

Research Article

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Assessment of indirect tensile stress and tensile–strength ratio and creep compliance in HMA mixes with micro-silica and PMB

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Abstract: This study aims to ascertain the effects of polymer-modified bitumen (PMB) and to utilize mineral filler with micro-silica (MS) on various properties of hot-mix asphalt (HMA). In this work, three specimens of an asphalt-concrete mixture were prepared. The first specimen represents a control mixture, the second specimen contains MS at rates 15, 30, and 45% by the total weight of the total aggregate as filler, and the third specimen contains MS and PMB with 4% novolac by the weight of bitumen and 15% hexamine by the weight of the novolac. The properties of designed mixes were evaluated using the indirect tensile strength test, tensile–strength ratio, and creep compliance. The test results showed an increase in the resistance of asphalt concrete to moisture damage, a reduction influence of water on asphalt concrete properties, creep compliance values indicating growing stiffness for asphalt mixture, and enhanced fatigue life. In conclusion, using 45% MS and PMB improved the properties of HMA and provided long-lasting mixtures for highway construction.

Keywords: creep compliance, hot-mix asphalt, indirect tensile strength, micro-silica, polymer-modified bitumen

1 Introduction

Asphalt pavements encountered considerable distress due to inadequacies in their elastic properties, heavy traffic

loading, and the weather's effect on the characteristics of hot-mix asphalt (HMA). Therefore, it is necessary to produce new materials that are resistant to these deformations to avoid reducing service life and increasing maintenance costs.

Qasim et al. [1] assessed the attributes of HMA utilizing nano-silica (NS) and micro-silica (MS) additions to determine the optimal modifier using various percentages 0, 2, 4, 6, and 8% by bitumen weight. This research showed that NS is the best modifier since it achieved maximum stability, better tensile strength, lowest flow, and lower rutting depth. In contrast, the other modifier achieved lower rates of mix performance.

Al-Zajrawi et al. [2] examined the practicality of adding micro- and nano-sized silica to enhance the properties of asphalt. Asphalt cement (AC 60/70) was prepared by incorporating 0, 2, 4, and 6% silica filler by weight of asphalt and examined in terms of the ductility, viscosity, penetration, and penetration index values. Generally, silica filler addition positively affected the rheological properties of asphalt binder. Additionally, the proportion of NS content reduced the ductility due to the high surface area and degree of agglomeration. Furthermore, research showed that 4% of NS powder and 6% of MS powder were appropriate for developing rheological properties.

Thakare and Chauhan [3] investigated the effects of lime, fly ash, and MS on the stabilization of black cotton soil. According to the findings, the ideal amounts of lime, fly ash, and silica for this stabilizing soil were, respectively, 5, 3, and 3%. Utilizing lime, fly ash, and silica and their mixture to stabilize black cotton soil, the soaked CBR was increased to around 6.5 times that of unsterilized soil, while the unsoaked CBR was increased to approximately 1.8 times.

Shafabakhsh et al. [4] studied the impact of MS powder on the engineering parameters of asphalt concrete mixtures and bitumen. The results of this study showed that adding MS to bitumen had a significant impact on the enhancement of permanent deformation of HMA. In addition, experiments on bitumen revealed that adding MS reduced penetration, ductility, and temperature susceptibility and improved softening point, stiffness, and viscosity. Several

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investigations have demonstrated that HMA mixtures with polymer-modified bitumen (PMB) are more resistant than blends with pure binders. For a polymer to be helpful in road applications, it should be mixed with the asphalt to enhance its resistance (cracking, rutting, stripping, fatigue, etc.).

Chafat *et al.* [5] investigated the bitumen modification with novolac and its cross-link hexamine to make HMA more resistant to moisture and creep compliance. As a result, moisture damage and creep compliance were decreased by modification.

This issue has repeatedly arisen because the asphalt mixture did not meet the requirements for the ideal design blend, either the binder or the asphalt mix. This study investigates how the use of MS, filler aggregate, and PMB affects the behaviors of HMA mixtures. The primary focus of the current research is the investigation of the asphalt mix qualities utilizing varied MS content levels (15, 30, and 45% by filler weight).

2 Materials

2.1 Asphalt cement

Asphalt cement is used in this current work type (40/50) grade. It is supplied from the Al-Nasiriyah refinery, located

in the southeast of Baghdad, and is more suited to highly hot climates in the surrounding area. The physical properties of asphalt-cement are shown in Table 1.

