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Laboratory Evaluation of SMA Mixtures Containing Different Additives

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Abstract: For many years, rutting in asphalt mixtures has been identified as one of the most critical types of distresses. To overcome this problem, Stone Matrix Asphalt (SMA) as a type of rut resistant asphalt mixture has emerged since 1970s. The use of different additives such as fibers or polymers seems to be essential in these mixtures to reduce the amount of binder drain down as the main problem of using this type of asphalt concrete. In this research, two types of additives such as Regular additives (styrene-butadiene-styrene and mineral fiber) and a Compound additive (Rheofalt® wkr-2) were used to improve the SMA mixture performance and decrease the binder drain down. Binder properties tests and mixture performance tests including Marshall test, Indirect Tensile Strength (ITS), moisture susceptibility and dynamic creep tests were performed to evaluate the performance properties of these mixtures. The results indicated that Rheofalt® wkr-2 had a positive effect on binder properties and SMA mixture performance. And as such, the effect of 10% of it was more considerable compared with other dosages. There was no need of using additional additive to reduce binder drain down when using Rheofalt® wkr-2 as a modifier. The effect of Rheofalt® wkr-2 was more than SBS and mineral fiber in terms of moisture sensitivity; however, SBS was more capable of improving Marshall and rutting properties of SMA mixtures than other additives. Based on the statistical analysis, it could be concluded that there are significant correlations between Marshall, indirect tensile strength and creep performance of SMA mixtures.

Key words: Stone matrix asphalt, antioxidant, additive, rutting, drain down

INTRODUCTION

As a rut resistant mixture, SMA is a type of gap-graded hot mix asphalt that acquires its resistance from stone skeleton of coarse aggregate. Coarse aggregate fraction of this type of mixture is glued together with a durable and moisture-resistant mortar comprising asphalt cement (typically 5.5-7%), filler (typically 8-12%) and stabilizing additive (Brown and Manglorkar, 1993). According to the reports, stone matrix asphalt has indicated more durability as a surface asphalt concrete (Al-Hadidy and Yi-qiu, 2009a). Some of positive properties of SMA mixtures comprise its high rut resistance, high skid resistance, high durability, improved resistance to reflective cracking, better drainage condition and reduced noise pollution (Nejad *et al*., 2010). The main reason of using a gap gradation in these mixtures is to establish stone on stone condition to resist against permanent deformation. Because of both gap graded nature of this mixture and high amount of binder, drain down has been regarded as the main problem in using this type of asphalt concrete. To prevent this problem, the use of some additives may be essential. There are two mainly types of additives used in these mixtures: *Fibers* and *Polymers*. Fibers such as polyester fiber, mineral fiber and cellulose fiber are often used in ordinary SMA mixtures to significantly decrease the amount of binder drain down (Tayfur *et al*., 2007; Behbahani *et al*., 2009). Fibers could relatively change the viscoelasticity of mixture; improves dynamic modulus, tensile strength and moisture susceptibility, creep compliance, rutting resistance and fatigue life (Abtahi *et al*., 2010) while significantly lowers the amount of draindown of asphalt mixtures. In contrast, a polymer is often used in asphalt mixtures to substantially improve the mechanical properties of asphalt mixtures and relatively decrease the binder drain down. Different types of polymers (such as Styrene-Butadiene-Styrene (SBS), Ethylene-Vinyl-Acetate (EVA), polyethylene or polypropylene) may be used to gain desired mixture properties (Al-Hadidy and Yi-qiu, 2009a). To combine binder with polymer, it is often necessary to heat the binder up to 180°C. This could bring about some problems in terms of aging of the binder which cause asphalt concrete to be more brittle during its service life. One way to solve this problem is by using antioxidants. The main aim of using antioxidant is to reduce the amount

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of oxidative hardening of the binder. Oxidation is a kind of irreversible chemical reaction of oxygen with binder. Oxidation of asphalt can occur throughout the life of an asphalt pavement such as during mixing, field placement and during its service life (Apeagyei, 2010).

