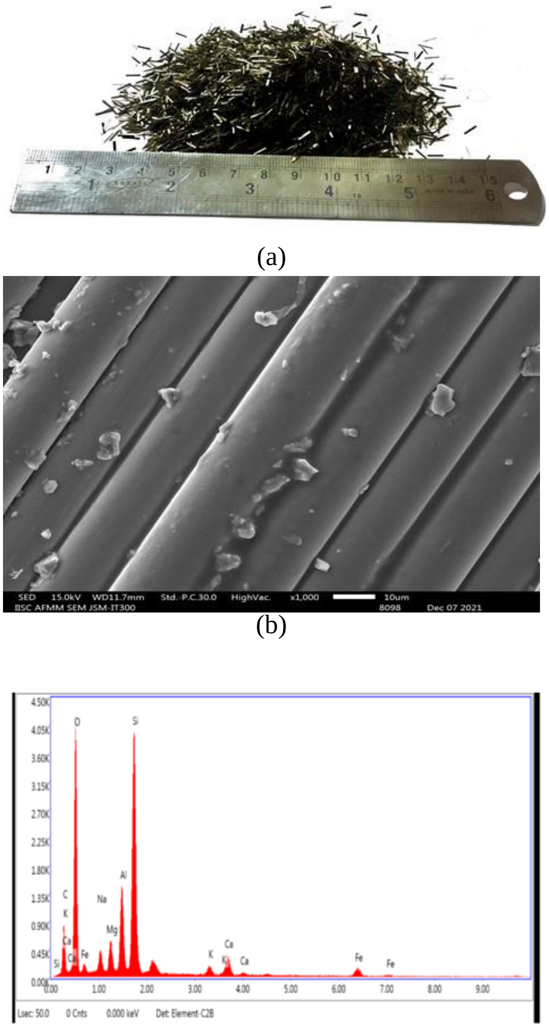
Properties	**Requirement**[a]	**Result**
LA abrasion value (%)	≤ 25	20
Aggregate impact value (%)	≤ 18	15
Water absorption (%)	≤ 2	0.15
Combined elongation and flakiness indices (%)	≤ 30	27

[a] IRC SP 79 (IRC 2008).

Table 3 Aggregate gradation

Sieve size (mm)	19	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.075
% passing (%)	100	95	60	21	16	14	12	10	8
Requirement[a] (%)	100	90-100	50-75	20-28	16-24	13-21	12-18	10-20	8-12

[a] IRC SP 79 (IRC 2008).

