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International Journal of Pavement Research and Technology 9 (2016) 376–386
www.elsevier.com/locate/ijprt

Experimental investigation of the effect of using different aggregate types on WMA mixtures

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Received 28 April 2016; received in revised form 11 September 2016; accepted 15 September 2016
Available online 22 September 2016

Abstract

In recent years, production of warm mix asphalt (WMA) mixtures with the help of chemical additives has been developed due to obvious advantages, such as reduction of pollution emissions, construction temperature and the possibility of carrying asphalt in long distances. Various additives can have positive or negative effects on the performance characteristics of WMA mixtures made from different types of aggregates. Although, effects of different types of aggregates have been more investigated on the performance of hot mix asphalt (HMA), the effects on WMA have been less studied. Therefore, in this study, three types of aggregates including: limestone (Li), siliceous (Si) and slag (Sl) from the metal production factories together with Sasobit and Zeolite additives were provided to be used for the WMA mixtures. After constructing the asphalt samples and determining the optimum binder, Marshall Stability, indirect tensile strength tests and resilient modulus test and the durability parameter determination were performed. Test results indicated that WMA-Sasobit mixtures have the greatest impact on reducing consumed percentage of binder in slag and siliceous aggregates compared to limestone aggregates. For both additives, WMA mixtures containing limestone aggregates showed higher resilient modulus and siliceous aggregates showed lower resilient modulus. Moreover, the results of indirect tensile strength of specimens containing limestone aggregates showed the highest value and siliceous aggregates showed the lowest one. TSR in the limestone and slag aggregates was improved using both additives, but Zeolite additives reduce TSR in the siliceous aggregates.

Keywords: Type of aggregate; Warm mix asphalt; Sasobit; Zeolite; Performance characteristics; Moisture susceptibility

1. Introduction

The warm mix asphalt (WMA) industry follows technological developments, which not only do not change its workability and the physical–mechanical properties of mixtures but also reduce the high mixing temperature of HMA mixtures [1].

The goal of WMA technologies is to obtain required strength and durability which is equivalent to or even better than HMA pavements [2,3]. In addition to have executive and environmental benefits WMA mixtures have some disadvantages such as the asphalt production cost and higher sensitivity to the stripping phenomenon due to reduced mixing temperature and the possibility of a reduction in bonding strength between binder and aggregates [4].

Since aggregate characteristics play a fundamental role on the performance of asphalt mixtures and features of pavement construction, previous studies recommended to use crushed limestone (LS) aggregates due to its advantages. However, siliceous aggregates may have resistance equal to or greater than limestone aggregates [5]. By improving and modification of properties of bitumen, it could take advantage of the vast part of siliceous aggregate

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Peer review under responsibility of Chinese Society of Pavement Engineering.

http://dx.doi.org/10.1016/j.ijprt.2016.09.006
1996-6814/

mines, both in terms of quality and economic. In some areas such as melting factories and slag production with good resistance, this type of aggregate can also be used. Two of the most widely used additives in the production of warm mix asphalt are Sasobit and Zeolite [6,7]. Sasobit additives in WMA can lead to reducing the temperature by 18–54 °C rather than those of HMA [8]. Literature review of the WMA production showed, the most commonly used additive is Zeolite, which contains 0.3% by the weight of total mix, and it has the possibility to reduce mixing temperature by 30 °C [8]. Resilient Modulus (MR) has been used in AASHTO Guide for Design of Pavement Structures (1993) and in Mechanistic-Empirical Pavement Design Guide (MEPDG) [9]. Topal et al. by comparing the properties of WMA mixtures containing limestone aggregates including natural and synthetic Zeolite, indicated that Resilient Modulus of WHA mixtures is higher than HMA mixtures at different temperatures [10]. Ameri et al. (2013) compared the behavior of WMA made from different aggregates and concluded that mixtures contained limestone aggregates (coarse limestone) have a better resistance performance than the steel slag aggregates [11].

Binder-aggregate stripping is a complex which depends upon many variables, such as the type and application of mix asphalt, the bitumen properties (viscosity), the aggregate characteristics and anti-strip additives which are used in blend. Investigating aggregate change effects on the mechanical performance and durability of asphalt mixture is important though complicated. Valdés-Vidal et al. investigated the changes in mechanical behavior of twelve different asphalt mixtures including several types of aggregates and two types of bitumen. They found out that type and surface texture of aggregates have an influence on stability and cracking resistance [12]. Several studies investigated the effect of aggregate type on durability and the moisture susceptibility, especially the effect of adhesion of bitumen to three aggregates (limestone, marble and granite), which showed acid aggregates (granite) have the lowest value of adhesion and resistance to moisture damage [13]. The stripping phenomena may occur naturally, even without the presence of moisture on some aggregates, this phenomenon has been found in some areas with very warm and dry climates like Saudi Arabia and Iran [14]. One of the main mechanisms of moisture damage is the loss of adhesion or molecular absorption at the interface between dissimilar objects which has the task of maintaining bond between mixtures [15].

Adding lime or cement to the aggregates, using of the hydrophobic aggregates or anti-strip additives are some methods to strengthen the adhesion properties of bitumen and aggregate. Kavussi et al. (2012) demonstrated that mixtures containing 3% Sasobit doesn't have negative effect on the durability of WMA which is measured by tensile strength ratio (TSR) [16]. They also showed Sasobit additive besides reducing the mixing temperature improves the workability of asphalt mixture and causes internal lubrication [17]. Shu et al. (2012) found that WMA mixtures containing recycled asphalt pavement (RAP) according to TSR criteria often met the minimum standard of 75% [18]. Ai et al. (2015) the moisture susceptibility of WMA mixtures was tested by boiling water test and the results showed the approximate value of 20% while its minimum value index is 15% [19]. Some filed researches claimed no difference between WMA mixtures compared to HMA ones in terms of rutting performance. Moreover, some practical researches showed improvement on asphalt mixture fracture resistance when WMA technology was used. However, WMA mixtures showed same tensile strength ratio (TSR) results compared to HMA ones. Based on Louisiana WMA mixture investigations, pull-off cohesion and adhesion property test results claimed that Sasobit additive can reduce the cohesion strength [20,21].