With regard to use different additives in SMA mixtures, Sharma and Goyal (2006) evaluated the effect of crumb rubber and natural fiber on performance of SMA mixtures. They concluded that the crumb rubber could positively affect the engineering properties of SMA mixtures such as resistance to moisture damage, rutting, aging and permeability more than natural fiber could. Al-Hadidy and Tan (2009) investigated the influence of Low Density Polyethylene (LDPE) on life of SMA mixtures and performed performance tests such as Marshall, moisture sensitivity and low-temperature cracking test and the benefit of modification was evaluated by mechanistic-empirical method. As they reported, it was observed that LDPE could efficiently reduce the binder drain down and improve the properties of asphalt binder as well as SMA mixture; 6% of LDPE could be the best dosage to construct the SMA mixtures. Moreover, the injection of LDPE to the SMA mixture resulted in a life of pavement 1.359 times more than unmodified SMA mixture. Kumar *et al*. (2007) added different types of fibers (natural and patented) and crumb rubber to SMA mixtures. Based on the results, natural fiber was comparable to the patented fiber in terms of Marshall, rutting and flexural fatigue tests; however, natural fiber resulted in a better condition in terms of aging of asphalt concrete. In addition, crumb rubber indicated better efficiency in improving the properties of SMA mixtures compared to the fibers. As presented by Al-Hadidy and Yi-qiu (2009c) polypropylene could also enhance the performance of SMA mixtures in terms of Marshall, moisture sensitivity and compressive strength. It did not need to add any fiber to decrease the amount of binder drain down when using polypropylene. This type of additive could also improve the service life of the SMA mixture 1.48 times more than unmodified one. A comparative study was performed by Tayfur *et al*. (2007) which included the rutting performance of SMA mixtures modified with different additives such as amorphous polyalphaolefin, cellulose fiber, polyolefin, bituminous cellulose fiber and styrene butadiene styrene. As the main results of this research, SBS showed the highest resistance to permanent deformation and fibers indicated the least improving effect among different used additives. Behbahani *et al*. (2009) used different fibers to construct SMA mixtures. Based on this research, German cellulose fiber had a better effect on properties of SMA mixtures rather than Iranian cellulose and mineral fibers. Al-Hadidy and Yi-qiu (2009b) also investigated the effect of SBS and Starch on life of SMA mixtures. Different performance tests such as Marshall, indirect tensile strength and resilient modulus were conducted to evaluate the SMA mixtures modified with 5% of aforementioned additives. Based on their report, Starch could be a good replacement of SBS; however, in the most performed tests SBS showed an insignificant better influence. The efficiency of starch was more than SBS in terms of reducing the moisture susceptibility of SMA mixture.

The main objective of this study was to perform a laboratory investigation on SMA mixtures containing regular additives (SBS and mineral fiber) and a compound additive (Rheofalt® wkr-2) which is a polymer-based modifier includes antioxidant to reduce the age-hardening of asphalt concrete.

MATERIALS AND METHODS

Materials used: Required aggregate was obtained from an asphalt plant in Roudehen around Tehran. The properties of aggregate were presented in Table 1. Moreover, Rock dust, Passed through sieve No.200 was used as mineral filler. The bulk specific gravity of used filler was 2.702 kg cm^{-3}.

Asphalt cement for this study was AC-60/70, provided from Tehran Refinery and Pasargad Oil Company, Tehran, Iran. Physiochemical properties of this cement were provided in Table 2.

Table 1: Properties of coarse and fine aggregates

Properties	Method (AASHTO, 2004)	Requirement	Values
Coarse aggregate			
Los angeles abrasion, (%)	AASHTO T96	30 max.	20
Water absorption, (%)	AASHTO T85	5 max.	0.8
Bulk specific density, (g cm^{-3})	AASHTO T85	-	2.654
Flat and elongated (3 to 1), (%)	ASTM D4791	20 max.	12
Soundness (sodium sulfate), (%)	AASHTO T104	15 max.	4.8
Crushed content (one face), (%)	ASTM D5821	100 min.	100
Crushed content (two faces), (%)	ASTM D5821	90 min.	100
Fine aggregate			
Water absorption (%)	AASHTO T84	-	1.4
Bulk specific density (g/cm^{-3})	AASHTO T84	-	2.617

As drain down inhibitors, mineral fiber and SBS were added to the SMA mixtures at the rate of 0.4% (by weight of the mixture) and 5% (by weight of the binder), respectively. Mineral fiber was uniformly mixed with aggregate before adding asphalt cement. The used SBS was ITERPRENE SBS/G-L®. In order to mix the binder with polymer, 5% of SBS by weight of asphalt cement was added to the heated binder (170°C) according to the previous studies (Yildirim, 2007). At this temperature, the rotation speed was regulated at 1500 rpm. After about 30 min the speed increased up to 4000 rpm for 1 h to make a homogeneous binder. The specification of the used SBS in this study is as shown in Table 3.

In addition, one type of compound additive was used in this study. The physical properties of Rheofalt® wkr-2 which consists of EVA, waxes and antioxidants is presented in Table 4. This type of additive does not need a high shear stirrer to blend with bitumen. A typical rotating stirrer is adequate for this purpose.

Mixture design: The mixing and compaction temperatures for constructing SMA specimens were selected in a way that the viscosities are 170±20 and 280±30 cSt, respectively (Brown and Manglorkar, 1993). This criterion was considered to determine the mixing and compaction temperature for base and modified binders. The selected dosages of Rheofalt® wkr-2 in this study were 5, 10 and 15% by weight of the binder. However, construction temperatures for SBS modified binder were 175°C and 165°C recommended by manufacturer. The mixture design method used for SMA was as proposed by NCHRP Report No. 425 (Brown and Cooley, 1999). To evaluate volumetric properties of mixtures with different gradation limits, a number of 12 samples (four identical samples for each) were fabricated according to the Marshall mix design (ASTM D-1559) procedure. Laboratory specimens were prepared using fifty blows of the Marshall hammer per side. Seventy-five compaction blows were not used since they would not result in a significant increase in density over that provided by 50 blows (Al-Hadidy and Yi-qiu, 2009b) and would also cause more breakdown in coarse aggregate (Asi, 2006). The optimum gradation should be selected in such a way that the VCA ratio was less than 1 in order to establish stone on stone condition in all SMA samples. After optimizing the gradation for SMA mixtures, it is important to select Optimum Binder Content (OBC) to meet the requirements presented in Table 5. With this regard, two series of SMA mixtures should be prepared for each set of the mixture to calculate the OBC for control/SBS/wkr-2 and mineral fiber modified mixtures. Different percentages of binder should be added to each subset to both evaluate volumetric properties of mixtures and determine the amount of OBC. It should be noted that the OBC for each subset in this section was considered in such a way that all specimens met 4% air void.

