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New Models for the Properties of Warm Mix Asphalt with Sasobit

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Abstract: Warm Mix Asphalt (WMA) is a set of technologies that uses additives to reduce binder viscosity and increase mixture workability, which provides a complete coating of aggregates at lower temperatures around 100 °C to 130 °C. Organic wax or Sasobit is one of the additives that can be used for this purpose. It reduces the viscosity at the melting point of the wax, which allows the production of asphalt mixes at lower temperatures. This attempt proposes new relationships for elastic modulus, indirect tensile strength (in dry and wet conditions), dynamic modulus, fatigue, and rutting resistance of WMA asphalt samples with various Sasobit percentages. Findings show that Sasobit improves modulus of elasticity, dynamic modulus, and rutting resistance. However, it lessens the tensile strength slightly. Although Sasobit enhances the flexural stiffness, it drops the number of loading cycles, which means lower fatigue resistance. Results also showed that at 20 °C and 10 Hz frequency, the resilient modulus, dynamic modulus, and flexural stiffness of WMA improved 53%, 27%, and 39%, respectively, compared with HMA. Rutting resistance at 60 °C improves 226% in WMA with 6% Sasobit compared to the HMA mix.

Keywords: resilient modulus; indirect tensile strength; dynamic modulus; warm mix asphalt (WMA); Sasobit; prediction models

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1. Introduction

The asphalt industry has regarded the sustainability concept with continuous efforts to reduce greenhouse gas emissions (GHG) and fossil fuel consumption [1–3]. Hot mix asphalt (HMA) is generally produced in the mixing plants at temperatures ranging from 150 to 170 °C. High temperatures are necessary to dry and uniformly coat the aggregates and provide the desired workability during placing and compaction of the mix. Warm mix asphalt (WMA) with lower emissions is produced at temperatures 20 °C to 40 °C lower than the temperatures required for HMA. WMA has become an increasingly viable option due to its merits in sustainability and mechanical properties [4]. Various types of WMA are vital in road construction, as they can contribute to saving costs, carbon footprint, and natural resources and reduce greenhouse gas emissions [5–7].

Sasobit is one of the modifiers or additives for making WMA. Sasobit is a synthetic wax made up of long-chain hydrocarbons. This material is obtained by polymerization during the Fischer–Tropsch process. It is used as a modifier in hot asphalt mix due to reduced temperature in the production and conduction of mixtures [1,8]. Sasobit expands the plastic limit and increases the melting temperature range of asphalt binders [9]. The melting point of Sasobit is approximately 100 °C, and bitumen can be thoroughly mixed at temperatures above 116 °C. Above the melting point of the Sasobit, the wax liquefies. Thus, the viscosity of the bitumen drops significantly and allows the production temperature of the asphalt mixture to reduce by 20–30 °C [10,11]. Below the melting temperatures, Sasobit forms a lattice structure in asphalt binder and provides better stability, according to field trial reports [12,13]. Furthermore, the use of Sasobit in the mix reduces waste materials and pollution caused by other products. Zhao and Guo [14] evaluated the workability of WMA containing Sasobit at different temperatures and frequencies in contrast with HMA.

The results showed that adding Sasobit to WMA reduced temperature up to 30 °C, and the workability of the WMA mix, which contained Sasobit, was as same as the HMA mix. Liu and Li [15] studied the performance of the WMA mixture modified with Sasobit at a low temperature. The results showed that the tensile strength reduces for both HMA and WMA at low temperatures, and thermal cracks rise with increasing Sasobit content. However, the increase in thermal cracks was negligible, which showed that adding Sasobit to mixtures at low temperatures had little effect on cracking resistance. Liu et al. [16] investigated the rutting resistance and moisture susceptibility of WMA containing Sasobit at low temperatures. Results showed Sasobit reduced mixing and compaction temperatures, improved workability, and rutting resistance, and had an insignificant effect on moisture susceptibility. The indirect tensile test results showed decreased WMAs tensile strength at low temperatures. In addition, adding Sasobit from 0 to 3% by weight of bitumen in the mixture increased the dynamic modulus by 18%. Raveesh et al. [17] examined using of Sasobit additive in WMA. In this study, Sasobit content was used 1 to 5% in the WMA mixture. The results showed that adding Sasobit to the mixture reduced the temperature of the asphalt mixture by up to 30%. Further, their experimental results show that Marshall's stability values increased with the addition of 3% and 4% to the modified bitumen compared to the HMA. However, the Sasobit reduces the amount of Marshall flow. In addition, adding 1–5% Sasobit in WMA reduces ITS values for unconditional and conditional samples by about 14–19% and 20–36%, respectively. Sobhi et al. [18] examined the effect of Sasobit on the mechanical properties and durability of asphalt mixtures. In this study, 3% Sasobit (by weight of binder) was added to the mix. Then, its effects were evaluated with various experiments, such as dynamic creep, modulus of elasticity, indirect tensile strength, and semi-circular bending test. The results showed that adding Sasobit increased the stiffness of the mixtures and enhanced their performances while negatively affecting the moisture sensitivity of WMA. Moreover, experimental results showed that the mechanical properties and durability of asphalt mixtures improved with the addition of Sasobit.

This study aimed to study the mechanical properties, especially fatigue, rutting, and durability, of warm mix asphalt containing Sasobit by presenting new models. These applied models predict the mechanical parameters of WMA mixtures in terms of the weight percentage of Sasobit. In this study, the mechanical properties and durability of WMA with Sasobit were investigated versus HMA. For this purpose, mechanical properties, including indirect tensile strength, modulus of elasticity, dynamic modulus, fatigue resistance, and rutting with three different Sasobit percentages (1.5%, 3%, and 6%), were examined.

2. Materials and Samples

2.1. Materials

Three sizes of aggregates, including 10 mm, 7 mm, and 5mm from a local quarry, were used. Adhesion agent or filler was also lime for 1.4% of the total mix (Main Road Western Australia requirement). The particle size distribution of aggregates with a maximum nominal size of 10 mm was under MRWA 200.1-2012 [19] and is shown in Figure 1. In addition, the physical properties of aggregates are presented in Table 1. Binder class C320 (bitumen), popular in Australia, was used for the research. The properties are presented in Table 2. In this study, Sasobit was chosen as the modifier due reducing of temperature preparation and conduction of mixtures. Sasobit or wax is a fine, crystalline, long-chain, aliphatic hydrocarbon with a melting point range between 85 °C and 115 °C. Thus, the base asphalt binder was modified by adding 1.5, 3, and 6% of Sasobit by weight of the asphalt binder. An image of the Sasobit used in this study is shown in Figure 2.

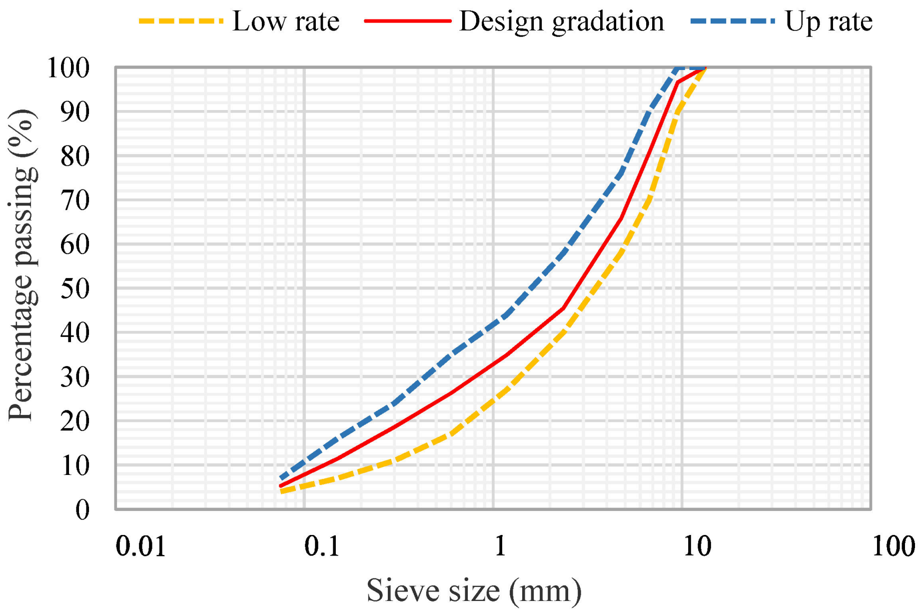


Figure 1. The particle-size distribution.

