Chapter 4

MARSHALL MIX DESIGN AND ANALYSIS

4.1 INTRODUCTION

Suitably designed bituminous mix will withstand heavy traffic loads under adverse climatic conditions and also fulfill the requirement of structural and pavement surface characteristics. The objective of the design of bituminous mix is to determine an economical blend through several trial mixes. The gradation of aggregate and the corresponding binder content should be such that the resultant mix should satisfy the following conditions.

(i) Sufficient binder to ensure a durable pavement by providing a water proofing coating on the aggregate particles and binding them together under suitable compaction.

(ii) Sufficient stability for providing resistance to deformation under sustained or repeated loads. This resistance in the mixture is obtained from aggregate interlocking and cohesion which generally develops due to binder in the mix.

(iii) Sufficient flexibility to withstand deflection and bending without cracking. To obtain desired flexibility, it is necessary to have proper amount and grade of bitumen.

(iv) Sufficient voids in the total compacted mix to provide space for additional compaction under traffic loading.

(v) Sufficient workability for an efficient construction operation in laying the paving mixture.

There are three principal bituminous mix design methods in general use. They are Marshall Method, Hveem Method and Superpave Method. Marshall mix design is the widely used method throughout India. In this method load is applied to a cylindrical specimen of bituminous mix and the sample is monitored till its failure as specified in the ASTM standard (ASTM D1559). For the present work, the bituminous mix is designed using the Marshall Method and arrived at the volumetric properties.

4.2 MARSHALL MIX DESIGN

This test procedure is used in designing and evaluating bituminous paving mixes and is extensively used in routine test programmes for the paving jobs. There are two major features of the Marshall method of designing mixes namely, density – voids analysis and stability – flow test.

Strength is measured in terms of the 'Marshall's Stability' of the mix following the specification ASTM D 1559 (2004), which is defined as the maximum load carried by a compacted specimen at a standard test temperature of 60˚C. In this test compressive loading was applied on the specimen at the rate of 50.8 mm/min till it was broken. The temperature 60˚C represents the weakest condition for a bituminous pavement.

The flexibility is measured in terms of the 'flow value' which is measured by the change in diameter of the sample in the direction of load application between the start of loading and at the time of maximum load. During the loading, an attached dial gauge measures the specimen's plastic flow (deformation) due to the loading. The associated plastic flow of specimen at material failure is called flow value.

The density- voids analysis is done using the volumetric properties of the mix, which will be described in the following sub sections.

4.2.1 Gradation of aggregates

Gradation of aggregates is one of the most important factors for the design of SMA mixture. The sieve analysis, blending and the specified limits of the SMA mixture are given in Table 4.1 as per NCHRP - 425, TRB.

4.2.2 Volumetric properties

Fundamentally, mix design is meant to determine the volume of bitumen binder and aggregates necessary to produce a mixture with the desired properties (Roberts et al., 1996). Since weight measurements are typically much easier, weights are taken and then converted to volume by using specific gravities. The following is a discussion of the important volumetric properties of bituminous mixtures.

The properties that are to be considered, include the theoretical maximum specific gravity G_{mm}, the bulk specific gravity of the mix G_{mb}, percentage air voids VA, percentage volume of bitumen V_b, percentage void in mineral aggregate VMA and percentage voids filled with bitumen VFB.

Table 4.1 Gradation of aggregates and their blends for SMA mixture

Sieve size (mm)	Percentage passing				Adopted Grading A: B: C: D 50:30:11:9	Specified Grading NCHRB, TRB
	20 mm (A)	10 mm (B)	Stone dust (C)	Cement (D)		
25.0	100	100	100	100	100	100
19.0	98	100	100	100	99	90 -100
12.5	20	100	100	100	60	50 - 74
9.50	4	58	100	100	39	25 - 60
4.75	0	6	100	100	22	20 - 28
2.36	0	0	92	100	19	16 - 24
1.18	0	0	77	100	17	13 - 21
0.6	0	0	64	100	16	12 - 18
0.3	0	0	45	100	14	12 - 15
0.075	0	0	6	96	9	8 - 10

Theoretical Maximum Specific Gravity of the mix (G_{mm}) is defined as

$$G_{mm} = \frac{\mathrm{W_{mix}}}{Vol.\ of\ the\ (mix\ -\ air\ voids)}$$

Where, W_{mix} is the weight of the bituminous mix, G_{mm} is calculated as per ASTM D 2041 – 95.

Bulk specific gravity of mix (G_{mb})

The bulk specific gravity or the actual specific gravity of the mix G_{mb} is the specific gravity considering air voids and is found out by

$$G_{mb} = \frac{\mathrm{W_{mix}}}{\text{Bulkvolume of the mix}}$$

It is obtained by measuring the total weight of the mix and its volume. Volume is determined by measuring the dimensions of the sample or for better accuracy it can be measured by the volume of water it displaces. However, while the sample is immersed in water, some water may be absorbed by the pores of the mix. Therefore, the mix is covered with a thin film of paraffin and the volume of the sample is measured by knowing the volume of paraffin used to coat its surface. The bulk specific gravity of paraffin-coated specimen is determined in accordance with ASTM standard test procedure D1188-96.

The phase diagram of the bituminous mix is given in Fig. 4.1. When aggregate particles are coated with bitumen binder, a portion of the binder is absorbed into the aggregate, whereas the remainder forms a film on the outside of the individual aggregate particles. Since the aggregate particles do not consolidate to form a solid mass, air pockets also appear within the bitumen-aggregate mixture. Therefore, as Fig. 4.1 illustrates, the four general components of HMA are: aggregate, absorbed bitumen, bitumen not absorbed into the aggregate (effective bitumen) and air.

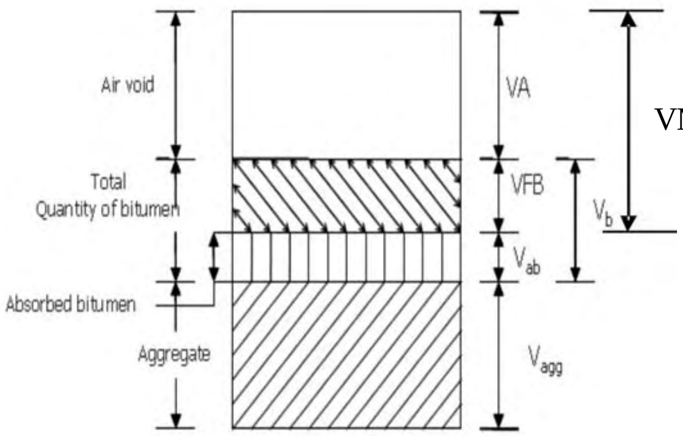

Fig. 4.1 Phase diagram of the bituminous mix

Effective Bitumen Content (P_{be})

It is the total bitumen binder content of the mixture less the portion of bitumen binder that is lost by absorption into the aggregate.

Volume of Absorbed Bitumen (V_{ab})

It is the volume of bitumen binder in the mix that has been absorbed into the pore structure of the aggregate. This volume is not accounted for the effective bitumen content.

Air voids percent (VA)

It is the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the bulk volume of the compacted paving mixture. The amount of air voids in a mixture is extremely important and closely related to stability, durability and permeability.

The voids in a compacted mixture are obtained in accordance with ASTM standard test method D3203-94. The following equation represents the percentage of air voids in the specimen.

$$VA = \frac{(G_{mm} - G_{mb)} 100}{G_{mm}}$$

where G_{mm} is the theoretical specific gravity of the mix and G_{mb} is the bulk specific gravity of the mix.

Voids in mineral aggregate (VMA)

The total volume of voids in the aggregate mix (when there is no bitumen) is called Voids in Mineral Aggregates (VMA). In other words, VMA is the volume of intergranular void space between the aggregate particles of a compacted paving mixture. It includes the air voids and the volume of bitumen not absorbed into the aggregate. VMA is expressed as a percentage of the total volume of the mix.

When VMA is too low, there is not enough room in the mixture to add sufficient bitumen binder to coat adequately over the individual aggregate particles. Also, mixes with a low VMA are more sensitive to small changes in bitumen binder content. Excessive VMA will cause unacceptably low mixture stability (Roberts et al., 1996). Generally, a minimum VMA of 17% is specified. VMA can be calculated as,

$$VMA = \left(1 - \frac{G_{mb} x P_s}{G_{Sb}}\right) 100$$

where P_s is the fraction of aggregates present, by total weight of the mix and G_{sb} is the bulk specific gravity of the mixed aggregates.

Voids Filled with Bitumen (VFB)

VFB is the voids in the mineral aggregate frame work filled with bitumen binder. This represents the volume of the effective bitumen content. It can also be described as the percent of the volume of the VMA that is filled with bitumen. VFB is inversely related to air voids and hence as air voids decreases, the VFB increases.

$$VFB = \frac{(VMA - VA)}{VMA} x100$$

where, VA is air voids in the mix and VMA is the voids in the mineral aggregate.

The decrease of VFB indicates a decrease of effective bitumen film thickness between aggregates, which will result in higher low-temperature cracking and lower durability of bitumen mixture since bitumen perform the filling and healing effects to improve the flexibility of mixture.

4.2.3 Role of volumetric parameters of mix

Bitumen holds the aggregates in position, and the load is taken by the aggregate mass through the contact points. If all the voids are filled with bitumen, the one to one contact of the aggregate particles may lose, and then the load is transmitted by hydrostatic pressure through bitumen, and hence the strength of the mix reduces. That is why stability of the mix starts reducing when bitumen content is increased further beyond a certain value.