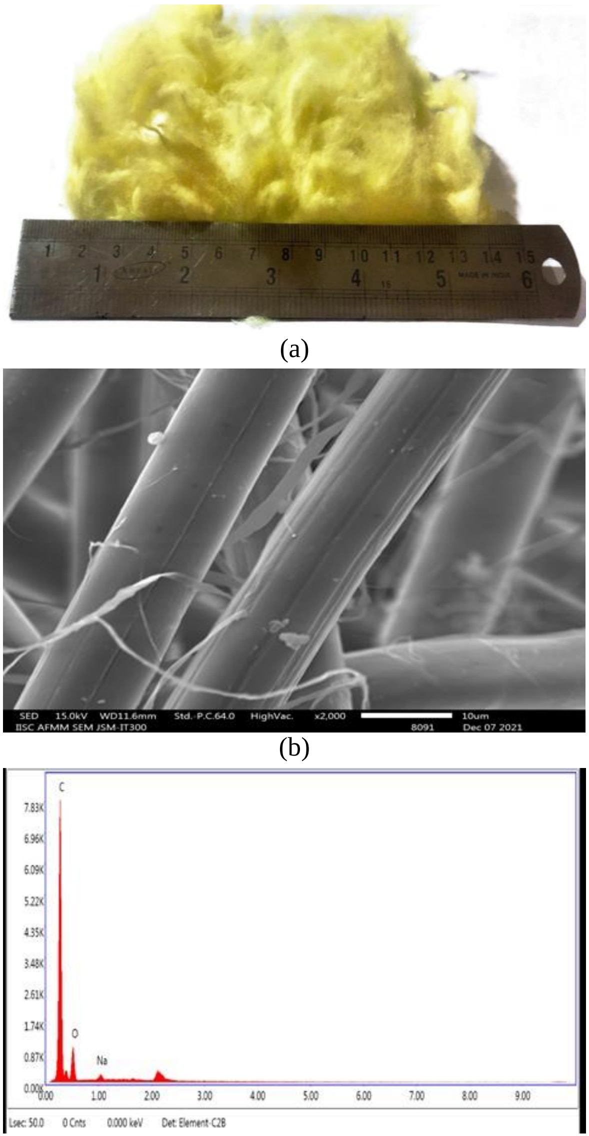


(a)

(b)

(c)

Figure (1): Basalt fibre morphology and chemical composition



(a)

(b)

(c)

Figure (2): Aramid fibre morphology and chemical composition

Methodology

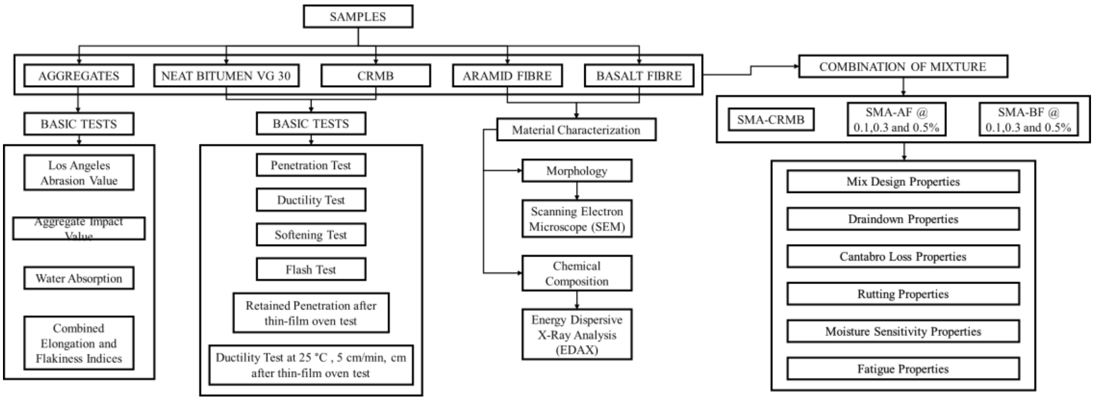


Figure (3): Methodology

Rutting, moisture sensitivity and fatigue properties of SMA mixtures, as well as evaluation of asphalt mix design, draindown and cantabro loss are all part of the experimental design (Fig. 3). To achieve the research goal, SMA mixtures modified by CRMB (SMA-CRMB), aramid fibre (SMA-AF) and basalt fibre (SMA-BF) were studied. Using the Marshall technique, the mix design properties of SMA-CRMB, SMA-AF and SMA-BF mixes were examined (Asphalt Institute, 1996). Further, draindown, cantabro loss and mechanical properties of SMA mixtures were examined at OBC. According to EN 12697-22, rutting properties (rut depth at 10,000 passes and dynamic stability) were evaluated in dry conditions at a testing temperature of 60 °C (Jain et al., 2021). The modified Lottman test was used to assess the moisture sensitivity properties of SMA-CRMB, SMA-AF and SMA-BF mixtures. Asphalt mixtures were compacted into cylindrical specimens with 7.0±0.1% air voids at OBC. The values of indirect tensile strength (ITS) of dry and wet specimens were determined. According to AASHTO-T283, the tensile strength ratio (TSR) was calculated as the ratio of ITS values of wet specimens over dry specimens. Using a repeated load test, the fatigue properties of SMA-CRMB, SMA-AF and SMA-BF combinations were determined. There was a total of seven mixtures tested to assess the findings, including SMA-CRMB, SMA-AF at dosages of 0.1%, 0.3% and 0.5%, as well as SMA-BF at dosages of 0.1%, 0.3% and 0.5%, as displayed in Table 4.