Table 1. Aggregate properties.

Test Description	Value	Test Standard
Los Angeles abrasion: granite and other rock types Basalt	35% Maximum 25% Maximum	WA 220.1-2012
Flakiness index	35% Maximum	WA 216.1-2016
Water absorption	2% Maximum	AS 1141.6.1
Wet strength	100 kN minimum	AS 1141.22
Wet/Dry strength variation	35% Maximum	AS 1141.22
Stripping test value	10% Maximum	AS 1141.50
Degradation factor	50 minimum	AS1141.25.2
Secondary mineral content	25% maximum	AS 1141.26
Petrographic examination	Statement of suitability for use as an asphalt aggregate	-

Table 2. Bitumen C320 properties (AS 2008–2013).

Test Description	Min	Max	Test Standard
Viscosity at 60 °C, Pa.s	260	380	AS 2341.2 AS 2341.3
Viscosity at 135 °C, Pa.s	0.4	0.65	AS 2341.2 AS 2341.3 AS 2341.4
Penetration at 25 °C, (100 g, 5 s), pu (1 pu = 0.1 mm)	40	-	AS 2341.12
Density at 15 °C, kg/m^3	1000	-	AS 2341.7
Flash Point, °C	250	-	AS 2341.14
Matter insoluble in toluene, percent	-	1	AS 2341.8

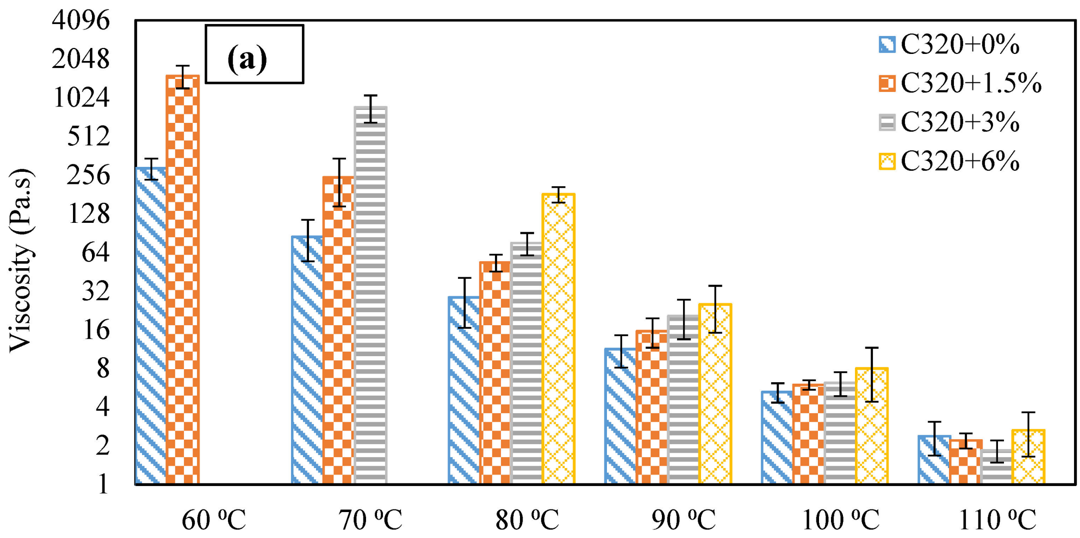
Figure 2. Sasobit.

2.2. Sample Preparation and Mixing Temperatures

In this study, bitumen was modified by adding 1.5%, 3%, and 6% Sasobit (by weight of the binder) at the temperature of 150 °C. In general, four types of bitumen samples are considered in this study. One base bitumen was used as a reference in the HMA mixture, and three Sasobit-modified binders with different weight percentages were used for WMA mixes.

Loose mix samples were produced in the laboratory according to the preparation of Asphalt Samples for Testing (AP T132/09). HMA aggregate was placed in the oven for drying at a temperature of 160 °C, attaining a mixing temperature of 155 °C. The bitumen was allowed to heat for three hours simultaneously with the aggregate, until it reached a temperature of 160 °C to comply with the required mixing temperatures. Then, the aggregate was dried in the oven at a temperature of 140 °C. This was to ensure the temperature of 135 °C for WMA mixes. The bitumen was allowed to heat for three hours simultaneously with the aggregate, until it reached a temperature of 160 °C. Immediately after the temperature required was reached, the bitumen (previously prepared with additive and lime) was added to the aggregates. Sasobit was melted at 120 °C and then mixed with enough hot bitumen to obtain a homogeneous mixture. HMA mix was conditioned to 150 °C, while WMA mixes were conditioned to 130 °C for one hour. Two ovens were used to ensure the temperatures were kept to the requirements, thus meaning the final test results were not affected. The last step of the mixing process was to mix all the pre-heated aggregates with the binder and Sasobit. This process was achieved with the use of a Hobart mixer.

Figure 3 shows the viscosity results at different temperatures for C320 bitumen mixed with Sasobit. As shown in Figure 3, the mixing and compaction temperatures for the unmodified mixture were 160 and 155 °C, respectively. However, the modified mixture with Sasobit had the mixing and compaction temperature of 135 °C [20]. For mixture preparation, Sasobit was melted at 120 °C and added to the bitumen with a temperature of 150 °C. Next, it was mixed with all the pre-heated aggregates with the modified binder [21]. The binder properties shown in Table 3. The rolling thin film oven (RTFO) test results are presented in Table 4 following AS 2341.10 [22].



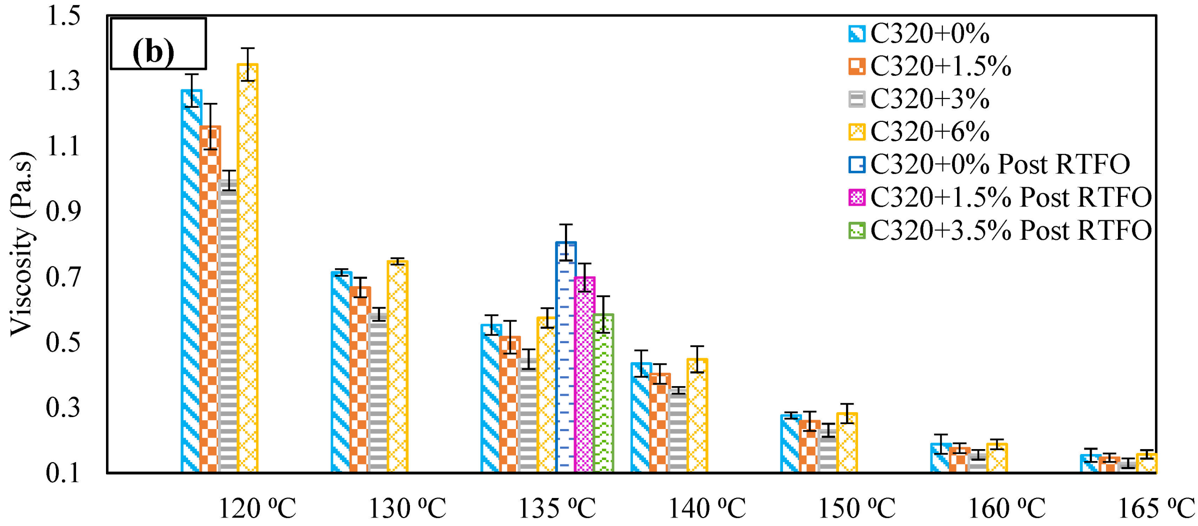


Figure 3. Viscosity results at different temperatures for C320 bitumen mixed with Sasobit: (**a**) viscosity at 60 °C to 110 °C; (**b**) viscosity at 120 °C to 165 °C.