During summer season, bitumen softens and occupies the void space between the aggregates and if void is unavailable, bleeding is caused. Thus, some amount of void is necessary in a bituminous mix, even after the final stage of compaction. However excess void will make the mix weak from its elastic modulus and fatigue life considerations. Evaluation and selection of aggregate gradation to achieve the specified minimum VMA is the most difficult and time-consuming step in the mix design process.

In the Volumetric method of mix design approach, proportional volume of air voids, binder and aggregates are analyzed in a compacted mixture, applying a compaction close to that of field compaction. SMA mixture design requirements is given in Table 4.2

Table 4.2 SMA mixture design criteria

Design Parameter	Design Criteria
Percent Air Voids	3 – 5%
Percent voids in mineral aggregate (VMA)	17 (minimum)
Stability value	6200 N(minimum)
Flow value	2 – 4 mm
Retained Stability (LS-283).	70% (minimum)
Draindown @ Production Temperature(AASHTO T305)	0.3 % (maximum)

4.3 MIX DESIGN

Laboratory mix designs of SMA mixtures are done by Marshall test procedure.

4.3.1 Specimen preparation

Approximately 1200g of aggregates and filler put together is heated to a temperature of 160-170˚C. Bitumen is heated to a temperature of 160˚C with the first trial percentage of bitumen (say 5.5% by weight of the mineral aggregates). Then the heated aggregates and bitumen are thoroughly mixed at a temperature of 160 - 170˚C. The mix is placed in a preheated mould and compacted by a hammer having a weight of 4.5 kg and a free fall of 45.7 cm giving 50 blows on either side at a temperature of 160˚C to prepare the laboratory specimens of compacted thickness 63.5+/-3 mm. Seventy five compaction blows were not given as in the case of dense graded bituminous mixes for heavy traffic condition, since in the gap graded mixes, this would tend to break down the aggregate more and would not result in a significant increase in density over that provided by 50 blows. SMA mixtures have been more easily compacted on the roadway to the desired density than the effort required for conventional HMA mixtures. In this research, the compaction of all the SMA samples are performed using fifty blows of the Marshall hammer on either side of the sample. The heights of the samples are measured and specimens are immersed in a water bath at 60˚C for 35±5 minutes. Samples (Fig. 4.2) are removed from the water bath and placed immediately in the Marshall loading head as shown in Fig. 4.3. The load is applied to the specimen at a deformation rate of 50.8 mm/minute. Stability is measured as the maximum load sustained by the sample before failure. Flow is the deformation at the maximum load. The stability values are then adjusted with respect to the sample height (stability corrections).

For the proposed design mix gradation, four specimens are prepared for each bitumen content within the range of 5.5 – 7.5% at increments of 0.5 percent, in accordance with ASTM D 1559 using 50 blows/face compaction standards. All bitumen content shall be in percentage by weight of the total mix. As soon as the freshly compacted specimens have cooled to room temperature, the bulk specific gravity of each test specimen shall be determined in accordance with ASTM D 2726. The stability and flow value of each test specimen shall then be determined in accordance with ASTM D 1559. After the completion of the stability and flow test, specific gravity and voids analysis shall be carried out for each test specimen to determine the percentage air voids in mineral aggregate and the percentage air voids in the compacted mix and voids filled with bitumen. Values which are obviously erratic shall be discarded before averaging. Where two or more specimens in any group of four are so rejected, four more specimens are prepared and tested.

The average values of bulk specific gravity, stability, flow, VA, VMA and VFB obtained above are plotted separately against the bitumen content and a smooth curve drawn through the plotted values. Average of the binder content corresponding to VMA of 17 % and an air void of 4% are considered as the optimum binder content (Brown, 1992). Stability and Flow values at the optimum bitumen content are then found from the plotted smooth curves and shall comply with the design parameters given in Table 4.2.

The optimum bitumen content (OBC) for the SMA mixture is determined and is found to be 6.42 % (by wt. of total mix). This SMA mixture without additives is considered as the control mixture for the subsequent studies.

Fig. 4.2 Marshall sample

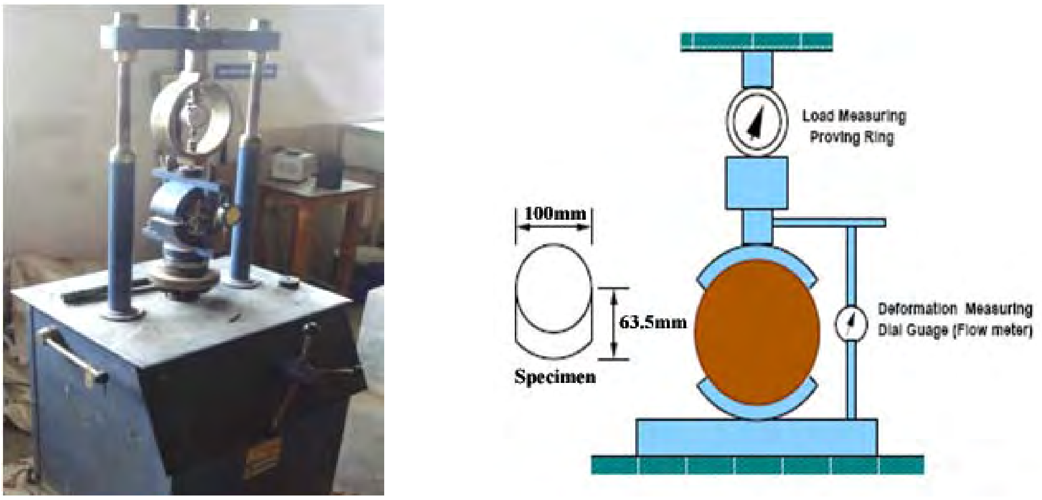

Fig. 4.3 Marshall test apparatus

4.3.2 Stabilized SMA

SMA mixtures with additives are taken as the stabilized SMA. An optimum bitumen content of 6.42 % (by wt. of total mix) as found from Marshall Control mix design is used in preparing all the stabilized mixes to maintain consistency throughout the study.

4.3.2.1 Preparation of Marshall Specimens

Marshall Stability test is conducted on stabilized SMA in more than 100 samples of 100 mm dia and 63.5 mm height by applying 50 blows on each face as per ASTM procedure (ASTM D1559, 2004). Bituminous mixes are prepared by mixing the graded aggregates with 60/70 penetration grade bitumen and additives. Three different natural fibres are used as additives in SMA mixture viz., coir, sisal and banana fibres. Waste plastics in shredded form and a polymer polypropylene are also tried as the additives. The fibre content in this research is varied between 0.1%, 0.2%, 0.3% and 0.4% by weight of mix and the polypropylene and the waste plastics content as 1%, 3%, 5%, 7% and 9% by weight of mix. The procedure adopted for the preparation of Marshall Specimen is the same as used in control mixtures (sec.4.3.1), except, the additives are added in heated aggregate prior to mixing them with heated bitumen (dry blending method). The fibre length in the mixture is preserved as a constant parameter with a value equal to 6 mm. The mixing and compaction temperatures are kept as 165˚C and 150˚C respectively (Brown and Manglorkar, 1993). A total of 120 Marshall samples for all percentages of different additives are prepared.

4.4 MOISTURE SUSCEPTIBILITY TEST

It is well known that presence of moisture in a bituminous mix is a critical factor, which leads to premature failure of the flexible pavement. The loss of adhesion of aggregates with bitumen is studied by utilising Retained Stability test to examine the effect of additive on resistance to moisture induced damage. This test measures the stripping resistance of a bituminous mixture. The test is specified in IRC: SP 53-2002 and is conducted as per ASTM D 1075-1979 specifications. The standard Marshall specimens of 100 mm diameter and 63.5 mm height are prepared. Marshall Stability of compacted specimens is determined after conditioning them by keeping in water bath maintained at 60˚C for 24 hours prior to testing. This stability, expressed as a percentage of the stability of Marshall specimens determined under standard conditions, is the retained stability of the mix. A higher value indicates lower moisture susceptibility (higher moisture damage resistance).

4.5 MARSHALL TEST RESULTS AND DISCUSSION

Results of mix design and their discussion for the fibre stabilized mixtures and the mixtures with waste plastics and polypropylene are given separately in this section.

4.5.1 Fibre stabilized mixtures

Test results of volumetric and mechanical properties of SMA mixtures using different fibres are tabulated in Table 4.3 and discussed in this section.

4.5.1.1 Marshall stability and flow value

From Table 4.3, it is evident that the presence of fibre in the SMA mixtures effectively improves the stability values, which will result in an improvement of mixture toughness. This result indicates that the mixture using fibre would result in higher performance than using the control mixture. Variation of Marshall stability and flow value with different fibre contents are given in Fig. 4.4.a and Fig. 4.4.b

Fig. 4.4.a indicates that the stability of fibre stabilized mixtures increases initially, reaches a maximum value and then decreases with increasing fibre content. Bituminous mixture is an inconsistent, non-uniform, multi-phased composite material consisting of aggregates and sticky bitumen. Therefore, excessive fibres may not disperse uniformly, while coagulate together to form weak points inside the mixture. As a result, stability decreases at high fibre contents.

Table 4.3 Variation of Marshall Properties of SMA with different % of fibres as additive.

