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Sustainable Pavement Solutions: Impact of Compaction Temperature on Organic Additive-based Warm Mix Asphalt

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ABSTRACT

In the construction industry, health and environmental considerations have been growing. This industry has developed several technologies and a variety of admixtures to reduce the temperature at which asphalt mixtures are manufactured, resulting in a truly innovative type of mix known as warm mix asphalt (WMA). In recent years, warm mix asphalt (WMA) has become an alternative to hot mix asphalt (HMA). Sasobit is a synthetic hard wax that is mixed with bitumen to be used in road construction. Sasobit additive can minimize WMA development temperatures. This study investigates the effect of Sasobit with variation in mixing and compaction temperatures on the properties of warm mixes. The present study is divided into four stages. In stage I, the physical properties of aggregates and bitumen were discussed. In stage II, the optimum binder content for the conventional DBM mix was determined. In stage III, the physical properties of Sasobit modified binder and the effect of Sasobit modified binders on properties of WMA at different mixing temperatures (165, 135, 125, 110ºC) and compaction temperatures (140, 120, 110, 95ºC) were determined. The optimum bitumen contents at all temperature ranges were determined and compared. In stage IV, the durability aspect of standard/control and modified mixes was determined. The moisture susceptibility using the Tensile Strength Ratio (TSR) of all the trial mixes was determined and compared. Based on test results, it has been observed that Sasobit resulted in improved physical properties of bitumen. Sasobit resulted in a reduction in the viscosity of bitumen. 2% Sasobit addition showed a reduction in the mixing temperature by 40°C and compaction temperature by 30°C. It will result in a reduction of fuel consumption in the production of bitumen mixes, which ultimately will protect the environment.

Keywords: Warm mix asphalt, WMA, Bitumen additive, Modified bitumen, Moisture susceptibility.

INTRODUCTION

Conventional hot mixes are made at temperatures over 160°C and compacted at temperatures between 120 and 140°C (Ingrassia et al., 2019; Sachdeva et al., 2023; Sattar et al., 2024). Warm mix asphalt (WMA) technology allows for the production of bituminous mixes at 100 to 150°C (Milad et al., 2022; Meena et al., 2018; Sachdeva & Sharma, 2018). This means that less energy is needed to heat the bituminous mix. During WMA production, fuel use often drops by 20 percent. The larger the temperature difference between the bituminous mix and the outside temperature, the faster the mix cools during paving work. Cold outside temperatures negatively affect hot mix asphalt, as quick cooling reduces its durability (Nithinchary et al., 2024). WMA cools more slowly than HMA, which makes it suitable for use at lower temperatures. Consequently, WMA extends the paving period and makes night paving much easier.

Additionally, WMA technology not only cuts down production time, but also shortens the time needed for road surfacing. This happens, because WMA aids in compaction, which lowers the time and energy required to compact the mixture, leading to cost savings (Prowell et al., 2011; Kushwaha et al., 2023). The lower temperatures enabled by WMA also allow more asphalt mix to be transported over greater distances, cutting transportation costs (Prowell et al., 2011). The key to these benefits is the use of additives, which can be water-based, organic, chemical, or hybrid. These additives help blend the asphalt binders and aggregates at lower temperatures by lowering the viscosity of the asphalt binder. As a result, the mixture is easier to handle and compact, reducing production time and costs.

Sasobit is a synthetic hard material made from coal gasification, with the chemical formula $C_nH_{2n} + 2$. Sasobit is used globally in bituminous road construction. It can reduce the viscosity of the binder, acting as an "asphalt flow improver" during the mixing and lay-down processes. With the lower viscosity, working temperatures can be reduced by 35°C. Sasobit dissolves in bitumen at temperatures above 115ºC. It then forms a crystalline structure in the binder at temperatures below its melting point, which enhances stability (Zhu et al., 2021; Sasobit, https://www.Sasobit.com/en/). This study aims to explore how lowering the mixing and compaction temperature affects the properties of Sasobit-modified binder.

LITERATURE REVIEW

WMA technology has attracted high attention due to several benefits, including low energy consumption and environmental concerns associated with HMA (Rubio et al., 2012; Kheradmand et al., 2013). Utilizing Sasobit allows preparing bituminous mixes at a significantly low temperature. Few studies have stated that the addition of Sasobit improves stability, stiffness and fatigue resistance of bituminous mixes (Kushwaha et al., 2025; Nagarwal et al., 2023; Sobhi et al., 2020).

Various studies have proved that organic additives enhanced the performance of WMA mixes. Rezaeizadeh et al. (2022) determined the effect of Sasobit on WMA samples with varying percentages of Sasobit. The authors concluded that Sasobit resulted in a decrease in the penetration and an increase in the viscosity and softening point of the binder. WMA has a higher modulus of stiffness value than the HMA control sample. Rahman et al. (2020) determined the effect of two additives on the rutting performance of airfield pavement. Sasobit and rediset were used in this study. Sasobit resulted in better rutting resistance at the traffic opening temperature than conventional HMA. It was found that the use of warm mixes using Sasobit may lead to a reduction in the overlay construction period by 4%-24%. Almeida et al. (2021) investigated utilizing plastic waste in WMA. Sasobit was used in the WMA compositions. Sasobit melts into bitumen at 85°C, which is 15ºC lower than that of Sasobit. It was concluded that the WMA mix with plastic showed improved performance against rutting. The moisture resistance of WMA with plastic was lower than that of conventional WMA. The addition of waste plastic resulted in improved stiffness and reduced fatigue resistance.