So far, simultaneous evaluation of the impact of aggregate type and additive type on the durability and the performance characteristics of WMA has not been concerned. Evaluating the effects of the different aggregate types may even help to understand the negative effects of additives on some aggregate performance. In this research, the most commonly used additives such as Sasobit and Zeolites (synthetic) was used to reduce the mixing temperature and WMA density. In order to evaluate the effect of additive type on the selection of aggregate type, three of the most widely used types of aggregate (limestone, siliceous and slag) were used. Then, tests of Marshall Stability, resilient modulus and moisture susceptibility were carried out to compare WMA mixtures. This research pursues two main objectives: (1) evaluating the effect of different types of aggregates on the performance of WMA mixtures and (2) economic evaluating of the effect of using various aggregates on changing the thickness of warm asphalt layer compared to a conventional one.

2. Materials and laboratory test

Three conventional aggregate types, Limestone, siliceous, and steel slag, were used in this paper. The materials employed in this research were obtained from commercial sources. This section presents the primary materials and test methods included in this study.

2.1. Aggregate

Limestone and siliceous aggregates were prepared from mountain minerals and steel slag from Alloy Steel Plant of Yazd. These aggregates are used to replace natural materials and to avoid waste production and also to observe environmental issues. The used filler is selected from the same aggregates because the effects of chemical properties of aggregate become completely identical and the impact of different filler material does not turn into an effective and new variable in this paper. Steel slag filler material due to its high stiffness was produced by ball mill circulating. Fig. 1 shows the appearance and microscopic image of mineralogy natural aggregates used in this study.

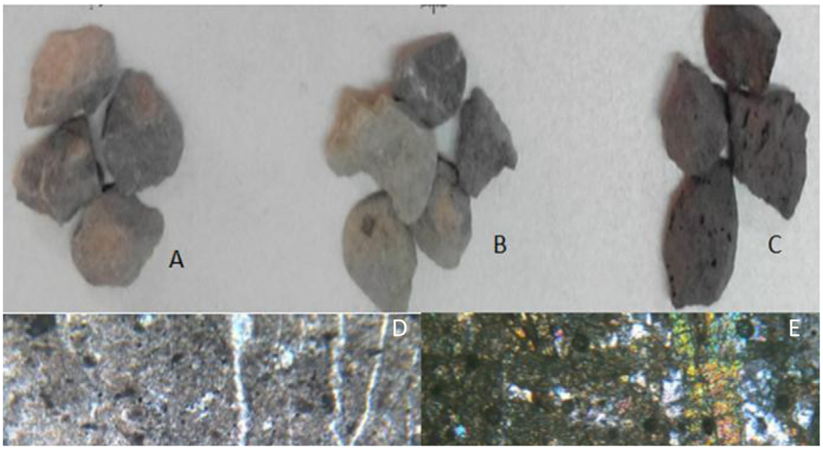

Fig. 1. Image of used aggregates; (a) limestone, (b) siliceous (c) steel slag (d) microscopic image of limestone (e) microscopic image of siliceous [22].

Limestone aggregate (a) is a sparite type with stiffness 3 and is free of allochem gain, but has arthochem of large sparite calcites. This stone is cross-cut by a random network of irregular thin vein which these veins filled by large sparitic calcites. Siliceous aggregate (b) with stiffness 7, the constituent minerals of this aggregate are amphibole rocks, quartz and epidote. The needle-like amphibole crystals are the most abundant minerals and the stone shows a lot of fractures which are filled by mineral quartz [22].

The gradation at the middle-level that used aggregates for Topeka layer in accordance with Iranian pavement regulations was selected. As shown in Fig. 2 the gradation with super-pave mix design specifies aggregate gradation indicates compliance with 12.5 mm nominal maximum aggregate size [23].

Table 1 shows the test results of determining the specific gravity, the water absorption of coarse aggregate (Sample residue on the sieve #8) and fine aggregate (Sample passed through a sieve #8). The specific gravity of coarse aggregate was determined in accordance with ASTM C127 and the specific gravity of fine aggregate was measured based on ASTM C128. The tests that were carried out to determine the properties related to the quality of aggregates (coarse and fine) were: Los Angeles abrasion resistance test (ASTM C131), fracture test (one or two faces) (ASTM D5821) and ductility test (BS 812) (see Fig. 3).

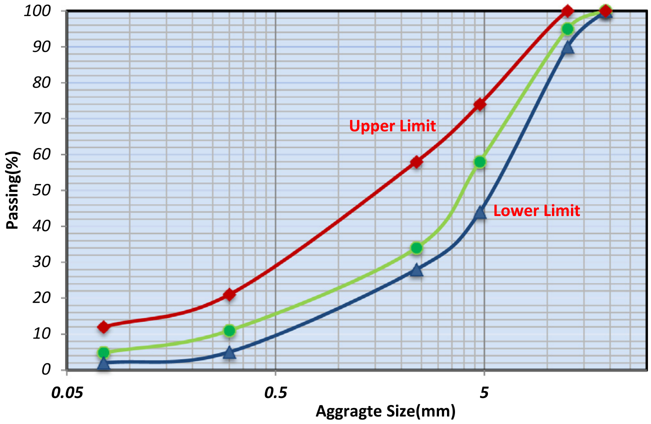

Fig. 2. Gradation diagram of used aggregate.

2.2. Bitumen and additive

The common additives used in the production of WMA are Sasobit and Zeolite, the physical-chemical properties of these two additives are shown in Table 2. Sasobit is an organic or Fisher Tropsch wax. The molecular lengths of the linear Sasobit hydrocarbon molecule range from C40 to C120 and have the general chemical formula of C_n-$H_{(2n+2)}$. Sasobit wax has a melting point of 98 °C (209° F), with a melting range of 70–114 °C (158–238°F). Fisher Tropsch wax is completely soluble in asphalt binder at temperatures higher than 115 °C. It has the ability to reduce the viscosity of asphalt binders [3]. Zeolite is a synthetic aluminosilicate of alkali metals with the following chemical formula: $Mn_2O \cdot Al_2O_3 \cdot XSiO_{2y}H_2O$ [10,24]. Due to the existence of H_2O molecules in Zeolite, the water is released when combining with bitumen in high temperatures and with creating a kind of foam it decreases viscosity.