Additive	%	Stability (kN)	Flow (mm)	Marshll Quotient (kN/mm)	Air void (%)	Bulk specific gravity	VMA (%)	VFB (%)
Nil	0	7.416	3.18	2.332	4	2.32	18.865	78.796
Coir fibre	0.1	8.19	3.14	2.609	4.14	2.318	18.935	78.135
	0.2	10.073	3.05	3.303	4.31	2.315	19.039	77.363
	0.3	**12.58**	**2.83**	**4.445**	**4.46**	**2.308**	**19.284**	**76.872**
	0.4	7.936	2.72	2.918	4.64	2.298	19.634	76.368
Sisal fibre	0.1	7.743	3.17	2.443	4.09	2.31	19.214	78.714
	0.2	8.701	3.07	2.834	4.24	2.3	19.564	78.328
	0.3	**11.862**	**2.86**	**4.148**	**4.37**	**2.291**	**19.879**	**78.017**
	0.4	8.742	2.77	3.156	4.54	2.278	20.333	77.672
Banana fibre	0.1	7.732	3.16	2.447	4.09	2.308	19.284	78.791
	0.2	8.703	3.09	2.817	4.22	2.296	19.704	78.583
	0.3	**11.854**	**2.86**	**4.145**	**4.34**	**2.286**	**20.030**	**78.333**
	0.4	8.643	2.76	3.132	4.50	2.275	20.438	77.982

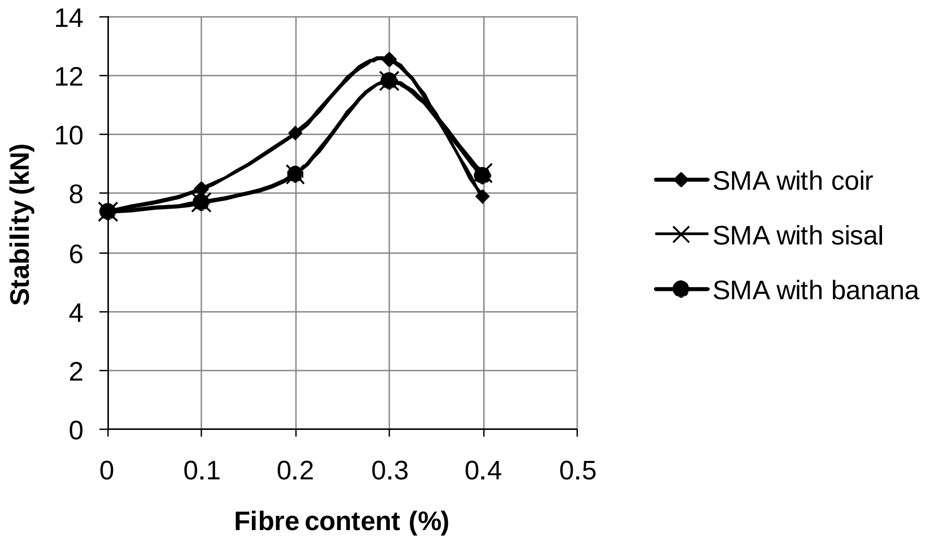

Fig. 4.4.a Variation of stability with different fibre %

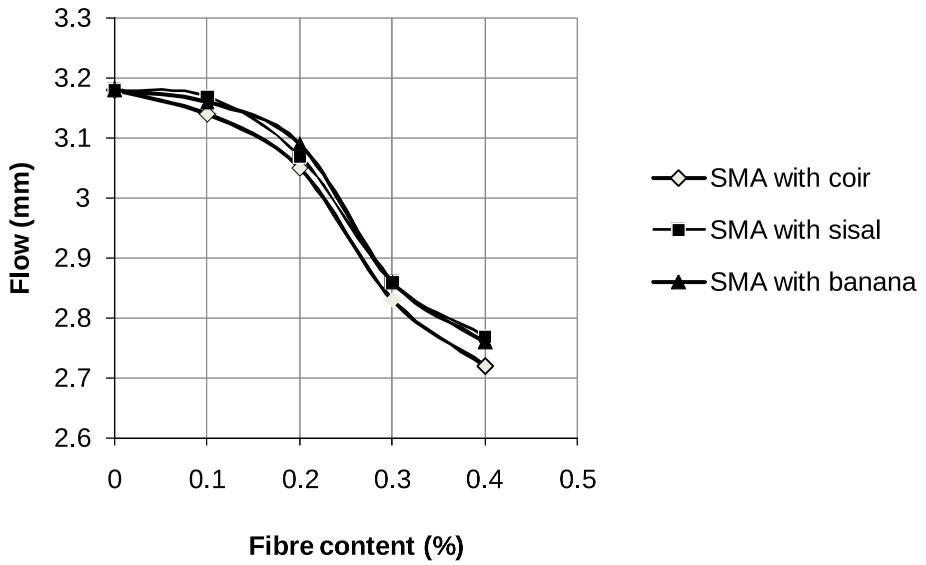

Fig. 4.4.b Variation of flow value with different fibre %

It may be noted that all fibre stabilized mixtures gave the maximum stability at 0.3% fibre content. Comparing different fibre stabilized mixtures, it is evident that the mixtures with coir fibre have the highest stability (12.58 kN), indicating their higher rutting resistance and better performance than mixtures with other fibres. The percentage increase in stability with respect to the control mixture is about 70% for SMA with coir fibre and about 60% for SMA with other fibres. This result could be attributed to fibre's adhesion and networking effects in the stabilized mixtures. The spatial networking effect was regarded as the primary factors contributing to fibre's reinforcement (Chen and Lin, 2005). This trend could be explained as follows: fibre performs as ‘‘bridge” when cracking of bitumen mixture appears and thus resists the propagation of cracking development, which is called bridging cracking effect (Li., 1992). In addition, due to the absorption of light component of bitumen (Serfass and Samanos, 1996), fibre improves the viscosity and stiffness of bitumen (Huang and White, 2001).

Flow value of SMA mixtures decreases after adding fibres, as shown in Fig. 4.4.b. Owing to the stiffness of fibres in the mixture, the mixes become less flexible and the resistance to deformation increases resulting in a low flow value. However, flow values are located within the required specification range of 2 to 4 mm (AASHTO T 245).

Marshall Quotient (MQ) also known as rigidity ratio is the ratio of stability to flow value of the mixture and the Marshall Quotient values of SMA with different fibre contents are shown in Fig. 4.4.c. It is found that MQ of the coir fibre stabilized SMA at 0.3 % fibre content is almost doubled with respect to the control mixture. It can be inferred that these stabilized SMA provide better resistance against permanent deformations due to their high stability and high MQ and also indicate that these mixtures can be used in pavements where stiff bituminous mixture is required.

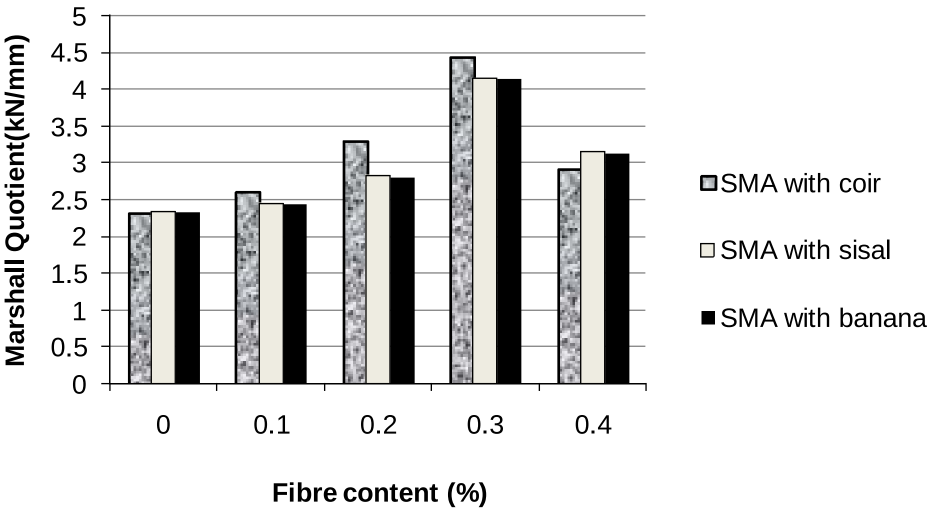

Fig. 4.4.c Variation of Marshall Quotient with different fibre %

4.5.1.2 Bulk specific gravity

The bulk specific gravity of bituminous mixture decreases with increasing fibre content in SMA as depicted in Fig. 4.4.d.

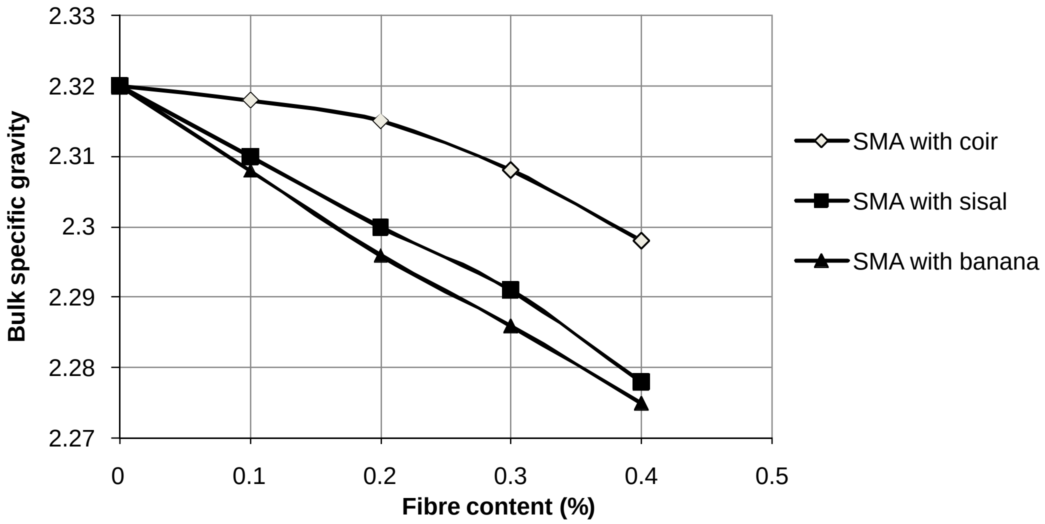

Fig. 4.4.d Variation of bulk specific gravity with different fibre %

This trend is in agreement with other research (Tapkın, 2008; Saeed and Ali, 2008). This result would be attributed due to the different specific gravities of different fibres and the much lower specific gravity of fibre than that of aggregates. Meanwhile, the elastic behavior of mixture increases with increase in fibre content, due to the elastic nature of fibres. As a result, at the same compaction effort (50 blows on both sides of Marshall sample), adding fibre reduces the specific gravity of the control mixture. However, it is noted that the coir fibre stabilized SMA has the highest specific gravity which is due to the fact that coir fibre has the maximum density (Table 3.3) as compared to other fibres. Considering the fact that higher specific gravity results in better design mixes, it can be inferred that coir fibre stabilized mixtures perform better than the other stabilized mixtures.