Liu et al. (2021) developed an asphalt binder to improve warm mix asphalt technology. In this research, Sasobit was used as an additive. Organic montmorillonite (OMMT) has also been used with Sasobit to increase UV aging resistance. It was found that the high-temperature performance of the binder improved with adding Sasobit and OMMT. Although the introduction of Sasobit resulted in a significant decrease in low-temperature performance, it could help restore OMMT moderately. OMMT resulted in improved UV ageing properties of WMA.

Similarly, Wang et al. (2020) investigated the addition of two carbon nano-materials; i.e., graphene oxide (GO)/polymer and styrene-butadiene styrene (SBS) composites, on the properties of asphalt binders. The ageing characteristics, rheological and fatigue damage characteristics of Sasobit and asphalt modified with polymer were analyzed. They found that Sasobit has lower viscosity, which helps reduce mixing temperatures. Tao and Mallick (2009) determined that utilizing 100% RAP on the properties of HMA as an addition of RAP results in a stiff mixture, Sasobit and zeolite were used as additives in this study. Sasobit was used in proportions of 1.5%, 3% and 5%, while zeolite was used in proportions of 0.3%, 0.5% and 0.7% by weight of bitumen. It was found that in both additives, the workability of 100% RAP HMA improved at 110 ºC. At temperatures below 80℃, the mixture becomes stiff, resulting in reduced workability, increased seismic moduli, and ITS. Sasobit performed well in improving the bulk specific gravity of the mix. Rahman et al. (2020) determined the effect of Sasobit and Rediset on the rutting of airfield pavement. It was observed that the addition of Sasobit resulted in improved rutting resistance at the traffic opening temperature compared to conventional HMA. It was found that the use of warm mixes using Sasobit may lead to a reduction in the overlay construction period by 4%-24%.

Hamzah et al. (2010) conducted a study to determine the reduction in CO_2 emissions on use of Sasobit. It was found that 2.8% and 3% heat energy and CO_2 were reduced by the addition of 1% Sasobit. Based on fatigue resistance test results, the optimum dosage of Sasobit was obtained as 1.6%.

Overall, Sasobit has been proven to be a versatile additive that enhances the performance of WMA by improving workability, reducing mixing temperatures, and increasing resistance to rutting and ageing. Its use in combination with other modifiers and additives continues to be an area of active research, intending to further optimize the properties of WMA for sustainable road construction (Milad et al., 2022).

Based on this detailed review, Sasobit is an effective additive to be used in bitumen for the production of WMA. The addition of Sasobit resulted in lowering the viscosity of the binder, resulting in easy coating of aggregates even at lower temperatures. However, a more detailed understanding of the physical characteristics of both unmodified and Sasobit-modified binders, as well as how varying temperature conditions affect Marshall characteristics, is needed. Further research is necessary to explore these aspects for a more accurate and optimized application of Sasobit in WMA production.

MATERIALS AND METHODS

This study aims to compare the characteristics of control mixes and Sasobit-modified mixes under varying mixing and compaction temperatures. The research focuses on a Dense Bituminous Macadam (DBM) mix (Grading II), in which stone aggregates and bitumen were procured locally. To ensure the quality of the raw materials, physical tests were conducted on the aggregates and bitumen following the relevant IS standards. Sasobit dosage, after going through the available literature was fixed at a 2% inclusion rate, and added to the bitumen. Its physical properties were compared to those of virgin bitumen. Following the Ministry of Road Transport and Highways (MoRTH) guidelines for Dense Bituminous Macadam (Grading II), the proportioning/gradation of the aggregates was carried out. The Marshall method was employed to prepare the DBM mixes. The Marshall properties and Optimum Binder Content (OBC) were compared at mixing temperatures of 110, 125, 135, and 165°C, and at compaction temperatures of 95, 110, 120, and 150°C, respectively (Cheraghian, 2020). Additionally, the Tensile Strength Ratio (TSR) was calculated for all the samples. The properties at various temperature ranges were analyzed, and conclusions were drawn based on these comparisons. The outlining of the stages followed in the research is presented in Figure 1.

