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Research Note

Effects of moisture on warm mix asphalt containing Sasobit

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Toughness;
Fracture energy.

Abstract. The asphalt industry has been at the forefront of sustainable development. Warm Mix Asphalt (WMA) has been developed to cope with issues such as high energy prices and air pollution. These mixes require less energy and generate fewer pollutants during production in comparison with conventional Hot Mix Asphalt (HMA). Although a promising technology, the durability of WMA is not clear because long-term WMA field performance data is limited. This study investigated the susceptibility of Sasobit-modified WMA to moisture, since moisture damage is a major cause of premature pavement failure in asphalt concrete. To this end, WMA samples were made using different concentrations of Sasobit and the results were compared with those from HMA mixtures. The effect of hydrated lime as an anti-stripping agent was also investigated. The tensile strength ratios indicate that the introduction of hydrated lime and Sasobit increased the resistance of asphalt mixtures to moisture. Fracture energy and toughness were used to evaluate the crack resistance of specimens under dry and wet conditions. In comparison with Sasobit, hydrated lime increased crack resistance of mixtures. The results indicate that hydrated lime can be used as a compatible and effective anti-stripping agent for WMAs containing Sasobit.

1. Introduction

Sustainable development in pavement construction calls for new approaches to the design, construction, and maintenance of pavement systems that require large amounts of material, energy, and investment. The asphalt industry has incorporated reclaimed asphalt pavement and other industrial by-products and waste materials into asphalt during the past few decades [1]. Over the last decade, Warm Mix Asphalt (WMA) technology has emerged, which lowers greenhouse gas emissions, reduces exposure of workers to asphalt fumes, and minimizes the use of natural resources [2]. This innovative technology significantly reduces the mixing and compaction temperatures of asphalt mixtures by lowering the viscosity of asphalt binders during mix production [3]. The biggest challenge is to produce durable mixtures while minimizing environmental concerns.

WMA production includes the use of organic additives, foaming, and chemical additives [3,4]. Sasobit is an organic additive extensively used for WMA. It is produced using the Fischer-Tropsch process from coal gasification and can be mixed directly with the binder or blown into the drum [5]. This organic additive forms a homogeneous solution with the base binder

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and reduces the binder viscosity at temperatures above 115°C [6,7]. Sasobit reduces mixing and handling temperatures by 10-30°C, significantly reducing the emission of asphalt binder fumes and CO_2 [6,7]; however, below its melting point, Sasobit tends to increase binder stiffness [8].

Although WMA has received considerable attention over the past decade, its in-service performance properties are not clearly known. The NCHRP Project 09-43 evaluated the volumetric properties of WMA and HMA mixtures and concluded that those properties were similar when binder absorption did not exceed 1.0%. Their research indicated that the coating, compactability, moisture sensitivity, and rutting resistance of WMA mixtures might differ from those of HMA mixtures of the same composition and that WMA was highly affected by the process and temperature [9].

The most premature distress that affects asphalt pavement performance relates to moisture damage. The detrimental effects of water cause loss of strength and durability in asphalt mixtures [10,11]. Moisture damage occurs due to loss of adhesion (water leaking into the asphalt-aggregate system and stripping away the asphalt film) and cohesion (softening of asphalt concrete mastic) [10,11]. Although the lower mixing temperatures in WMA technology reduce emissions and energy consumption, they can adversely affect the aggregate drying process and cause moisture-induced damage. Foaming uses steam as a means to reduce the viscosity of the binder, but the water trapped in the coated aggregate can cause damage [12,13]. Although wax does not release water into the asphalt mixture, because it increases lubrication of the binder, uncertainty exists about chemical reactions occurring between the aggregate, binder, and wax [12,13].

A number of additives are available that mitigate moisture sensitivity of asphalt mixtures. These treatments can be introduced directly to the asphalt binder as a modifier or can be applied to the aggregate [14]. Hydrated Lime (HL) is the most commonly-used anti-stripping agent that decreases moisture susceptibility [15]. HL makes the migration of Ca^{++} to the aggregate surface reacting with carboxylic acid and 2-quinolone groups in asphalt binder to form insoluble salts. These reactions facilitate strong bonding between asphalt binder and the aggregate surface. In addition, the presence of deleterious materials such as clay on the aggregate is inevitable, and the pozzolanic reaction of hydrated lime flocculates the materials that cover the aggregate surface [11,14,15].