Table 4. Experimental design of mix design, draindown, abrasion loss and mechanical properties

Response properties	Type of mixture	Binder content	No. of specimens
Mix design properties	7	3	3x21=63
Draindown properties	7	1	3x7=21
Cantabro loss properties	7	1	3x7=21
Moisture-induced damage properties	7	1	6x7=42
Rutting properties	7	1	3x7=21
Fatigue properties	7	1	3x7=21

RESULTS AND DISCUSSION

Mix Design Properties

Mix design parameters, such as VTM, VFA, VMA and G_{mb} of SMA-CRMB, SMA-AF and SMA-BF mixtures, were examined at OBC (Table 5). G_{mb} values for SMA-CRMB, SMA-AF and SMA-BF mixtures were found to be in the range of 2320-2355 (kg/m^3). The results clearly show that aramid-fibre and basalt-fibre incorporation resulted in lower density when compared to SMA mixtures with CRMB. For example, SMA-0.3%AF and SMA-0.3%BF mixtures reduced density by 0.6% and 0.7%, respectively, when compared to SMA-CRMB mixtures. SMA-CRMB, SMA-AF and SMA-BF mixtures achieved 4% VTM at OBC more than 5.8% (IRC SP 79). SMA-CRMB, SMA-AF and SMA-BF mixtures had VMA and VFA values ranging from 17.4% to 18.4% and from 76.3% to 78.4%, respectively. The results clearly show that VMA was greater than 17% and VFA values were within the limits for all mixtures (IRC SP 79). In addition, the VMA and VFA values increased with increasing fibre content. Stability and flow were 15.3–15.9 kN and 3.3–3.7 mm for SMA-CRMB, SMA-AF and SMA-BF mixtures, respectively. In addition, an increase in fibre content was associated with an improvement in stability and a reduction in flow values. In comparison to SMA-CRMB mixtures, SMA-0.3%BF and SMA-0.3%AF mixtures exhibited equivalent mix design properties. Moreover, VCA_{DRC} is exclusively dependent on aggregate qualities and proportions and it was revealed to be between 39.3 and 39.8 %, which was greater than the VCA_{MIX} values of all combinations, showing good stone-to-stone contact (Sarang et al., 2016).

Table 5. Mix design properties

Mix	**SMA-CRMB**	**SMA-0.1%AF**	**SMA-0.3%AF**	**SMA-0.5%AF**	**SMA-0.1%BF**	**SMA-0.3%BF**	**SMA-0.5%BF**
OBC (%)	6.5	6.3	6.1	6.0	6.4	6.3	6.2
VMA (%)	18.4	17.4	17.8	18.0	17.7	18.1	18.2
VFA (%)	78.4	78.0	77.3	76.3	77.2	76.5	75.9
Gmb (kg/m^3)	2355	2345	2340	2335	2330	2325	2320
VCA_{MIX}	37.7	35.1	35.5	35.9	36.2	36.6	36.8
VCA_{DRC}	39.8	39.3	39.3	39.3	39.6	39.6	39.6
VCA_{MIX}/VCA_{DRC}	0.95	0.89	0.90	0.91	0.91	0.92	0.93
Stability (kN)	15.9	15.3	15.5	15.6	15.6	15.7	15.8
Flow (mm)	3.7	3.4	3.3	3.2	3.5	3.4	3.3