4.5.1.3 Air void, VMA and VFB

Excessive air voids in the mixture would result in cracking due to insufficient bitumen binders to coat on the aggregates, while too low air void may induce more plastic flow (rutting) and bitumen bleeding. Here the test results (Fig. 4.4.e) show that air void increases after adding fibres into bituminous mixtures. This may be due to the net working effect of the fibre within the mix (lower G_{mb} correlates to higher air voids). The mixtures with coir fibre has the highest air voids than the other mixtures. However, the air voids of mixtures are located within the specification range of 3% to 5% (AASHTO T 312) which support the use of these additives.

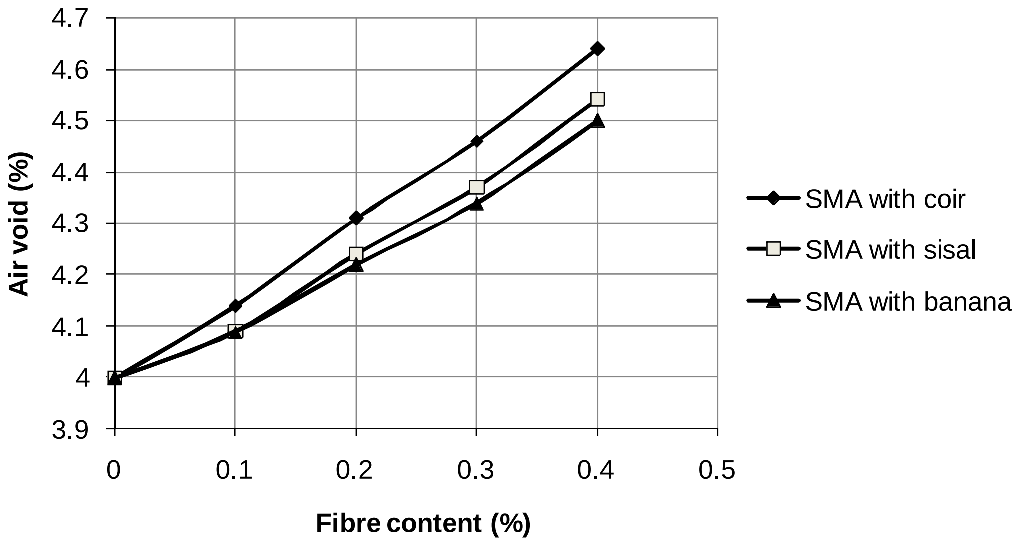

Fig. 4.4.e Variation of air void with different fibre %

Increasing the fibre content increases the VMA of SMA mixtures as shown in Fig. 4.4.f, while reduces VFB as shown in Fig. 4.4.g. With respect to the control mixture, when fibre content increases from 0% to 0.3%, air void increases by about 11.5%, VMA increases by 2.2%, while VFB decreases by 2.4% for coir fibre stabilized mixtures and the corresponding percentage changes are respectively about 9.25% increase, 5.4% increase and 1% decrease for sisal fibre stabilized mixtures and 8.5% increase, 6.2% increase and 1% decrease for banana fibre stabilized mixtures with respect to the control mixture. But all the results are within the required specification range which also supports the use of these additives.

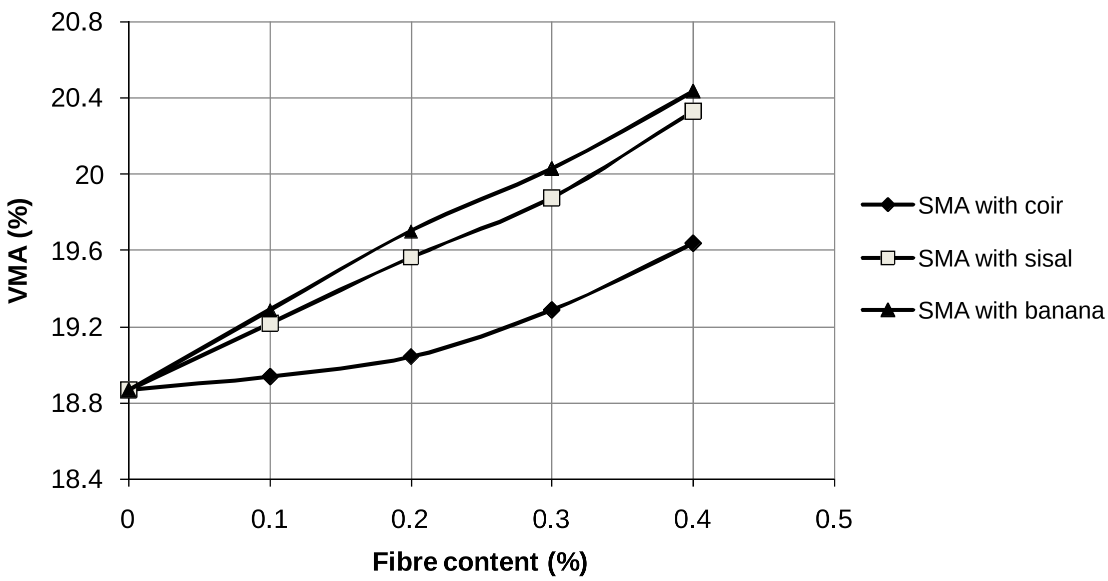

Fig. 4.4.f Variation of VMA with different fibre %

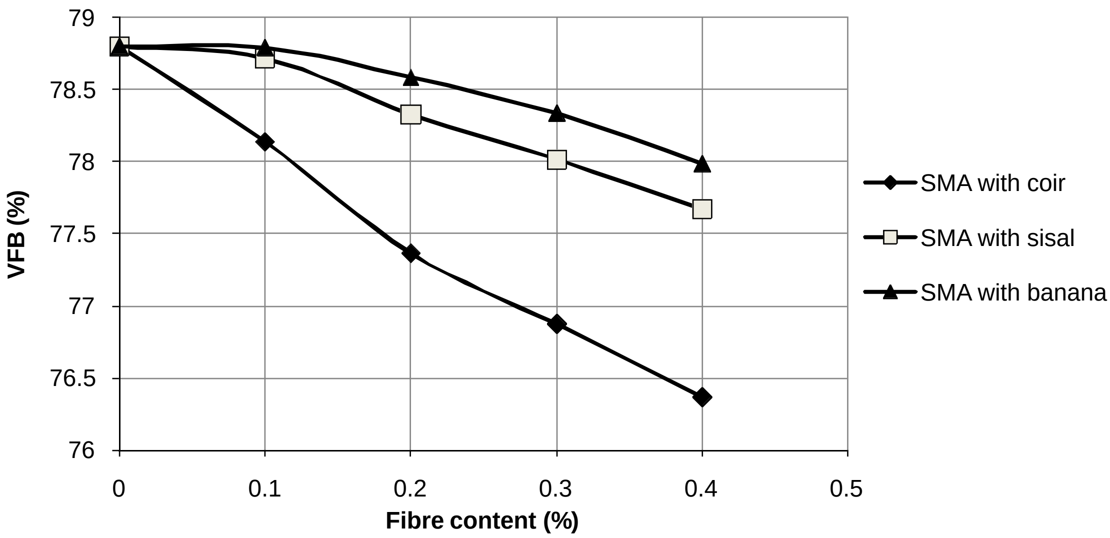

Fig. 4.4.g Variation of VFB with different fibre %

4.5.2 Waste plastics and polypropylene stabilized mixtures

The variation in different Marshall properties for various percentages of waste plastics (WP) and polypropylene (PP) contents are determined for each mix design and is given in Table 4.4.

Table 4.4 Marshall Properties of waste plastics and polypropylene stabilized SMA.

Additive	%	Stability (kN)	Flow (mm)	Marshall Quotient (kN/mm)	Air void (%)	Bulk specific gravity	VMA (%)	VFB (%)
Nil	**0**	**7.416**	**3.18**	**2.332**	**4**	**2.32**	**18.865**	**78.796**
WP	1	8.717	3.025	2.882	3.95	2.326	18.655	78.826
	3	11.18	2.916	3.834	3.91	2.33	18.515	78.882
	5	13.12	2.818	4.656	3.82	2.336	18.305	79.132
	7	**13.7**	**2.794**	**4.903**	**3.66**	**2.346**	**17.955**	**79.616**
	9	10.6	2.876	3.686	3.41	2.356	17.606	80.631
PP	1	8.252	3.085	2.675	3.94	2.328	18.585	78.800
	3	10.213	2.923	3.494	3.86	2.338	18.235	78.832
	5	**12.843**	**2.828**	**4.541**	**3.75**	**2.346**	**17.955**	**79.115**
	7	11.25	2.83	3.975	3.59	2.355	17.641	79.646
	9	10.52	2.872	3.664	3.34	2.368	17.186	80.566

4.5.2.1 Marshall stability and flow value

Fig. 4.5.a and 4.5.b represent the effect of waste plastics and polypropylene content on stability and flow value of the SMA mixtures. The figure indicates that as the additive content increases, the stability value increases initially, reaches a maximum and then decreases. The addition of 5% PP raises the Marshall stability of control mix by 73% and the percentage increase for 7% WP is 85%. This was attributed to the specific gravity of additive (less than 1) which is less than that of bitumen (Table 3.6). This serves to penetrate between particles and enhanced the interlock of aggregates, which increases the stability and decreases the flow value. Beyond this percentage of additive content the stability value decreases. This is related to the decrease in interlocking offered by bitumen binder and additive coated aggregate particles while excess additive occupy the space to be occupied by the bitumen. Test results indicate that the mixtures with waste plastics have the higher stability (13.7 kN) than mixtures with polypropylene, indicating their higher rutting resistance.