This study evaluates the moisture susceptibility of HMA and WMA mixtures modified with HL and Sasobit by employing the conventional TSR method [16], and the concept of facture and toughness energy.

2. Research objectives and methodology

The present study investigated the effects of hydrated lime and Sasobit on the moisture susceptibility of asphalt mixtures. HMA samples modified with HL and WMA samples containing different concentrations of Sasobit were made and tested. The samples and control HMA samples were tested using AASHTO T 283 standards for moisture susceptibility. To accommodate different moisture conditions for each type of mixture, six samples with 7 ± 0.5% were divided into two subsets, dry and wet, in such a way that the average air voids for two subsets were approximately equal. A total of 48 samples were made. Table 1 outlines the experimental design for this research.

3. Materials and testing

3.1. Materials

Sasobit is a long-chain aliphatic hydrocarbon which melts at 115°C that reduces binder viscosity. After crystallization, it forms a lattice structure that becomes the basis of the structural stability of the binder. To create homogenous WMA binders for testing, Sasobit was melted by heating to 120°C and then added to the binder in a low shear mixer (350 rpm) at 135°C and mixed for 10 min. The concentrations tested were 1.5%, 2.5%, and 3.5% (wt) of the base binder. A PG 64-22 asphalt binder from Tehran refinery was used. Binders were graded in accordance with AASHTO M320 and the results are shown in Table 2.

Modification of the binder with Sasobit resulted in higher complex moduli and phase angles compared

Table 1. Experimental design of mixtures used in this study.

Mixture	Acronyms	No. of levels	Description of levels
HMA	Control, HL%	4	No additive (control) 1%, 1.5%, and 2% HL
WMA	Saso%	4	1.5%, 2.5%, and 3.5% Sasobit 1.5% Sasobit + 1.5% HL

Table 2. Superpave performance grading for asphalt binders.

Specimen	Continuous grade (°C)			Performance Grade (PG)
	High temperature	Intermediate temperature	Low temperature	
Neat	65.2	19.8(22)	−23.7	64-22
Saso 1.5%	70.0	24.5(25)	−17.1	70-16
Saso 2.5%	73.5	26.5(28)	−14.5	70-10
Saso 3.5%	74.9	27.3(28)	< -10	70-06

Table 3. Physical properties of aggregate.

Test	ASTM standard	Measured value	Limit
Bulk specific gravity (coarse agg.)	C127-01	2.683	—
Bulk specific gravity (fine agg.)	C128-01	2.687	—
Los Angeles abrasion	C131-01	12%	Max 45%
Coarse aggregate angularity	D5821-95	96%	Min 90%
Flat and elongated particles	D4791-99	5.5%	Max 10%
Water absorption (%)	C127, C128	$> 1\%$	—

to the control binder, which can be attributed to the formation of Sasobit crystals [8,17]. These effects can be associated with a better performance at high temperatures, but cause brittleness at low temperatures; however, discussing this complex interaction solely on the basis of rheological analysis without consideration of morphology and the microstructure of Sasobit modification is not a reasonable approach. It should be noted that investigation of chemical binder-Sasobit reactions is not the objective of this study.

Table 3 shows the physical properties of the aggregate. Aggregate gradation with a nominal maximum size of 19 mm was used in accordance with AASHTO MP 2, as shown in Figure 1.

Table 4 shows the chemical composition of the passing #200 HL used in accordance with ASTM C1097-01. There are several methods for introducing HL into an asphalt mixture. Here, HL slurry was added to the dry aggregate and the lime-treated aggregate was then marinated for 24 h prior to preparation of specimens.

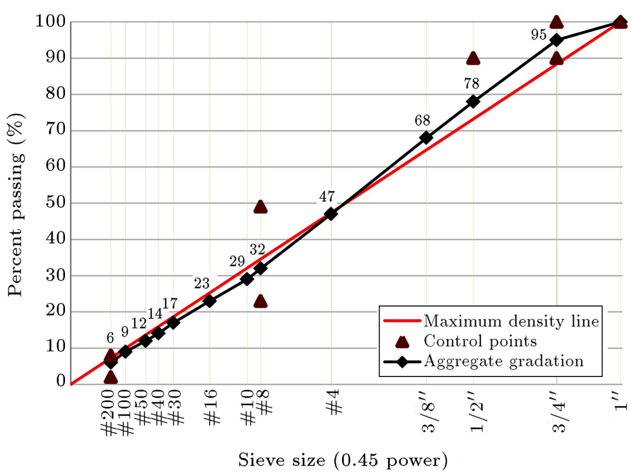


Figure 1. Aggregate gradation with 19 mm nominal maximum size.