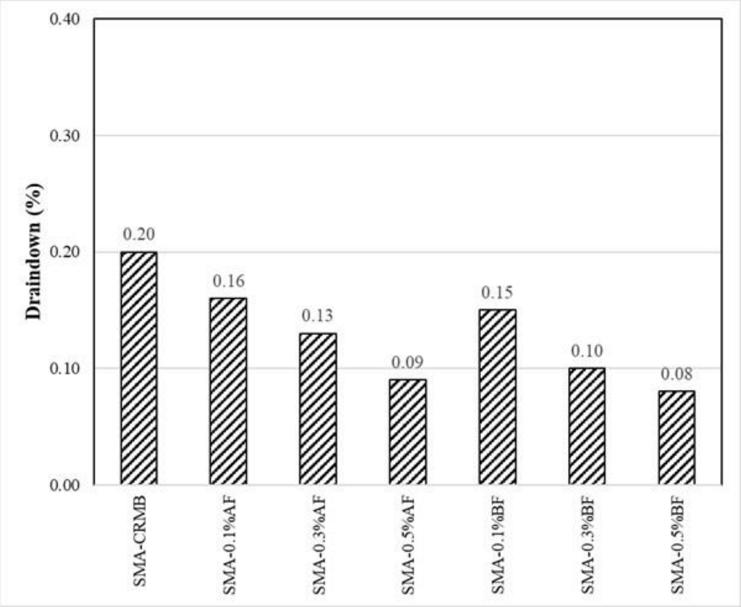


Figure (4): Results of draindown test

Draindown Properties

Figure 4 shows the results of draindown test of SMA-CRMB, SMA-AF and SMA-BF mixtures performed at OBC. SMA-CRMB, SMA-AF and SMA-BF mixtures had draindown values ranging from 0.08% to 0.20%. The maximum asphalt draindown is 0.3%, according to the regulations (ASTM D6390-11). It is observed that SMA-CRMB, SMA-AF and SMA-BF mixtures had draindown less than 0.3%. Results clearly indicate that the increase in fibre content decreases the draindown of SMA mixtures. SMA-AF and SMA-BF mixtures with 0.5% fibre content had negligible draindown, which may be because they are exceptionally stiff and strong fibres with high elasticity moduli. Asphalt mixes that contain fibre assist to make the bitumen more viscous. This is due to the network of fibres that the bitumen is trapped in and cannot flow through. The fibres also aid in enhancing the bond between the bitumen and the aggregates. This is so that the fibres can better interlock with the aggregates thanks to their rough surface. The higher OBC allows the binder to flow and the addition of aramid fibre and basalt fibre prevents SMA mixtures from draining. Furthermore, draindown was found to be greater in SMA-CRMB mixtures than in SMA-AF and SMA-BF mixtures.

Cantabro Loss Properties

As shown in Figure 5, cantabro loss test was performed at OBC for SMA-CRMB, SMA-AF and SMA-BF mixtures. Cantabro loss values for SMA-

CRMB, SMA-AF and SMA-BF mixtures were in the range of 4.1 % to 6.2 %. The results clearly show that increasing the fibre content reduces the draindown of SMA mixtures. Furthermore, cantabro loss was found to be greater in SMA-CRMB mixtures than in SMA-AF and SMA-BF mixtures.