Table 2: Physical properties of asphalt cement

Parameter measured	Test method (AASHTO, 2004)	Test value
Specific gravity at 25°C (g cm^{-3})	AASHTO T228	1.01
Penetration at 25°C (0.1 mm)	AASHTO T49	63.00
Softening point (R and B) (°C)	AASHTO T53	51.00
Viscosity at 135°C (centistokes)	AASHTO T201	361.00
Ductility at 25°C (cm)	AASHTO T51	>100.00

Drain down: In order to evaluate the potential of drain down for SMA mixtures, a test procedure described by NCHRP Report No. 425 was conducted for all mixtures. Thus, for each set of mixture, a standard wire basket containing uncompacted SMA sample along with a plate were placed in an oven at the mixing temperature. After about 1 h, the amount of binder drain down was calculated by Eq. 1:

$$\text{Draindown}\,(\%) = \frac{B-A}{W}\times 100 \tag{1}$$

Where:

A = Initial plate mass
B = Weight of plate plus drained materials
W = Loose sample mass

Marshall test: Although, Marshall test is usually carried out for HMA mixtures in order to perform the process of mixture design, Marshall stability and flow values for SMA mixtures are generally measured for information but not for acceptance. The Marshall stability for SMA mixtures is significantly lower than that for dense graded mixtures (Brown and Manglorkar, 1993). This is not an

Table 3: Properties of ITERPRENE SBS/G-L®

Properties	Test method	Unit	Typical value	Specification limits
Specific weight at 23°C	ASTM D792	g L^{-1}	0.94	0.92-0.95
Styrene content	ASTM D1416	wt. (%)	32.00	30.5-33.5
Ash content	ASTM D1416	wt. (%)	0.90	≤1
Oil content	ASTM D1416	phr	0.00	<2
Volatiles content	ASTM D1416	(%)	0.60	<1
Hardness	ASTM D2240	Shore A	75.00	72-78

Table 4: Physical properties of rheofalt® wkr-2

Properties	Values
Physical state at 25°C	Solid
Congealing point (°C)	102-108
Flash point (°C)	>190
Viscosity at 160°C (mPa.s)	3600
Penetration at 25°C (0.1 mm)	0-4

Table 5: SMA mixtures specifications for marshall hammer compacted designs (Brown and Cooley, 1999)

Property	Requirement
Air void (%)	3-4
VMA (%)	17 min.
VCA_{MIX}	Less than VCA_{DRC}
TSR (%)	70 min.
Drain down @ production temperature (%)	0.30 max.

indication that dense graded mixtures are more stable than SMA mixtures but it declares that Marshall stability may not be appropriate for SMA samples. The volumetric properties might be more applicable in designing SMA mixtures than Marshall stability.

The Marshall quotient is calculated as the ratio of the Marshall stability to the flow. This ratio clearly represents the performance properties of asphalt mixture such as stiffness, resistance to the shear stress and permanent deformation (Mirzahosseini *et al*., 2011). The higher Marshall quotient value a mixture has, the more resistant to cracking it should be.

To prepare desired specimens, three identical samples for each type of SMA mixtures were compacted at 4% of air void. Designing the mixtures at 3% air voids definitely results in a higher probability of fat spots and permanent deformation (Brown *et al*., 1997a). All specimens were submerged in 60°C water for 30-40 min before the test.

Moisture sensitivity

Mechanism and concept: Moisture can affect asphalt mixtures in three different ways: loss of cohesion, loss of adhesion and aggregate degradation. The loss of cohesion and adhesion are more prominent to the process of stripping. A reduction in cohesion results in a reduction in strength and stiffness. The loss of adhesion is the physical separation of the asphalt cement and aggregate, primarily caused by the action of moisture (Khosla and Harikrishnan, 2007). There is a close relationship between the permeability of the mixture and possibility of moisture damage to occur. If asphalt pavements are impenetrable, moisture damage would seldom happen; however, it may result in a excessive permanent deformation of pavement under heavy traffic and occurrence of bleeding phenomenon at high temperatures (Terrel and Al-Swailmi, 1994).

In the case of moisture damage measurement, tensile strength is one of the most critical parameters to be always taken into consideration for performance evaluation. This test is used to determine the tensile properties of the asphalt concrete which can be further related to the cracking properties of the pavement. The tensile strength is primarily a function of the binder properties. The amount of asphalt binder in a mixture and its stiffness affect the tensile strength. Tensile strength also depends on the absorption capacity of the used aggregates (Khosla and Harikrishnan, 2007).

The moisture sensitivity of a mixture could be evaluated by performing the AASHTO T-283 test. As defined in this procedure, the indirect tensile strength of mixtures should be measured by applying compressive loads along a diametrical plane through two opposite loading strips for both dry and preconditioned specimens. This test does not seem to be a very accurate indicator of stripping but it could help to minimize the problem (Brown *et al*., 2001).