Depending on the climatic conditions, bitumen with the appropriate penetration grade was usually selected. For this study, PEn60-70 Penetration grade bitumen obtained from Isfahan refinery was used, the results of tests on bitumen and bitumen containing additives are shown in Table 3. In order to mix the above additives to binder, by reviewing the previous studies, it was concluded that for this type of additives either a manual or mechanical mixing method can be used [27]. At first, the bitumen gradually heated to a temperature of 140 °C and stirred with speed of 200 rpm by the stirred bubble then, the additives gradually added to the binder and the stirrer speed increases to 240 rpm. The asphalt binder and asphalt additives mixed for 20 min.

2.3. Sample preparation and laboratory studies

Marshall Stability and flow test was conducted on specimens in accordance with ASTM-D1559. The Marshall

Table 1
Properties of used aggregates.

Water absorption (%)	Specific gravity of aggregates)g/cm^3(		Gradation	Fractured particle test (%)	Flakiness and elongation index test		Los Angeles abrasion resistance (%)	Type of aggregate
	Apparent specific gravity	True specific gravity			Elongation index (%)	Flakiness index (%)		
0.6	2.734	2.689	Sieve residue #8	97	12	10	22	Limestone
1.4	2.674	2.594	Sieve passing#8					
1.4	2.558	2.450	Sieve residue#8	100	18	13	20	Siliceous
1.9	2.606	2.374	Sieve passing#8					
1.7	2.928	2.830	Sieve residue#8	100	16	12	18	Slag
2	2.890	2.755	Sieve passing#8					

Quotient (MQ) is the ratio of stability (KN) to flow (mm), which may use as a criterion for anticipation of the asphalt mixtures resistance against rutting. By increasing the stability ratio the Marshall quotient increases, which increases the resistance to deformation. Although repetitive loading experiments were not carried out, a higher MQ value indicates a stiffer mixture and a better resistance to permanent deformation [28].

Resilient modulus of asphalt mixes, which is determined according to ASTM D4123-04 method, is one of the stress–strain measurements used to evaluate the elastic properties of these mixes. UTM-14P device was used to determine resilient modulus. This device can perform different tests based on the equipment accessories. For an applied dynamic load of P in which the resulting horizontal dynamic deformation is measured, the total M_r value is calculated from Eq. (1)

$$M_r = \frac{P(\mu + 0.27)}{t\delta_h} \tag{1}$$

where P is maximum dynamic load, N; μ is Poisson's ratio (assumed 0.35); t is specimen length, mm; and δ_h is total horizontal recoverable deformation, mm [9].

Indirect tensile strength (ITS) was carried in accordance with AASHTO T283; this standard includes the method of test sample preparation and measuring the tensile strength of the asphalt mixtures. In this test a cylindrical sample is subjected to compressive loads between two loading strips, which create tensile stress along the vertical diametric plane causing a splitting failure. The tensile strength of specimen is calculated according to Eq. (2).

$$\mathrm{ITS} = \frac{2\mathrm{Pmax}}{\pi \mathrm{Dt}} \tag{2}$$

where ITS: is the tensile strength of specimens in MPa, Pmax is the applied load at failure in N; D is the diameter of the specimen in mm; t is the thickness of the specimen in mm [9,29].

Hills and Robertsand and Kiggundu compared and assessed the different testing methods of moisture susceptibility and showed that results of Latman (NCRP246) and modified Lattman researches over 75% have been successful. Results from the moisture susceptibility test may be used to predict the potential for long-term stripping [30].

Express the resistance to moisture damage as a ratio of the unconditioned sample tensile strength that is retained after the conditioning, in other words, the ratio of residual tensile strength exposed to moisture and freeze–thaw cycles to the initial tensile strength. In this study, the moisture susceptibility is calculated by Latman laboratory methods (NCHRP246) and according to Eq. (3):

$$\mathrm{TSR} = \frac{\mathrm{ITS_{con}}}{\mathrm{ITS_{uncon}}} \times 100 \tag{3}$$

where $\mathrm{ITS_{con}}$: average tensile strength of conditioned specimens, MPa and $\mathrm{ITS_{uncon}}$: average tensile strength of unconditioned specimens, MPa [30,31].

Fig. 3. Used additives appearance and physical state (A) Zeolite (B) Sasobit.

Table 2
Properties of additives, Zeolite and Sasobit used in this study [24–26].

Zeolite		Sasobit	
Properties	Specification	Properties	Specification
Appearance form	Fine powder	Congealing temperature	Min 100
Color	White	Penetration at 25 °C	1 max
Percentage of weight Reduction at 800 °C	22–18	Penetration at 65 °C	13 max
Density g/cm^3	Max 0.5	Melting point	Min75
%5 PH suspension	10.5–12	Flash point	98
(%) SiO_2	31–35	PH	199
(%) Na_2O	17–19	Polydispersity index	133
Non-structural alkalinity Na_2O (%)	Max.3.5	Density	622
Aluminum percentage Al_2O_3	26–29	Brookfield viscosity at 135 °C	10–14
The average particle size (μ)	10	Visual color	White
Crystallography	Positive	Physical state	Pastilles
Whiteness (%)	Min.94	Odor	No odor

Table 3
Summarizes the rheological properties of the conventional binder binders and Binder+ additive.

Results	Asphalt binder type				
	Conventional asphalt binders	PEn60-70+Zeolite3%	PEn60-70+Zeolite2%	PEn60-70+Sasobit3%	PEn60-70+Sasobit2%
Penetration (25 °C)	63	55	57	54	55
Softening point	49	53.1	52.5	54.1	53.6
Viscosity at 135 °C	412	320	345	305	328

3. Results and discussion

After preparing the WMA and HMA mixtures, at first, the optimum percentage of bitumen content of each mixture was determined. Then, the necessary samples were prepared for Marshall tests, resilient modulus and moisture susceptibility in accordance with their standards, finally results of the study were analyzed and compared. The result of tests and their interpretation are presented at tables and diagrams. According to Table 4; the abbreviations were used for aggregate types, type and percentage of additives in diagrams and tables of the study.

3.1. Effects on the percentage of optimum bitumen and resistance of mixture

According to Table 5, WMA mixtures generally presented higher Marshall Stability than their HMA counterparts. However, Marshall Values of WMA-Li and WMA-Sl are within the standard allowable range and WMA-Si is less than allowable range. This was confirmed by research of Jamshidi et al., they found that Sasobit WMA mixtures containing limestone has higher Marshall Value than HMA mixtures [26,27].