Table 3. Asphalt binder properties.

Bitumen Type		**C320**	**C320 Modified 1.5% Sasobit**	**C320 Modified 3% Sasobit**	**C320 Modified 6% Sasobit**
Test Discerption	Test Standard			Values	
Dynamic viscosity at 60 °C (Pa.s)	AS 2341.2	289	1510	-	-
Kinematic viscosity at 135 °C (mm^2/s)	AS2341.2 AS 2341.4	0.553	0.516	0.4483	0.575
Softening point (°C)	AS 2341.18–1992	56.1	65.7	82.15	92.75

Table 4. Rolling thin film oven test: C320 AS 2341.10.

Test Description	Min	Max	Test Standard
Viscosity of residue at 60 °C as percentage of original	-	300	AS 2341.2 AS 2341.3
Ductility at 15 °C, mm	N/A		AS 2341.11
Durability value	N/A		AS/NZS 2341.13 WA 716.1

3. Experimental Methods

3.1. Resilient Modulus

The resilient modulus of the specimen was measured under indirect tensile cyclic loads using a universal testing machine (UTM 25) according to AS 2891.13.1-1995 methods [23]. The frequency and temperature used in this research are 10 Hz and 25 ± 5 °C, respectively. The samples used for resilient modulus testing were produced using the gyratory compactor (Servopac) [24].

3.2. Indirect Tensile Strength (ITS) and Moisture Sensitivity

TSR measures the stripping potential of an asphalt mix by measuring the strength of an unconditioned and conditioned specimen. For the investigation, testing was performed according to method AGPT/T232. MRWA specification 510 specifies limits for TSR testing of 850 kPa for an unconditioned specimen and 750 kPa for a conditioned specimen [25].

3.3. Dynamic Modulus

Dynamic modulus testing was carried out using the method AASHTO TP62-07 [26]. An asphalt mixture performance tester (AMPT) machine was used for testing, including an environmental chamber and a measuring system. Dynamic modulus values were tested at 4 °C, 20 °C, and 40 °C with a frequency of 0.1 Hz, 1 Hz, and 10 Hz to generate a master curve. Three laboratory samples (cylinders) were produced for each temperature, and a Servopac gyratory compactor was used for compaction to obtain air void of 5 ± 0.5% at a specific temperature. Strain gauges were fixed to the specimens and used to measure strain under sinusoidal conditions to calculate the dynamic modulus and phase angle data. The specimen was made with D = 100 mm and H = 150 mm [27].

3.4. Fatigue Test

Three beams were prepared for each control hot mix and Sasobit-modified mix. The test was conducted based on the Austroads method AGPT/233 at 20 °C with 10 Hz frequency and 400 μ strain, and the beam dimensions were 390 ± 5 mm length, 63.5 ± 5 mm horizontal width, and 50 ± 5 mm vertical depth [28].

3.5. Wheel Track Test

The wheel track test was performed according to the AGPT/T231 test [29]. The specimens were produced using a slab compactor, and all samples were compacted to the required 5 ± 1.0% air voids. The samples were conditioned for a minimum of 6 h at 58 °C, and rutting depths were measured at 10,000 cycles at 60 °C.

4. Results and Discussions

4.1. Resilient Modulus

The results of the elastic modulus are presented in Table 5 and Figure 4. In addition, the results clearly show that all WMA samples are within the typical values of modulus of elasticity for dense grade asphalt, as shown in Table 6 [30]. As can be seen from Figure 4, the resilient modulus value for WMA samples containing modified bitumen with Sasobit is higher than HMA control samples. The reason for this increase might be due to the interaction between the Sasobit crystals, which form a network and reduce the temperature of the bitumen, causing it to harden and stiffen the binder; the result is an increase in the resilient modulus of the asphalt mixture [18,31]. Figure 4 showed that the resilient modulus for WMA mixtures increased 0.4, 18.2, and 52.8% by the inclusion of 1.5, 3, and 6% of the Sasobit compared to the HMA, respectively. Hence, increasing the modulus of elasticity obtained from mixtures containing Sasobit can reduce the thickness of the asphalt layer, improve the strength of the mix against heavy traffic loads, and increase the pavement service life.

Table 5. Average resilient modulus results.

Mixes Type	Specimen *N*	Average Rise Time (ms)	Average Force (N)	Average of Five Pulses (MPa)	Standard Deviation (MPa)	Average Resilient Modulus (MPa)	Sasobit Effects Compared to HMA Mix
HMA Control	1	24	1822	4397	310.9	4472	-
	2	37	2068	4814			
	3	39	1784	4206			
WMA 1.5% Sasobit	1	18	1984	4061	606.7	4490	0.4%
	2	31	2102	4919			
WMA 3% Sasobit	1	37	2436	5370	84.5	5286	18.2%
	2	43	2467	5286			
	3	42	2425	5201			
WMA 6% Sasobit	1	37	3364	6611	235.8	6835	52.8%
	2	41	3231	6812			
	3	36	348	7081			

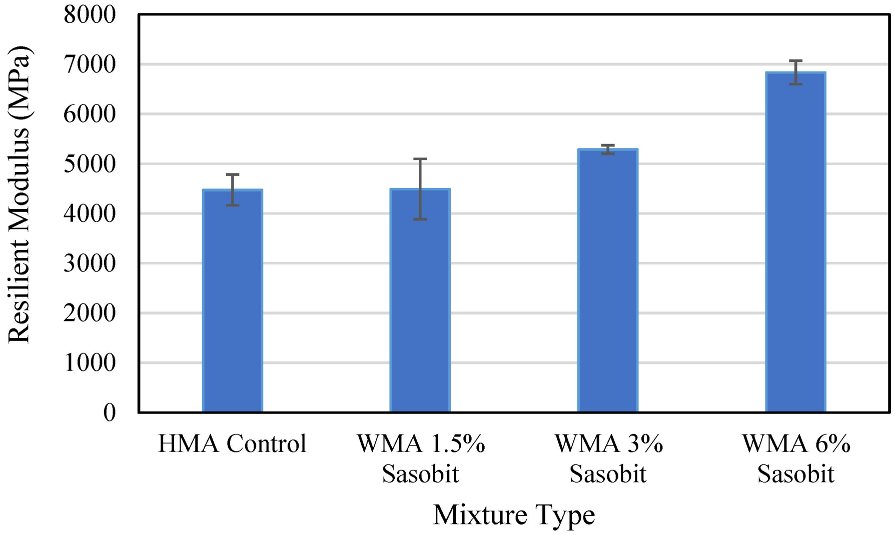


Figure 4. Resilient modulus test results of different asphalt mixtures.

Table 6. Typical resilient modulus values for various mixes in Australia [30].