Specimen preparation and test procedure: Each SMA mixture in this phase should be compacted at 6±1% of air void by adjusting the number of blows as described by NCHRP Report No. 425. Two subsets (three identical samples for each) were produced in the laboratory for each set of mixtures. One subset was tested dry at 25°C and the other one was preconditioned before testing in warm-water bath for 24 h at 60°C. Maximum applied force was measured for each set; then, Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR) were calculated by Eq. 2 and 3:

$$ITS = \frac{2P}{\pi tD} \tag{2}$$

$$TSR\ (\%) = \frac{ITS_{WET}}{ITS_{DRY}} \times 100 \tag{3}$$

Where:

ITS = Tensile strength (MPa)
P = Maximum load (N)
T = Specimen thickness (mm)
D = Specimen diameter (mm)

As mentioned by NCHRP Report No. 425, SMA mixtures should meet applicable specification (70% minimum) as their TSR values. Therefore, mixtures with TSR less than 70% are moisture susceptible and it might be necessary to use antistripping additives or adjust mixtures to meet the requirement.

Dynamic creep test

Basic concept: As a general description, rutting is the longitudinal settlement of the pavement surface along the wheel load path due to the progressive movement of paving materials under traffic loading. The amount of the depression could significantly depend on the quality of asphalt concrete as well as other layers (Tapkin, 2008). Based on previous researches, rutting was considered as the most important distress in asphalt pavement. Although aggregate, asphalt cement and air void are the three important parameters of asphalt concrete which influence the rutting performance of pavements, aggregate shape and texture have a significant role in determining the level of aggregate interlocking and also the amount of pavement rutting (Xiao *et al*., 2010). Therefore, the main reason why SMA mixtures have been widely used is that the texture of these types of mixture causes them to be superior to conventional hot mix asphalt in terms of permanent deformation. However, the type of stabilizer can seriously affect the SMA rut resistance capabilities (Brown *et al*., 1997a).

Various experimental tests such as static creep, dynamic creep, wheel tracking and indirect tensile tests are normally used to assess the potential of permanent deformation of asphalt mixtures. Among the mentioned methods, dynamic creep test is found to be one of the best methods to evaluate the rutting performance of asphalt mixtures (Kaloush *et al*., 2002). In addition, the findings indicated that there is a very good correlation between the measured rut depth obtained from the wheel tracking test and the deformation strain obtained from the uniaxial creep test.

The most commonly used device in dynamic creep test is the Universal Testing Machine (UTM-5) which it can be considered as the first generation of UTM. This device is usually employed to determine the important mechanical properties of asphalt mixtures under similar field conditions (i.e., similar loading and temperature). As indicated in Fig. 1, The creep curve could be divided into three zones: (1) primary zone, (2) secondary zone and (3) tertiary zone. During the primary zone, the mixture volume decreases due to densification and accumulated strain increases dramatically. In the secondary zone which can be identified as a transition zone between the primary and the tertiary zones, the relationship between accumulated strain and cycles is linear. The tertiary zone can be named as appearance of the second mechanism of rutting in which the shear deformation starts and rutting increases again. As a comparison criterion, Kaloush *et al*. (2002) used Flow Number (FN) as a point at which the tertiary zone in creep curve begins (Kaloush *et al*., 2002).

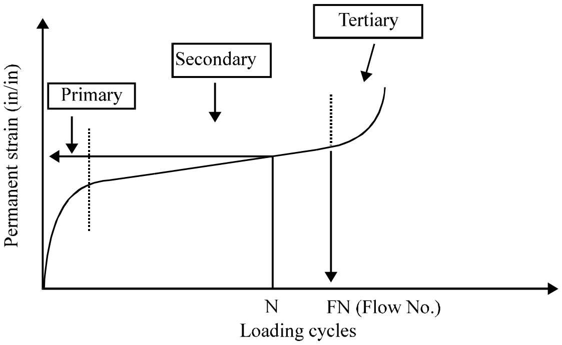

Fig. 1: Typical creep curve (Witczak, 2006)

In order to evaluate the creep behavior of SMA mixtures the UTM-5P in the laboratory of Iran University of Science and Technology was used. The load on the specimens was uniaxial and dynamic, representing the repeated application of axle loads on the pavement structure. All specimens for each alternative were prepared by Marshall compactor in order to reach 4% of air void. Other conditions were also the same for different type of mixtures; a loading level of 400 KPa (58.4 psi) was applied to all specimens; the shape of loading was rectangular with a load and rest period of 1s; all specimens were placed at 45°C for 4 h before testing; the test was continued for each sample until 10000 cycles or the loaded specimen reach its tertiary stage.

Statistical analysis: To investigate how different properties of SMA mixtures could relate to each other, a statistical analysis should be performed. In this research, the relationship between performance tests results such as, Marshall stability, Marshall Quotient, Indirect Tensile Strength (ITS) and dynamic creep test was inspected using linear regression by conducting the Statistical Package for the Social Sciences (SPSS V19) program. In addition, for each existed association, the relevant equation with the corresponding information was provided.

