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Laboratory performance of stone matrix asphalt mixtures with two aggregate gradations

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Abstract Stone matrix asphalt (SMA) is a gap-graded bituminous mixture which can be used in surface layer of high volume pavements. The mixture has higher concentrations of coarse aggregates, providing strength and rut resistance to the mixture, and higher asphalt content giving durability. There must be a proper stone-to-stone contact between the coarse aggregates of SMA, and hence aggregate gradation is an important factor in this mixture. In the current study, two aggregate gradations, with nominal maximum aggregate sizes (NMAS) 16 and 13 mm were adopted to prepare SMA mixtures and their laboratory performances were compared. Polymer-modified bitumen (PMB) was used as the binder material and no stabilising additive was used, since drain down was within permissible limits for both mixtures with PMB. Conventional cylindrical specimens were prepared in superpave gyratory compactor with bitumen contents 5.0 %, 5.5 %, 6.0 %, 6.5 % and 7.0 % by weight of aggregates, and volumetric and Marshall properties were determined. Tensile strength, behaviour to repeated loading etc. were checked for cylindrical specimens prepared at optimum bitumen content, whereas specially prepared slab specimens were used to check the rutting resistance of SMA mixtures. From the laboratory study, it was observed that, out of the two SMA mixtures, the one with NMAS 16 mm performed better compared to the other. These improved properties may be attributed towards the larger coarse aggregate sizes in the mixture.

Keywords Stone matrix asphalt · Stone-to-stone contact · Drain down · Aggregate gradation · Nominal maximum aggregate size

1 Introduction

Stone matrix asphalt (SMA) is a gap-graded HMA developed in Germany in the 1960's, to resist the wear and tear on pavements caused by studded tyres. Later the mix was found to be more rut resistant and durable than conventional dense-graded mixtures and this encouraged other European countries also to utilise this mixture [1]. Some transportation agencies from USA conducted a study tour to Europe in 1990 and they were impressed with the performance of SMA [2]. This led to detailed laboratory and field investigations on SMA and its successful performance made the mixture one of the primary choices for pavement engineers.

Stone matrix asphalt has higher proportion of coarse aggregates and binder mortar compared to conventional mixtures. Good stone-to-stone contact exists between the aggregates forming coarse aggregate skeleton, which provides better strength and rut resistance to the mixture. The coarse aggregate skeleton contributes to the shear strength and effective loading distribution pattern of vehicles to endure heavier traffic loads compared to the dense-graded mixtures [3–5]. The rich binder mortar consisting of fine aggregates, bituminous binder, mineral filler and generally a stabilising additive also provides durability to the mixture due to higher binder and filler content. Stabilising additive is used to control drain down, which is a usual phenomenon

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in gap-graded mixtures with higher bitumen and filler content like SMA, where a portion of bitumen and fines may be separated and flow down from the mixture during the elevated temperatures of production, transport, laying and compaction.

1.1 Aggregate gradation

Many researchers have observed that the gradation of aggregates is having a significant effect on the performance of different types of HMA's [6–9]. Brown and Bassett [6] studied the effects of maximum aggregate size (MAS) on the properties of asphalt aggregate mixtures by conducting studies on five different aggregate gradations with five MAS's. Xie et al. [10] and Cooley and Hurley [11] studied the performance of SMA mixtures with different nominal maximum aggregate sizes (NMAS) (9.5 and 4.75 mm). The basic principle of SMA lies on the coarse aggregate skeleton, and it is very important to achieve proper stone-to-stone contact with good quality aggregates for any SMA mixture. Coarse aggregates with Los Angeles abrasion value <30 % were observed to give better performance to SMA [12]. Inferior quality aggregates may lead to aggregate break down during mixing and compaction, which could alter the mix gradation, potentially causing a loss of stone-on-stone contact between the coarse aggregate particles [13].

Generally, SMA has about 70 % coarse aggregates and comparatively higher filler and bitumen content. There is a 30-20-10 thumb rule, traditionally followed by many agencies for SMA gradation. As per this rule, SMA mixture should have 30 %, 20 % and 10 % materials passing through standard sieves 4.75, 2.36 mm and 75 µ, respectively [14]. Different countries and agencies developed aggregate gradations for SMA mixture. To check the stone-to-stone contact between coarse aggregates, determination of voids in coarse aggregates (VCA) method was suggested by Brown and Mallick [15]. VCA for aggregates in dry-rodded condition ($\mathrm{VCA_{DRC}}$) and also for the entire mixture ($\mathrm{VCA_{MIX}}$) were calculated using Eqs. 1 and 2, and for stone-to-stone contact to exist, $\mathrm{VCA_{MIX}}$ should be less than $\mathrm{VCA_{DRC}}$.