2.2 Aggregate

The aggregate used in this work is a crushed aggregate supplied from Al-Badra quarry in the East of Iraq. This type of aggregate is widely used in the asphalt pavement industry. The test results for both coarse and fine aggregate are shown in Table 2.

2.3 Filler

This work utilized limestone dust (LD) and MS as mineral fillers. The physical and chemical characteristics of two types of mineral filler passed through sieve No. 200 (0.075 mm) are shown in Tables 3 and 4, while Figure 1 shows the chemical composition of LD and MS.

2.4 Additives

The polymer used in this study was novolac (phenol formaldehyde solid resin) with a ratio of 4% and its cross-linking agent hexamine (HMTA) with a percentage of 15%. Novolac is often a thermoplastic elastomer usually generated from the reaction of phenol with formaldehyde in an acidic medium. Due to its solid thermal stability through specific rigidity characteristics and its ability to withstand high temperatures during mechanical load with minimum deformation or moisture damage, the novolac polymer was used in this research as a new technique to

Table 1: The physical of properties the asphalt-cement

No.	Tests	Reference standard	Test value (measured)
1	Penetration	D5 [6]	46
2	Flash point	D92 [7]	300
3	Softening point	D36 [7]	50
4	Specific gravity	D70 [8]	1.04
5	Apparent viscosity	D4402 [9]	475
6	Ductility	D113 [10]	131

Table 2: The results of the coarse and fine aggregate tests

Property	Coarse of aggregate		Fine of aggregate	
	Value	ASTM standards	Value	ASTM standards
Bulk specific gravity (g/cm ³)	2.631	C 127 [11]	2.527	C128 [12]
Apparent specific gravity (g/cm ³)	2.659	C127	2.642	C128
Water absorption (%)	1.40	C127	0.93	C128
Los Angeles coefficient (LA)	23	C131 [13]	—	—
Percent of crushed surfaces in coarse aggregate particles (%)	96	D5821 [14]	—	—
Angularity for coarse aggregate	96%	D 5821 [15]	—	—
The sand equivalent value of fine aggregate (%)	—	—	62	D2419 [16]
Flakiness indexes	22	D4791 [17]	—	—

Table 3: The physical properties of limestone dust and MS

Property	LD	MS
Bulk specific gravity	2.56	2.23
Passing of sieve No. 200 (%)	97	95

enhance the properties of neat asphalt. After the asphalt binder had been heated to 160°C in a kiln and put in a mechanical shear mixer, the mixture was added to the asphalt while still dry. The shear mixer equipment for this study offers a speed of mix of 2,500 rpm of 45 min for asphalt in a closed chamber with electronics heating of control as shown in Figure 2. Figure 3 displays the superposed image obtained from a field emission scanning electron microscope (FESEM) and energy-dispersive X-ray spectroscopy (EDX). The polymer modified improved the asphalt binder leading to in large semi-spherical the crystals that merged into one surface and developed a small crack during the

Table 4: The chemical characteristics of limestone dust and MS

Chemical compositions	% content	
	MS	LS
Silica, SiO ₂	90.48	4.1
Sulfuric anhydride, SO ₃	0.45	2.08
Aluminum oxide, Al ₂ O ₃	0.78	1.42
Iron oxide, Fe ₂ O ₃	0.44	0.96
Lime, CaO	0.9	43.7
Magnesia, MgO	1.18	0.038
Loss on ignition	3.11	41.53
Non-soluble substances	—	4.82

homogenization procedure of the polymer particles, making the asphalt substrate less flexible than it would have been in its initial state without the polymer additives. This indicates that the composition bonding procedure for asphalt has been