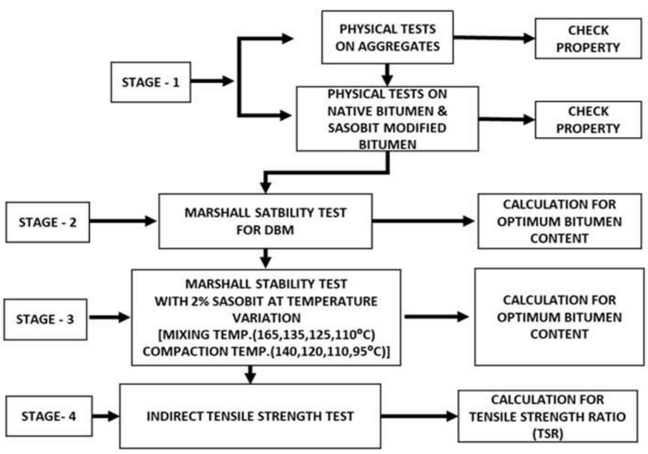


Figure 1. Stages of the work

Materials

For determining the quality of materials, all the physical tests were performed on the materials and their values are compared with the specifications of MoRTH.

Aggregates

Stone aggregates of size 20mm, 10mm and stone dust used in this study were locally procured. To judge the suitability of aggregates to be used as a construction material in the DBM (Grading II) layer, various tests suggested by the specification for road bridge works, MoRTH, were conducted in the laboratory. Table 1 shows the obtained results and their specified values.

Table 1. Physical tests on aggregates

Property	Test	Specification	Result (%)
Cleanliness	Grain Size Analysis	5% Passing 0.075mm (Max.)	2.69
Particle shape	Flakiness and Elongation Index	35% Combined (Max.)	21.09
Strength	Impact Value Test	27% (Max.)	17.74
	Abrasion Value Test	35% (Max.)	25.14
Water Absorption	Water Absorption	2% (Max.)	1.7
Specific Gravity	20mm	2.5 - 3	2.73
	10mm		2.71
	Stone Dust		2.53
Stripping	Stripping Test	95% coating (Min)	>95

Bitumen

Bitumen is responsible for the binding between the aggregates. Bitumen of VG-30 grade was used in this study. To judge the suitability of bitumen for DBM (Grading II), all physical tests were conducted as suggested by MoRTH specification. Table 2 shows the obtained results and their specified values.

Table 2. Physical tests on bitumen

Test	Specifications as per IS 73	Test Result
Ductility	40cm (Min.)	43.57 cm
Specific Gravity	0.99 (Min.)	1.01
Softening Point	>47˚C	59 ˚C
Flash and Fire Points	Flash 175 ˚C and Fire 175 + 5 ˚C	177 ˚C and 242 ˚C
Viscosity	350cST (Min.)	387 cST

Organic Warm Mix Additive

Sasobit is a white granular synthetic hard wax that reduces the viscosity of bitumen at lower temperatures and helps achieve coating at reduced temperatures. The melting point of Sasobit is 115°C, and its flash point is 285°C (Gokalp, 2021). Sasobit is produced using the Fischer-Tropsch process, a catalytic method developed by Franz Fischer and Hans Tropsch in the 1920s. This process converts synthesis gas into liquid hydrocarbons while releasing gases, such as H_2, CO_2, and CH_2, through gasification. Based on previous research, it was observed that Sasobit is added to bitumen in varying quantities ranging from 0.8% to 4% by mass, improving workability and reducing viscosity (Hurley & Prowell, 2005; Ghuzlan & Al Assi, 2016). When added in quantities more than 4% by mass, Sasobit modified mixes exhibited rutting problems in the mix (Nithinchary et al., 2024). At temperatures below its melting temperature, it forms a crystalline network model in the binder, providing extra stability potential (Zhu et al., 2021; Meena et al., 2018). For the present study, Sasobit quantity was fixed at 2%, and an initial trial was conducted on the properties of virgin binder modified with 2% Sasobit.

Bituminous Mix Design

For DBM (Grading II), the required grading according to MoRTH and the achieved grading are given in Table 3. Table 500-17 of MoRTH specification mentions the upper and lower limits of DBM (Grading II). Proportions of aggregates for the mix were finalized as 30% of 20-mm aggregate, 30% of 10-mm aggregate and 40% of stone dust. Figure 2 shows that the achieved grading lies between the upper and lower limits.

Table 3. Composition of DBM, grading II (MoRTH, 2013)

Sieve Size (mm)	20 mm (30%)	10 mm (30%)	Stone Dust (40%)	Obtained Gradation	Desired Gradation
37.5	30.00	30.00	40.00	100	100
26.5	30.00	30.00	40.00	100	90 – 100
19	22.86	30.00	40.00	92.86	71 – 95
13.2	6.4	27.2	40.00	73.6	56 – 80
9.5	1.05	22.58	40.00	63.63	-
4.75	0	11.32	40.00	51.32	38 – 54
2.36	0	5.08	35.88	40.96	28 – 42
1.18	0	2.05	30.4	32.45	-
0.6	0	1.07	23.37	24.44	-
0.3	0	0	11.86	11.86	7 – 21
0.15	0	0	5.88	5.88	-
0.075	0	0	2.21	2.21	2 – 8