$$\mathrm{VCA_{DRC}} = \frac{(G_{\mathrm{CA}} Y_{\mathrm{W}} - Y_{\mathrm{S}})}{G_{\mathrm{CA}} Y_{\mathrm{W}}} \times 100, \tag{1}$$

$$\mathrm{VCA_{MIX}} = 100 - \left(\frac{G_{\mathrm{MB}}}{G_{\mathrm{CA}}} \times P_{\mathrm{CA}}\right), \tag{2}$$

where G_{CA} is the bulk specific gravity of the coarse aggregate fraction, Y_{W} is the unit weight of water (998 kg/m^3), Y_{S} is the unit weight of coarse aggregate fraction in dry-rodded condition (kg/m^3) (determined in accordance with ASTM C 29), G_{MB} is the Bulk specific gravity of compacted mixture, P_{CA} is the Percent coarse aggregate in the total mixture.

In India, based on the guidelines provided by Kandhal [16], Indian Roads Congress (IRC) has issued a special publication for SMA [17] in 2008, but the implementation of this mixture in field is very limited. Compared to other bituminous mixtures, aggregate gradation is more significant in the case of SMA mixtures. The main objective of this investigation is to prepare SMA mixtures with two different aggregate gradations and compare them based on their performance in various laboratory tests. Two different aggregate gradations with two NMAS were adopted for SMA and mixtures were prepared to satisfy the requirements as per IRC. The type and source of aggregates, bituminous binder and all other constituent materials were same so that the difference between mixtures is only due to the aggregate gradation and NMAS.

2 Materials used

Crushed granite aggregates collected from nearby quarry were used to prepare SMA mixtures. The aggregates were having good quality and satisfied the necessary requirements for SMA. The physical properties of aggregates were tested and are presented in Table 1. Generally, a modified bituminous binder is suitable in SMA to control drain down, or else suitable stabilising additive should be used. Polymer-modified bitumen (PMB) manufactured with polymer (elastomeric or plastomeric) as the modifier under carefully controlled conditions, results in enhanced properties and this makes it suitable for wearing course application under high traffic and rainfall [18]. PMB grade 70 is recommended by IRC for atmospheric temperature of 35–45 °C, and the same was used in this investigation. Basic properties of PMB were tested and are reported in Table 2. Quarry dust and hydrated lime were used as mineral filler, and quantity of lime was limited to 2 % by weight of aggregates.

In this study, two different aggregate gradations with NMAS 16 and 13.2 mm were considered to prepare SMA mixtures and they are named as SMA 1 and SMA 2, respectively. Gradation for SMA with 16 mm NMAS (SMA 1) was adopted from Chinese specifications [19] and that with 13.2 mm NMAS (SMA 2) from IRC [17] and are presented in Table 3. The SMA mixture requirements as per IRC are presented in Table 4.

3 Experimental investigation

SMA mixtures with both aggregate gradations were prepared with bitumen contents 5.0 %, 5.5 %, 6.0 %, 6.5 %

Table 1 Properties of coarse aggregates

Property	Results	IRC SP 79 requirements
Aggregate impact value	15.89 %	24 % maximum
Los Angeles abrasion value	16.40 %	25 % maximum
Water absorption	0.35 %	2 % maximum
Specific gravity test	2.64	–
Combined flakiness and elongation index	23.5 %	30 % maximum

Table 2 Properties of PMB

Property	Results obtained
Penetration (100 gramme, 5 s at 25 °C) (1/10th of mm)	60.4
Softening point, °C (Ring & Ball Apparatus)	59
Ductility at 27 °C (5 cm/min pull) (cm)	> 100
Flash point (°C)	244
Viscosity at 150 °C, poise	3.5
Test on residue for thin film oven tests	
Loss in mass (%)	0.088
Increase in softening point (°C)	4
Reduction in penetration of residue (at 25 °C %)	22.5
Elastic recovery of half thread in ductilometer at 25 °C (%)	65

and 7.0 % by weight of aggregates. Specimens were compacted in superpave gyratory compactor (SGC) by giving 100 gyrations and maintaining the ram pressure, gyration angle and rate of gyration as 600 kPa, 1.25° and 30 rpm respectively. For all tests other than rutting test, minimum three specimens were prepared for each SMA mixture and the average of the three values was considered, whereas two SMA slabs were prepared for each mixture to evaluate rutting.