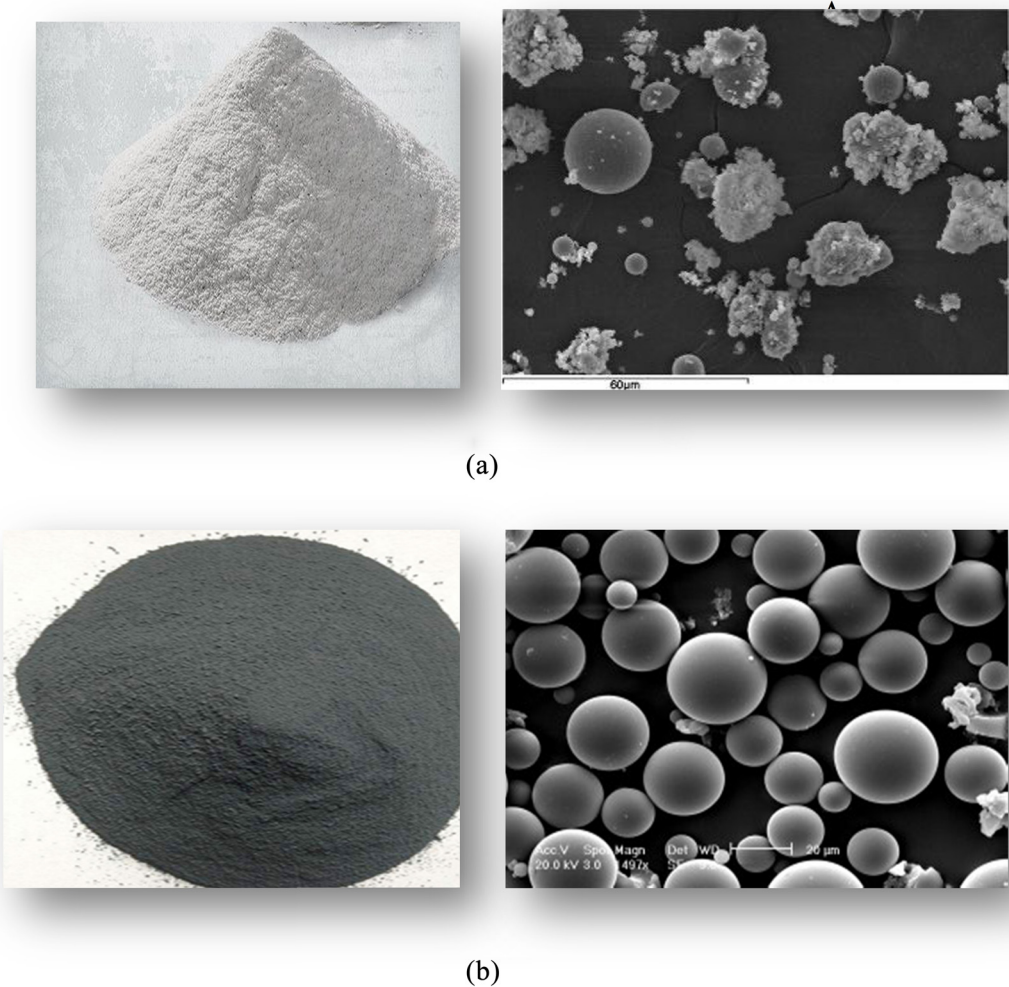


Figure 1: The chemical composition of limestone dust and MS. (a) Limestone dust and (b) micro silica.

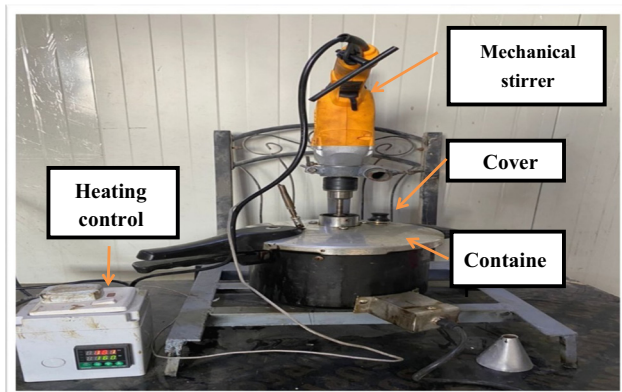


Figure 2: Mechanical of the shear mixer.

made possible and expedited by the addition of polymers. Table 5 shows the physical properties of PMB (Figure 4).

3 Methodology

This research is based on laboratory tests. The samples were produced using the Marshall testing method according to ASTM D6927. The mix design incorporated aggregates graded for the dense-graded, intermediate of specifications

Table 5: The physical properties of the PMB

Tests	Pure asphalt	4% of novolac with 15% of HMTA from the weight of novolac
Penetration (1/10 mm)	46	13
Flashpoint (°C)	300	>300
Softening point (°C)	50	60
Ductility (cm)	131	20
Apparent viscosity c.p.	135°C 480	787.3
	165°C 116	166.8
After thin film oven test ASTM D1754 [18]		
% retained penetration of original	55	63
Ductility of residue (cm)	70	22
%Mass of loss at 163°C, 5 h, 50 g	0.072	0.1