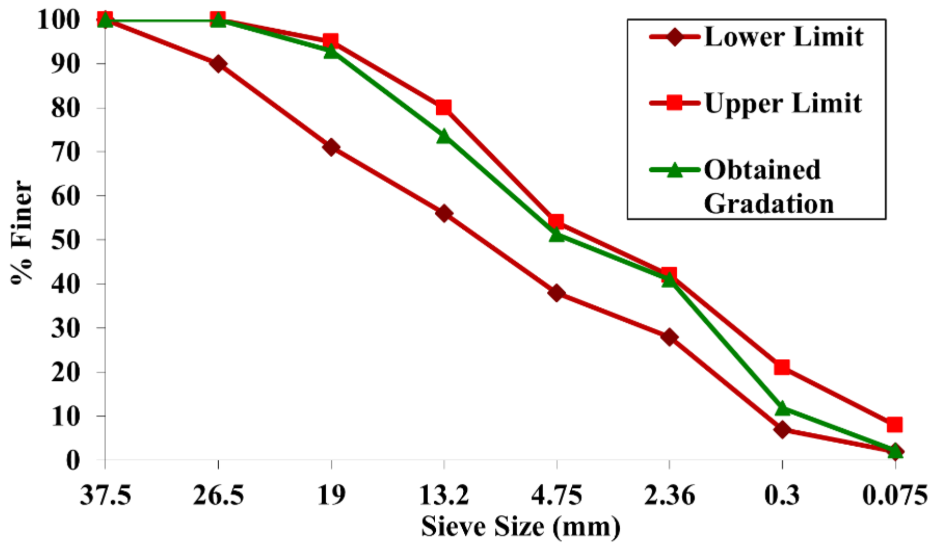


Figure 2. Gradation of DBM (grading II)

Test on Bituminous Mixes

Marshall stability test is conducted for the design of bituminous mixes. The main sources of stability in the pavement are internal friction and cohesion. Internal friction refers to the interlocking of aggregate and resistance to friction. Cohesion refers to the adhesion provided by the binding material. Bituminous pavements are highly subjected to heavy traffic loads, so stability and flow values are very important. For designing bituminous pavement, the proportioning of aggregates is carried out.

The percentage of aggregates is selected as such that the particle size distribution comes within the upper and lower limits specified by MoRTH (MoRTH, 2001, Section 500). Each batch of the aggregate was heated to the designated mixing temperature to prepare Marshall specimens. The heated aggregate was thoroughly mixed with the binder using an asphalt mixer. The resulting mix was then placed into a mould and compacted by providing 75 blows on each side using a 4.86-kg hammer (450 mm free fall). After compaction, the bituminous specimens were cooled at room temperature for 24 hours. The specimens were conditioned in a water bath at 60ºC for 30 minutes and subsequently tested using the Marshall stability machine.

Marshall Stability Test (ASTM D 1559)

The Marshall stability test is conducted to determine various properties of bituminous mixes. The test specimen is weighed in both air and water. The volumetric parameters of bituminous mixes are calculated using this weight. After that, the specimen is put through a Marshall stability test machine, which applies a load at the rate of 50 mm/min to determine its stability and flow value. A total of 75 specimens were prepared, with bitumen content varying from 3.5% to 5.5% across different combinations. The details of mixing temperature, compaction temperature and additive content are summarized in Table 4.

Table 4. Details of various mixes prepared

Sample Number	Mixing Temperature	Compaction Temperature	Mix Type	Additive Content
M0	165˚C	140˚C	HMA	NIL
M1	165˚C	140˚C	WMA	Sasobit 2%
M2	135˚C	120˚C	WMA	Sasobit 2%
M3	125˚C	110˚C	WMA	Sasobit 2%
M4	110˚C	95˚C	WMA	Sasobit 2%

Indirect Tensile Strength (ITS) Test (ASTM D6931)

Pavement engineers focus on the tensile properties of mixes because of concerns related to cracking. WMA has been shown to have reduced performance when exposed to moisture. To evaluate these properties, the Marshall specimen is loaded along its diametric plane by applying a compressive force at a constant rate, aligned with the vertical diameter of the specimen.

Tensile Strength Ratio (TSR) Test (AASTHO T283)

Water sensitivity was assessed using the TSR test, calculated by dividing the tensile strength of a water-conditioned specimen (ITS_{wet}, 60°C for 24 hours) by that of an unconditioned specimen (ITS_{dry}). A higher TSR value indicates improved moisture resistance and overall performance of the mix.

A total of 30 samples were prepared at OBC for all temperature variations to test for moisture susceptibility.

RESULTS AND DISCUSSION

Physical Properties of Bitumen

Sasobit is added during the melting process of bitumen. It was added in a proportion of 2% by weight of bitumen. All the physical parameters were determined as per the relevant IS codes. Table 5 shows the results of physical tests on virgin binder and on bitumen modified using Sasobit additive.