In WMA mixtures containing 2% or 3% of Sasobit and Zeolite additives, Marshall Stability of WMA-Sl mixtures show the maximum value and WMA-Si mixtures show the minimum value. In WMA mixtures containing 3% Sasobit, Marshall Stability of Si -mixtures are less than standard levels, but in other cases, they are in the range of standard limit. Also, in WMA-Si mixtures containing 2 or 3% Zeolite additives, Marshall Stability is lower than standard levels and in other aggregates Marshall Stability is within the allowable ranges [23]. Furthermore, according to Table 5, the percentage of void of specimens is in the allowable range.

Alvarez et al. (2012) used Asphamin, Evotherm and Sasobit for WMA mixture production. Results of wma mixtures constructed of lime aggregates showed a decrease in void when Sasobit additive percentages increased. This paper demonstrates the same results [32].

As Fig. 4 indicates, in WMA mixtures containing 2% Sasobit, the percentage of optimum bitumen of Li aggregates shows maximum amount and Si-aggregates shows minimum one, but in the case of Zeolite additives, the percentage of optimum binder for all three types of aggregates is approximately similar.

Also, in WMA mixtures containing 3% Sasobit the percentage of optimum bitumen of Li aggregate shows maximum amount and Si-aggregates shows minimum one, and in mixtures containing 3% Zeolite, Sasobit the percentage of optimum binder of Li aggregate shows maximum amount and Si-aggregates shows minimum one. Results of previous studies showed the percentage of optimum binder in WMA mixtures generally declines compared to HMA mixtures [6].

According to Fig. 5, the porosity and the roughness of the Sl aggregates are higher than that of the Li and Si aggregates. Specially, in the case of surface porosity, this difference caused the surface of Sl aggregates have more coarse than limestone aggregates, consequently have a better cohesion with binder. Li and Si aggregates contained very little porosity; some small pores, about a micron, while Sl aggregates contained a coarser surface texture with highly porous surface (1 μ to 1 mm) [33]. Therefore, producing asphalt mixtures, consisting of Li aggregate and Li fillers with a high specific surface, needs a maximum percentage of binder. Sl aggregates have a better cohesion between the binder and aggregate and need a less percentage of binder content in WMA and HMA mixtures. Also, Si aggregates show the minimum value of the percentage of bitumen (see Fig. 6).

3.2. The effects of Marshall quotient

The ratio of stability to flow (Marshall quotient (MQ)) shows in Zeolite WMA with the increase in the amount of Zeolite this quotient increases so that specimen containing 3% Zeolite presents higher Marshall quotient than the specimen containing 2% Zeolite.

This trend is reverse for HMA mixtures containing Sasobit, thus MQ of mixtures containing 2% Sasobit shows a higher value than mixtures containing 3% Sasobit, which is in good agreement with other similar studies [27]. Also, in a constant percentage of additive, WMA mixtures containing Sl aggregates show the maximum value of MQ and Si aggregates show the minimum value. The other studies tested by Asphalt Pavement Analyzer on the effect of changes of rutting in WMA mixtures, confirmed the reduction of rutting phenomenon compared to HMA mixtures [6].

Table 4
Abbreviations of specimen.

Type of aggregate	Control specimen	Type and percentage of additives			
		S (Sasobit)		Z (Zeolite)	
		2	3	2	3
Li(limestone)	Li	Li2s	Li3s	Li2z	Li3z
Si (siliceous)	Si	Si2s	Si3s	Si2z	Si3z
Sl (Slag)	Sl	Sl2s	Sl3s	Sl2z	Sl3z

3.3. Effect of resilient modulus and indirect tensile strength (ITS)

Based upon the results presented in Fig. 7, WMA containing 2% additives in three types of aggregates (Li, Si, Sl), the difference between resilient modulus of WMA-Zeolite and WMA-Sasobit is less than mixtures containing 3% additives, which was also found by other similar studies including a study [10]. Also, WMA mixtures containing 3% additives in three types of aggregates show higher resilient modulus than WMA mixtures containing 2% additives. The studies of Sangus et al. found that resilient modulus of specimen containing more amount of Zeolite, increases [34].

However, some studies shown the increasing of resilient modulus of WMA mixtures compared to HMA mixtures not only are not perceptible, but also are even almost equal [6]. Usage of Sasobit additive in WMA mixtures shows higher resilient modules compared to Zeolite additive. Also, the suitable effect of Li-aggregate compared to Si and Sl aggregates can be due to improved elastic behavior of these mixtures because of an increased percentage of asphalt binder. The higher resilient modulus may reduce the thickness of asphalt layers in the primary phase of design.

Indirect tensile strength is used to determine moisture sensitivity of asphalt and indicate resistance to the pavement cracking [35]. As shown in Fig. 8, ITS specimen containing 3% additives shows a higher value than the specimen containing 2% additives in the conditioned and unconditioned except Si-aggregates. ITS value of WAM mixtures also containing 2% and 3% additives for Li aggregates shows a maximum value and Si aggregates show minimum value. The better indirect tensile strength is due to the better adhesion of aggregates to binder, which is in good agreement with other similar studies that showed ITS of limestone specimen containing Sasobit is higher than slag specimen [36].

Table 5
Volumetric properties and stability of compacted specimen.

Type of aggregate and filler	Percent	Marshal stability (kg)		Air voids V_a		True specific gravity G_{mb}	
Additive		Zeolite	Sasobit	Zeolite	Sasobit	Zeolite	Sasobit
Sl	0	1033.3		4.81 ± .08		2.77	
Li		806.2		4.47 ± .26		2.35	
Si		650.21		4.31 ± .18		2.18	
Sl	2	1055.25	1814.60	4.82 ± .09	3.59 ± .18	2.47	2.47
Li		814.42	1225.08	3.84 ± .15	3.38 ± .14	2.12	2.25
Si		684.84	1050.32	4.09 ± .2	4.79 ± .22	2.00	1.98
Sl	3	1205.32	1334.14	3.98 ± .18	3.34 ± .28	2.5	2.5
Li		874.13	925.75	4.35 ± .2	3.01 ± .06	2.15	2.25
Si		719.18	742.21	5.00 ± .06	5.00 ± .07	2.00	1.98

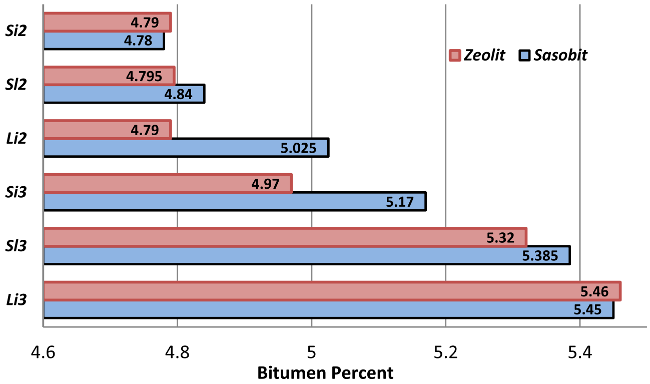

Fig. 4. Comparative diagram of optimum bitumen percentage changes in mixtures.