Binder Type	10 mm		14 mm		20 mm	
	Range	Typical	Range	Typical	Range	Typical
Class 170	2000–6000	3500	2500–4000	3700	2000–4500	3300
Class 320	300–6000	4500	2000–7000	5000	3000–7500	5200
Class 600	3300–5000	6000	4000–9000	6500	4000–9500	7000
Multigrade	1500–5000	4500	3000–7000	5000	4000–7000	5500
SBS	1500–4000	2200	2000–4500	2500	3000–7000	3000
EVA	–	–	3000–6000	5600	–	–

The correlation of the resilient modulus versus Sasobit percentages was attempted by nonlinear regression analysis. It is expressed as Equation (1) with the coefficient of determination ($R^2 = 0.99$).

$$\frac{E_{WMA,Sa}}{E_{HMA}} = \frac{1}{1 - 0.036Sa^{1.28}} \tag{1}$$

where Sa is the percentage of Sasobit, which is used as the percentage by weight of bitumen in the WMA mixture. In Figure 5, the results of the predicting model were compared with other researcher's studies (Sobhi et al. [18], Behroozikhah et al. [32], Ghuzlan and Ar'ar [33], and Behbahani et al. [34]). As can be seen from Figure 5, there is a good correlation between the results of the resilient modulus in the proposed model and other researchers' studies.

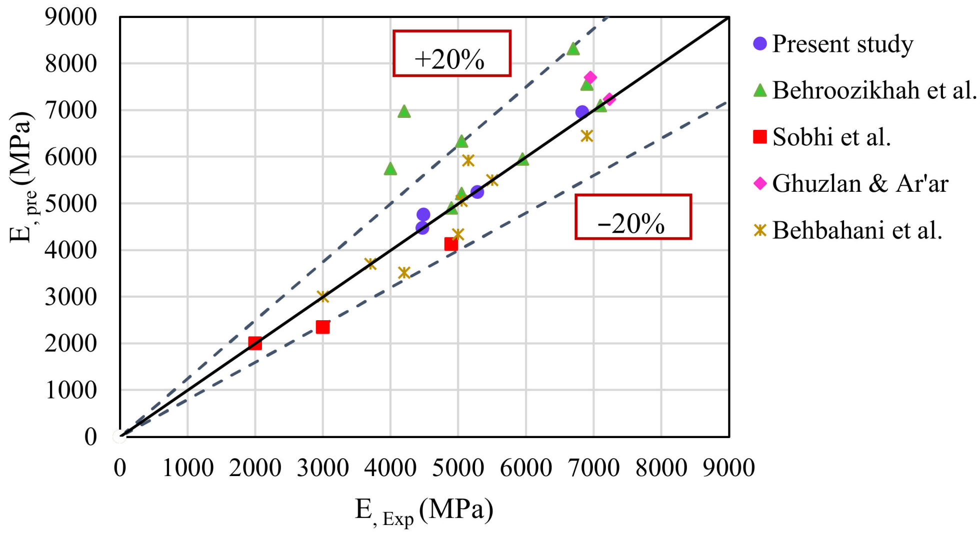


Figure 5. Comparison of the resilient modulus between the proposed model and the laboratory results of other researchers.

4.2. Indirect Tensile Strength (ITS)

The results of the ITS experiment are presented in Figure 6 and Table 7 for both conditioned and unconditioned samples. Adding Sasobit to the asphalt mixture reduces ITS significantly for conditioned and unconditioned samples. Adding 1.5–6% of Sasobit reduces the ITS values by about 2.6–7.4% and 2.1–3.8% for conditioned and unconditioned mixtures, respectively. These indicate a higher moisture sensitivity of WMA containing Sasobit in contrast to HMA mixtures; based on the previous research on moisture sensitivity for WMA with Sasobit, this might be due to the adhesion reduction between binder and aggregate [35,36]. Furthermore, TSR results for different asphalt mixtures are presented in Table 7 and Figure 7. TSR values were significantly lower in WMA mixtures containing Sasobit compared to HMA although in higher percentages of Sasobit, the TSR of the samples was less reduced. As can be seen in Figure 7, an increase in Sasobit content showed a positive effect on TSR values. Moreover, the average TSR results for HMA and WMA show that all mixtures had enough moisture sensitivity, as they were more than the minimum of 80% as required in the standard. Sasobit can increase moisture sensitivity in asphalt mixtures by reducing the adhesion between aggregate and binder. Furthermore, the brittle behavior of the mixture containing Sasobit can change the fracture mechanism.

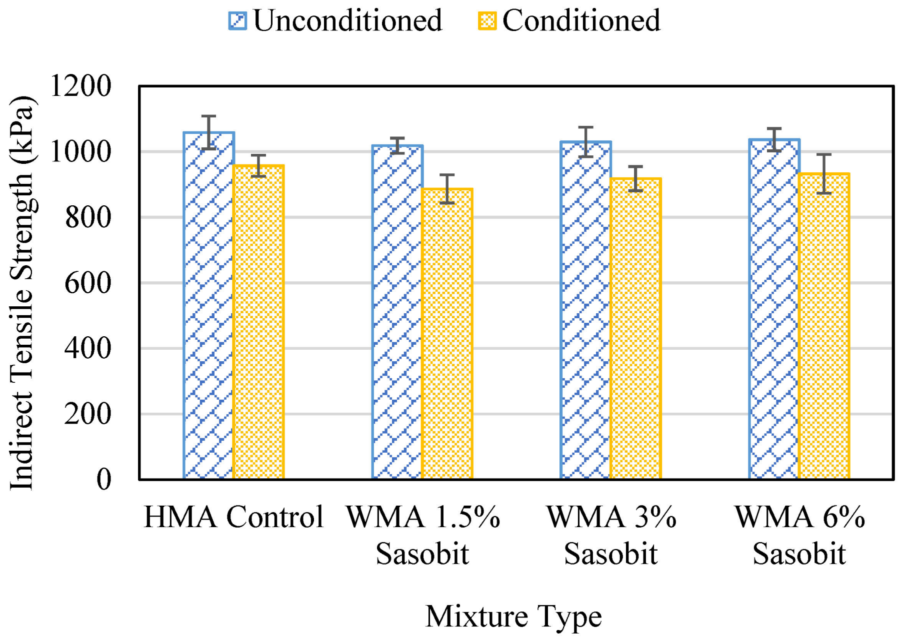


Figure 6. The results of indirect tensile strength of different asphalt mixtures.

Table 7. TSR average results for HMA and WMA.

Test Method Used	HMA Control	WMA 1.5% Sasobit	WMA 3.0% Sasobit	WMA 6.0% Sasobit	Specification
Dry set air voids (%) (Average of 3 tests)	8.1	8	7.9	8.1	-
Dry tensile strength at 25 °C (kPa) (Average of 3 tests)	1058.3	1018.2	1029.3	1036.5	850
Standard deviation (kPa)	50	23	45	34	
Wet set air voids (%) (Average of 3 tests)	7.9	8.2	8	8.1	-
Wet tensile strength at 25 °C (kPa) (Average of 3 tests)	956.8	886.2	917.6	932.4	750
Standard deviation (kPa)	32	43	37	59	
Tensile Strength ratio (%)	90.4	87.0	89.1	90	80.0

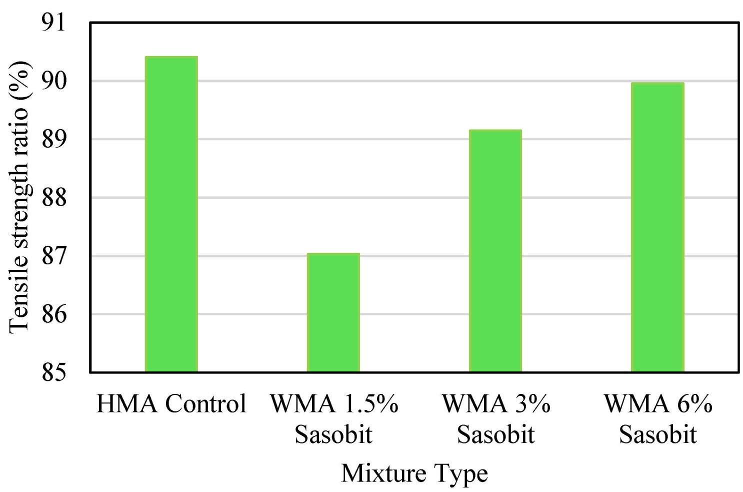


Figure 7. TSR values of different asphalt mixtures.