ASTM D3515, with a range of binder percent from 4.0 to 6.0%. Fifteen samples were produced for the control mix and the asphalt mixture blends with MS proportions of 15, 30, and 45%. Using a Marshall compactor, all specimens were compressed with 75 blows on each side. The optimum asphalt content (OAC) for the control mix was estimated using volumetric properties and analysis. To improve the performance of the mixtures used the different ratios 10,

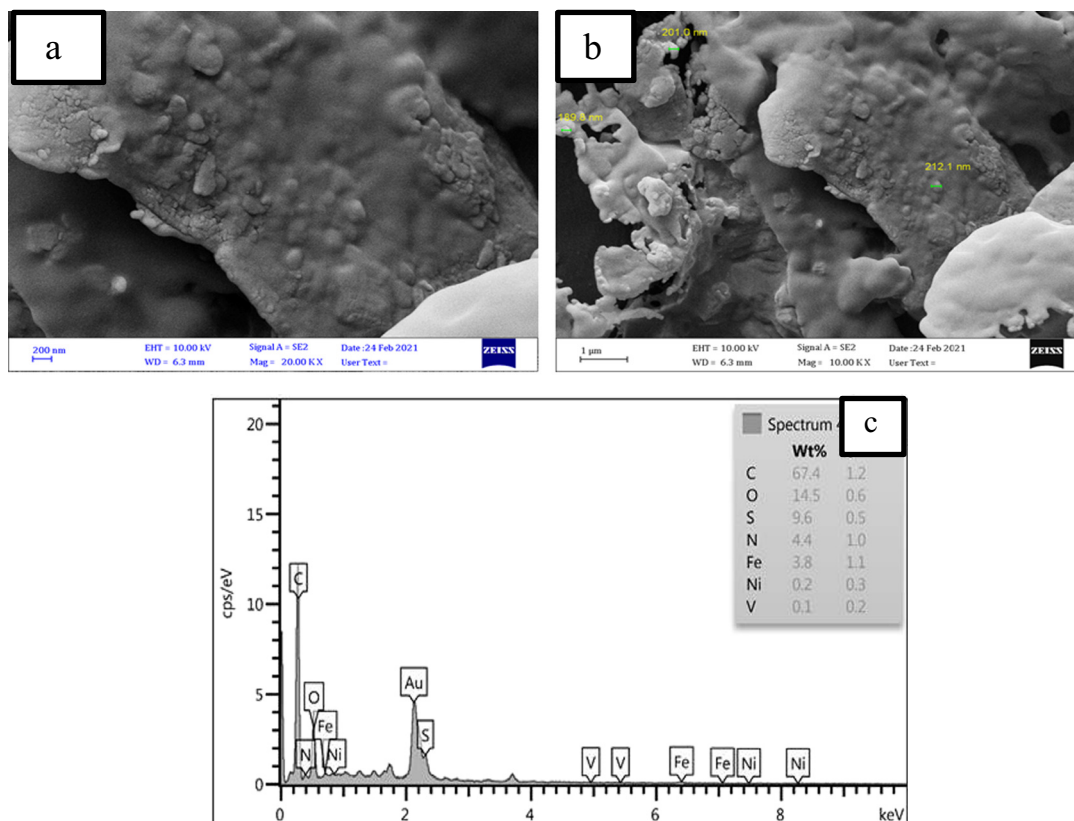


Figure 3: (a and b) FESEM images and (c) EDX of asphalt in the presence of phenol-formaldehyde and hexamine polymers.