Table 5. Physical test results of non-modified and Sasobit-modified bitumen

Property	Specifications as per IS 73	Indian Standards Followed	Virgin Bitumen	Bitumen with Additive
Ductility	-	IS – 1208	99 cm	99 cm
Specific Gravity	Minimum 0.99	IS – 1202	1.01	1.04
Softening Point	>47˚C	IS – 1205	59 °C	73.55 °C
Viscosity	Minimum 350 CST	IS – 1206	387 cST	359 cST

The addition of Sasobit to bitumen resulted in enhanced properties of the bitumen binder. Sasobit is added to bitumen; it melts at around 100-115°C. When it melts, it dissolves in the bitumen and reduces its internal friction. It results in reduced viscosity and improved workability during mixing and compaction. The reduced viscosity leads to better homogeneity and reduced oxidative ageing in the bitumen that can stretch without breaking, thus increasing ductility. When Sasobit cools and crystallizes within the bitumen, it forms a fine crystalline lattice that makes the binder stiffer and more resistant to deformation at higher temperatures. This results in an increase in the softening point of bitumen (Kolapkar & Sathe, 2023). To ensure the optimal performance of a bituminous mixture, the quantity of binder added must be carefully considered. It is important to strike a balance between adding enough binder to fully coat the aggregates and seal the voids within the bituminous material to enhance the pavement's durability and impermeability while preventing the aggregates from being dislodged due to the abrasive forces of moving vehicles. However, adding an excessive amount of binder would destabilize the bituminous pavement, thereby reducing its resistance to deformation under traffic loads. Therefore, it is essential to design the optimum amount of binder content to maintain the stability and functionality of the bituminous pavement.

A reduction in the viscosity of the binder was observed on the addition of Sasobit. Sasobit reduces the viscosity of bitumen by acting as a flow improver through its waxy, thermoplastic nature, reducing intermolecular friction and enhancing lubrication, which leads to easier mixing and compaction at lower temperatures (Hurley & Prowell, 2005; Qin et al., 2014).

Marshall Parameters

For DBM, binder content proportions of 3.5%, 4%, 4.5%, 5% and 5.5% were taken. Three major properties of the mix; i.e., bulk density, air voids, and stability, were considered while determining the OBC. Three molds were prepared for each bitumen content. Figures 3 and 4 demonstrate the variation of stability and flow values of the specimen with increasing bitumen content. It was observed that the control mix demonstrated the maximum stability values, but at the same time, samples modified with Sasobit and compacted at a lower temperature displayed load-carrying capacity above the minimum requirement of 9 kN specified in Specifications for Road and Bridge Works, MoRTH (2013). A sudden reduction in the stability value of M1 mix was observed. This is due to a reduction in viscosity on the addition of Sasobit, resulting in excess binder coating, reduced aggregate interlock and lower binder stiffness at testing temperature (60°C). However, the reduction in mixing and compaction temperature in M2, M3 and M4 mixes increased the viscosity values of the binder. The increment in viscosity contributed to an increase in the stiffness of the mixes, which in turn resulted in higher stability values. Figure 4 shows that the addition of Sasobit lowers the flow value of the Marshall specimen at the same mixing and compaction temperatures. This happens due to the formation of a crystalline structure formed after cooling, which restricts deformation under load. The packing loosens on reducing the mixing and compaction temperatures for M2, M3, and M4 mixes, resulting in a further increase in flow values.

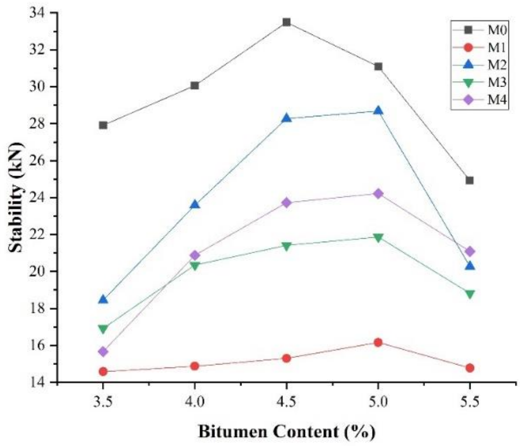


Figure 3. Marshall stability variation with bitumen content in different Marshall mixes