However, the little amount of ITS of Si-WMA mixtures containing Sasobit and Zeolite is due to the lower percentage of asphalt binder and the weaker bond compared to Li and Sl aggregates.

3.4. Durability and moisture susceptibility

The trend of ITS changes in the conditioned of Sl and Li aggregates are similar to the unconditioned. But this trend is reverse in the SI-mixtures containing Zeolite with the presence of moisture. This reverse trend is attributed to the effect of Si aggregate and Zeolite additive in the moisture condition. Because the Si aggregate and Zeolite additive have the equal loads and repel with each other, they reduce the strength of adhesion which was improved in the unconditioned and make a more negative effect.

According to Fig. 9, in the WMA mixtures containing Zeolite and Sasobit, the TSR value of Li aggregate shows maximum value, which is attributed to the better adhesion of aggregates to binder containing additives. Moreover, Si aggregate has the lowest TSR values. The study of Ameri et al. showed Li aggregates containing Sasobit have higher TSR values than SL aggregates [11]. Li aggregates and Sl aggregates containing 2% or 3% of Sasobit and Zeolite which have TSR values of 80% or higher, are in a standard range, but Si aggregates due to the high value of Si element and being hydrophilic, show a great resistance to moisture and TSR value is lower than the standard value. In addition, WMA mixtures containing 2% additives show a less TSR value than WMA mixtures containing 3% additives (except Si mixtures containing Zeolite). It means that with an increase in the percentage of additives, the moisture sensitivity of WMA increases. As presented in Fig. 9, Li and Sl WMA mixtures containing Zeolite show a higher TSR value but in Si aggregates due to presence of Silica in the Zeolite structure, in mixtures with these aggregates

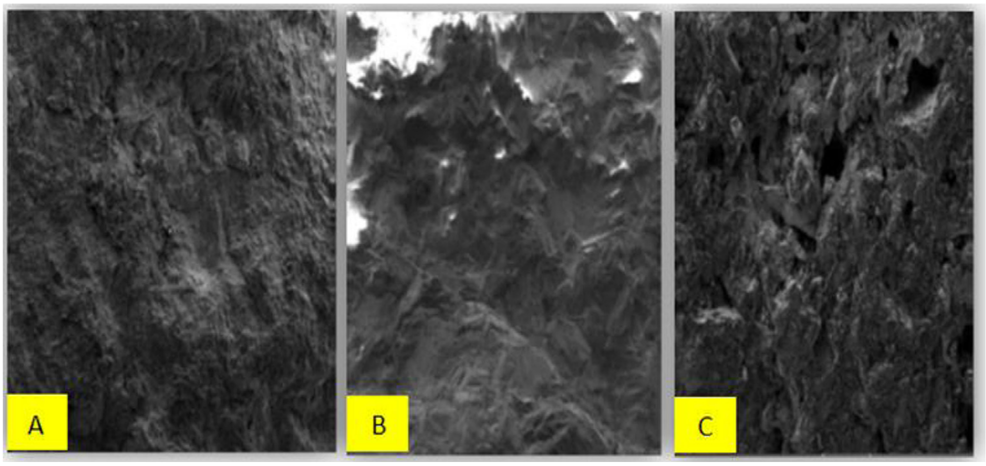

Fig. 5. Microscope image of the surface texture of 3 types of aggregates: (a) Si (b) Li (c) Sl.

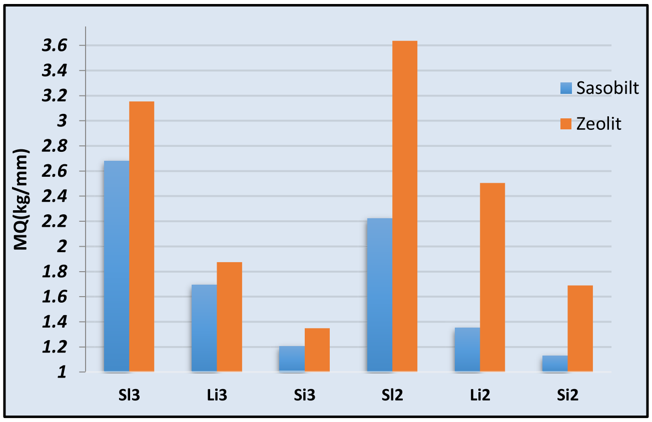

Fig. 6. Changes of MQ in the asphalt specimen.

moisture damage intensifies and has lower TSR value than Si mixtures with Sasobit mixtures. Generally, considering the results, adding Sasobit to bitumen with each 3 aggregates improves the sensibility of warm mixtures in comparison to HMA. But about the additive Zeolite in combination with bitumen and mixing with Li aggregates and S1 aggregates, considering this point that this additive contains alkali metals and these kinds of metals cause improvements in resistance to water; in this case, these alkali metals have a more positive effect than the negative one of element Si. On the other hand, in combination of Zeolite with Si aggregates, total negative effects of existing element Si in additive and aggregates are more than alkali metals and intensify Moisture Sensitivity.