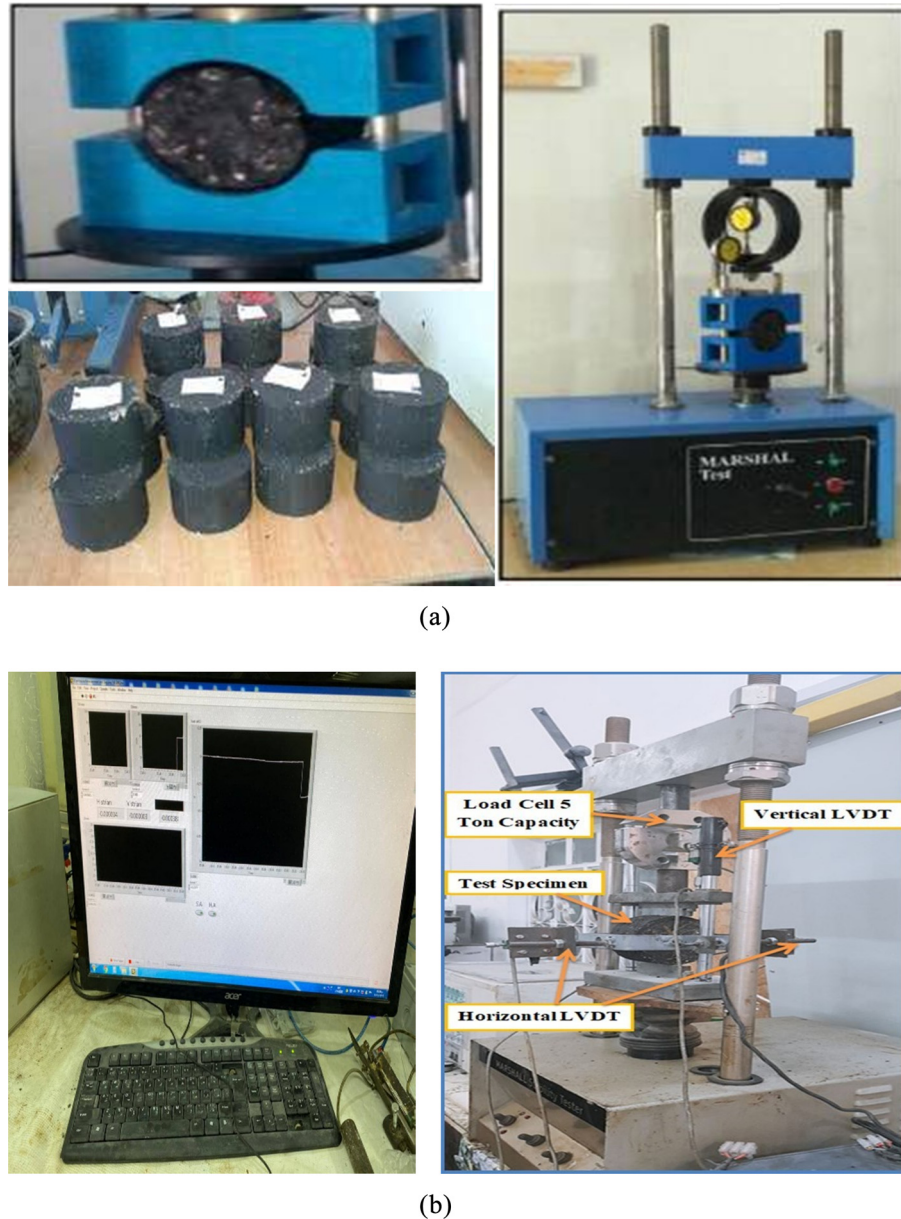


Figure 4: The tests on asphalt mixture. (a) The specimens of marshall test and (b) the creep compliance of test machine.

15, and 45% MS as mineral filler + 4% PMB was prepared to show the combined effect of aggregate gradation by the MF and the modification of the asphalt properties by the use novolac and its cross-linking agent (hexamine) modifier in the mixture for wearing layer. As shown in the Laboratory work flowchart in Figure 5, the performance tests used the OAC value, including indirect tensile strength (ITS), tensile-strength ratio (TSR), and creep compliance. The modified Lottman test was used to assess the moisture susceptibility of the mixtures according to the procedures described in

AASHTO T 283 [19]. The test specimens were prepared with 7 + 0.5% air voids. The creep compliance test was used to determine the mixture's fatigue life. Creep compliance tests were conducted at 0°C (32°F) on cylindrical specimens having a diameter of 101.6 mm and a height of 50 mm, as described in AASHTO T322 [20]. Where steady-static stress is applied along the sample's diametric axis for 100 s, the horizontal and vertical deformations at the center of the sample as a function of time were calculated to determine the tensile creep compliance [21].