3.1 Drain down

Drain down test was conducted as per ASTM D 6390 in a wire basket made up of standard sieve cloth of 6.3 mm size (shown in Fig. 1), at temperatures 160 and 170 °C. A known weight of SMA mixture is prepared and poured in the basket and is hung in an oven maintained at test temperature. The material drained during the test period of 1 h is collected in a catch plate and weighed. The ratio of weight of material drained to the initial weight of mixture is known as drain down. In this study, drain down was observed to be <0.3 %, the specified maximum limit, for both SMA 1 and SMA 2.

Table 3 Aggregate Gradation for SMA

IS sieve size (mm)	Cumulative % by weight of total aggregate passing			
	SMA 1 (NMAS 16 mm)		SMA 2 (NMAS 13 mm)	
	Range	Adopted	Range	Adopted
19	100	100	100	100
16	90–100	95	–	–
13.2	60–80	70	90–100	95
9.5	40–60	50	50–75	62.5
4.75	20–32	26	20–28	24
2.36	18–27	22	16–24	20
1.18	14–22	18	13–21	18
0.6	12–19	16	12–18	16
0.3	10–16	14	10–20	14
0.15	9–14	12	–	–
0.075	8–12	10	8–12	10

Table 4 SMA mixture requirements

Mix design parameters	Requirements
Air void content (%)	4.0
Bitumen content (%)	5.8 minimum
Voids in mineral aggregates (VMA) (%)	17 minimum
Voids in coarse aggregates mix (VCA_{MIX}) (%)	Less than VCA in the dry-rodded condition (VCA_{DRC})
Asphalt drain down (%)	0.3 maximum
Tensile strength ratio (TSR) (%)	80 minimum

3.2 Volumetric and Marshall properties

Maximum theoretical specific gravity (G_{MM}) was determined for each mixture in loose uncompacted form using asphalt density tester, as per ASTM D 2041. Cylindrical SMA specimens were prepared in SGC and their dimensions and weights were measured to calculate the volumetric properties like bulk specific gravity (G_{MB}), air voids (V_A), voids in mineral aggregates (VMA) and voids filled with bitumen (VFB). G_{MM} was observed to be between 2.43–2.50 and 2.41–2.49 g/cm^3 for SMA 1 and SMA 2 mixtures respectively, and G_{MB} between 2.34–2.37 and 2.33–2.35 g/cm^3. VMA was above 17 % for both mixtures and V_A was in the range 3.0 %–6.6 %. Marshall test was conducted as per ASTM D 6927 to determine the stability and flow of each specimen. Marshall stability was observed between 14.6–20.1 and 14.5–19.4 kN, respectively, for SMA 1 and SMA 2 mixtures. SMA 1 mixtures have comparatively better properties than SMA 2, including G_{MM}, G_{MB}, Marshall stability etc. VCA_{DRC} depends only

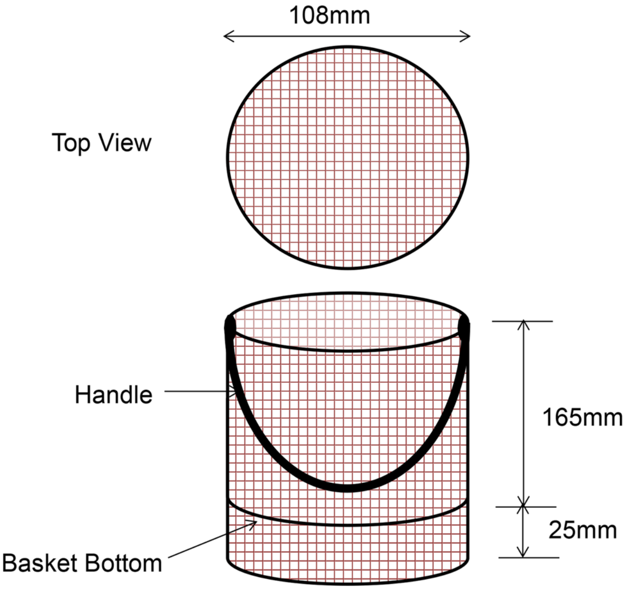

Fig. 1 Wire basket assembly for drain down test

on the aggregate properties and gradation, and was obtained as 42.68 % and 43.47 % for SMA 1 and SMA 2, respectively. For all mixtures of SMA 1 and SMA 2, VCA_{MIX} values were less than the corresponding VCA_{DRC} values, and this ensured stone-to-stone contact between the coarse aggregates. Volumetric characteristics and Marshall properties of both SMA mixtures at bitumen contents 5 %–7 % are presented in Table 5.