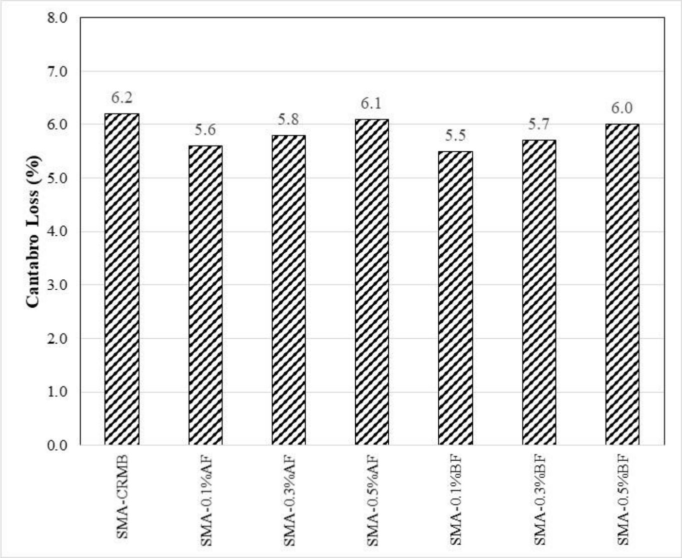


Figure (5): Results of cantabro loss test

Rutting Properties

Figure 6 depicts the rutting properties of SMA-CRMB, SMA-AF and SMA-BF mixtures. Rut depths in SMA-CRMB, SMA-AF and SMA-BF mixtures ranged from 3.7 to 6.3 (mm). SMA-CRMB, SMA-AF and SMA-BF mixtures had dynamic stability in the range of 3200-4000 (mm/min). When compared to SMA-AF and SMA-BF, the results clearly show that SMA-CRMB mixtures had more resistance to rutting. For instance, reduction in 11.9% and 7.5% of rut depth values was noticed with 0.3% of SMA-AF and SMA-BF compared to SMA-CRMB mixtures. As a result, it is possible to conclude that SMA-AF and SMA-BF combinations have lower rut resistance than SMA-CRMB mixtures. Furthermore, SMA-CRMB and SMA mixtures with 0.3% fibre content had equivalent rut depth and dynamic stability characteristics. This could be because the inclusion of CRMB, 0.3% aramid fibre and 0.3 % basalt fibre produced a stiffer combination with a higher rut resistance.

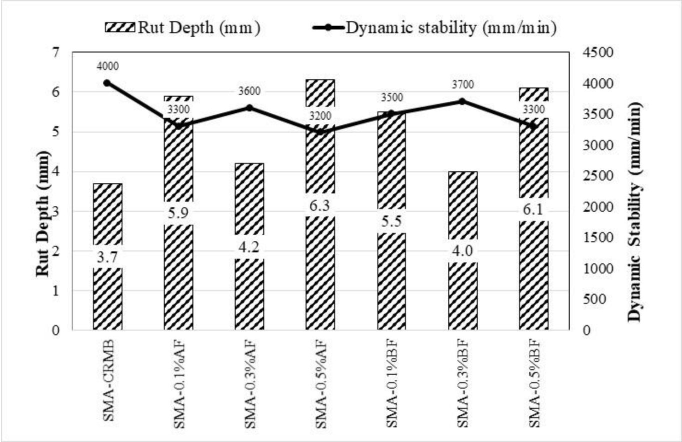


Figure (6): Rut test results

Moisture Sensitivity Properties

Table 6 demonstrates the variance of ITS_{dry} and ITS_{wet} values, as well as TSR values, for SMA-CRMB, SMA-AF and SMA-BF combinations. SMA-CRMB, SMA-AF and SMA-BF mixtures had ITS$_{dry}$ values ranging from 745 to 810 (kPa). Similarly, the ITS$_{wet}$ values of SMA-CRMB, SMA-AF and SMA-BF mixtures ranged from 648 to 740 (kPa). The results of the ITS test clearly show that SMA-CRMB combinations had relatively higher ITS values than SMA-AF and SMA-BF mixtures. For instance, a decrease of 12.4% and 6.3% of ITS$_{wet}$ values was noticed with 0.1% of SMA-AF and SMA-BF compared to SMA-CRMB mixtures, which may be because fibres developed a spatial networking structure in the asphalt mixture, functioning as reinforcement and toughening. Exfoliation of the aggregates under water action was difficult because of the enhanced adhesion capability between the asphalt and the aggregates (Lou e al., 2021).

It should be noted that various United States Departments of Transportation have determined a minimum ITS value based on the possibility for resistance to moisture damage. The Illinois Centre for Transportation, for instance, suggests a minimum ITS value of 414kPa. In contrast, SMA-CRMB, SMA-AF and SMA-BF combinations met the minimum requirements for ITS$_{dry}$ and ITS$_{wet}$ values. In addition, the TSR values of SMA-CRMB, SMA-AF and SMA-BF combinations fell within the range of 87-91.4 %. In contrast, the (AASHTO-283-07) standards mandate a minimum TSR of 85% for SMA mixtures. Further, it was noticed that SMA-CRMB mixtures and SMA mixtures with 0.3% fibre content had comparable ITS and TSR values.