3.5. Analysis of the effect on changes in the asphalt layer thickness

Using WMA instead of HMA leads to decline costs of fuel energy consumption and environmental costs, such as reducing smoke and dust and reduce temperature. In the use of asphalt, apart from the cost of production, asphalt thickness or volume of consumed aggregates is also important [6]. In this section, according to the results of laboratory tests, the economic analysis of produced asphalt was offered, regardless of the cost of procurement of raw materials and mixtures in this study. Also, due to various costs of material at different countries and locations, as variation in resilient modules of asphalt layer leads to variation in final thickness of asphalt layer and thus variation in final cost, accomplished analysis is carried out based on thickness variation of different conditions. This is obvious due to Eqs. (4) and (5) from MEPDG [9]

$$SN = a_1 + a_2m_2D_2 + a_3m_3D_3 \tag{4}$$

$$a_1 = .4\mathrm{Log}(E_A/3000\ \mathrm{Mpa}) + .44 \tag{5}$$

By regarding Eq. (4) the amount of a_1D_1 is equal to the constant amount of

$$SN = (a_2m_2D_2 + a_3m_3D_3) \tag{6}$$

So:

$$D_1 = \frac{\text{constant}}{a_1}. \tag{7}$$

When the layer coefficients increase compared to conventional asphalt, the thickness of the required layer decreases and the cost of the mentioned layer decreases.

In these relations: SN: structural layer, a_1 = layer coefficient (1) base layer (2) subbase layer, m_3 = drainage coefficient (2) base layer (3) subbase layer, D_1 = the thickness of layer (2) base layer (3) subbase layer and E_A = elastic modulus.

According to Eq. (4), for constant amount of SN and equal amounts of $m_2D_2m_3D_3$, by increasing the amount of a_1 the amount of D_1 (the thickness of asphalt layer) decreases. To compare the numerical results of the resilient modules for different asphalts and the amount of asphalt layer coefficient calculated by Eq. (4), the corresponding values has been brought in Table 6.

According to Table 6, the production of WMA mixtures with li and Si aggregates has a decline trend in thickness, but in other cases due to an increase in thickness the usage of this mixture may be uneconomical.

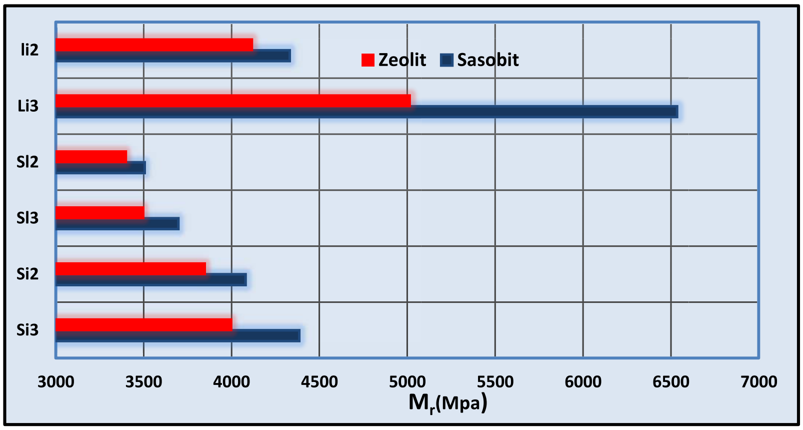

Fig. 7. Changes of resilient modulus in the asphalt specimen.

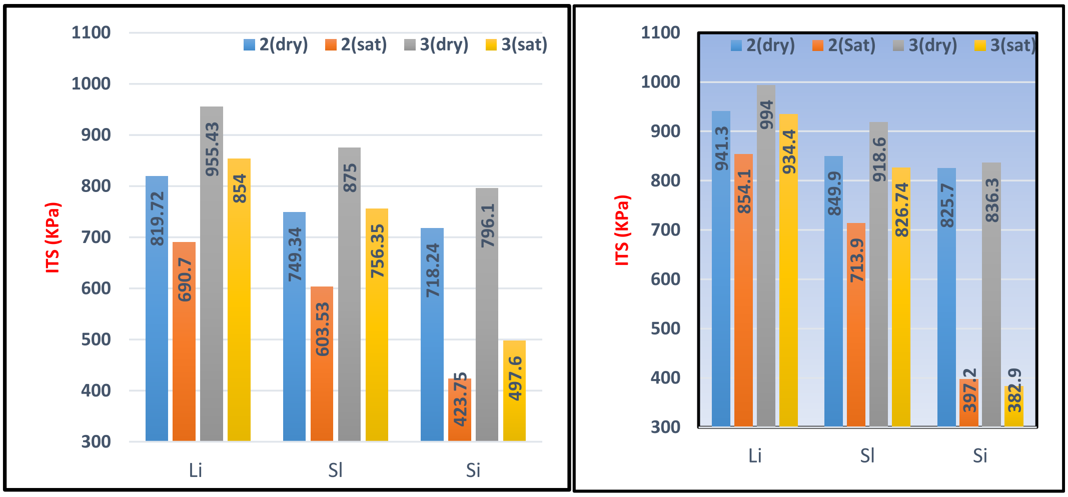

Fig. 8. ITS changes in WMA mixtures containing different additives in conditioned and unconditioned.

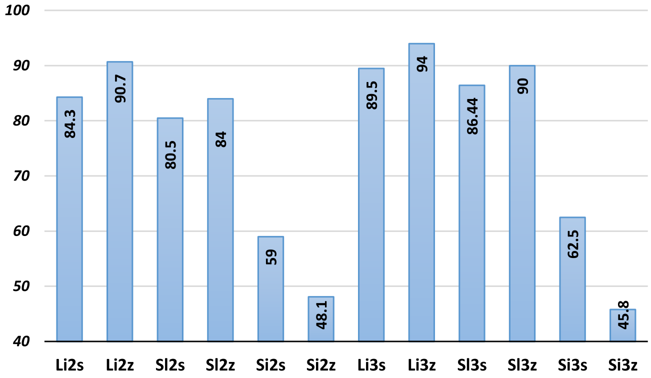

Fig. 9. Comparison of TSR changes in WMA mixtures.

4. Conclusion

In this paper, two types of additives (Sasobit and Zeolite) were used in order to evaluate the effect of aggregate type on WMA mixture production. Three laboratory tests including; Marshall Stability, resilient modulus and moisture susceptibility were conducted on different WMA mixtures that contained varied additives and aggregates. Initially, each mixture type was constructed with different bitumen percentages. Then optimum bitumen percentage of each mixture was determined based on Marshall Stability and volumetric characteristics. Subsequent tests (i.e. resilient modulus and moisture susceptibility were carried out on each mixture constructed at optimum bitumen percentage. Based on the test results and data analyses, the following conclusions are drawn out.