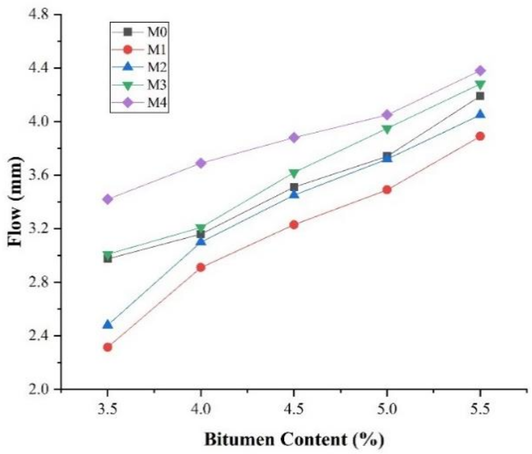


Figure 4. Flow variation with bitumen content in different Marshall mixes

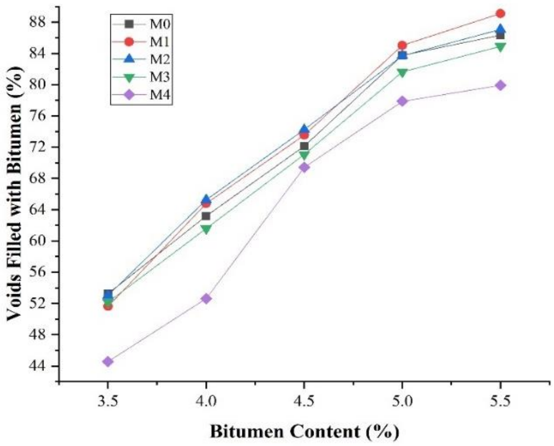


Figure 5. VFB variation with bitumen content in different Marshall mixes

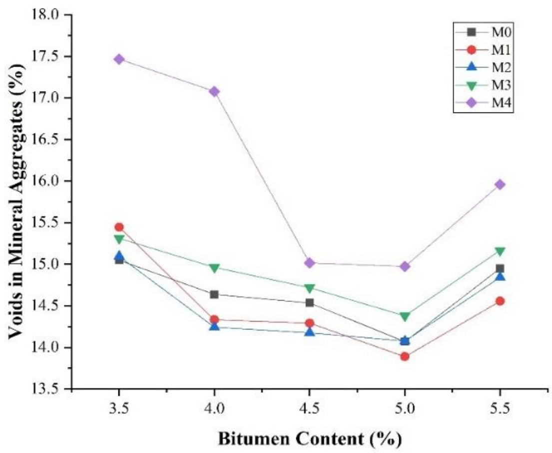


Figure 6. VMA variation with bitumen content in different Marshall mixes

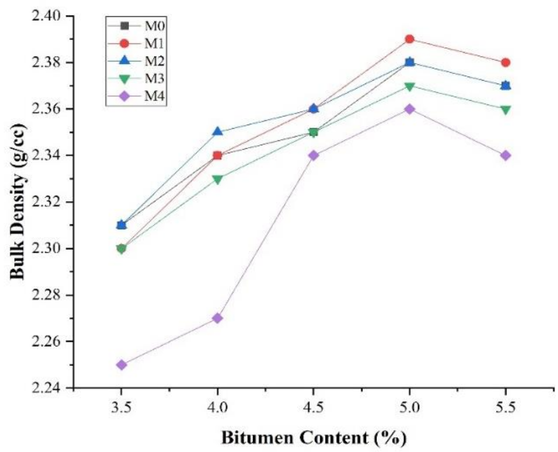


Figure 7. Bulk density variation with bitumen content in different Marshall mixes

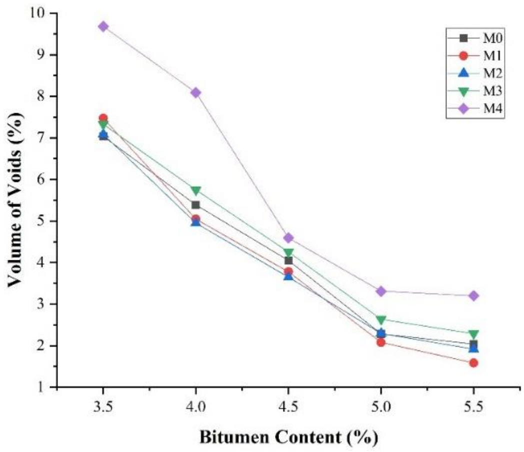


Figure 8. Volume of voids variation with bitumen content in different Marshall mixes

Figures 5, 6, 7 and 8 represent the variation in various Marshall properties of WMA produced using 2% Sasobit on the reduction of mixing and compaction temperatures. It was observed that on the reduction of temperatures, the various Marshall properties were affected.

Figures 5 and 6 show the VFB and VMA values of the Marshall specimens at all mixing and compaction temperatures. The denser-packed mix showed higher VFB and lower VMA properties of the Marshall specimen at the same mixing and compaction temperature. The reduction in temperatures resulted in a further reduction in VFB and an increment in VMA values. This is due to increased stiffness of the binder at lower temperatures, resulting in higher resistance to compaction. The VFB values also simulate with the bulk density and volume of voids values shown in Figures 7 and 8. Denser packing shows higher bulk density and lower voids, while looser packing in M2 to M4 mixes showed lower bulk density and higher voids compared to the M1 mix.

Finally, it was observed that the addition of Sasobit lowers the viscosity of bitumen during mixing and compaction, resulting in better aggregate coating and higher density. This resulted in a reduction in stability and flow values at similar mixing and compaction temperatures (M1) compared to those of the control mix (M0). A moderate temperature reduction (M2) improved the Marshall stability and flow values. This is due to the resistance provided by bitumen to the reduction in mixing and compaction temperatures.As Sasobit compensates for the temperature reduction, Marshall parameters are better than in the M1 mix. On further reduction in temperature values, the Marshall test results of the M3 mix are comparable to those of the control mix (M0). Further temperature reduction may compromise the quality of the DBM mix. To analyze the results, trial samples were made at a mixing temperature of 110℃ and a compaction temperature of 95℃ (M4). It was observed that the properties of the DBM mix are lower than the properties of the control mix (M0). There is no scope for further reduction in temperature. Hence, the trial samples are kept till M4 mix.