Mixtures of both gradations with all bitumen contents satisfied the SMA mixture requirements and hence only air voids were considered as the determining factor for optimum bitumen content (OBC), and bitumen content corresponding to 4 % air voids is taken as the OBC. For SMA 1, it was 6.00 %, whereas for SMA 2 it was slightly higher (6.12 %). The increased density of SMA 1 caused less air voids and this provided less OBC value. The volumetric and Marshall properties of both mixtures at corresponding OBC are presented in Table 6.

Table 6 Volumetric and Marshall properties at OBC

Property	Mixture	
	SMA 1	SMA 2
OBC (%)	6.00	6.12
G_{MM} (g/cm^3)	2.463	2.445
G_{MB} (g/cm^3)	2.366	2.347
VMA (%)	17.33	18.86
VFB (%)	75.72	78.73
MS (kN)	19.60	19.13
FV (mm)	3.99	3.52
MQ (kN/mm)	4.91	5.43
VCA_{MIX}	39.37	38.52
VCA_{MIX}/VCA_{DRC}	0.922	0.886

3.3 Indirect tensile strength (ITS)

Indirect tensile strength is a measure of tensile strength of bituminous mixtures measured along the diametral plane of cylindrical specimens, as per AASHTO T 283 specification. In this method, specimens are tested in normal conditions and also after subjecting to accelerated weathering phenomenon. Accelerated weathering is induced in laboratory by conditioning the specimens for a single freeze–thaw cycle. The specimen is subjected to freezing at −15 ± 3 °C for a minimum duration of 16 h and then kept in hot water bath maintained at 60 °C for 24 h. The specimens were tested for tensile strength as shown in Fig. 2. The ratio of ITS value of conditioned specimens to that of

Table 5 Volumetric and Marshall properties of SMA mixtures

Mixture	SMA 1					SMA 2				
Property	Bitumen content by weight of aggregate					Bitumen content by weight of aggregate				
	5.0	5.5	6.0	6.5	7.0	5.0	5.5	6.0	6.5	7.0
G_{MM} (g/cm^3)	2.498	2.48	2.463	2.446	2.43	2.483	2.466	2.449	2.432	2.416
G_{MB} (g/cm^3)	2.34	2.359	2.369	2.361	2.363	2.332	2.342	2.345	2.348	2.343
VA (%)	6.32	4.90	3.81	3.50	2.77	6.09	5.03	4.25	3.47	3.03
VMA (%)	17.45	17.19	17.21	17.90	18.22	18.51	18.55	18.83	19.11	19.66
VFB (%)	62.28	69.96	76.45	79.12	83.46	67.10	72.91	77.45	81.83	84.57
MS (kN)	14.64	17.66	20.1	19.17	17.83	14.58	15.69	19.35	18.83	15.06
FV (mm)	3.05	3.60	4.10	4.15	4.55	3.15	3.35	3.50	3.60	3.75
MQ (kN/mm)	4.80	4.90	4.90	4.62	3.92	4.63	4.68	5.53	5.23	4.02
VCA_{MIX}	39.40	39.23	39.28	39.82	40.08	38.18	38.24	38.49	38.73	39.18
VCA_{MIX}/VCA_{DRC}	0.923	0.919	0.92	0.933	0.939	0.878	0.880	0.885	0.891	0.901
OBC (%)	6.00					6.12				

Fig. 2 ITS test setup

Table 7 ITS test results

SMA Mix	ITS (MPa)		TSR (%)
	Unconditioned	Conditioned	
SMA 1	1.110	1.013	91.26
SMA 2	0.867	0.773	89.16

normal specimens is known as tensile strength ratio (TSR), which is a measure of moisture resistance of bituminous mixtures. The results are presented in Table 7 and it can be seen that, ITS is better for SMA 1 mixtures for both conditioned and unconditioned cases and were having slightly higher TSR value compared to SMA 2 mixtures.

3.4 Stripping

Stripping or Boiling test is conducted to visually observe the stripping behaviour of mixture, which also gives an indication about the mixture's water sensitivity. In this study, loose SMA mixtures were tested for stripping as per both ASTM and Indian Standards (IS) methods. In ASTM method, the mixture is immersed in boiling water for 10 min, whereas in IS method, the mixture is kept in water bath at 60 °C for 24 h. In both cases, stripping is determined by visual observation after the test duration. For both SMA 1 and SMA 2 mixtures, very negligible stripping was observed.