Nonlinear regression analyses were used to reach a normalized equation for the indirect tensile strength versus Sasobit percentages for both conditioned and unconditioned samples. They are expressed as Equations (2) and (3), respectively, with the coefficient of determination ($R^2 = 0.79$ and 0.81 for conditioned and unconditioned samples, respectively).

$$\frac{f_{con,WMA,Sa}}{f_{con,HMA}} = \frac{1}{(1 + 0.033 * sa - 0.005 * sa^2)} \quad (2)$$

$$\frac{f_{uncon,WMA,Sa}}{f_{uncon,HMA}} = \frac{1}{(1 + 0.022 * sa - 0.003 * sa^2)} \quad (3)$$

For further validation of the proposed model for both conditioned and unconditioned samples, the results of the predicting model for the ITS compared in Figure 8 with other researcher's studies that are mentioned in the literature (Raveesh et al. [17], Fakhri et al. [36], Gong et al. [31], and Goh et al. [37]). As can be seen from Figure 8, the results of the ITS in the proposed model are in agreement with other researchers' studies.

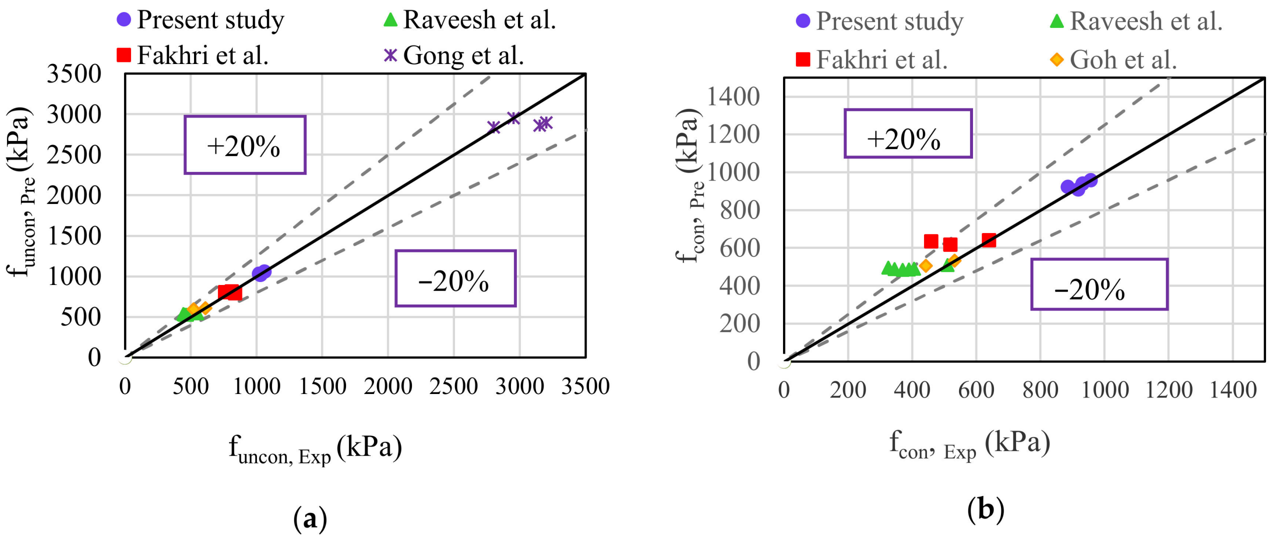


Figure 8. Comparison of the tensile strength results between the proposed model and the laboratory results of other researchers: (**a**) conditioned samples; (**b**) unconditioned samples.

4.3. Dynamic Modulus

The master curve parameters and master curve for each mixture are presented in Table 8 and Figure 9, respectively. Based on the results, it can be concluded that the mixture's response, which is under cyclic loading conditions, is dependent on the temperature and frequency. The mean values of the dynamic modulus for the WMA samples containing Sasobit and HMA at different temperatures and frequencies are presented in Figure 9 and Table 8. As shown in Figure 10, the dynamic modulus decreases significantly with increasing temperature, while the dynamic modulus increases with increasing frequency. Additionally, it can be seen from Figure 10 and Table 9 that the dynamic modulus for WMA samples is higher than the HMA control samples. At 20 °C and 10 Hz frequency, the addition of 3% and 6% of Sasobit increases the dynamic modulus by 16.4% and 26.6%, respectively. However, the amount of 1.5% Sasobit in the modified WMA mixture reduces the dynamic modulus by 7.6%. The increase might be due to the presence of larger wax crystals in the asphalt bitumen containing Sasobit than reference bitumen [1,11]. Furthermore, adding Sasobit to the asphalt mixture lowers the bitumen temperature, makes the binder stiffen, and increases the dynamic modulus.f

Table 8. Master curve parameters.

Mixes Type	δ	α	β	γ	a_1	a_2	T_R	T	f	f_r	a_T
HMA Control	2.71	1.66	−2.68	−0.03	0.12	0.0073	20	4	10	−0.50432	−0.05
WMA 1.5% Sasobit	2.71	1.66	−2.68	−0.03	0.12	0.0073	20	4	10	−0.50432	−0.05
WMA 3.0% Sasobit	3.08	1.46	−1.58	−0.0051	0.12	0.0073	20	4	10	−0.50432	−0.05
WMA 6.0% Sasobit	3.08	1.46	−1.58	−0.0051	0.12	0.0073	20	4	10	−0.50432	−0.05