Table 6. Results of ITS tests (a) ITS principles and (b) Values of TSR

Mix		SMA-CRMB	SMA-0.1%AF	SMA-0.3%AF	SMA-0.5%AF	SMA-0.1%BF	SMA-0.3%BF	SMA-0.5%BF
ITS$_{dry}$	Value	810	745	770	760	780	805	790
	SD	0.07	0.01	0.10	0.07	0.04	0.01	0.06
ITS$_{wet}$	Value	740	648	685	670	694	730	708
	SD	0.03	0.13	0.01	0.02	0.01	0.02	0.16
TSR	Value	91.4	87.0	89.0	88.2	89.0	90.7	89.6
	SD	0.02	0.01	0.20	0.15	0.11	0.05	0.09

Fatigue Properties

In order to evaluate the fatigue properties, the number of fatigue cycles to failure of SMA mixtures was measured by applying 10% of the original tensile stress till 5-mm cracking. Three specimens were prepared for each mixture and the average of the test results is presented in Figure 7. The fatigue life of SMA-CRMB, SMA-AF and SMA-BF mixtures ranged from 7,540 to 8,125 (cycles). The results of the fatigue test show that SMA-CRMB mixtures displayed relatively higher fatigue cycle values than those of SMA-AF and SMA-BF mixtures. This is because the high elastic modulus and superior elongation at the break of BFs can effectively prevent the extension of fatigue fracture and improve the recovery of asphalt deformation (Hui et al., 2022). For instance, reductions of 4.5% and 0.9% in fatigue cycle values were noticed with 0.3% of SMA-AF and SMA-BF compared to SMA-CRMB mixtures. Further, it was noticed that SMA-CRMB mixtures and SMA mixtures with 0.3% fibre content had comparable fatigue cycle values.

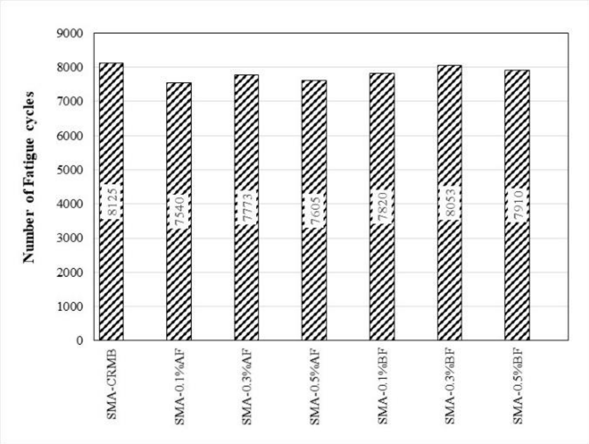


Figure (7): Fatigue test results

CONCLUSIONS

On the basis of test results, the following conclusions were drawn:

- Incorporation of aramid fibre and basalt fibre controls draindown of binder and reduces abrasion loss in SMA mixtures. Further, draindown and abrasion loss in SMA-CRMB mixtures were more compared to those in SMA mixtures with fibre additives.

- Mix design properties of SMA-CRMB, SMA-AF and SMA-BF meet the required specifications. SMA-AF and SMA-BF mixtures exhibited lower density, VMA and VFA values compared to SMA-CRMB mixtures. Further, incorporation of aramid fibre and basalt fibre increased stability and decreased flow values irrespective of fibre content.
- SMA-AF and SMA-BF mixtures were less susceptible to moisture sensitivity than SMA-CRMB mixtures. In addition, SMA-CRMB, SMA-AF and SMA-BF mixtures fulfilled the minimum TSR requirement.
- SMA-CRMB mixtures exhibited higher resistance to rutting and fatigue compared to those in SMA-AF and SMA-BF mixtures. However, it was noticed that SMA-CRMB mixtures and SMA mixtures with 0.3% fibre content had comparable mix design, draindown, cantabro loss and mechanical properties.

According to the study results, adding basalt and aramid fibres to SMA mixtures can decrease abrasion loss and regulate binder draindown. Comparing SMA-CRMB mixtures to SMA-AF and SMA-BF mixtures, SMA-CRMB mixtures showed greater resilience to moisture, rutting and fatigue. However, in terms of mix design, draindown, cantabro loss and mechanical characteristics, SMA mixtures with 0.3% fibre content were equivalent to SMA-CRMB mixtures. Overall, the research points to SMA mixtures with CRMB and fibre additives as a viable sustainable choice for road building that can offer increased performance in a number of areas.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability

No data, models or codes were generated or used during the study.

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