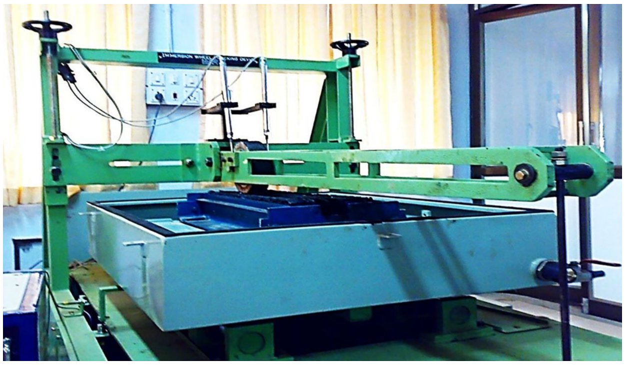

Fig. 3 Wheel-tracking device

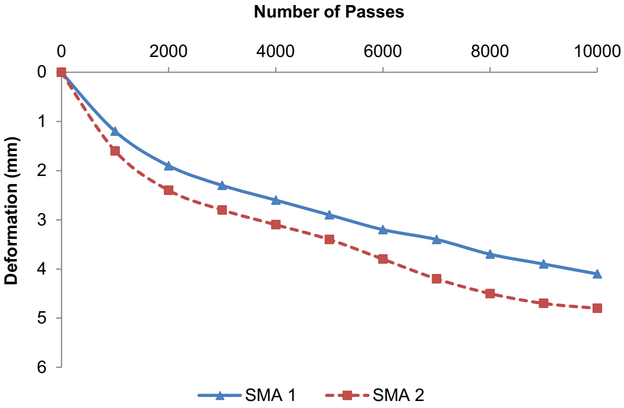

Fig. 4 Rutting test results for SMA mixtures

3.5 Rutting characteristics

Rutting or permanent deformation is a major distress observed in flexible pavements. Rutting behaviour of SMA mixtures prepared in the study was assessed by wheel-tracking test. The test was conducted using the wheel-tracking device, shown in Fig. 3, on slabs with 600 × 200 × 50 mm size prepared at OBC for both SMA 1 and SMA 2 mixtures. The device has a loaded wheel and a confined steel mould in which the slab is rigidly restrained on all sides and placed on a platform. The wheel makes to and fro travel of 600 mm in the lengthwise direction along the middle of the slab. The deformation caused on the slab surface by this movement is recorded by means of two linear variable differential transducers (LVDTs) fixed on either side of the wheel and is displayed [20, 21].

The test was continued for 10,000 wheel passes and the final deformation was observed as 4.1 and 4.8 mm for SMA 1 and SMA 2, respectively. From the results depicted

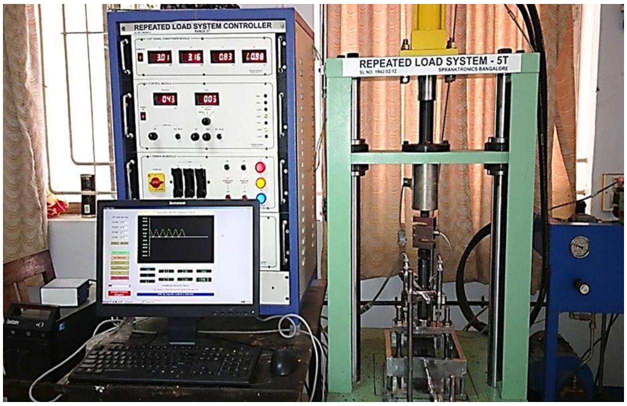

Fig. 5 Repeated load testing machine

Fig. 6 Specimen arrangement in repeated load testing machine

in Fig. 4, it can be seen that SMA 2 slab was having slightly more rut depth at all wheel passes.