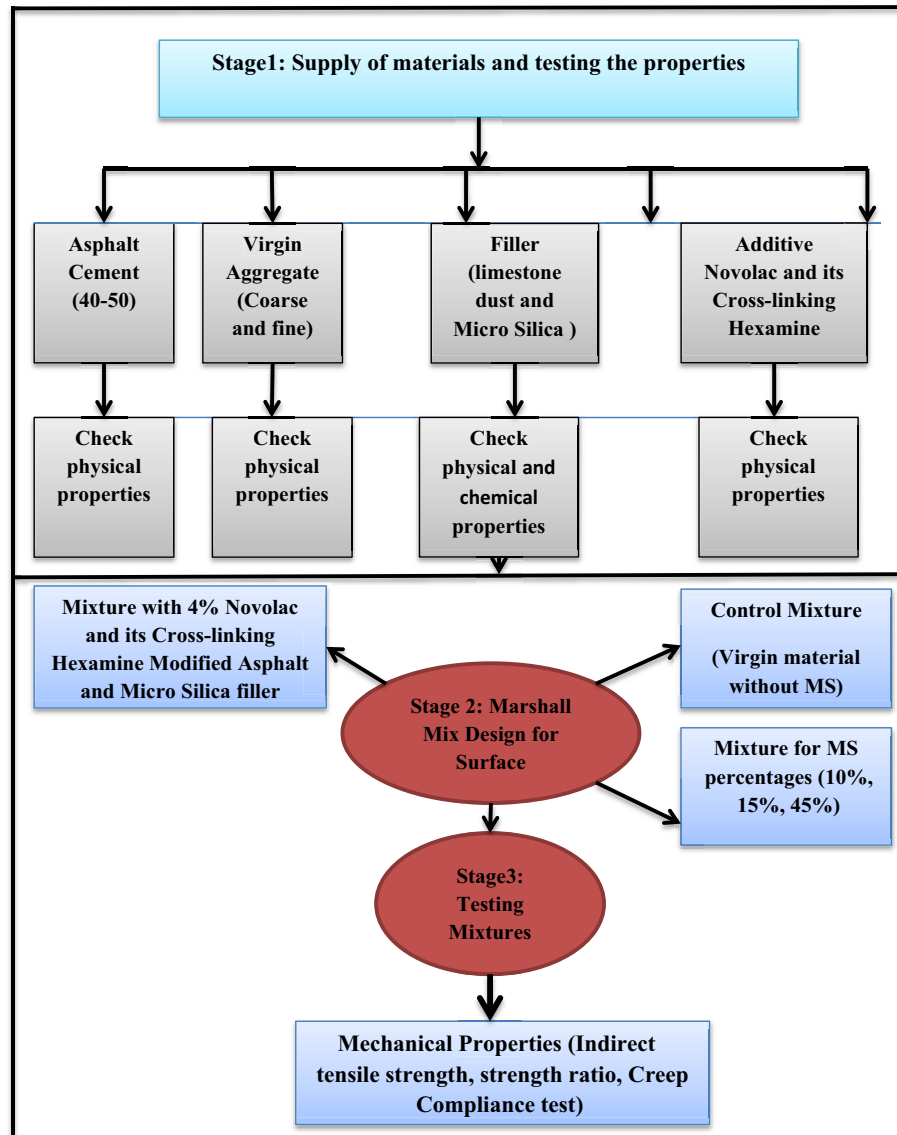


Figure 5: The laboratory of work flowchart.

4 Results

Figure 6 illustrates the ITS values for unconditioned and conditioned examples of HMA blends produced with varying ratios of MS filler and pure bitumen. The result indicated that HMA blends containing MS filler have significantly higher cracking resistance when compared to control blends. This is related to the shape and surface area of the MS filler particle; this property improves the tensile strength resistance and reinforces the bituminous mastic between the aggregates.

The ITS results for unconditioned and conditioned samples of HMA mixes made with various percentages of MS and PMB are shown in Figure 7. The findings demonstrate

that the ITS for HMA mixtures novolac modified is higher than that of the control mixture. This means that mixes containing PMB have better tensile strength at failure values, which also showed increased cohesive strengths of novolac-modified mixtures and improved adhesion and cohesion of binder, and prevented the striping of bitumen from the aggregate surface.

Figure 8 shows the findings of ITS for HMA mixtures produced with unmodified and modified bitumen and HMA mixtures with various amounts of MS filler. According to AASHTO T283, the results indicated TSR higher than 80%, which is below the minimum limit. The addition of MS filler and PMB improves the TSR values of all blends significantly.