Failure in bituminous mixtures can occur within the binder (cohesive failure) or at the aggregate-binder interface (adhesive failure). It can be considered that adhesive bond strength controls the failure mechanism in the Marshall Stability test (Kok and Kuloglu, 2007). The presence of additives in the bituminous mixtures resulted in, increased adhesive bond strength which leads to increased stability values of the mixtures.

Flow value of SMA mixtures decreases initially (up to 7% WP and 5% PP) and after that there is an increase as shown in Fig. 4.5.b. This may be due to the decrease in the stone to stone contact of SMA mixtures at higher additive contents. However, flow values are located within the required specification range of 2 to 4mm (AASHTO T 245).

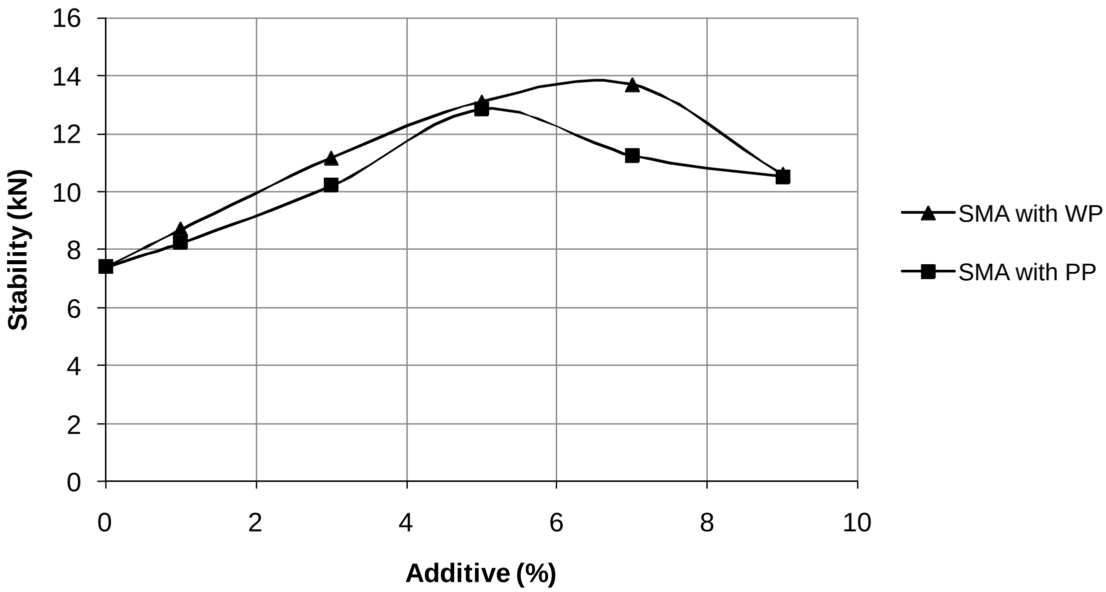

Fig. 4.5.a Variation of stability with different additive %

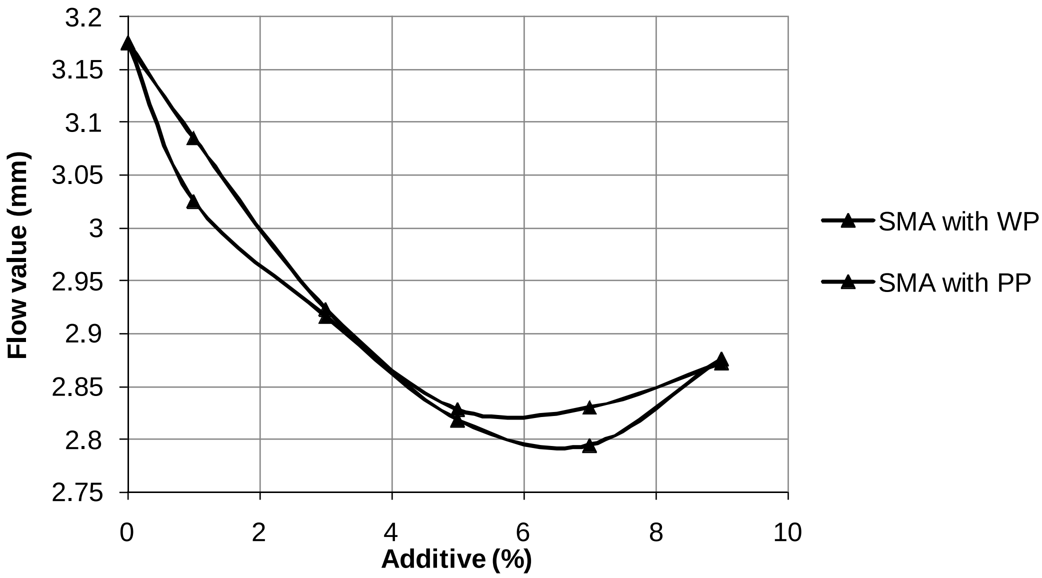

Fig. 4.5.b Variation of flow value with different additive %

From the sited results in Fig. 4.5.c, it is found that the Marshall Quotient almost doubled with respect to the control mixture at 5% PP content and 7% WP content and is found that it is slightly higher with waste plastics additive. It can be inferred that these stabilized SMA provide better resistance against permanent deformations than the control mixture.

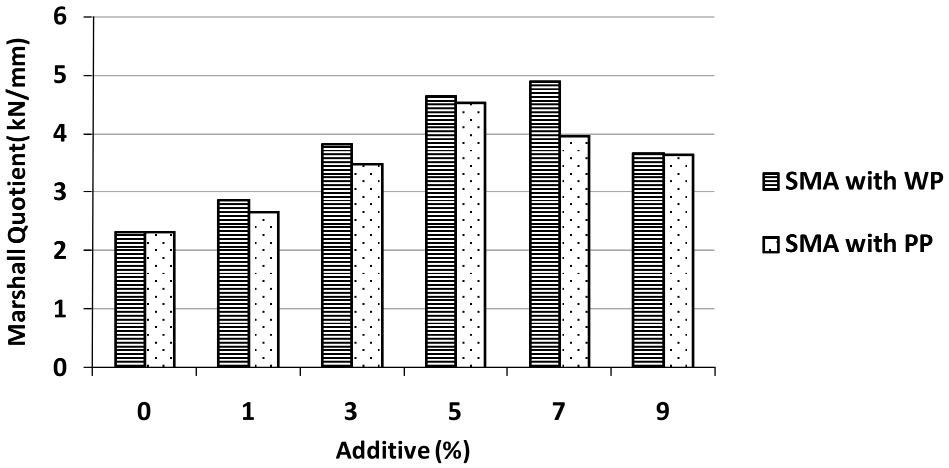

Fig. 4.5.c Variation of Marshall Quotient with additive content

4.5.2.2 Air void and bulk specific gravity

The density of WP and PP is much less than that of aggregates and they will penetrate into the aggregates and a proper coating is formed over it. Owing to the filling property offered by these additives resulting in a less air void in the stabilized mixture as compared to the control mixture (Fig. 4.5.d). But the values are within the specified limit of 3 to 5% which support the use of these additives. Bulk specific gravity of SMA mixture depends on the air voids. Less air voids lead to reduction in bulk volume of the SMA mixture, as a result bulk specific gravity of SMA mix increases with an increase in additive content as shown in Fig. 4.5.e.

4.5.2.3 VMA and VFB

It can be observed from Fig. 4.5.f that VMA decreases by the addition of additives to the bituminous mixtures. This may be due to the decrease of bulk specific gravity as indicated by equation for VMA (Section 4.2.2). But all the results are within the specification range which also supports the use of these additives. VFB of mixtures have an increase after adding additive into the mixture, as shown in Fig. 4.5.g. VFB which represents the volume of the effective bitumen content in the mixture is inversely related to air voids and hence as air voids decreases, the VFB increases. Both additives, waste plastics and polypropylene show the similar trend.

