Laboratory Investigation of Rheological and Moisture Susceptibility of WMA Mixtures

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ABSTRACT: Warm mix asphalt (WMA) technology is showing an increasingly potential in decreasing the energy consumption and emissions associated with conventional hot mix asphalt (HMA) production. The objective of this study was to investigate and evaluate the moisture susceptibility of the WMA mixtures. The experimental design for this study included the utilizations of one binder source (PG 64-22), two aggregate sources, and three WMA additives and control. The performed properties include viscosity, dynamic shear rheometer, beam bending rheometer of WMA binders as well as indirect tensile strength (ITS), tensile strength ratio (TSR), and flow of WMA mixtures. The results indicated that the WMA additive can result in a slight decrease in viscosity and an increase in failure temperature. In addition, the moisture susceptibility results illustrate that the mixtures containing WMA additives generally have a slightly lower ITS values than conventional HMA mixtures.

KEY WORDS: WMA, RTFO, PAV, DSR, BBR, ITS, TSR.

1 INTRODUCTION

"Warm mix asphalt" (WMA) is widely being used in HMA industry as a mean of reducing energy requirements and lowering emissions. WMA can significantly reduce the mixing and compacting temperatures of asphalt mixtures, by either lowering the viscosity of asphalt binders, or causing foaming in the binders. Reduced mixing and paving temperatures decreases the energy required to produce HMA, reduces emissions and odors from plants, and makes for better working conditions at both the plant and the paving site (Kristjansdottir et al. 2007; Prowell et al. 2007).

The phenomenon of breaking the bond between the aggregate and the binder is known as stripping. A typical situation is the gradual loss of strength over the years, which causes

many surface manifestations like rutting, corrugations, shoving, raveling, cracking, etc. (Kringos et al. 2008; Xiao et al. 2009; Xiao and Amirkhanian 2009; Xiao et al. 2010). Moisture damage is usually not limited to one mechanism rather than the result of a combination of many processes. From a chemical standpoint, the literature is clear that though neither asphalt nor aggregate has a net charge, but components of both have nonuniform charge distributions, and both behave as if they have charges that attract the opposite charge of the other materials (Abo-Qudais, et al. 2005). WMA additive makes the charge re-distribution more complex and thus may affect the moisture susceptibility of the mixture. Especially, at the mixture temperature of 100 to 140 ℃ (212 to 280 ℉), the aggregate may not be completely dried during mixing process though some of the states in the United States and other countries have specifications that require a completely dry aggregate in WMA mixtures (Prowell 2007; Xiao et al. 2009). From chemical standpoint, the reactions amongst aggregate, binder, and WMA additive are not clear in detail. Especially, some chemical reactions between hydrated lime and WMA additive may occur at a high mixing temperature (around 110 ℃) and thus may result in the loss of bond in the mixture. Although Harvey and Prowell (2005a, 2005b) at National Center for Asphalt Technology (NCAT) completed some research projects conducted in the area of determining the effects of the WMA additives on moisture damage, more research is needed in many states based on various aggregate and newly developed WMA additive types.

2 EXPERIMENTAL MATERIALS AND TEST PROCEDURES

2.1 Materials

The experimental design detailed in this study included the use of Control (C) and three WMA additives (Asphamin (A), Sasobit (S), and Evotherm (E)), hydrated lime, one binder grade (PG 64-22), and two aggregate sources (designated as I, and II). The chemical and physical properties of WMA additives are shown in Table 1. Asphamin is Sodium–Aluminum–Silicate which is hydro thermally crystallized as a very fine powder. It is added to the mixture at a rate of 0.3% by weight of the mixture. Sasobit is a long chain of aliphatic hydrocarbons obtained from coal gasification using the Fischer-Tropsch process. Sasobit forms a homogeneous solution with the base binder on stirring (1.5% by weight of the binder). Evotherm made from the modified tall oil fatty acid and polyamine condensate was added into binder (0.5% by weight of the binder) before mixing with aggregate. The mixtures without any WMA additive were referred to as Control mixture. Hydrated lime is commonly used for anti-stripping of the mixture by being added to the aggregate (1% by weight of dry aggregate).