- By adding Sasobit, it was shown that compared to HMA mixture the percentage of optimum bitumen of Sl aggregates was lowered to 10.7%, 8.95% and 8.3% for S1, Si and Li aggregates, respectively. This indicates the greater influence of this additive on Sl and Si aggregates than that of Li aggregates. In the case of adding Zeolite, it also showed better effect on reduction of Li, S1 and Si aggregates by 12.6%, 11.5% and 8.8%, respectively; indicating the greater effect of Zeolite in reduction of the percentage of bitumen than the Sasobit. Marshall Stability tests demonstrated that Marshal Stability of Sl-WMA mixtures that contained 2% or 3% additives showed the maximum value and Si-WMA mixtures show the minimum value.
- By considering constant amount of additives, WMA mixtures that contained Sl aggregates had the maximum MQ whereas WMA mixtures that contained Si aggregates had the minimum value. So the produced mixtures that contained Sl aggregates were found to have higher initial stability and less possibility of permanent deformation rutting while the mixtures that contained Si aggregates showed less initial stability and greater possibility of permanent deformation.
- According to resilient modulus diagrams, WMA mixtures that contained Sasobit irrespective of aggregate type had a higher value than WMA mixtures that

Table 6
Calculated values of layer coefficient.

Type of asphalt mixture	Resilient modulus (MPa)	Layer coefficient a_1	The percent of increase and decrease of thickness (%)
Li	3711	0.48	–
Si	3409	0.46	*4.2 Increase*
Sl	3130	0.45	*6.25 Increase*
Li2s	6536	0.575	*19.8 Decrease*
Li3s	4330.5	0.504	*5 Decrease*
Li2z	5015.5	0.53	*10.42 Decrease*
Li3z	4117.5	0.495	*3.12 Decrease*
Si2s	4385	0.506	*5.42 Decrease*
Si3s	4079	0.493	*2.71 Decrease*
Si2z	3999.5	0.49	*2.1 Decrease*
Si3z	3849	0.483	*0.625 Decrease*
Sl2s	3697.5	0.476	*0.83 Increase*
Sl3s	3506	0.467	*2.71 Increase*
Sl2z	3497.5	0.467	*2.71 Increase*
Sl3z	3400	0.462	*3.75 Increase*

contained Zeolite. In each of the WMA mixtures that contained Li aggregates had a maximum value of resilient modulus and Sl aggregates had a minimum amount.

- According to ITS test results, WMA mixtures that contained 3% additives for any type of aggregates in the unconditioned state showed a higher ITS than WMA mixtures that contained 2% additives. In both types of additives, ITS of mixtures that contained Li aggregates showed the maximum value and Si aggregates showed the minimum value.
- According to moisture sensitivity, WMA mixtures that contained Li aggregates showed the maximum value of sensitivity and WMA that contained Si aggregates showed a minimum value of resistance to the stripping phenomenon. By increasing one percent in Sasobit, the resistance of moisture sensitivity in Li, Sl, Si aggregates was increased to 6.2%, 7.4% and 5.9%, respectively. Also, by increasing one percent in Zeolite additive, the resistance of moisture sensitivity in Li and Sl aggregate was increased to 3.6% and 7.1% however it was decreased to 4.8% when Si aggregate was used.
- Li-mixtures contained 3% of Sasobit and Zeolite additives not only caused a thickness reduction by 19.8%, 10.4%, but also improved the mixtures workability due to an increase in resilient modulus.
- Future research recommends evaluating the effect of different types of aggregates and comparing their actual performance. Also, the construction of samples with coarse and fine aggregates, comparing their performance results and performing performance based tests such as fatigue, permanent deformation and creep tests and comparing the results can be the topics of future research.

Acknowledgments

This work is supported by the Farshrah and Behdash-Shimi companies that cooperate with material preparing. The authors would like to thank Dr. Fazaeli for his supportive ideas through correct laboratory tests.

References

[1] John A. D'Angelo, Eric E. Harm, et al., Warm-mix asphalt european practice, US Department of Transportation, Federal Highway Administration, Number 01098935, 72p, 2008.

[2] O. Kristjansdottir, Warm mix asphalt for cold weather paving, Master of Science in Civil Engineering, University of Washington, Civil and Environmental Engineering, Seattle, WA 98109, pages 107, 2006.

[3] I. Omari, V. Aggarwal, S. Hesp, Investigation of two warm mix asphalt additives, Int. J. Pavement Res. Technol. 9 (2) (2016) 83–88, http://dx.doi.org/10.1016/j.ijprt.2016.02.001.

[4] A.E. Abu El-Maaty Behiry, in: Laboratory evaluation of resistance to moisture damage in asphalt mixture, Ain Shams Eng. J. 4 (2013) 351–363, http://dx.doi.org/10.1016/j.asej.2012.10.009.

[5] S. Cui, R.K. Blackman Bamber, J. Kinloch Anthony, C. Taylor Ambrose, in: Durability of asphalt mixtures: Effect of aggregate type and adhesion promoters, Int. J. Adhes. Adhes. 54 (2014) 100–111, http://dx.doi.org/10.1016/j.ijadhadh.2014.05.009.

[6] A. Chowdhury, J.W. Button, A review of warm mix asphalt, Project 473700-00080, Southwest Region University Transportation Center, DOT F 1700.7 (8–72), December 2008, 75 page, 2008.

[7] H. Kim, S. Lee, S.N. Amirkhanian, Rheology of warm mix asphalt binders with aged binders, Constr. Build. Mater. 25 (1) (2011) 183–189, http://dx.doi.org/10.1016/j.conbuildmat.2010.06.040.

[8] G.C. Hurely, B.D. Prowell, Evaluation of potential processes for use in warm mix asphalt, J. AAPT 75 (2007) 53–102. Association of Asphalt Paving Technologists, USA.

[9] Y.H. Huang, in: Pavements Analysis and Design, Prentice Hall (2004).

[10] A. Topal, B. Sengoz, B.V. Kok, M. Yilmaz, P.A. Dokandari, J. Oner, D. Kaya, Evaluation of mixture characteristics of warm mix asphalt involving natural and synthetic Zeolite additives, Constr. Build. Mater. 57 (2014) 38–44, http://dx.doi.org/10.1016/j.conbuildmat.2014.01.093.

[11] M. Ameri, S. Hesami, H. Goli, Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag, Constr. Build. Mater. 49 (2013) 611–617, http://dx.doi.org/10.1016/j.conbuildmat.2013.08.034.