Table 4. Chemical composition of hydrated lime.

Chemical composition	Measured value	Limit
Calcium and magnesium oxides	90%	Min 90%
Carbon dioxide	3%	Max 50%
Hydrated calcium and magnesium oxides	3%	Max 5%
Free moisture of dry hydrates	0	Max 2%

3.2. Mix design

Appropriate temperatures for mixing and compaction correspond to viscosity ranges of 0.17 ± 0.02 Pa.s and 0.28 ± 0.03 Pa.s, respectively, in accordance with AASHTO T 312. NCHRP Report 691 demonstrated that the true temperature of WMA processes was not merely a matter of the relationship between viscosity and temperature; the coating, workability, and compatibility of mixtures should also be evaluated in preliminary trial specimens [5]. Considering the mentioned parameters, the mixing and compaction temperatures for WMA mixtures were 135°C and 125°C and for HMA were 150°C and 140°C, respectively.

Specimens were made in accordance with AASHTO R 35. Aggregates were heated to 10°C above mixing temperature for 3 h prior to specimen fabrication to eliminate undesirable moisture content. Because binder absorption was less than 1%, the volumetric properties of the WMA and HMA mixtures were almost the same [5]. The optimum binder content was 5.5% (wt of aggregate) for the control HMA mixture and 5.3% for the WMA mixture, although the addition of HL lowered the binder content to 5% for all mixtures.

3.3. Test methods

The resistance of compacted bituminous mixtures to moisture-induced damage was measured in accordance with AASHTO T 283. Six specimens with 7.0 ± 0.5% air voids were made; the first three specimens remain unconditioned and the other three were subjected to vacuum saturation of 70% to 80% (degree of saturation). Afterwards, the vacuum-saturated samples were conditioned in a 60°C water bath for 24 h and then all samples were submerged in a 25°C water bath for 2 h to achieve a constant temperature prior to testing. During the test, the load was applied along the diameter of the specimens at a constant rate of 50 mm/min vertical deformation until failure.

The parameters measured were Indirect Tensile Strength (ITS), Tensile Strength Ratio (TSR), fracture energy to failure (Γ_{fa}), Fracture Energy Ratio (FER), Toughness (T), and Toughness Ratio (TR). ITS (kPa) is expressed as:

$$\text{ITS} = \frac{2000 \times P}{\pi.t.d}, \tag{1}$$

and TSR (%) is expressed as:

$$\text{TSR} = \frac{\text{ITS}_{\text{wet}}}{\text{ITS}_{\text{dry}}} \times 100, \tag{2}$$

where P is the maximum vertical load applied (kN), t is the average height of the specimen (m), and d is the average diameter of the specimen (m).

Figure 2 shows Γ_{fa} (N.m), which is defined by Witczak et al. [16] as the area under the load vertical deformation curve up to deformation incurred at maximum load for both dry and wet samples. FER (%) can be expressed as:

$$\text{FER} = \frac{\Gamma_{fa\text{wet}}}{\Gamma_{fa\text{dry}}} \times 100. \tag{3}$$

T (N/mm), as shown in Figure 2, is defined as the area under the ITS deformation curve up to a deformation of twice that incurred at maximum tensile stress [18]. TR (%) is expressed as:

$$\text{TR} = \frac{T_{\text{wet}}}{T_{\text{dry}}} \times 100. \tag{4}$$

4. Results and discussion

4.1. ITS analysis

The minimum TSR is 0.80 as specified in AASHTO M 323. A comparison of TSR values with the minimum acceptable value may not be sufficient; some recent studies [10,19] specify an additional criterion for a minimum value for wet ITS and a minimum TSR. Figure 3 shows the results for TSR and Figure 4 shows the results for ITS. All wet ITS results were well above the limit 448 kPa (65 psi), indicating that minimum TSR was the governing criterion.