Table 1 Properties of WMA additives

Properties	Asphamin	Sasobit H8	Evotherm
Ingredients	Sodium aluminosilicate $Na_2O.\ Al_2O_3.\ 2SiO_2.$	Solid saturated hydrocarbons	Modified tall oil fatty acid polyamine condensate water
Physical state	Granular Powder	Pastilles, flakes	Viscous Liquid
Color	White	Off-white to pale brown	Amber. (Dark)
Odor	Odorless	Practically odorless	Fishy, Amine-like
Molecular weight	365	Approx. 1000 g/mole	
Specific Gravity	2 (20C)	0.9 (25C)	1.03-1.08
Vapor density	-	-	<1
Bulk density	500-600 kg/m3	-	1.03 g/cm^3
Ph values	11~12	Neutral	9~11
Boiling Point	-	-	>100C
Flashpoint	-	285C (ASTM D92)	-
Solubility in water	Insoluble	Insoluble	Water soluble

2.2 Binder testing

A Brookfield rotational viscometer was used to test the viscosity of the modified binders at four different temperatures (e.g. 120^{o}C, 135^{o}C, 150^{o}C and 165^{o}C) in accordance with AASHTO T316. The high temperature rheological properties of each binder (unaged and rolling thin film oven (RTFO)) and the intermediate temperature rheological properties of pressurized aging vessel (PAV) binder were measured using a dynamic shear rheometer (DSR) according to AASHTO T315. Each binder was measured in terms of the complex shear modulus (G*) and phase angle (δ) values starting from 64ºC (PG 64-22) until failed in accordance with Superpave mix design specifications. In addition, the PAV residue of each binder was tested by beam bending rheometer (BBR) according to AASHTO T313.

2.3 Mix Design, Sample fabrication and testing

The mix design included the aggregates used for a 12.5 mm mixture that satisfied the specifications set forth by the South Carolina Department of Transportation (SCDOT). The design aggregate gradations for each aggregate source were the same when using different WMA additives (Control, Asphamin, Sasobit, and Evotherm). The temperatures, shown in Table 3, were determined and reported in previous research projects (Xiao et al. 2009; Gandhi 2008). The mixing temperatures of materials (Table 2) were employed after a series of trial processes to achieve a mixing temperature of 121-127^{o}C. The compaction temperature of 115-121^{o}C was used in this study regardless of WMA and aggregate types.

Table 2 Mixing and compaction temperatures of mixes

Mix type	Mixing temperatures (℃)	Compaction temperatures (℃)
Control	145-150	132-137
Control+ A	121-127	115-121
Control + S	121-127	115-121
Control + E	121-127	115-121

For this study, the optimum binder content was defined as the amount of binder required to achieve 4.0% air voids in accordance with SCDOT volumetric specifications. Table 3 shows some of the mix design information. It should be noted that rall mixes from one aggregate source used the same mix design regardless of the WMA additives. Six Superpave gyratory compacted specimens were prepared with 7 ± 1% air voids and were tested in accordance with SC T 70, *Laboratory Determination of Moisture Susceptibility (*SCDOT Test Procedures, 2007*).*

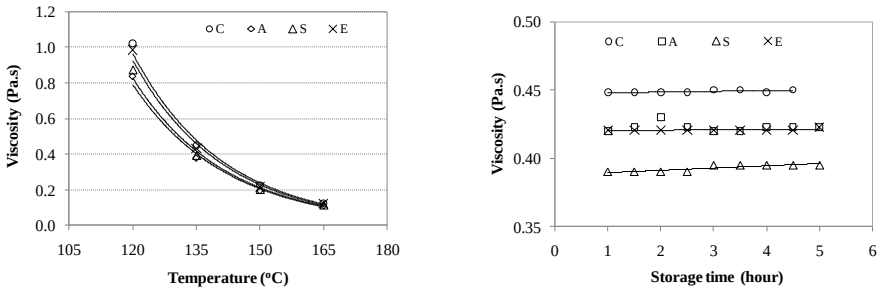
Table 3 Superpave mix design of mixes

Mix type	OBC	BSG	MSG	VMA	VFA	Dust/Asphalt ratio
Agg. I	4.80%	2.541	2.634	15.2	77.3	1.05
Agg. II	5.75%	2.326	2.421	16.8	76.6	0.92