[12] G. Valdés-Vidal, A. Calabi-Floody, R. Miró-Recasens, J. Norambuena-Contreras, in: Mechanical behavior of asphalt mixtures with different aggregate type, Constr. Build. Mater. 101 (2015) 474–481, http://dx.doi.org/10.1016/j.conbuildmat.2015.10.050, Part 1.

[13] C. Shuang, R.K. Bamber, A. Blackman, J. Kinloch, C.T. Ambrose, Durability of asphalt mixtures: effect of aggregate type and adhesion promoters, Int. J. Adhes. Adhes. 54 (2014) 100–111, http://dx.doi.org/10.1016/j.ijadhadh.2014.05.009.

[14] M. Solaimanian, J. Harvey, M. Tahmoressi, V. Tandon, Test methods to Predict Moisture Sensitivity of Hot-mix Asphalt Pavements, Transportation Research Board National Seminar, San Diego, California, 2003, pp. 77–110.

[15] P.S. Kandhal, Field and laboratory investigation of stripping in asphalt pavements: state of the art report, Transp. Res. Rec. 1454 (1994) 69–72.

[16] A. Kavussi, L. Hashemian, Laboratory evaluation of moisture damage and rutting potential of WMA foam mixes, Int. J. Pavement Eng. 13 (5) (2012) 415–423, http://dx.doi.org/10.1080/10298436.2011.597859.

[17] J.E. Penny, An evaluation of heated reclaimed asphalt pavement (RAP) material and wax modified asphalt for use in recycled hot mix asphalt (HMA) (Master of Science thesis), Worcester Polytechnic Institute, 2006, 52 page.

[18] X. Shu, B. Huang, E.D. Shrum, X. Jia, Laboratory evaluation of moisture susceptibility of foamed warm mix asphalt containing high percentages of RAP, Constr. Build. Mater. 35 (2012) 125–130, http://dx.doi.org/10.1016/j.conbuildmat.2012.02.095.

[19] C. Ai, Q.J. Li, Y. Qiu, Testing and assessing the performance of a new warm mix asphalt with SMC, J. Traffic Transp. Eng. (Eng. Ed.) 2 (6) (2015) 399–405, http://dx.doi.org/10.1016/j.jtte.2015.10.002.

[20] A. Raghavendra, M. Medeiros Jr, M. Hassan, L. Mohammad, W. King Jr., in: Laboratory and construction evaluation of warm-mix asphalt, J. Mater. Civ. Eng. 28 (7) (2016), http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001506, 04016023.

[21] N. Wasiuddin, N. Saltibus, L. Mohammad, Effects of a wax-based warm mix additive on cohesive strengths of asphalt binders, T&DI Cong. 2011 (2011) 528–537, http://dx.doi.org/10.1061/41167(398)51.

[22] M. Fallah, Studies investigating the causes of friction loss the field of asphalt roads and procedure strategies in Yazd province, a research project report or Yazd road and urban development department, 2015, pages 195.

[23] Iran highway asphalt paving code, Vice Presidency for Strategic Planning and Supervision", The Ministry of Road and Urban Development, Iran. Publication Number 234, 2011, pages 279.

[24] G.C. Hurley, B.D. Prowell, Evaluation of sasobit for use in warm mix asphalt, NCAT Report 05-06 277, Technology Parkway Auburn, 2005, Page 1–32.

[25] B. Sengoz, TopalA, C. Gorkem, Evaluation of natural zeolite as warm mix asphalt additive and its comparison with other warm mix additives, Constr. Build. Mater. 43 (2013) 242–252.

[26] A. Jamshidi, M.O. Hamzah, Z. You, Performance of warm mix asphalt containing Sasobit: state-of-the-art, Constr. Build. Mater. 38 (2013) 530–553, http://dx.doi.org/10.1016/j.conbuildmat.2012.08.015.

[27] A. Jamshidi, M.O. Hamzah, M.Y. Aman, Effects of Sasobit® content on the rheological characteristics of unaged and aged asphalt binders at high and intermediate temperatures, Mater. Res. 15 (4) (2012) 628–638, http://dx.doi.org/10.1590/S1516-14392012005000083, São Carlos.

[28] M.M. Pradhan, Permanent deformation characteristics of asphalt-aggregate mixtures using varied materials and molding procedures with Marshall method (Doctoral dissertation), Montana State University, Bozeman, 1995, pages 305.

[29] ASTM D4123, Indirect tension test for resilient modulus of bituminous mixtures, vol. 04.03, ASTM Book of Standards, USA, 2003.

[30] L. Santucci, Moisture sensitivity of asphalt pavements, Technology Transfer Program, Institute of Transportation Studies, Pavement Research Center, UC Berkeley, 2003, pages 341.

[31] AASHTO, Resistance of Compacted Bituminous Mixture to Moisture Induced damage, Test Method T283-85, Part2: Methods of Sampling and Testing, Washington D.C., USA, 1986

[32] A.E. Alvarez, N. Macias, L.G. Fuentes, Analysis of connected air voids in warm mix asphalt, Dyna 79 (172) (2012) 29–37.

[33] A. Aksoy, K. Samlioglu, S. Tayfur, H. Ozen, Effect of various additives on the moisture damage sensitivity of asphalt mixtures, Constr. Build. Mater. 19 (2005) 11–18, http://dx.doi.org/10.1016/j.conbuildmat.2004.05.003.

[34] A. Kavussi, M. Jaliliqazyzadh, A. Ziaei, Moisture sensitive evaluation of asphalt mixtures containing steel slag electric arc furnace (EAF), in: The Eighth National Congress of Civil Engineering, Department of Civil Engineering, Babol university, 2011, pp. 1–8.

[35] S.W. Goh, K. Akin, Z. You, X. Shi, Effect of deicing solutions on the tensile strength of micro-nano modified asphalt mixture, Constr. Build. Mater. 25 (2011) 195–200, http://dx.doi.org/10.1016/j.conbuildmat.2010.06.038.

[36] A. Kavussi, A. Modarres, A model for resilient modulus determination of recycled mixes with bitumen emulsion and cement from ITS testing results, Constr. Build. Mater. 24 (11) (2010) 2252–2259, http://dx.doi.org/10.1016/j.conbuildmat.2010.04.031.