The ITS and TSR of the control HMA mixtures were the lowest. WMA samples were more resistant to the detrimental effects of moisture conditioning than the control HMA, but not as resistant as HL-treated HMA. Increasing the Sasobit content slightly increased the TSR. This can be attributed to the effect of Sasobit lattice structure on increasing binder stiffness and the use of fully-dried aggregates. The bond between aggregate and binder can be negatively affected by the existence of moisture in aggregates during production of asphalt mixtures. To prevent this, the aggregates were preheated for 3 h to eliminate any undesirable moisture and the results were satisfactory. WMA mixing and compaction temperatures were well above the Sasobit melting point, ensuring that the aggregate was fully coated. Moreover, the high angularity and rough surface texture of the aggregates resulted in better aggregate interlock leading to high tensile strength.

The addition of 1% HL produced a 16% change in the TSR of the control sample, indicating that HL-treated specimens meet the proposed criteria. The TSR slightly increased as the HL content increased from 1% to 2%. Note that the total filler content of mixtures was constant; consequently, HL replaced a

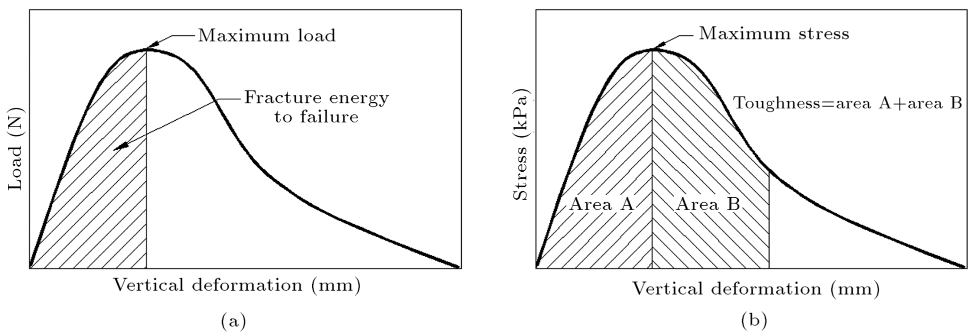
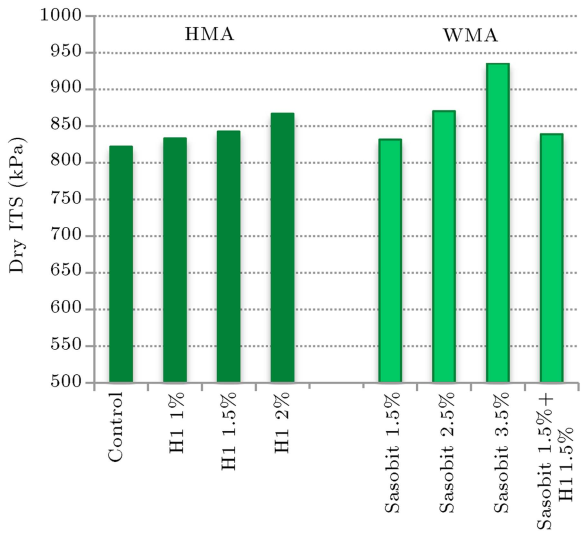
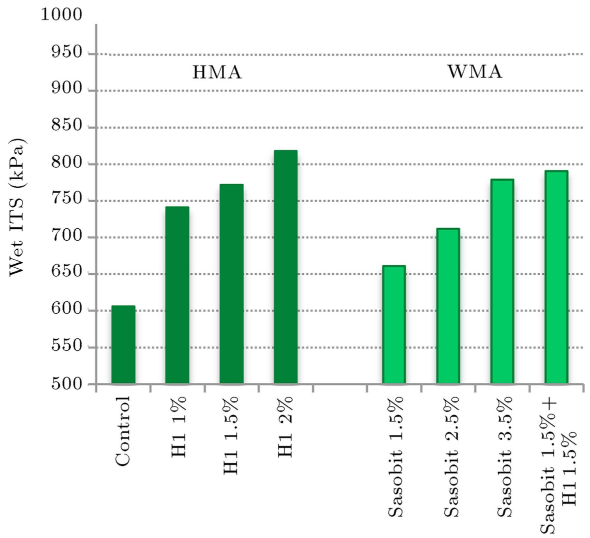


Figure 2. Schematic presentation of (a) fracture energy to failure [16], and (b) toughness [18].