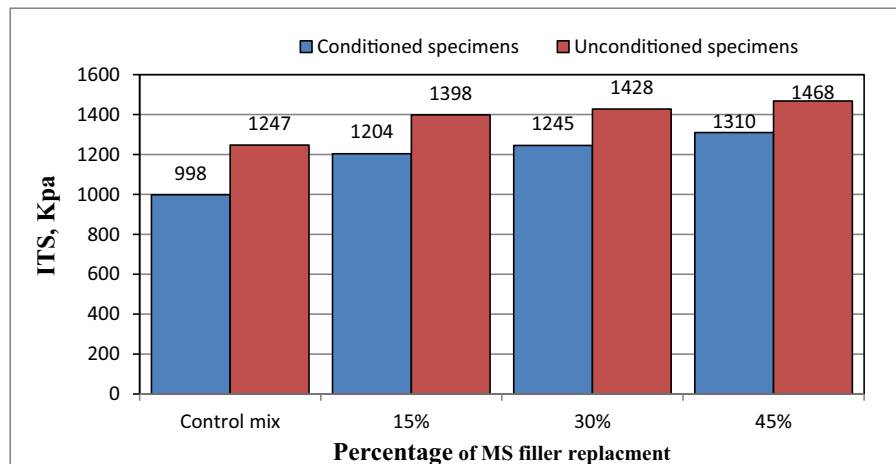


Figure 6: Results of ITS tests for samples with various percentages of MS with unmodified asphalt binder.

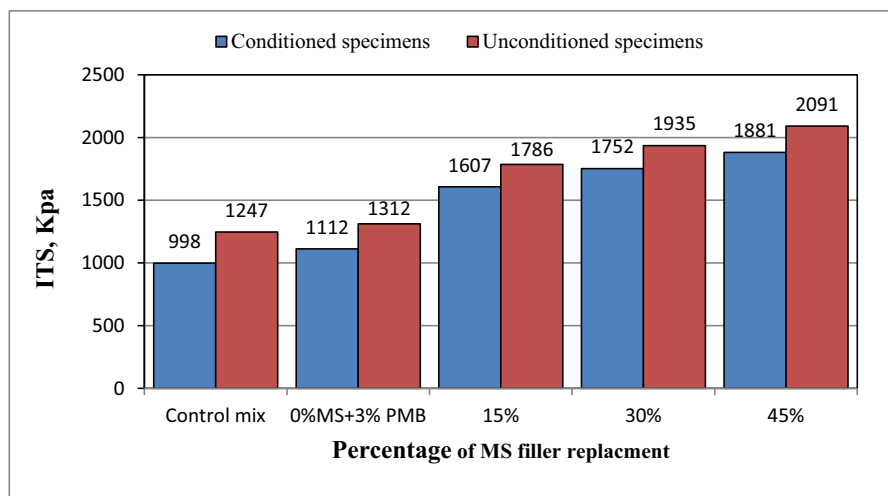


Figure 7: Results of ITS tests for samples containing various percentages of MS with modified asphalt binder.

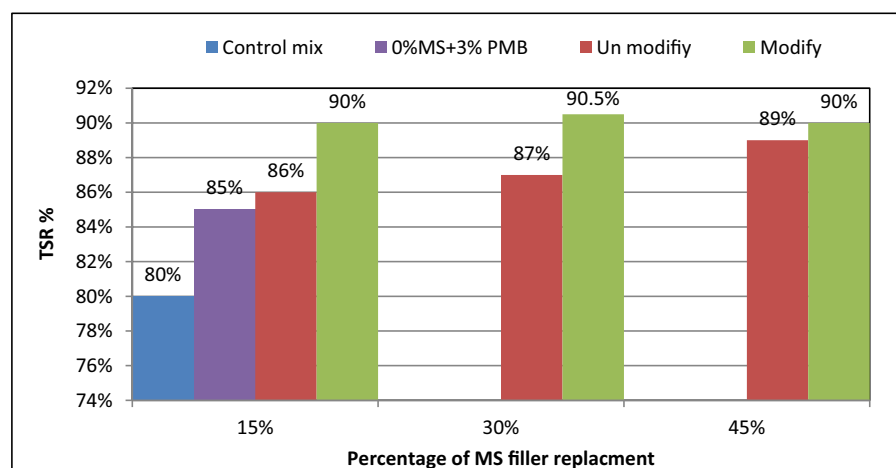


Figure 8: Results of TSR tests performed on samples using various percentages of MS concentrations on both unmodified and modified asphalt binder.