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Unaged binders

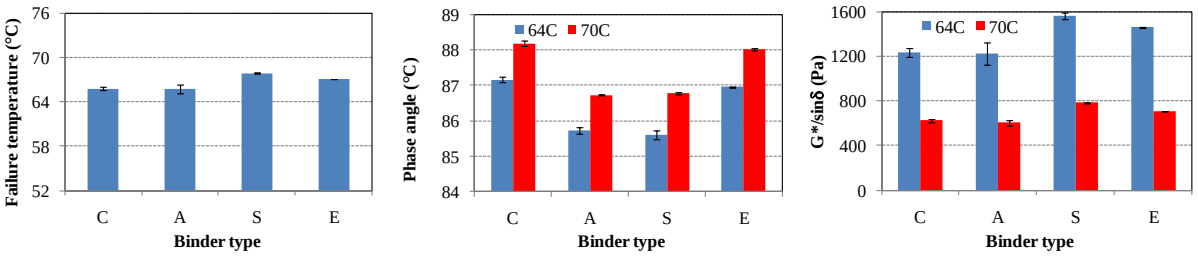
As shown in Fig. 1(a), the test results from four binders in terms of various test temperatures indicate that, as expected, the viscosity value decreases as WMA additive was added to the asphalt binder. These values decrease more rapidly from 120°C to 135°C than 150°C to 165°C. In addition, it can be noted that the viscosity value of binder containing Sasobit, in general, is the lowest. Moreover, as shown in Fig. 1(b), it can be found that, at 135 ℃, the increase of storage time does not result in an obvious increase in viscosity value of WMA binder.



(a) (b)

Fig. 1 viscosity values of WMA binders

Failure temperature and G*/sin δ values of unaged binders are shown in Fig. 2. It can be noted that the addition of WMA additive slightly increases the failure temperature. In general, the binder containing Sasobit has the highest failure temperature (Fig. 2(a)). In addition, Fig. 2(b) illustrates that the WMA additive reduces the phase angle value of the binder, in other words, the elastic behavior of the binder containing WMA additive is more significant compared to control binder due to greater phase angle. The test results shown in Fig. 2(c) indicate that the binder containing Asphamin has a similar G*/sin δ value compared to control binder while the binders containing Sasobit and Evotherm have higher values at 64°C or 70°C.

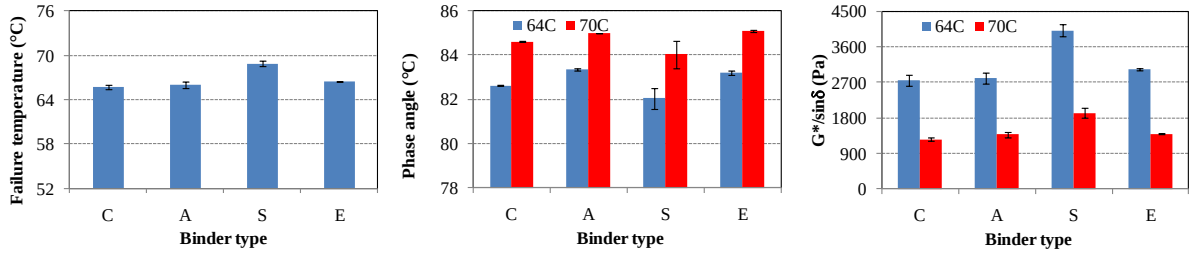


(a) (b) (c)

Fig. 2 Binders at the unaged state, (a) Failure temperature; (b) Phase angle; and (c) G*/sin δ,

3.2 RTFO binders

The residues of RTFO binders were performed same DSR tests with unaged binders. The results were shown in Fig. 3. Similar to unaged binder, the addition of WMA additive slightly increases failure temperature of binders. The binder containing Sasobit has the highest failure temperature in comparison with other binders. Moreover, Fig. 3(b) shows that, unlike the unaged binder, RTFO binders containing Asphatmin and Evotherm generally have slightly higher phase angle values. The G*/sin δ values of RTFO binders shown in Fig 3(c) illustrate that Sasobit has a positive effect on improving the high temperature resistance of RTFO binders.