(a)



(b)

Figure 3. Results of (a) dry ITS, and (b) wet ITS.

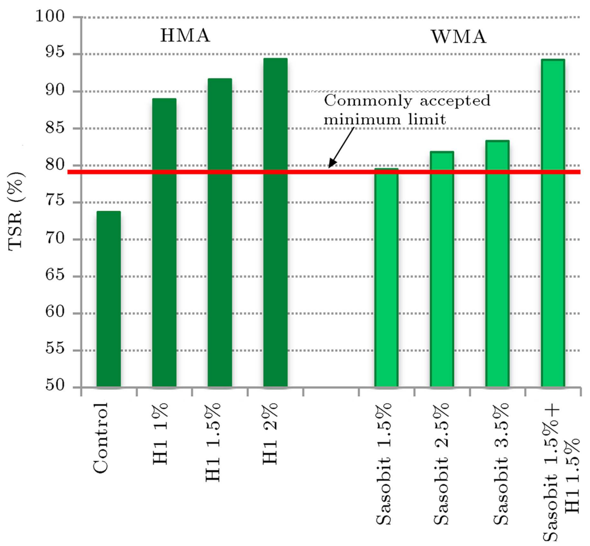


Figure 4. TSR results for HMA and WMA.

part of the aggregate filler. This result allows better understanding of the effects of HL on the aggregate-binder bond in the presence of water.

Although the minimum acceptable TSR value is 80% for most agencies, the WMA samples with TSRs ranging from 79.5% to 84.5% only show marginal performance. This indicates that the use of anti-stripping agent is necessary. To overcome this deficiency, WMA mixtures were made with 1.5% Sasobit (wt of base binder) and the aggregate was treated with 1.5% HL (wt of aggregates). This resulted in a significant increase in the TSRs, making them comparable to those for HMA with 2% HL.

4.2. Fracture energy analysis

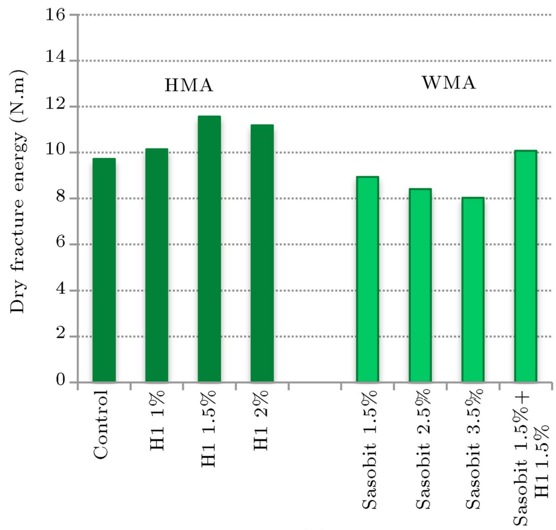
The energy absorbed up to the point of failure (fracture energy) calculated using the IDT strength test is an excellent indicator of the resistance of mixtures to cracking and of the fact that higher fracture energy values correspond to higher cracking resistance [18]. Fracture energy analysis considers both the stress and strain results of the test. Figure 5 shows that the mixtures treated with HL had greater dry and wet fracture energies than the control HMA mixtures. This indicates a greater capacity to absorb the mechanical work induced by repeated tire loading on pavement [18,20].

Unlike the ITS and TSR values, the fracture energy of WMA mixtures was less than that of the control HMA mixtures. Modification of WMA samples with HL increased the dry and wet fracture energies. The FER in Figure 6 shows that WMA samples responded similarly to the control HMA and the HL-treated WMA behaved similarly to the HL-treated HMA.