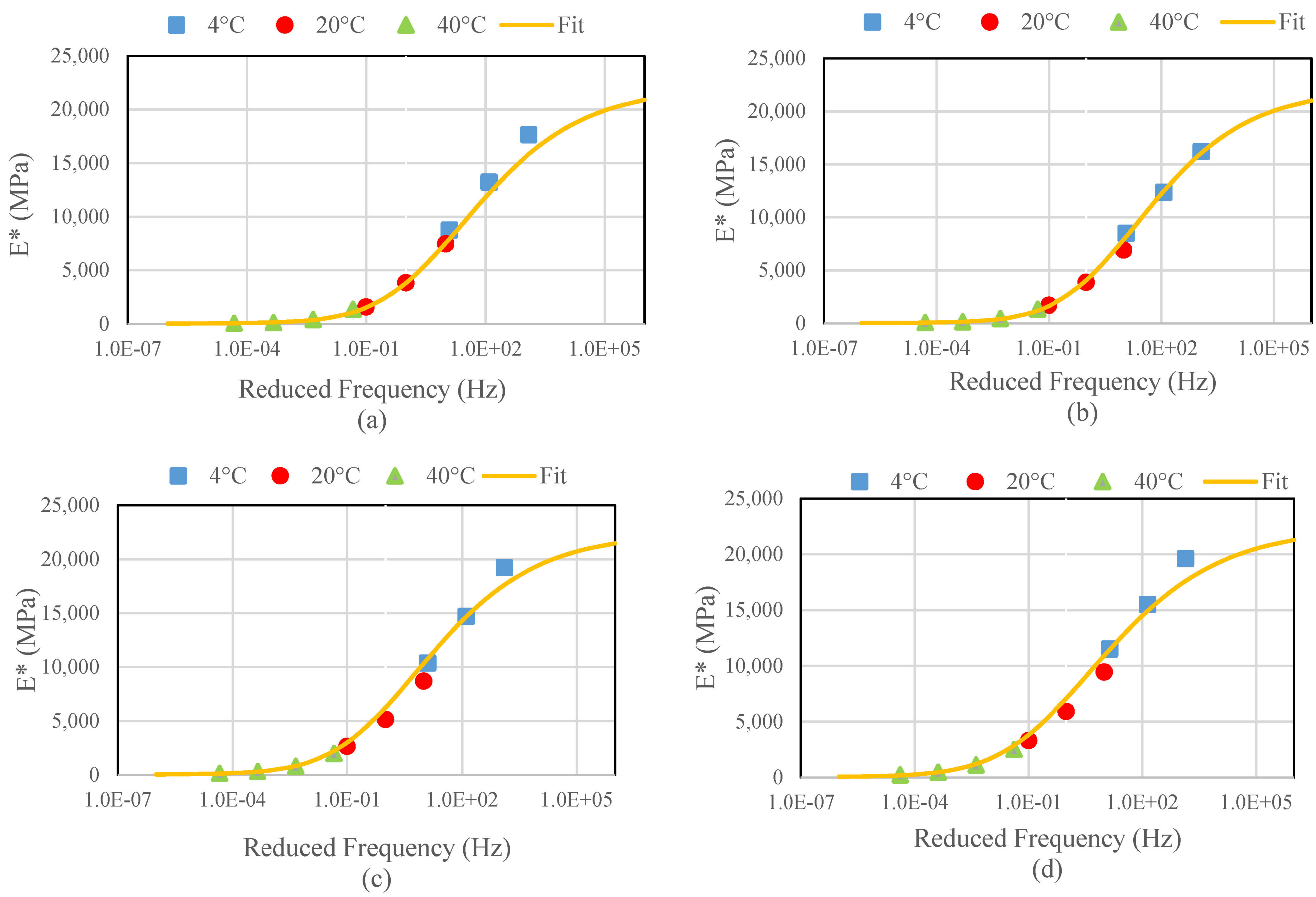


Figure 9. Master curves results: (**a**) HMA samples; (**b**) WMA with 1.5% Sasobit; (**c**) WMA with 3% Sasobit; (**d**) WMA with 6% Sasobit.

Table 9. Laboratory results of WMA and HMA for dynamic modules.

Mixes Type	Temperature (°C)	Dynamic Modulus (MPa)		
		0.1 (Hz)	1 (Hz)	10 (Hz)
HMA Control	4	8732.7	13,208.6	17,621.9
	20	1572.9	3829.4	7464.2
	40	125.6	399.9	1356.1
WMA 1.5% Sasobit	4	8478.8	12,346.2	16,191.5
	20	1701	3866.3	6898.9
	40	144.8	447.9	1347.7
WMA 3.0% Sasobit	4	10,375.8	14,687.5	19,214.1
	20	2646.5	5138.8	8687
	40	312.7	803.7	1990.6
WMA 6.0% Sasobit	4	11,495.4	15,499.7	19,611.2
	20	3311.7	5923.2	9451.2
	40	474.7	1119.2	2516.9

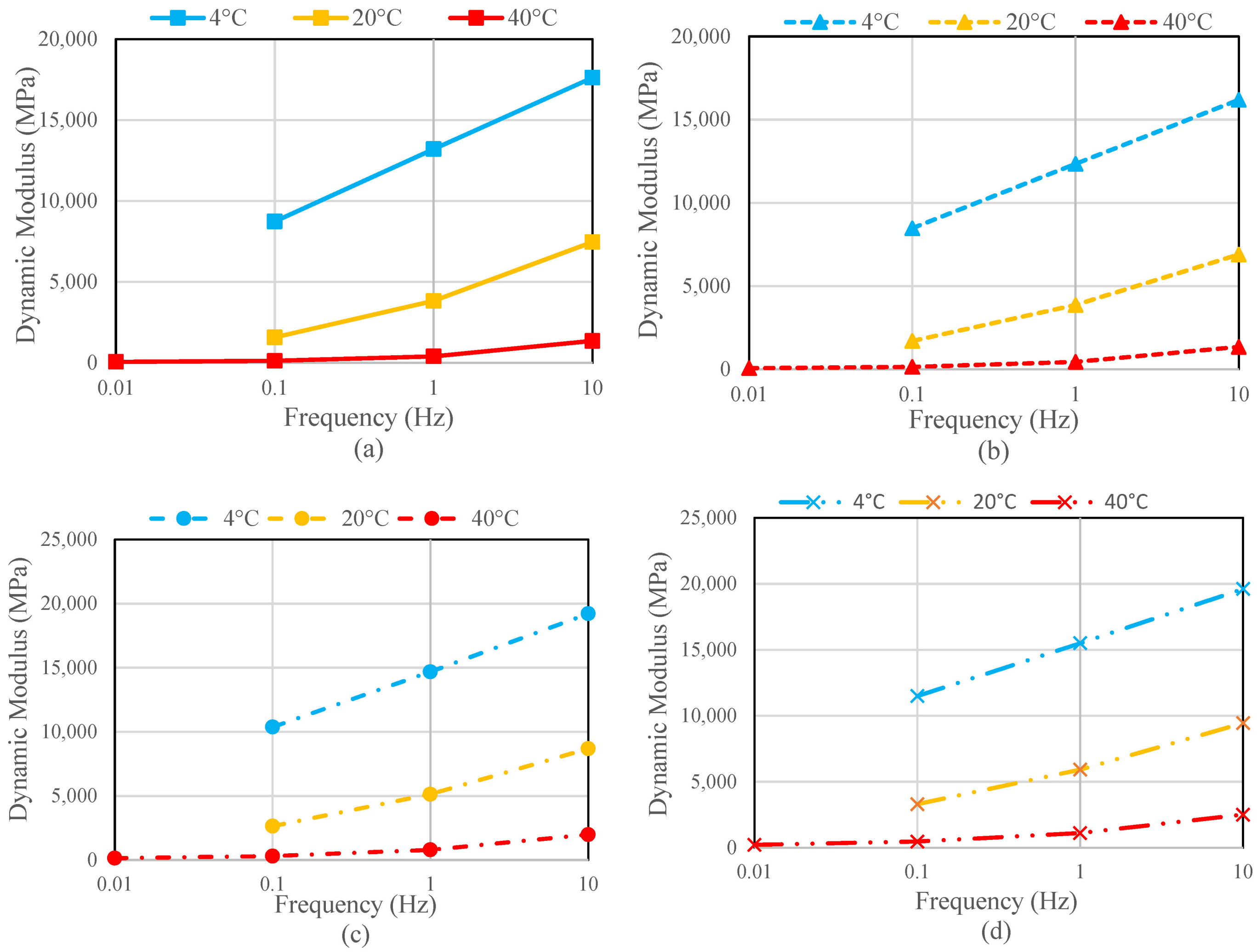


Figure 10. Dynamic modulus results: (**a**) HMA samples; (**b**) WMA with 1.5% Sasobit; (**c**) WMA with 3% Sasobit; (**d**) WMA with 6% Sasobit.

The correlation of the dynamic modulus at 20 °C and 10 Hz frequency versus Sasobit percentages was attempted by nonlinear regression analysis, which is expressed as Equation (4) with the coefficient of determination ($R^2 = 0.88$).

$$\frac{E^*{}_{WMA,Sa}}{E^*{}_{HMA}} = \frac{1}{1 - 0.032Sa^{1.14}} \quad (4)$$

Figure 11 compared the proposed model with Liu et al. [16] and Zelelew et al. [38]. As shown in Figure 11, the results of the dynamic modulus in the proposed model are in acceptable agreement with other researchers' studies.