RESULTS AND DISCUSSION

Rheological tests: The Rheological tests including Penetration and Softening Point tests were performed for unmodified and modified binders and the value of Penetration Index (PI) was measured for each type of binder. Penetration Index is a term which describes the sensitivity of the binder to the temperature. Temperature susceptibility is the rate at which the consistency of binder changes. To evaluate the potential of temperature sensitivity of asphalt binder, penetration index could be calculated by using Eq. 4:

$$\begin{aligned}&\text{PI} = [(20 - 500\text{A})]\\&\text{A} = [(\log \text{pen.@T} - \log 800) / (\text{T} - \text{T}_{\text{R\&B}})]\end{aligned} \qquad (4)$$

Table 6: Volumetric properties of different limits of gradation

Gradation	Binder content (%)	Additive	G_{mb}	G_{mm}	G_{sb}	G_{CA}	γ_S	VCA_{DRC}	VCA_{MIX}	VCA ratio	VMA	V_a
Upper limit	6.2	None	2.301	2.436	2.652	2.654	1572	40.65	41.45	1.02	18.61	5.54
Middle limit	6.2	None	2.289	2.46	2.653	2.654	1548	41.56	38.52	0.927	19.07	6.95
Lower limit	6.2	None	2.272	2.478	2.653	2.654	1517	42.73	35.76	0.837	19.68	8.31
Selected gradation	6.2	None	2.297	2.442	2.653	2.654	1570	40.73	39.92	0.98	18.78	5.94

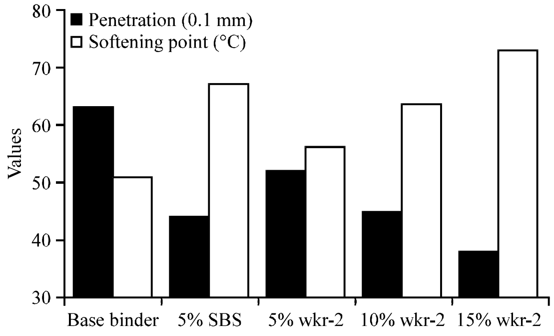

Fig. 2: Results of binder properties tests

Where:

T = Testing temperature

$T_{R\ and\ B}$ = Ring and Ball softening point

Figure 2 presents the results of binder tests. From Fig. 2, it could be inferred that all percents of wkr-2 have the capability of improving the binder properties. For example, 5, 10 and 15% of this additive could reduce the binder penetration by 17, 29 and 40% and increase the softening point of the binder by 10, 24 and 43%, respectively. However, the improving effect of SBS on penetration and softening point of the binder were 30 and 24% which could express that the influence of 15% wkr-2 on asphalt cement properties was more significant than that of SBS. Moreover, as an indicator of temperature sensitivity of binder, PI values were provided in Fig. 3. It can be realized from Fig. 3 that both SBS and wkr-2 increased the P.I. value which could indicate that the temperature sensitivity of binder decreased after adding SBS and different percents of wkr-2.

Mixture design: According to Fig. 4, the mixing and compaction temperatures of base binder for preparing control and mineral included SMA specimens were 158°C and 146°C, respectively. From Fig. 4, it could be observed that the construction temperatures for wkr-2 modified binders were more than that for base binder; for instance, 15% of wkr-2 increased the mixing temperature up to 177°C.

To optimize the gradation, three limits (upper, middle and lower) were first considered as shown in Fig. 5. In addition, 6.2% of binder was initially added to the mixture according to the report. The volumetric properties of SMA mixtures needed to calculate the parameters such as VCA, VMA and Va are presented in Table 6. As shown in Table 6, the VCA ratio for middle limit is 0.927 at 6.95 percent of air void. This amount of air void in these samples seems to be relatively high to be filled with binder and it seems not logical to select the middle limit as optimum gradation. A more wisely way is to select the optimum gradation between upper and middle limits in a way that the VCA ratio is nearer to 1. The aim of this is to produce mixtures more economically in terms of the amount of used binder. Therefore, the optimum gradation is as shown in Fig. 5. The properties of specimens prepared with this optimum gradation are presented in Table 6. It is obvious that all VMA values were more than 17% specified in Table 5.

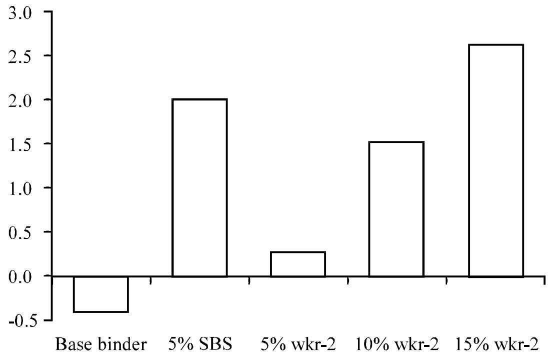

Fig. 3: PI Values for modified binders

The results of binder optimization showed that the amount of 7.1% for control/SBS/wkr-2 and 6.7% for mineral modified mixtures were considered as OBC (Table 7). The main reason for selecting the same OBC for control, SBS and wkr-2 modified mixtures is to make binder consistency be constant for all these mixtures.

Drain down: The results of the drain down test were presented in Fig. 6 which indicates that the drain down value for conventional mixture exceeded the required specification. However, different additives were successful in reducing the amount of binder drain down. For instance, different percents of wkr-2 could decrease the amount of drain down in such a way that 15% wkr-2 was more efficient than 5% of SBS. As could be expected, the capability of mineral fiber was more than other additives which is in support of ideas developed by Brown *et al.* (1997b). Therefore, based on the results, there would not be any problems in using these additives in terms of binder drain down.