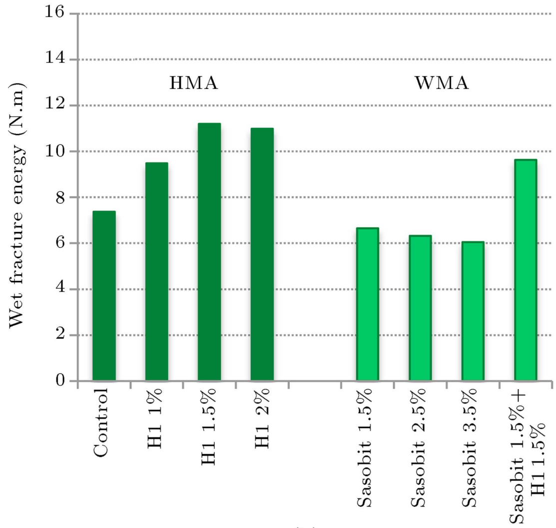
4.3. Toughness analysis

Similar to fracture energy analysis, toughness analysis relates to the energy absorbed in the IDT strength test. Figure 7 shows the dry and wet toughness values. It is evident that the mixtures containing WMA additives generally produce lower toughness values than the control mixture, which can be attributed to the lower deformation of WMA samples as a result of crystallization of Sasobit wax. Although the Sasobit content increased the tensile strength of the samples, their strain resistance decreased as the binder stiffness increased, which decreased the calculated fracture energy.

Figure 8 shows the TR and indicates that there was no significant improvement in moisture susceptibility of WMA mixtures compared with control HMA samples. It is evident that the TR increased in lime-treated mixtures of HMA and WMA.



(a)



(b)

Figure 5. Results for (a) dry fracture energy, and (b) wet fracture energy.

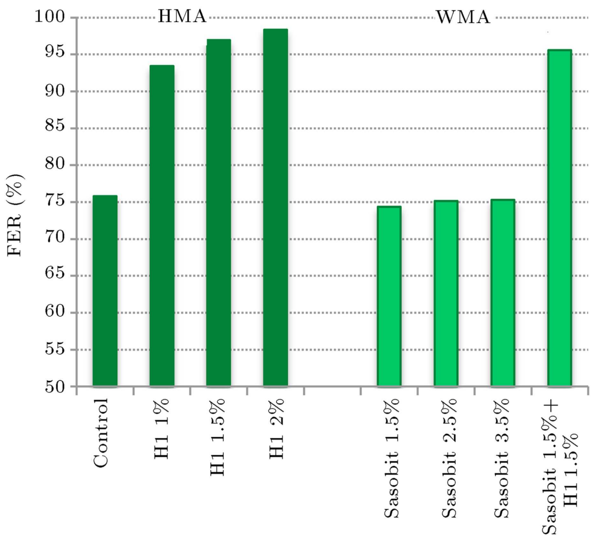
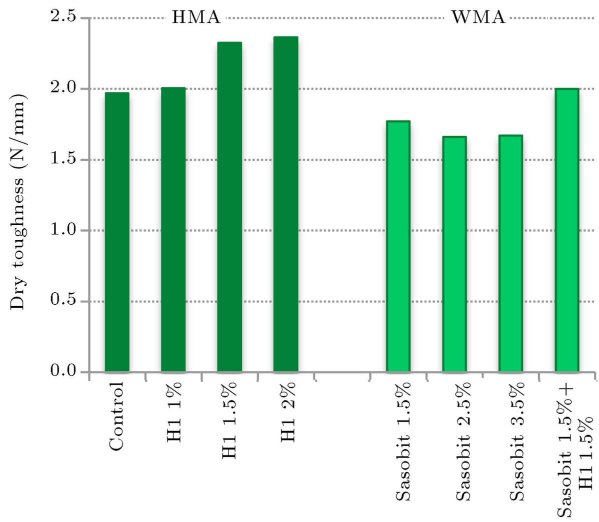
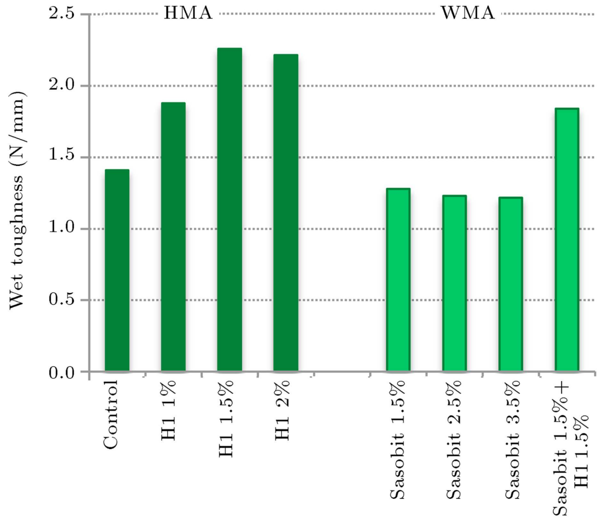


Figure 6. FER results for HMA and WMA.