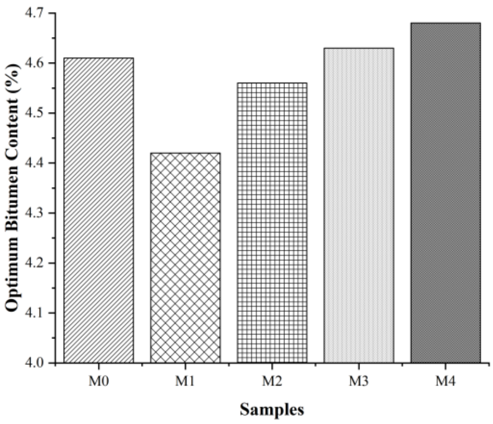


Figure 9. OBC variation with bitumen content in different Marshall mixes

The values of OBC for all trial mixes are depicted in Figure 9. The optimum binder content is determined as the average of bitumen content corresponding to maximum bulk density, maximum stability and 4% air voids. The OBC was found to be 4.6% with respect to the total mix. The OBC obtained is higher than the minimum bitumen content of 4.5% specified by MoRTH. It can be observed that the control mix has an OBC value of 4.6%, which is above the minimum desired range of 4.5% by MoRTH.

The addition of Sasobit resulted in better aggregate coating, which reduced the OBC value of M1 mix to 4.42%. Reduction in mixing and compaction temperatures further resulted in higher viscosity values for the modified mixes (Meena et al., 2018). This further increased the OBC values of the subsequent mixes. The M3 mix showed an OBC value similar to that of the control mix. On further reducing the temperature range (M4), an increase in OBC value is observed (4.68%).

Moisture Susceptibility

Test results of the Tensile Strength Ratio (TSR) at all mixing and compaction temperatures are shown in Figure 10. As per Table 500-11 MoRTH specifications, the DBM (grading II) mix must have a minimum TSR value of 80%. From the test results shown in Figure 10, for M0 and M1 mixes, it has been observed that the TSR value reduced on the addition of Sasobit. This was because of a reduction in the viscosity of the binder, resulting in reduced adhesion between binder and aggregates. On reducing the temperature, the viscosity increased, resulting in improved TSR values for M2 and M3 mixes. For the M4 mix, the temperature is very low for proper coating and binding of the aggregates, resulting in further reduction in TSR values. Figure 11 shows the variation of ITS_{wet} and ITS_{dry} values.

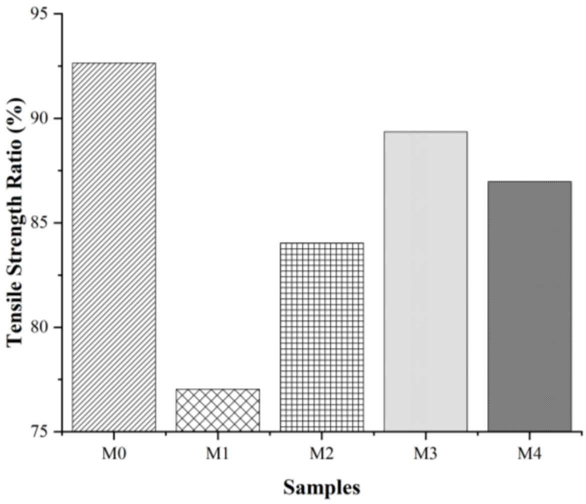


Figure 10. TSR value variation for M0, M1, M2, M3 and M4

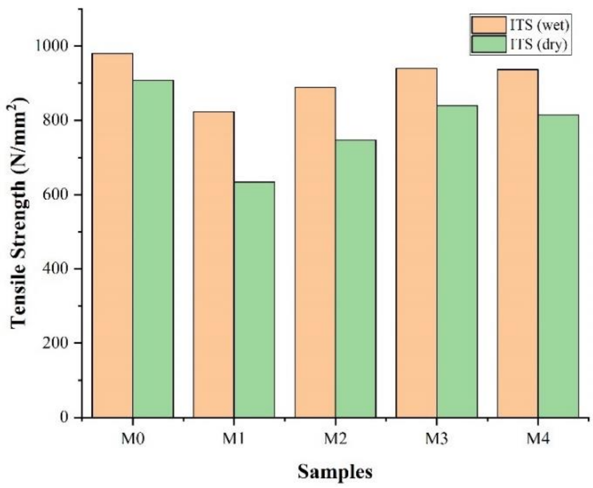
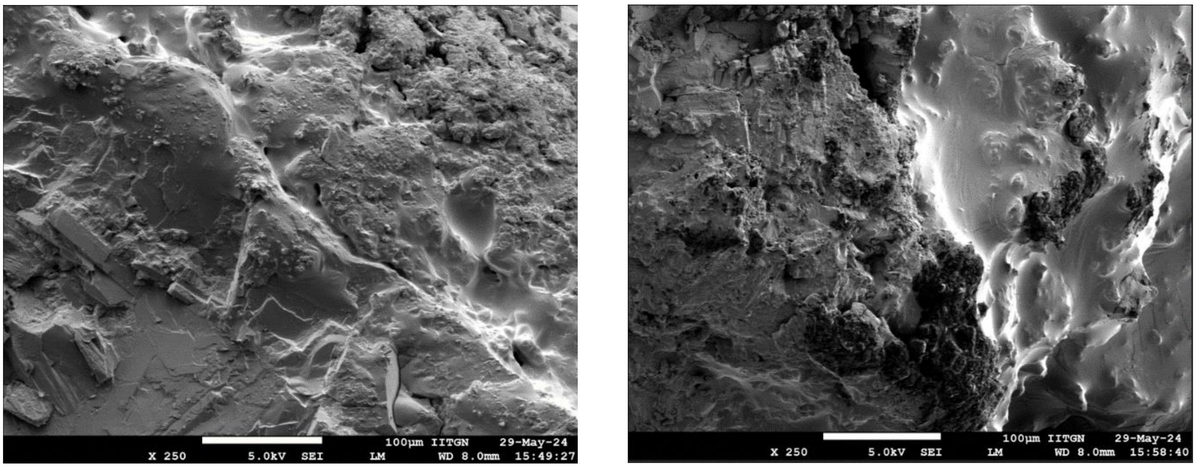