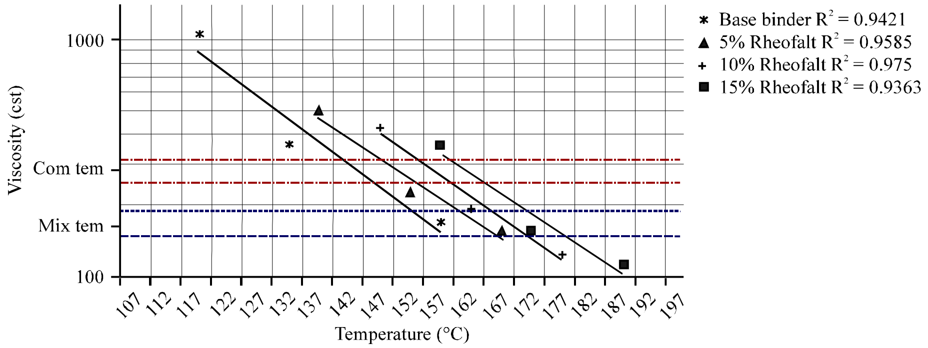

Fig. 4: Temperature-viscosity relationship for modified binders

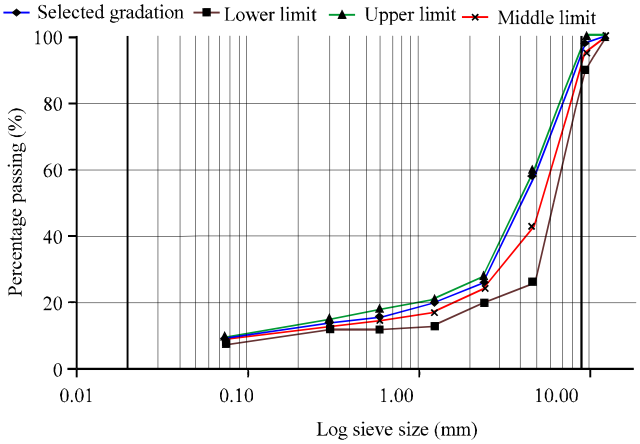

Fig. 5: Proposed limits and selected gradation of SMA-9.5

Table 7: Results of selecting optimum binder content

Gradation	Additive	V_a (%)	OBC (% mixture)
Selected gradation (previous section)	Control/SBS/wkr-2	4±0.1	7.1
	Mineral	4±0.1	6.8

Marshall test: As indicated in Fig. 7, all modified mixtures had higher Marshall stability and less flow value than control mixtures which clearly describes that different additives had positive effect on Marshall properties of SMA mixtures. Among various SMA mixtures, those modified with SBS indicated the best performance with the highest values of stability and quotient (6.56 and 2.02, respectively) and the least value of flow (3.24). Based on the results, 10% of wkr-2 showed the best performance in Marshall test considering the results of different percents of wkr-2. The obtained results clearly endorse the previous researches on positive effect of SBS in increasing the Marshall properties of SMA mixtures investigated by Al-Hadidy and Yi-qiu (2009c). In addition, mineral fiber could improve the performance of SMA mixtures but this improvement was insignificant.

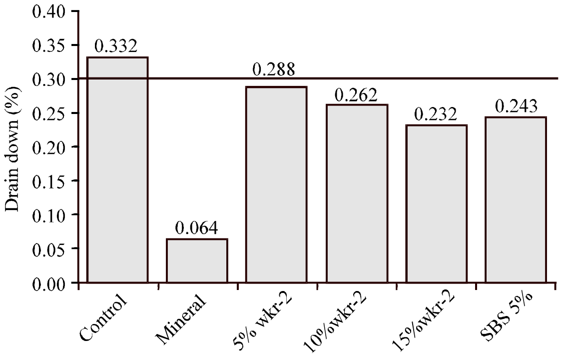

Fig. 6: Results of drain down test

Moisture sensitivity: As could be seen in Table 8, mineral fiber could relatively increase TSR value of control mixture by 4%. Meanwhile, different percents of wkr-2 were also efficient in decreasing the moisture susceptibility of SMA mixtures so that the effect of 10 and 15% of this additive was more than 5% of SBS. The important point in this section is that although the ITS_{dry} value for 10% wkr-2 modified mixture was more than that of 15% modified one, the TSR value was more for 15% wkr-2 modified mixture compared to the 10% modified mixture. This could be