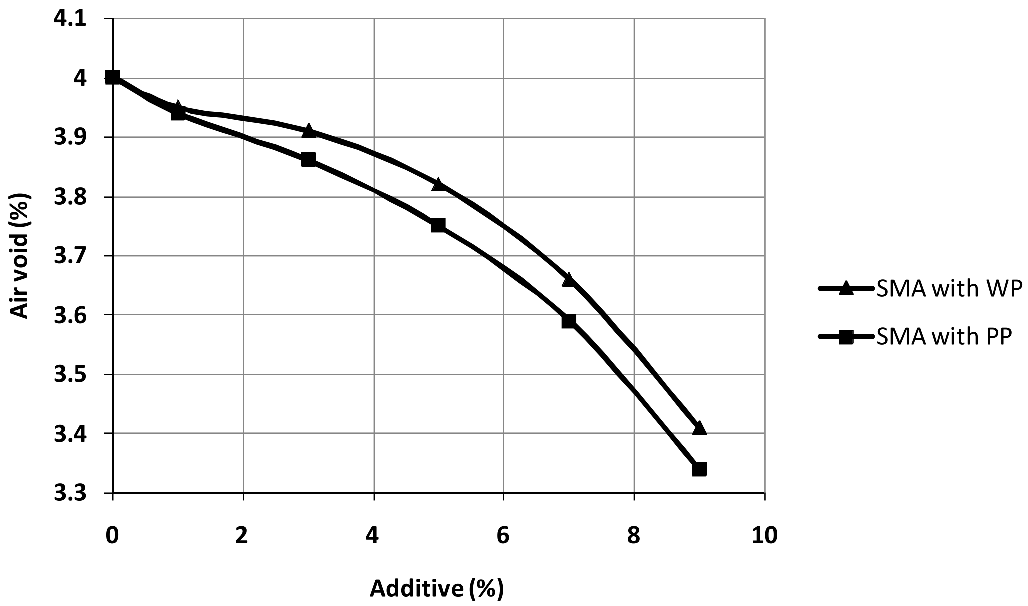

Fig. 4.5.d Variation of air void with different additive %.

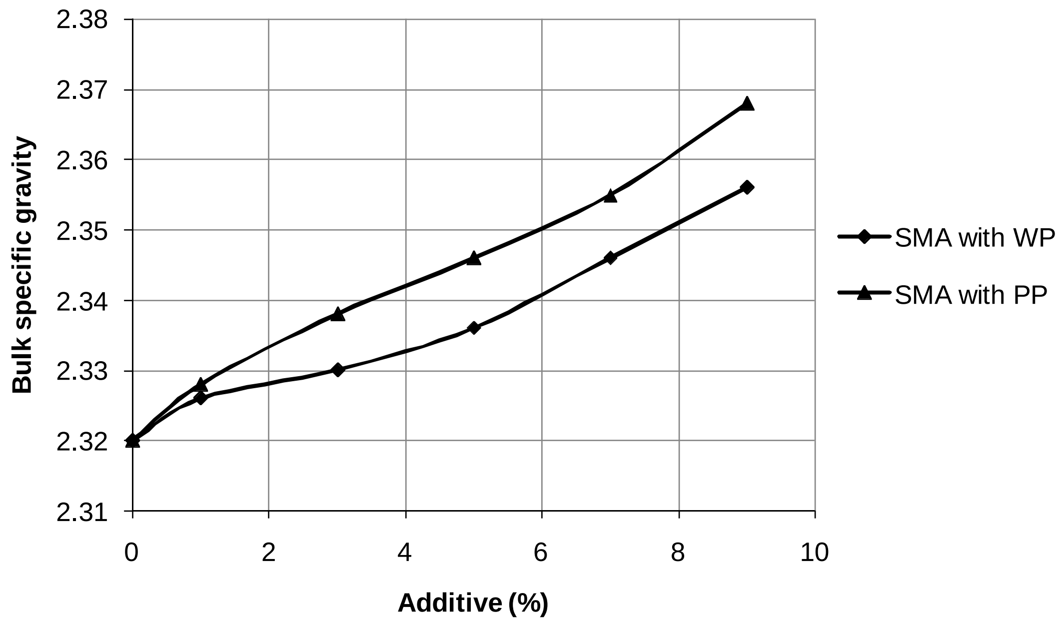

Fig. 4.5.e Variation of bulk specific gravity with different additive %

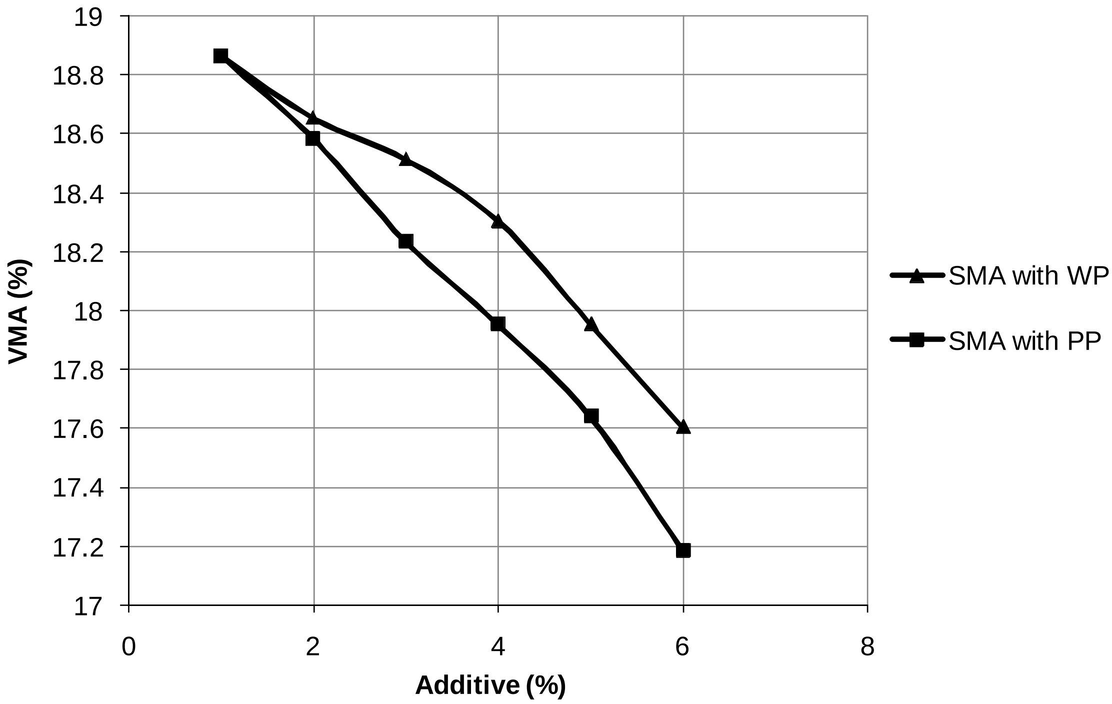

Fig. 4.5.f Variation of VMA with different additive %

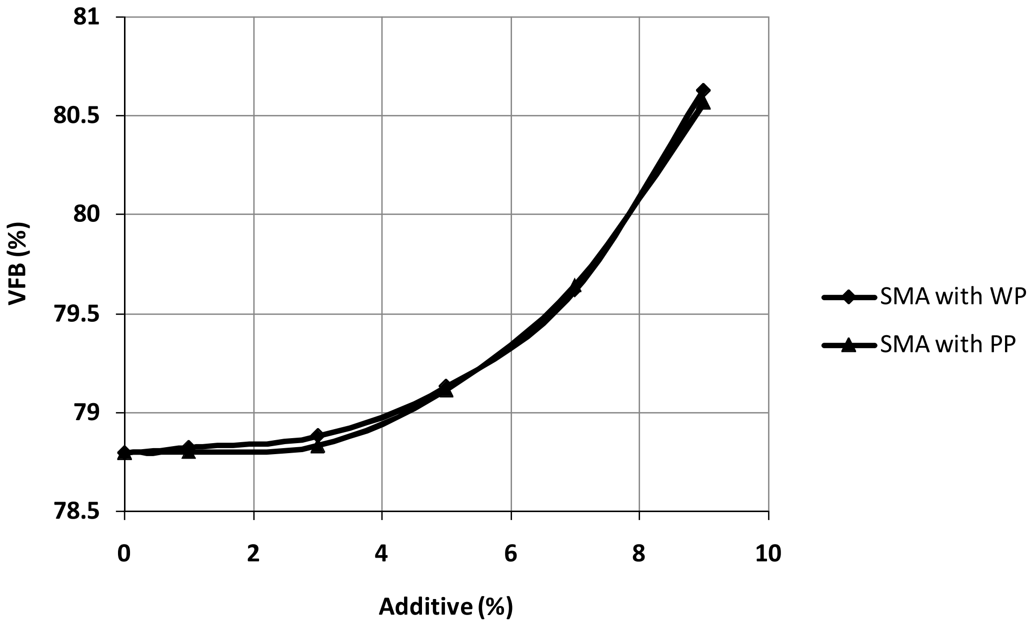

Fig. 4.5.g Variation of VFB with different additive %

4.5.3 Moisture susceptibility

From Table 4.5 and 4.6, it can be observed that the retained stability is significantly higher in the stabilized SMA mixtures as compared to the control mixture. Retained stability value of more than 70% (Table 4.2) is suggested as a criterion for a mixture to be resistant to moisture induced damages. It is seen that for the control mixture, it is only 69 %, supporting the need for an additive in SMA mixture. It also shows that the retained stability of the mixture increases with increasing additive content initially up to 0.3% for fibre, 7% for waste plastics and 5% for polypropylene and beyond these contents, the value is found to be decreasing. Addition of 7% waste plastics in SMA resulted in the highest retained stability of 98%. Among the fibre stabilized mixtures, coir fibre stabilized mixture exhibits the maximum value (95%). These results show that the presence of additives in the Stone Matrix Asphalt mixture leads to a higher protection against water damage.

Both the cohesive properties of the bitumen and the adhesion of the bitumen to the aggregate surfaces may affect as a result of exposing the bituminous mixtures to moisture. Additive incorporation into bituminous mixtures helps to reduce the high level of moisture damage that was noted in the control mix. Among the fibre stabilized mixtures, the coir fibre stabilized mixes showed lower moisture susceptibility than those of the other fibre mixes at the same fibre concentration. 0.3% fibre concentrated mixes showed better resistance to water damage than that at other concentration. Higher fibre concentration may have far too high void contents (balling effect) which allow more water penetration into SMA mixtures.