(a)



(b)

Figure 7. Results for (a) dry toughness, and (b) wet toughness.

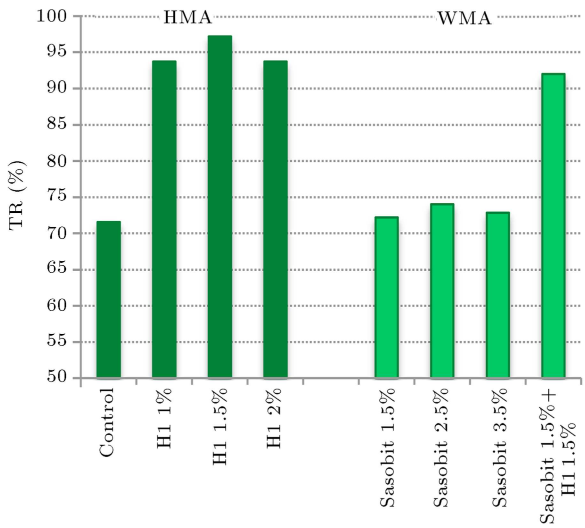


Figure 8. TR results for HMA and WMA.

5. Summary and conclusion

The present study evaluated the moisture susceptibility of WMA mixtures containing Sasobit and the effect of hydrated lime as an anti-stripping agent. The following conclusions can be drawn for the materials tested:

- Moisture resistance in the control HMA and WMA samples (without anti-stripping) was inadequate or only marginally better than the generally accepted minimum value of 80%;
- Mixing and compaction temperatures and aggregate properties such as angularity, roughness, and moisture content play key roles in the aggregate-binder bond and in the resulting ITS, especially in WMA mixtures;
- The TSR indicated that HL was an effective anti-stripping agent for both HMA and WMA mixtures. The TSR increased as the HL content increased;
- FER and TR analyses yielded results that were similar to the TSR for HMA mixtures, but were different than the results for the WMA mixtures. FER and TR analyses showed a relationship of moisture susceptibility with both the indirect tensile strength and strain resistance of mixtures;
- The TSR, FER, and TR analyses indicated that the use of HL as an anti-stripping agent is required to compensate for the relatively poor moisture resistance of the WMA-Sasobit mixtures, especially where the lower production temperatures for WMA mixtures increase the risk of moisture in the aggregates.

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Biographies

Hadi Nabizadeh received his BSc degree in Civil Engineering from Ferdowsi University of Mashhad in 2009. He pursued his MSc degree at Sharif University of Technology in the field of Pavement Engineering and performed his thesis research project on the performance properties of hot mix asphalt modified with hydrated lime in 2012. Currently, he is continuing his education as a PhD student at University of Nevada, Reno, and working as a Research Assistant at Western Regional Superpave Center. His area of research is mainly focused on the evaluation of super-heavy loads on flexible pavements.

Behzad Naderi received his BSc degree in Civil Engineering in 2008. He then continued his education as a graduate student in the field of Pavement Engineering at Sharif University of Technology (SUT) and successfully defended his thesis titled "Evaluation of WMA Containing Sasobit" in 2011. He is currently studying as a PhD candidate at Tarbiat Modares University (TMU), Tehran, Iran. His research is focused on predicting fatigue life of asphalt mixtures.

Nader Tabatabaee has been a member of the Civil Engineering Faculty at Sharif University of Technology (SUT) since 1991. He teaches and conducts research on pavement materials and design, particularly on modified asphalts and asphalt mixtures. He received his BSc from the University of California at Berkeley and his MSc and PhD from The Pennsylvania State University. He has published more than 75 peer reviewed publications and conference papers in his field as well as many technical reports for various public and private agencies. He served as Chair of the Department of Civil Engineering at SUT during from 1997 to 2001 and as Dean of Graduate Studies from 2001 to 2006. Dr. Tabatabaee is a founding member of the Civil Engineering Congress in Iran and the Middle East Society of Asphalt Technologists (MESAT) and is a member of TRB, AAPT, ISAP, and RILEM. His areas of research interest include pavement instrumentation, pavement design, maintenance and management, and asphalt technology.