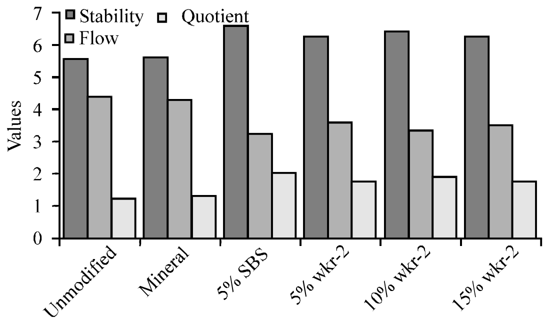

Fig. 7: Results of marshall test

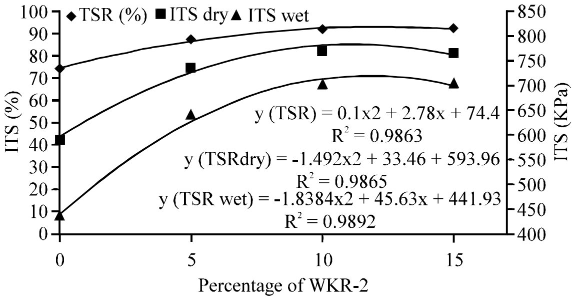

Fig. 8: Relationship between Percents of wkr-2 and ITS/TSR values of SMA Mixture

Table 8: Moisture susceptibility results of SMA mixtures

	P_{dry} (KN)	P_{wet} (KN)	ITS_{dry} (Kpa)	ITS_{wet} (Kpa)	TSR (%)
Unmodified	6.48	4.80	590	437	74
Mineral	6.76	5.27	611	477	78
5% SBS	8.72	7.76	799	711	89
5% wkr-2	8.12	7.06	735	640	87
10% wkr-2	8.42	7.66	768	699	91
15% wkr-2	8.35	7.68	764	703	92

because of the highly decreased aging of the wkr-2 modified binder compared with the SBS modified binder. All in all, the values of TSR for all constructed specimens were above the desired requirement. This fact could explicitly indicate that there would not be any problem in using these mixtures in terms of moisture sensitivity; however, some of these mixtures were more resistant to the detrimental effect of the moisture.

To evaluate the variation of ITS and TSR values with the percent of wkr-2, a binomial trend line was considered with the corresponding equation and accuracy using the SPSS program. It could be inferred from Fig. 8 that there was a very good relationship between the ITS or TSR parameters and percents of wkr-2. The R^2 values for each predicted equation were above 0.98 which could clearly show that these equations are significantly accurate.

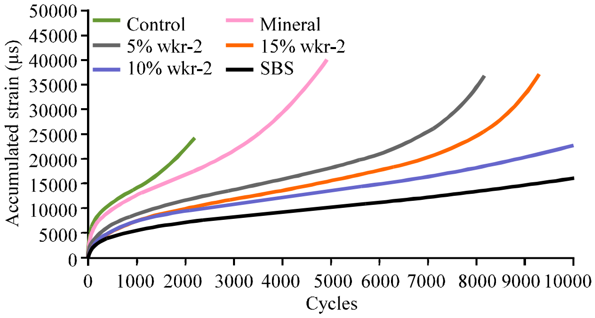

Fig. 9: Dynamic creep curves for SMA specimens

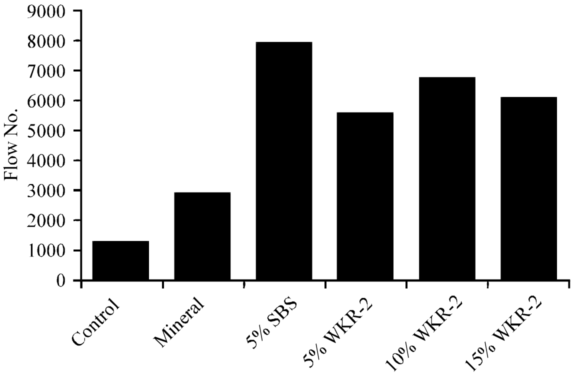

Fig. 10: Flow Numbers corresponding to different SMA mixtures

Dynamic creep test: Figure 9 presents the variation of accumulated strain versus the number of cycles for all constructed SMA specimens. As could be expected, unmodified SMA mixture has the least resistance to rutting. Mineral fiber had a positive effect in increasing the rutting performance of SMA mixtures; however, this effect does not seem to be significant as expected based on the study previously performed by Brown and Manglorkar (1993). In addition, it can be inferred from Fig. 9 that among wkr-2 modified mixtures, those modified with 10% had more stability to resist permanent deformation. Although, the effect of wkr-2 was considerable in terms of permanent deformation, SBS was more effective in decreasing the accumulated strain of asphalt mixture. The better capability of SBS compared to the mineral fiber to reduce the rutting potential of SMA mixtures has been antecedently proven by Brown *et al.* (1997b) and Tayfur *et al.* (2007).

The point at which each creep curve enters to its tertiary zone was considered as Flow Point and the corresponding number of cycles was regarded as Flow Number (FN). Flow number values for different types of SMA mixtures were obtained from Fig. 9 and are presented in Fig. 10. As presented in Fig. 10, the SBS modified mixture has the service life about 6 times more than unmodified mixture in terms of rutting resistance