3.6 Fatigue behaviour

Table 8 Repeated load test results

Mix type	Average load applied (kg)	% of ITS load	Fatigue life (No. of cycles)
SMA 1	176.45	15.04	7562
	386.81	32.98	2993
	579.65	49.42	1269
SMA 2	137.13	14.97	7256
	306.78	33.49	2645
	459.36	50.15	1093

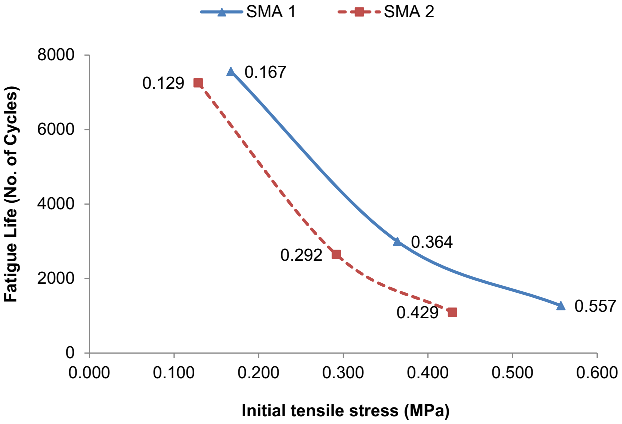

Fig. 7 Variation of fatigue life with initial tensile stress

Behaviour of bituminous mixtures to repeated load application is a serious matter of concern. In this study, cylindrical SMA specimens were subjected to repeated dynamic loading in the repeated load testing machine, and the number of cycles required for the specimen to fail was considered as the fatigue life (FL). The machine, shown in Fig. 5, has a hydraulic loading system which applies dynamic load to the specimen, and a cooling system to control the temperature. The load is applied through a loading shaft, that can be moved in the vertical direction and the specimen is kept in a rigid rectangular frame below the shaft. The load is applied in positive half sine-wave pattern, with a loading frequency of 1 Hz and a rest period of 0.9 s. Two horizontal and two vertical LVDTs (H1, H2, V1 and V2) are present in the set up to measure the deformation of specimen. The specimen arrangement is shown in Fig. 6. The machine is controlled and the data are recorded through a computer connected to it [22].

Specimens of SMA 1 and SMA 2, prepared at OBC, were subjected to approximately 15 %, 33 % and 50 % of the corresponding ITS failure loads. Loading frequency was set as 1 Hz, provided rest period of 0.9 s and the failure was considered at deflection of 5 mm. From the results presented in Table 8 and Fig. 7, it can be observed that FL decreases with the increase in applied load and initial tensile stress (σ_i). SMA 1 mixture performed better than SMA 2 in this test. Even though the applied load was more in the case of SMA 1, they withstood for more cycles. From the plot in Fig. 7, FL corresponding to constant σ_i values for both mixtures can be calculated.

4 Discussion and conclusion

In this study, two aggregate gradations for SMA were adopted, SMA 1 and SMA 2, with NMAS 16 and 13.2, respectively. Same materials like, aggregate, bitumen and mineral filler were used and also same test conditions were maintained for both mixtures. The main difference between these gradations were in the NMAS and in the coarse aggregate sizes, but other important factors of gradation affecting the mixture performance were kept as uniform. The fraction of materials passing 4.75 mm sieve was 26 % and 24 %, respectively for SMA 1 and SMA 2, and 75 μ passing material was 10 % for both mixtures. From the investigation, it can be seen that mixture with larger NMAS and more coarse aggregate sizes (16, 13.2, 9.5 and 4.75 mm) performs better than the other mixture, having coarse aggregate sizes 13.2, 9.5 and 4.75 mm. SMA 1 mixtures showed higher density, stability and tensile strength, and were observed to be more rut resistant and having higher FL compared to SMA 2 mixtures. The improved performance of mixture with NMAS 16 mm may be attributed towards the presence of larger size coarse aggregates. For SMA 2, approximately 70 % of the aggregates retain only on 9.5 and 4.75 mm sieves, whereas the same aggregate content is almost equally distributed among sieves 13.2, 9.5 and 4.75 mm, in the case of SMA 1 mixture. The presence of more coarse aggregate sizes helps in attaining more density and strength for SMA 1 mixture.

From the laboratory investigation, following conclusions can be drawn.

- Both SMA mixtures satisfied drain down requirements without any stabilising additive and this is due to the usage of PMB as binder material.
- SMA 1 mixtures have comparatively higher density, stability and other volumetric and Marshall properties. OBC was found to be slightly less for these mixtures.
- For SMA 1 mixtures, tensile strength was 28 %–31 % higher than the other mix and moisture resistance was also slightly better.
- SMA 1 mixture was better resistant to rutting, and in wheel-tracking test, deformations were 0.4–0.7 mm less than SMA 2 slab for all wheel passes. After 10,000 passes rut depth was 4.1 mm for SMA 1, compared to 4.8 mm in the case of SMA 2 slab.
- At different proportions of ITS loads, fatigue life of SMA 1 mixes were about 10 % higher than SMA 2, whereas at constant tensile stress, the improvement can be minimum 21 %.

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