In plastics stabilized and polypropylene stabilized SMA mixtures, the coating of molten-plastics or polypropylene over the aggregate results in lesser voids and a reduction in the water absorption of the mix. This, obviously results in higher retained stability for the stabilized mixtures than the control mixture.

Table 4.5 Retained stability of SMA mixtures with fibres

Additive (%)	**Retained stability (%)**		
	Coir fibre	**Sisal fibre**	**Banana fibre**
0	69	69	69
0.1	84	82	81
0.2	90	89	88
0.3	**95**	**93**	**93**
0.4	92	90	90

Table 4.6 Retained stability of SMA mixtures with WP and PP

Additive content (%)	Retained stability (%)	
	Polypropylene	Waste plastic
0	69	69
1	82	81
3	89	86
5	**96**	92
7	94	**98**
9	90	97

4.5.4 Influence of additive content on Optimum binder content

All the results discussed above are based on the tests conducted on SMA samples with different additives at a binder content of 6.42%, which is the optimum binder content (OBC) of the Control SMA mixture. In order to study the influence of additive content on OBC, the binder content is varied from 5.5 to 7.5% at an increment of 0.5% for each percentage of additive content for different additives. A total of 230 samples are prepared for this purpose and the Marshall tests have been conducted. The OBC is obtained for each fibre stabilized mixtures at fibre contents of 0.1%, 0.2%, 0.3% and 0.4%. It is the average of the bitumen content corresponding to 4% air void and 17% VMA and is given in Table 4.7. For PP and WP stabilized mixtures, additive content is varied from 1% to 9% at an increment of 2% and the corresponding OBC is tabulated in Table 4.8.

Table 4.7 Optimum Binder Content at various % of fibre content

Fibre Content (%)	Optimum Binder content (%)		
	Coir	Sisal	Banana
0	6.42	6.42	6.42
0.1	6.46	6.45	6.45
0.2	6.52	6.51	6.52
0.3	**6.58**	**6.56**	**6.57**
0.4	6.54	6.52	6.53

Table 4.8 Optimum Binder Content at various % of WP and PP content

Additive content (%)	Optimum bitumen content (%)	
	SMA with WP	SMA with PP
0	6.42	6.42
1	6.45	6.44
3	6.50	6.47
5	**6.52**	6.50
7	6.50	**6.52**
9	6.48	6.50

Test results show that the OBC varies depending on the type and dosage of additives and it increases initially and then decreases with increasing additive content. OBC increases by about 2.5% when fibre content increases from 0% to 0.3% and by about 1.6% when PP content increases from 0% to 5% and WP content from 0% to 7%.

This result is explained as follows: Adding fibre requires more bitumen to wrap onto its surface due to its absorption of light components of bitumen as compared to polymer (Serfass and Samanos, 1996). With an increase in fibre content, specific surface area increases and fibre absorbs more bitumen and thus OBC increases (Wo D., 2000). However, after the fibre content reaches a certain value, excessive fibres are unable to disperse uniformly in the mixture and susceptible to coagulate, which actually does not improve the total specific areas, thus OBC decreases.

The resulted OBC for the fibres can be ranked in a decreased order as follows: coir fibre > banana fibre > sisal fibre > no fibre. This result is primarily due to the different specific areas and the resulted different bitumen absorptions of different fibres. The coir fibre has a loose structure with the highest specific surface area, which results in the highest absorption of bitumen among these fibres (Table 4.7). But when all the additives for the present investigation are analysed, it is evident that waste plastics stabilized mixtures having the least bitumen content is more economical.

4.6 COMPARISON OF VARIOUS STABILIZED MIXTURES

Test results have illustrated that type of additive and its content play significant role in the volumetric and mechanical properties of bituminous mixtures. Meanwhile, results have clearly shown that different additives have different reinforcing effects. Therefore, choice of appropriate additive type, design of optimum bitumen content, and design of optimum additive content would be among the primary objectives for the design of additive -reinforced bituminous mixtures.

Based on the Marshall test results discussed previously, an optimum fibre content of 0.3% is recommended for fibre stabilized SMA mixtures, with which fibre mixture exhibits the highest stability, Marshall Quotient and the residual stability and also the specified volumetric characteristics. For the other additive stabilized mixtures, the optimum additive content is 7% for waste plastics and 5% for polypropylene respectively. The choice of additive type would consider both additive characteristics and its reinforcement effects.

The variations of volumetric and mechanical properties of SMA at the optimum additive content with different additives are shown in the Fig. 4.6.a to Fig. 4.6. h. It is observed that the additives have great impact on the properties of the gap graded SMA mixture with rich binder content. There is significant improvement in the characteristics of control mixture after adding additives, showing the influence of additives on Stone Matrix Asphalt.

The percentage increase in stability value is significant at the optimum additive content. The flow value of SMA mixtures decreases with an increase in additive content. Stability and the Marshall quotient are almost doubled. Retained stability result indicates that the extent of moisture induced damage is more for the control mixture and it doesn't fulfill the minimum criteria of 70%. But for all stabilized mixtures, the value is more than 90% which supports the role of additives in SMA mixture to reduce the moisture induced damages. Less flow value for the SMA mixture with waste plastics shows the increased resistance of the mixture to plastic flow. Regarding the voids, fibre stabilized mixtures show higher air voids and voids in mineral aggregates than the other mixtures, but the voids filled with bitumen is more in plastics stabilized mixtures. But in all stabilized mixtures, all the volumetric characteristics are within the specification range which also supports the use of these additives.

Among the fibre stabilized mixtures, coir stabilized SMA mix gives the best results as compared to the other two stabilized mixtures. But, among all the mixtures investigated, waste plastics stabilized SMA exhibits the highest stability, retained stability, Marshall Quotient and bulk specific gravity as compared to the other mixtures. So this waste material can be used as an effective additive in SMA instead of expensive polymers and fibre additives.