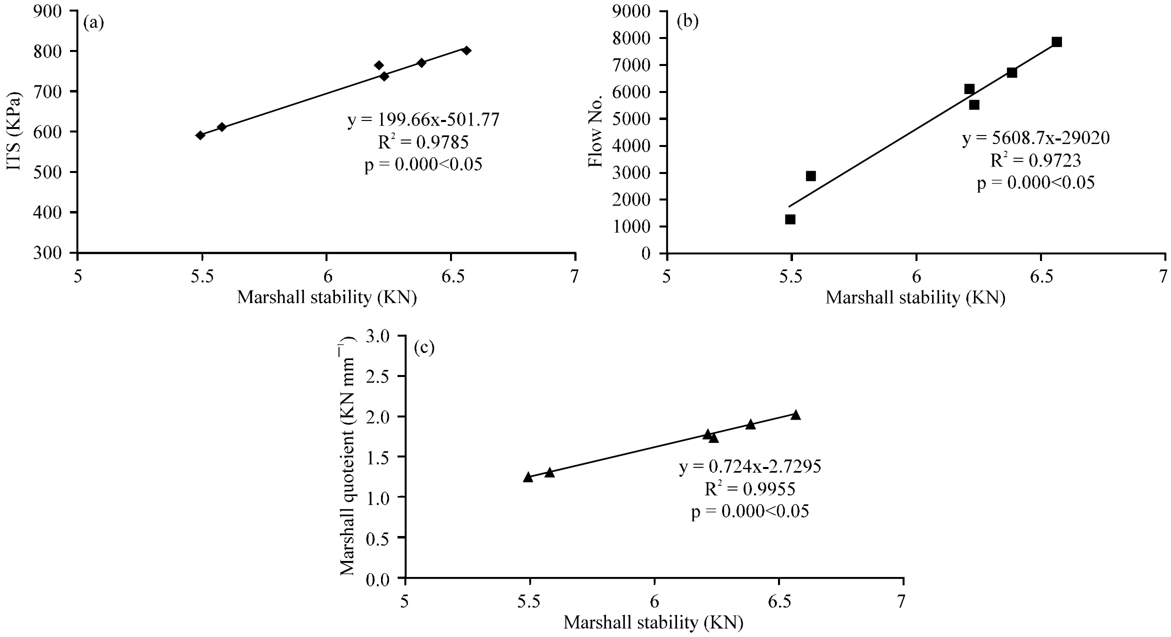

Fig. 11: Results of statistical analysis

which could clearly represent the efficiency of SBS in this way. Moreover, 10% of wkr-2 can increase the rutting life of asphalt mixture more than 5 times compared to the unmodified mixture.

Statistical analysis of performance tests results: In order to correlate the results of performance tests, linear regression was used. The accuracy of presented equations was verified by the R^2 coefficient and significant (p, 2-tailed). For each test, three identical samples were used. Each point in Fig. 11 represents the average of those three samples. According to Fig. 11, it was observed that there are very good correlations between different mixture tests that could illustrate that it is possible to predict the results of each test from the others. The R^2 values for all established correlations were higher than 0.97 which indicate that the predicted equations are accurate enough. Moreover, the calculated p values for these correlations were less than 0.05 that could represent that the relationships were significant enough.

CONCLUSIONS

Based on this research, the following conclusions could be drawn:

- According to the results of Binder properties tests, it could be observed that Rheofalt® wkr-2 had positive effect on increasing the softening point and decreasing the penetration of asphalt binder so that the effect of 15% Rheofalt® wkr-2 was more significant than that of 5% SBS. In addition, both SBS and Rheofalt® wkr-2 were capable of reducing the temperature sensitivity of asphalt cement; however, the effect of 15% Rheofalt® wkr-2 was more significant
- Rheofalt® wkr-2 needed more temperature to reach the required viscosity range compared to the unmodified binder which clearly indicate that the initial cost of asphalt concrete production may increase when using Rheofalt® wkr-2 to modify SMA mixture
- Lower and middle limit of gradation recommended by NCHRP Report No. 425 are not suitable for constructing SMA mixtures with these used materials (aggregate and asphalt binder), because they resulted SMA mixtures at high air void percent even with 6.2% of binder. Also, upper limit did not meet the VCA requirement. Therefore, the final gradation was selected between upper and middle limits to reach the desired criteria
- All additives were efficient in reducing the drain down to an allowable level. As expected, mineral fiber was more effective in this way. Different percents of Rheofalt® wkr-2 were also capable of enhancing the mixture in terms of drain down
- Although, the results of Marshall test for SMA mixtures have been usually considered as unreliable data, it was observed that there were good

correlations between different performance properties of SMA mixture and Marshall test results. This fact could explicitly describe that Marshall test should be regarded as a valid test to compare different types of SMA mixtures but the achieved data would not represent the real performance of these mixtures

- By using Rheofalt® wkr-2 in SMA mixtures, moisture susceptibility of these mixtures improved greatly so that this type of additive could considered as a better modifier compared to SBS in terms of moisture sensitivity; however, the values of ITS (in both dry and wet conditions) for SBS modified mixtures were higher than those for Rheofalt® wkr-2 modified mixtures. As a result, Rheofalt® wkr-2 could be an appropriate replacement for typical additives in regions with high amount of rainfall
- Based on the results of dynamic creep test, mineral fiber had insignificant effect in decreasing the permanent deformation of SMA mixture. In contrast, SBS was superior in improving the rutting performance of SMA mixtures. Among various percents of Rheofalt® wkr-2, 10% of it could be the best dosage in terms of rutting. It seems that higher percents of Rheofalt® wkr-2 decrease the integrity of asphalt mixture
- Significant correlations were found between different properties of SMA mixtures. It could be concluded that it would be possible to estimate different performance properties of SMA mixtures from each other

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