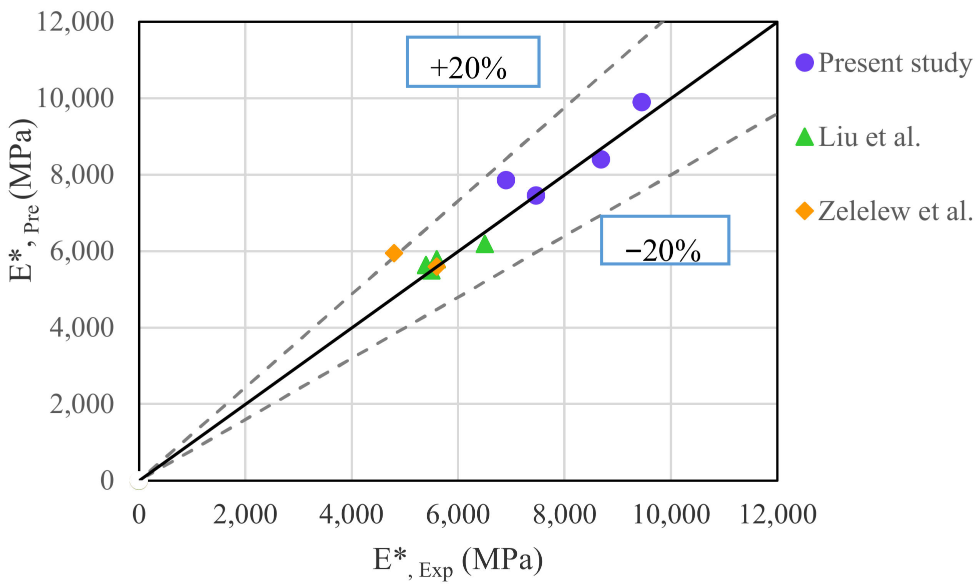


Figure 11. Comparison of the dynamic module results between the proposed model and the laboratory results of other researchers.

4.4. Flexural Stiffness

The results of fatigue resistance and initial flexural stiffness for both WMA and HMA samples are shown in Table 10.

Table 10. Fatigue beam results.

Mixes	Beam N	Air Voids (%)	Initial Flexural Stiffness (MPa)	Termination Stiffness (50% of the Initial Stiffness (MPa))	Cycle Count of 1,000,000
HMA Control	1	5.2	5296	2648	220,990
HMA Control	2	5.3	5115	2557	473,310
HMA Control	3	4.9	5617	2809	457,630
Average		5	5343	2671	383,977
Standard deviation		0.2	254.2	127.6	141,368.2
WMA Sasobit (1.5%)	1	5	6474	3237	192,270
WMA Sasobit (1.5%)	2	4.8	6220	3110	151,940
WMA Sasobit (1.5%)	3	4.9	6138	3069	196,700
Average		5	6277	3139	180,303
Standard deviation		0.1	175.2	87.6	24,663
WMA Sasobit (3.0%)	1	5.1	6228	3114	182,210
WMA Sasobit (3.0%)	2	5.2	6369	3185	130,870
WMA Sasobit (3.0%)	3	5.1	6411	3205	180,400
Average		5	6336	3168	164,493
Standard deviation		0.1	95.9	47.8	29,132.7
WMA Sasobit (6.0%)	1	5	7825	3913	145,340
WMA Sasobit (6.0%)	2	4.9	7565	3783	106,080
WMA Sasobit (6.0%)	3	4.9	6834	3813	77,000
Average		5	7408	3836	109,473
Standard deviation		0.1	513.8	68.1	34,296.1

As can be seen from Table 10, the average percentage of air voids in all samples is about 5%. In addition, the average fatigue life of HMA and WMA mixtures is shown in Figure 12. HMA control and WMA with 1.5% Sasobit had the best performance for fatigue resistance. Increasing the percentage of Sasobit in WMA improves the flexural stiffness but reduces the number of cycles because Sasobit makes asphalt mixtures more brittle. Hence, WMA samples had less fatigue resistance in comparison to HMA. As can be seen from Figure 12, WMA mixtures made with Sasobit have the highest initial flexural stiffness compared to the HMA control samples. Initial flexural stiffness values increased 17.5, 18.6, and 38.6% by adding 1.5, 3, and 6% Sasobit in WMA mixtures compared to HMA, respectively. Furthermore, as the number of cycles increases, the initial flexural stiffness in all mixes decreases, as shown in Figure 12.

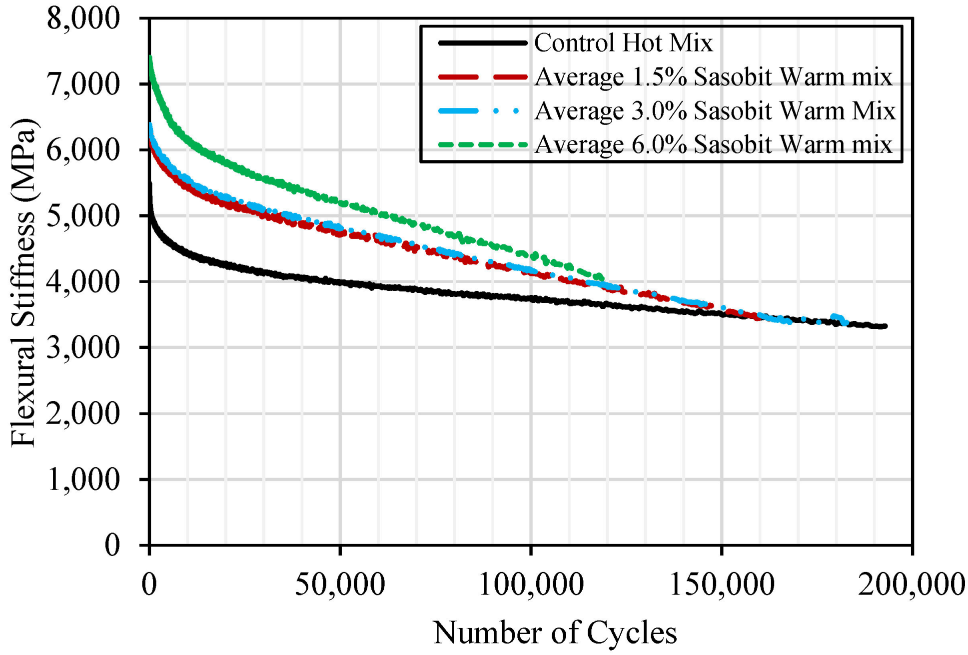


Figure 12. Comparison of average fatigue resistance for HMA and WMA.

Figure 13 shows a comparison between elastic modulus, dynamic modulus, and initial flexural stiffness for all samples. The addition of Sasobit to the asphalt mixture has a more significant effect on the dynamic modulus, so adding 6% of Sasobit to the WMA mixture increases the elastic modulus, initial flexural stiffness, and dynamic modulus by 26.6, 38.6, and 52.8% compared to the control HMA, respectively.