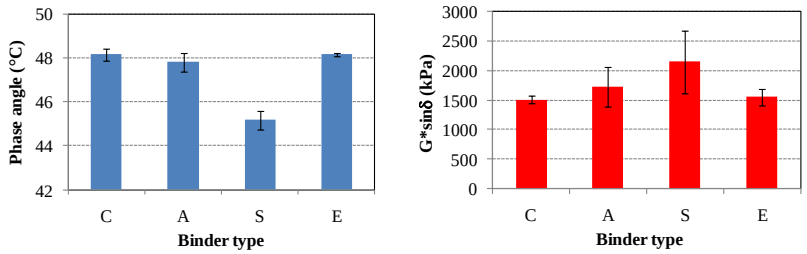


(a) (b) (c)

Fig. 3 Binders at the RTFO state, (a) Failure temperature; (b) Phase angle; and (c) G*/sin δ,

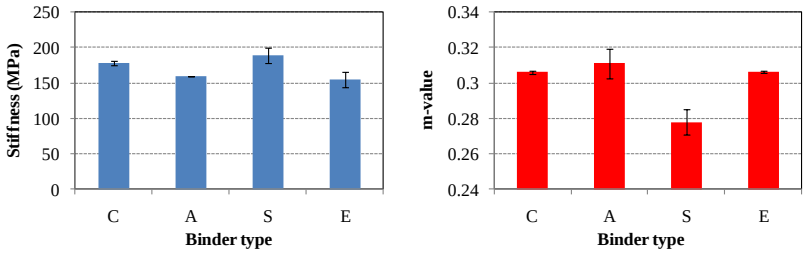
3.3 PAV binders

For the PAV samples, at an intermediate test temperature of 25°C and a low temperature -12°C, DSR and BBR tests were performed, respectively. DSR results are shown in Fig. 4(a), it can be noted that the phase angle of binder containing Sasobit is the lowest (i.e., the highest elasticity) while the binders containing Asphamin and Sasobit generally have the closer phase angle values compared with control binder. In addition, Fig. 4(b) indicates that the addition of WMA additive increases the fatigue factor (G*sin δ) value of the PAV binder. Moreover, as shown in Fig 5(a), the stiffness of the binder containing Sasobit is the highest while the binders containing Asphamin and Evotherm exhibit the lowest stiffness values. As a result, the effect of WMA additive on the stiffness values of PAV residues is different. Additionally, Fig. 5(b) indicates that Sasobit reduces the m-value of PAV residue and this value is less than 0.3, a minimum m-value specified by Superpave mix design.



(a) (b)

Fig. 4 Binders at the PAV state, (a) Phase angle and (b) G*sin δ



(a) (b)

Fig. 5 Binders at the PAV state, (a) Stiffness and (b) m-value

3.4 ITS and TSR analysis

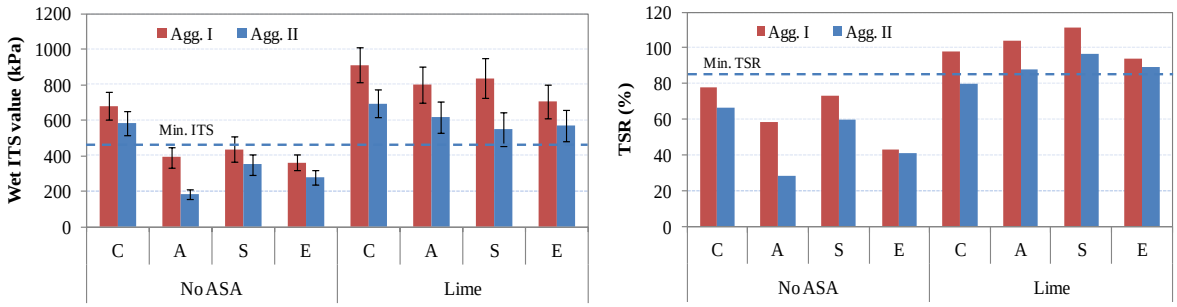
The wet ITS results shown in Fig. 6(a) indicate that, whether with hydrated lime or not, the ITS values of specimens without WMA additive are higher while the mixtures containing Asphamin, Sasobit, and Evotherm show lower ITS values regardless of the aggregate types. In addition, the mixture with WMA additive has the ITS value greater than 448 kPa, a minimum wet ITS value set by SC DOT. Statistical analysis shown in Table 4 also illustrate, although there is a significant difference in dry ITS value between HMA and WMA mixtures, there is no significant difference in wet ITS value amongst any mixtures (i.e., HMA or WMA mixtures).