Figure 11. Variation in ITS values for different Marshall mixes

Micro-structural Analysis

Figure 12 displays the micro-structure of WMA modified with Sasobit and compacted at reduced temperatures of 135°C and 125°C. It can be observed that the dispersion and thickness of the binder are uniform. The SEM images of conventional bituminous mixes typically reveal an uneven and heterogeneous micro-structure. The aggregate surfaces are not well coated, and noticeable voids and micro-cracks are often present. The binder film appears patchy, with discontinuous distribution—indicating less effective adhesion between aggregates and binder. SEM images of Sasobit-modified mixes show a much denser and more uniform micro-structure. The aggregates appear to be more thoroughly coated by the binder, resulting in fewer visible voids or micro-cracks. The binder film becomes more continuous and homogeneous, which enhances the adhesion between aggregate particles. SEM images confirm that adding Sasobit to bitumen results in a noticeably improved micro-structure, which is characterized by better coating, reduced voids, and a denser, more homogeneous matrix compared to unmodified mixes. This micro-structural enhancement helps explain the observed improvements in the mechanical and durability properties of Sasobit-modified bituminous mixes.



(a) (b)

Figure 12(a) and (b). SEM images at 250 times resolution for WMA modified with Sasobit at mixing temperatures of 135°C and 125°C

CONCLUSIONS

This paper evaluates the physical properties of Sasobit-modified bitumen. It also examines the effect of Sasobit-modified bitumen with different temperature combinations on the properties of DBM mixes. The following conclusions have been drawn:

- Sasobit enhanced the bitumen's viscosity, leading to increased specific gravity and softening point.
- Inculcation of Sasobit resulted in a reduction in the OBC value compared to the control mix. However, the OBC value increased as mixing and compaction temperatures decreased. The M3 mix (125°C mixing temperature and 110°C compaction temperature) achieved OBC values nearly equivalent to those of the control mix.
- At standard temperatures (M1), the addition of Sasobit initially led to significant variation in Marshall parameters due to lower binder viscosity. However, when mixing and compaction temperatures were reduced (M2 and M3), the increase in binder viscosity balanced the effect of Sasobit, resulting in improved parameters for M2 and values comparable to the control mix for M3. Further temperature reduction (M4) caused deterioration in Marshall properties.
- Sasobit helps maintain the TSR values at reasonable temperature reductions (M3), but at very low mixing/compaction temperatures (M4), TSR values tend to drop due to insufficient coating and compaction. The control mix (M0) and M3 mix showed similar moisture resistance, while, on further reduction in temperature, the moisture durability of the mix reduces.
- Micro-structural analysis confirms that Sasobit modified bitumen can be dispersed into the

bituminous mastic uniformly, even at low temperatures, thereby providing better coatability of the aggregate at a reduced temperature.

Based on the results, the addition of Sasobit improved the physical properties of bitumen by reducing its viscosity. At a mixing temperature of 125°C and a compaction temperature of 110°C (M3 mix), Sasobit successfully achieved Marshall parameters and OBC values comparable to the control mix (M0). However, further temperature reduction led to deteriorated Marshall parameters and increased OBC values. The addition of Sasobit also reduced moisture susceptibility within the same temperature range, with better results observed at lower temperatures. Therefore, incorporating 2% Sasobit is recommended for producing warm mixes, enabling a 40°C (24.24%) reduction in mixing temperature and a 30°C (21.43%) reduction in compaction temperature. This adjustment maintains mix properties while lowering fuel consumption during bitumen production, contributing to environmental sustainability.

This research addresses the urgent need for eco-friendly construction materials by focusing on warm mix asphalt, which reduces energy consumption and emissions compared to traditional hot mix asphalt. This study signifies the potential use of Sasobit as an additive in reducing the mixing and compaction of the asphalt mixes. This will contribute to reduced fuel consumption, low carbon emissions and economic benefits, thereby promoting environmentally responsible and sustainable construction practices that align with green infrastructure goals.

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