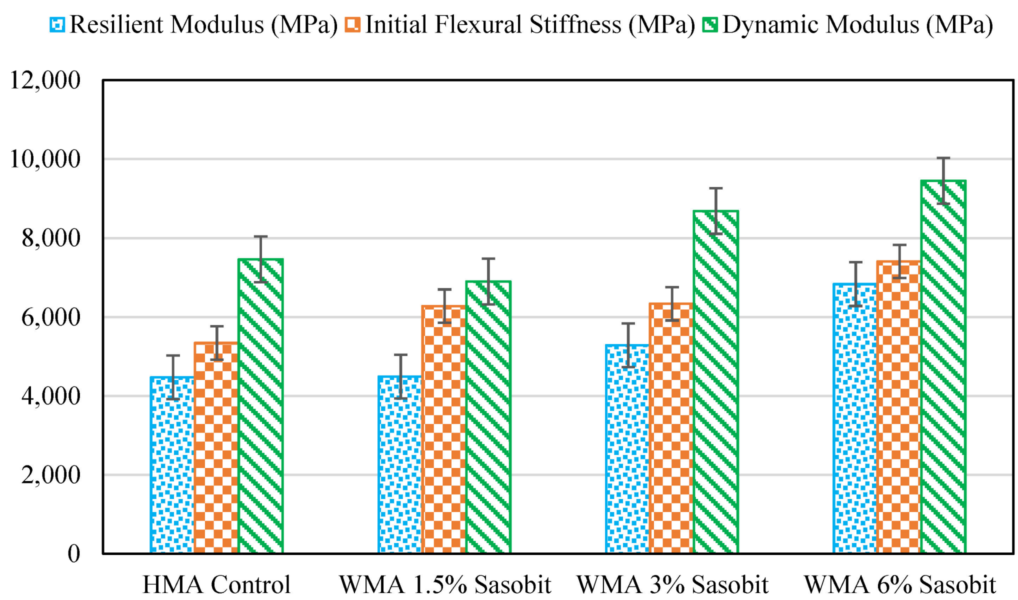


Figure 13. Comparison moduli at 20 °C and 10 Hz loading rate.

The correlation of the flexural stiffness for WMA mixtures versus Sasobit percentages was attempted by nonlinear regression analysis. It is expressed as Equation (5) with the coefficient of determination ($R^2 = 0.98$).

$$\frac{S_{WMA,Sa}}{S_{HMA}} = \frac{1}{1 - 0.092Sa^{0.6}} \quad (5)$$

Figure 14 compared the proposed model with Liu et al. [16] and Alinezhad and Sahaf [39]. As shown in Figure 14, there is a good correlation between the results of the flexural stiffness in the proposed model with other researchers' studies.

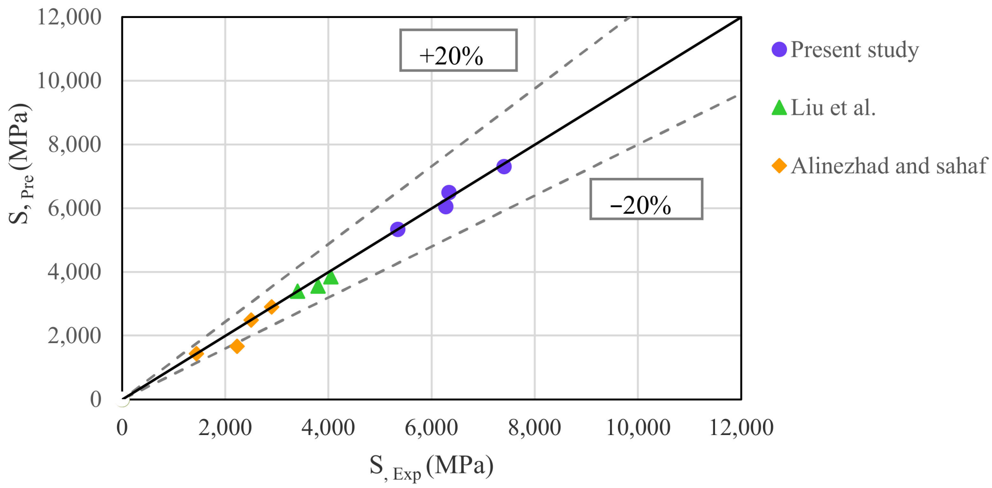


Figure 14. Comparison of the r flexural stiffness results between the proposed model and the laboratory results of other researchers.

4.5. Rutting

The results of the wheel track test for HMA and WMA are presented in Figure 15. As can be seen from Figure 15, the average rutting of specimens increases with the growing number of wheel passes while adding a high percentage of Sasobit in WMA (3% and 6% of Sasobit in this study) improves rutting. The reason can be due to the presence of larger wax crystals in the asphalt bitumen, which causes the formation of a lattice structure in the asphalt bitumen and creates better stability in mixtures, thus reducing the depth of the rutting.

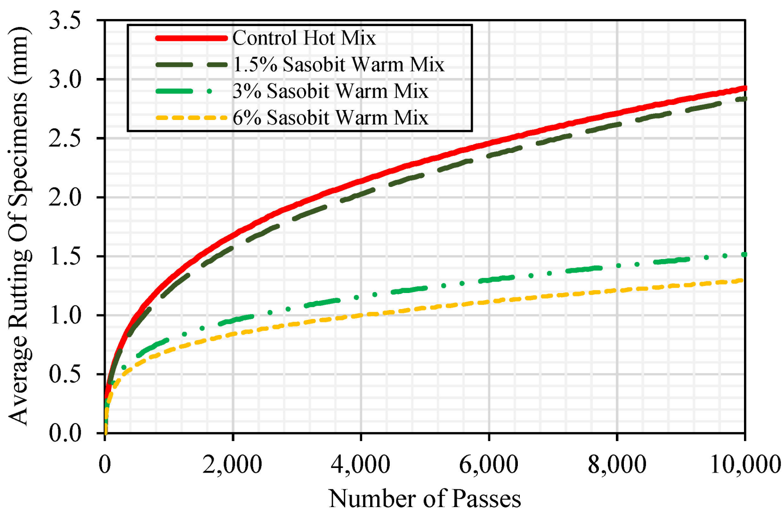


Figure 15. Comparison of wheel tracking results for HMA and WMA.

The above results provide a better understanding of the benefits of an additive, such as Sasobit, to improve asphalt quality and increase the durability and sustainability of road material. There is much research to incorporate other by-products, such as waste plastic, with the help of other additives, such as nanoparticles, to offset their drawbacks. [40,41]. However, new prediction models are highly demanding to extrapolate design parameters out of laboratory testing conditions for asphalt or even base course layers [42–45].

With the help of new models for design modulus or fatigue, WMA mixes can now be applied with novel insights about their long-term properties.

5. Conclusions

In this study, Sasobit's effect on the mechanical properties and durability of HMA and WMA in the laboratory were investigated by developing new models. Thus, mechanical properties, including indirect tensile strength, elastic modulus, dynamic modulus, fatigue, and rutting resistance with three different percentages of Sasobit (1.5%, 3%, and 6%), were evaluated. The results of this study can be summarized as follows:

1. Increasing the percentage of Sasobit increased the softening point of bitumen and viscosity and decreased the penetration point.
2. The resilient modulus value for WMA is higher than the HMA control sample. The modulus of elasticity values increases by 0.4%, 18%, and 53% by adding 1.5, 3, and 6% of Sasobit to mixtures, respectively.
3. TSR values were significantly lower in mixtures containing modified Sasobit bitumen than HMA. Adding 1.5–6% of Sasobit in WMA reduces the ITS values for the unconditional and conditional samples by about 2.6–4.7% and 2.8–3.1%, respectively.
4. The dynamic modulus values decrease significantly with increasing temperature, while increasing frequency improves dynamic modulus. At low temperatures, regardless of the frequency level, the dynamic modulus has the highest value in WMA with 6% Sasobit.
5. HMA control and WMA with 1.5% Sasobit had the best fatigue-resistance performance. Increasing the percentage of Sasobit in WMA increases the flexural stiffness but reduces the number of cycles due to fatigue. Initial bending stiffness values were obtained by adding 1.5, 3, and 6% of Sasobit in WMA mixtures to increase flexural stiffness 18, 19, and 39%, respectively, compared to the control HMA.
6. For rutting, the addition of Sasobit up to 1.5% does not have a considerable impact. However, higher Sasobit for 6% causes a significant rutting improvement due to formation of a lattice structure inside asphalt matrix.

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