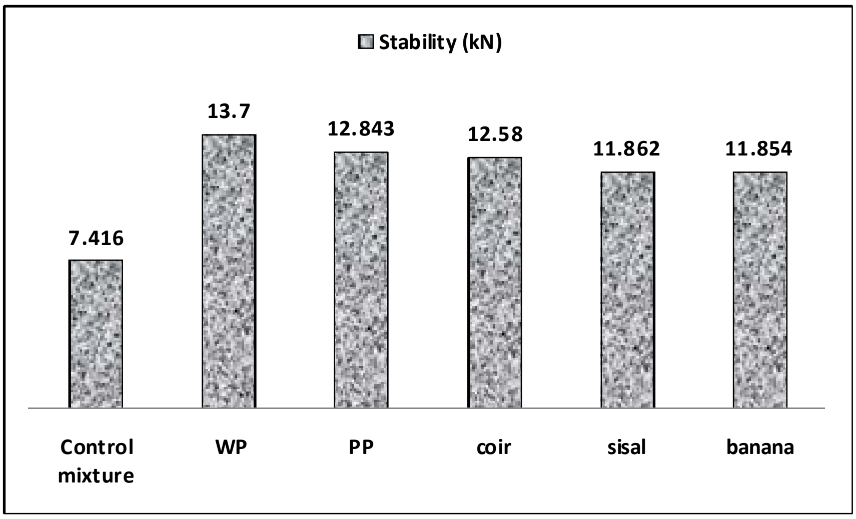

Fig. 4.6.a

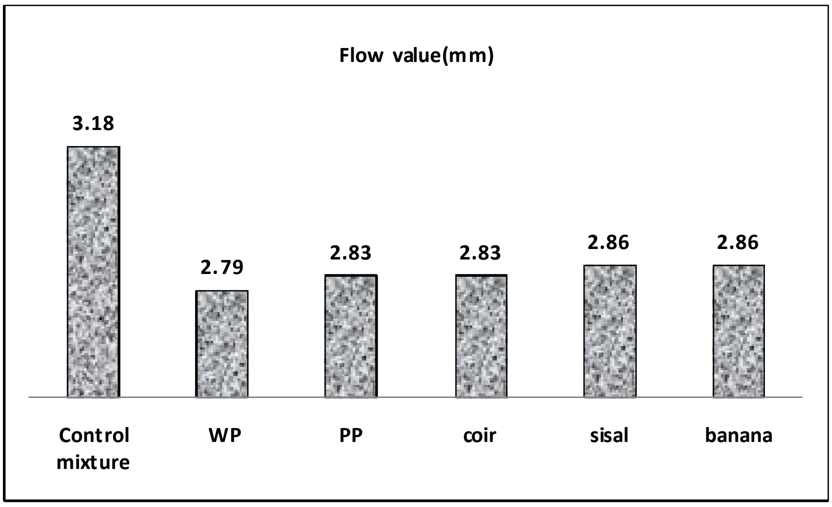

Fig. 4.6.b

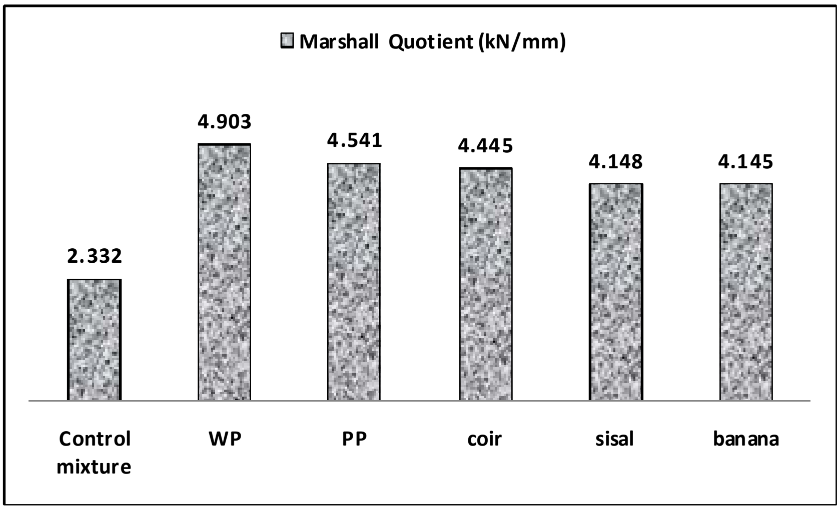

Fig. 4.6.c

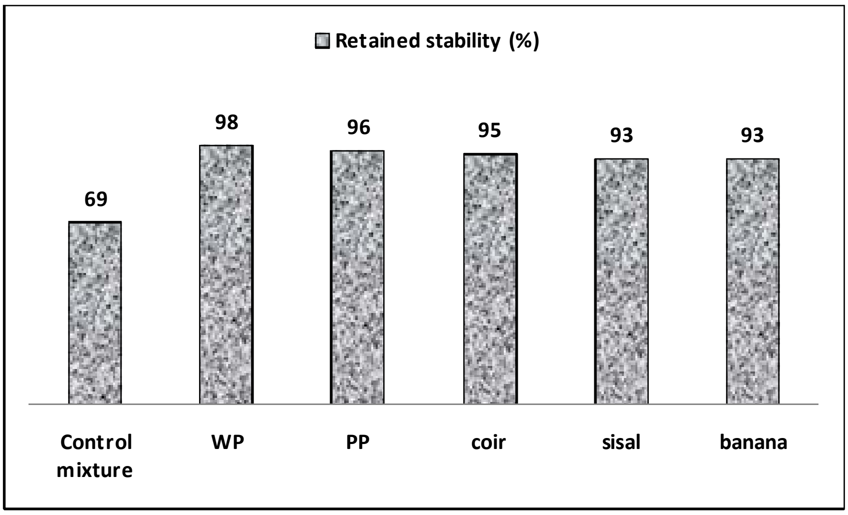

Fig. 4.6.d

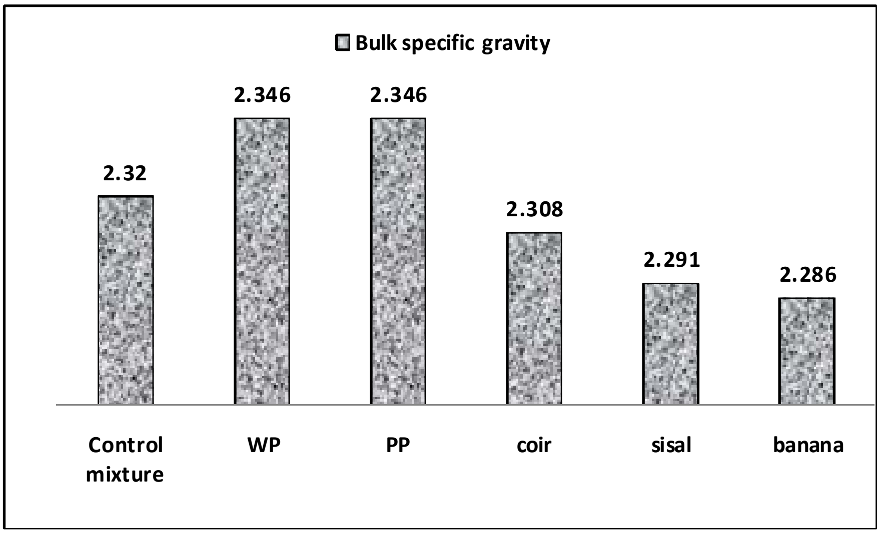

Fig. 4.6.e

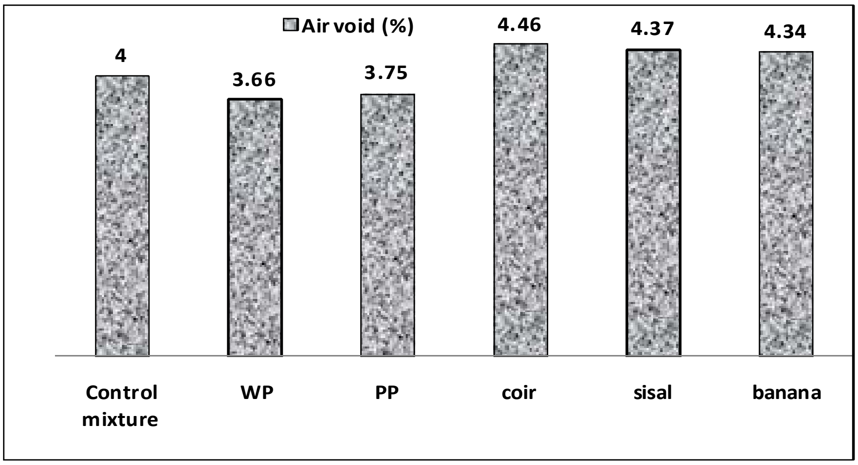

Fig. 4.6.f

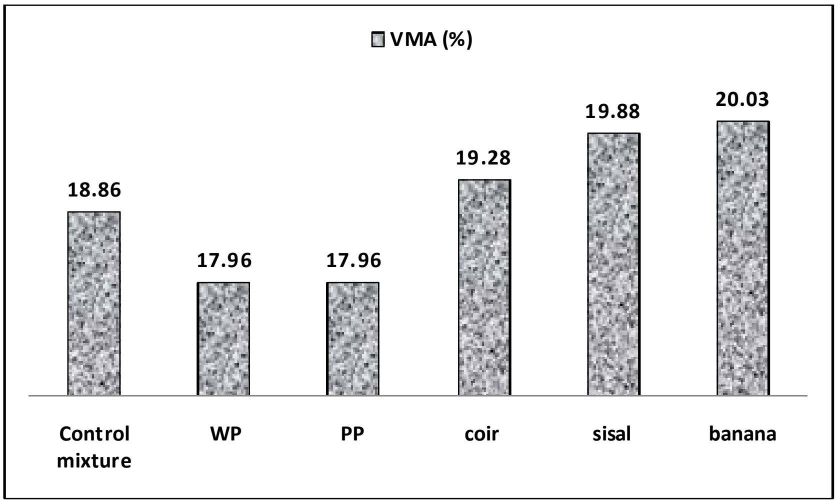

Fig. 4.6.g

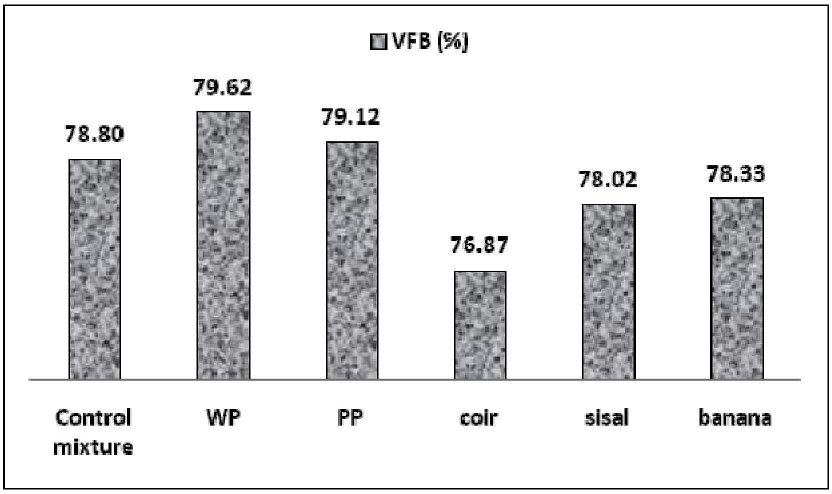

Fig. 4.6.h

Fig.4.6 Comparison of the volumetric and mechanical properties of different stabilized mixtures.

4.7. SUMMARY

The mix design and analysis of SMA mixtures stabilized with three natural fibres (coir, sisal and banana), a waste material (shredded waste plastic) and a polymer (polypropylene) are discussed in this chapter.

While increasing the percentage of additives in the mixture, Marshall stability and retained stability of the mixture increases with respect to the control mixture and obtained the maximum value at 0.3% fibre, 5% polypropylene and 7% waste plastic content, beyond which these values show a decreasing trend. The flow value of the mixtures decreases with respect to the control mixture. At any stage in all cases, the values are within the required specified limits. As percentage fibre additive increases in the SMA mixture, bulk specific gravity and VFB decreases while VMA and air void increases irrespective of the type of fibre. In the case of other additives, the increase in additive content resulted in an opposite trend for the above volumetric properties. But all the results are within the specified limits.

Adding additives to Stone Matrix Asphalt mixture has shown improvement in the volumetric and mechanical properties of the mixture. It can be inferred that these stabilized SMA provide better resistance against permanent deformations (rutting) and also indicate that these mixtures could be used in pavements where stiff bituminous mixture is required.

Among the natural fibres, based on Marshall Mix design, coir fibre gives the best result at 0.3 % fibre content with a percentage increase in stability value of about 70% and Marshall Quotient of 90% with respect to the control SMA. The retained stability value is 95%. It can be observed that the highest Marshall stability is achieved by specimens with 7% waste plastics and the percentage increase is about 82% with respect to the control SMA. This mixture also exhibits the highest retained stability of 98%. The Marshall quotient is also doubled with respect to the control mixture. It can be concluded that waste plastics stabilized Stone Matrix Asphalt mixture provide better resistance against permanent deformations due to their high stability and high MQ and it contributes to recirculation of plastic wastes as well as to the protection of the environment. The effective utilisation of the waste plastics for SMA mixtures will result in substantial increase in the scrap value for this otherwise "undesirable waste material", which are getting littered all over the urban areas. This will also lead to an ecofriendly sustainable construction method.

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