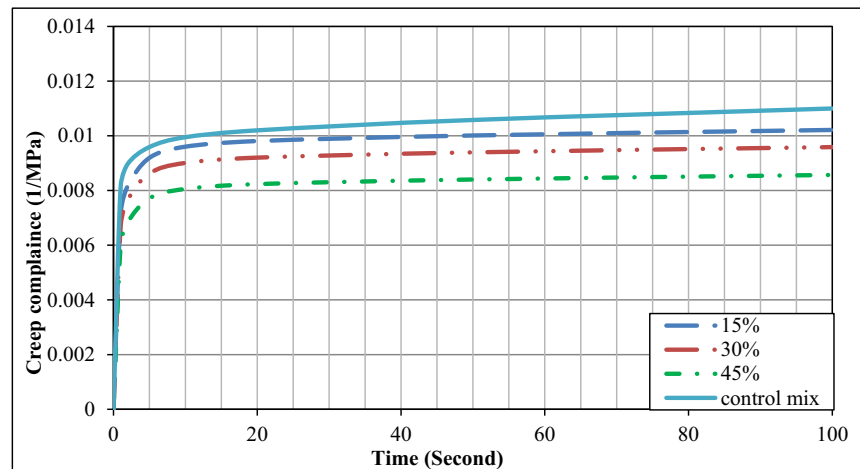


Figure 9: Results of creep compliance tests for samples with various percentages of MS with unmodified asphalt binder.

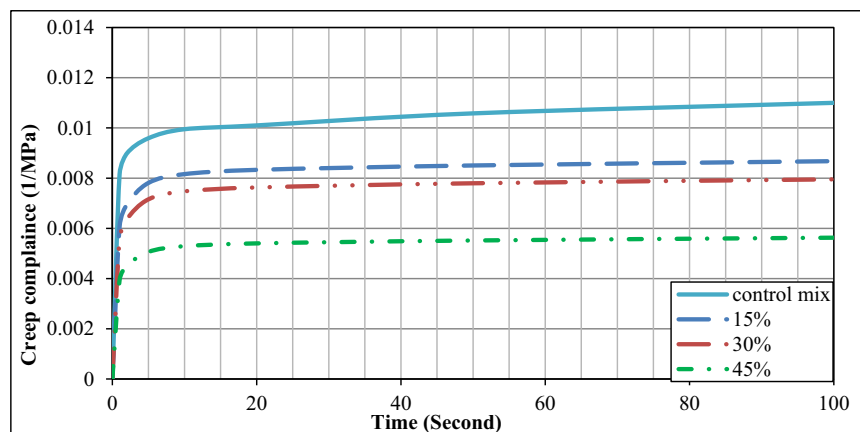


Figure 10: Results of creep compliance tests for samples containing various percentages of MS with modified asphalt binder.

Figure 9 displays the creep compliance data for various replacement percentages of MS mineral filler following 100 s of an application under a steady load at 0°C. The findings demonstrated that adding MS as a mineral filler to HMA prepared with pure bitumen greatly lowered the creep compliance values, increasing the stiffness of the mix and enhancing its crack resistance. This might be explained by the form of the particle and the increased surface area of the MS in the mixture, which decreases the creep compliance and increases the crack resistance of HMA.

The results of the creep compliance test utilizing PMB rather than pure bitumen are shown in Figure 10 for the previously addressed MS mineral filler percentages. The creep compliance values were reduced compared to control mixes and mixes made with only pure bitumen. This proves that using PMB increases the stiffness of HMA and the resistance to crack initiations.

5 Conclusion

The current study investigates the impact of MS and PMB on the properties of HMA blends. For this purpose, three different mixes were prepared by replacing mineral filler with MS in different proportions. In accordance with the findings, the best blend was selected. Then, to increase the mechanical strength of HMA made with the best blend, the MS with partial replacement of LD at 15, 30, and 45% was used. Based on the findings of the tests, the main conclusions are given below:

1. The performance of HMA-containing MS filler can be significantly improved by utilizing PMB binder, which is produced by blending novolac and hexamine with pure bitumen.
2. From the tensile strength test, HMA contained MS filler and PMB was improved compared to the control mixture. It has been found that the addition of 45% MS to

asphalt mixture containing PMB shows the maximum increase in ITS.

3. The HMA mixture containing PMB significantly improved the TSR value for the specimens produced with MS and those produced with MS filler.
4. The creep compliance test results showed that all HMA, including MS filler and PMB, decrease the creep compliance values, which indicates that HMA is becoming stiffer and enhances the fatigue life.

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Data availability statement: Most datasets generated and analyzed in this study are in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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