Table 4 Statistical analysis of ITS and flow values

α = 0.05	ITS					
	C~A	C~S	C~E	A~S	A~E	S~E
Dry	Y	Y	Y	N	N	N
Wet	N	N	N	N	N	N
	Flow					
Dry	N	N	N	N	N	N
Wet	N	N	N	N	N	N

Note: C-Control;A-Asphamin; S-Sasobit; E- Evotherm; Y: P-value < α = 0.05 (significant difference); N: P-value > α = 0.05 (No significant difference);

The TSR results are presented in Fig. 6(b). It can be noted that the specimens containing 1% hydrated lime generally have TSR values higher than 85% (the minimum value set forth by SCDOT) regardless of WMA and aggregate types. However, overall mixtures without ASA additive have the TSR values less than 85%.

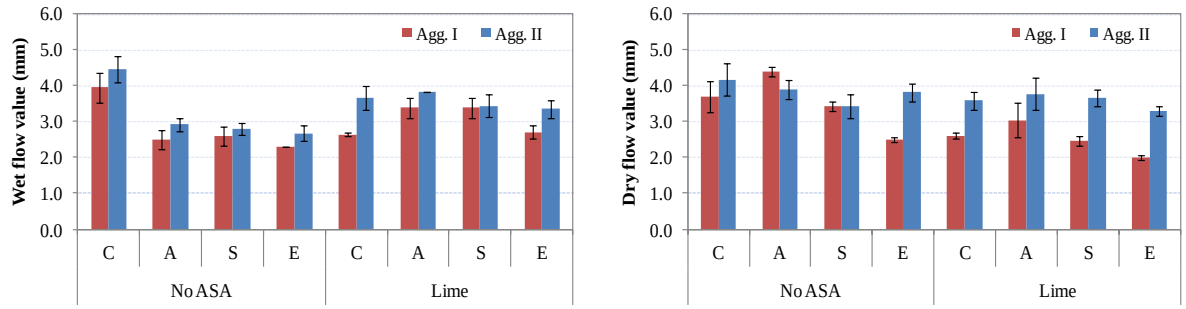


(a) (b)

Fig. 5 HMA and WMA mixtures, (a) Wet ITS and (b) TSR

3.5 Deformation analysis

The deformation (flow) resistance of dry ITS specimens, a measure of the material's resistance to permanent deformation in service and it is related to its stiffness, was used for moisture susceptibility analysis of the mixture. As shown in Fig. 6(a), the deformation results indicate that, in general, the mixture made with aggregate I shows a lower wet flow value than aggregate II. Beside the aggregate properties, another contributing reason is the fact that mixtures made from aggregate II had higher optimum asphalt binder contents. In addition, no obvious trend in dry flow values can be found for the mixtures containing various WMA additives (Fig. 6(b)). Similar to the wet flow, the dry flow value of the mixture from aggregate I is less than that of mixture from aggregate II. Statistical analysis shown in Table 4 illustrate that there are no significant differences in any two mixtures from various aggregates regardless of WMA types.



(a) (b)

Fig. 5 HMA and WMA mixtures, (a) Wet ITS and (b) TSR

4 FINDINGS AND CONCLUSIONS

The following conclusions were drawn based upon the results obtained from the limited HMA and WMA mixtures used in this study:

- The viscosity of binders containing various WMA additives are generally less than that of control binder, but this reduction is not significant.

- WMA binders have higher failure temperatures than conventional HMA binders tested in this research project, and thus can resist a relatively higher performance temperature.
- After a long-term performance testing (long-term aging), the binder containing Sasobit additive generally shows a weaker fatigue resistance.
- WMA mixtures generally have a lower wet ITS values than conventioinal HMA mixtures but can satisfy the specification set by SC DOT.
- Aggregate type plays a key role in determining the flow value of HMA and WMA mixtures. In addition, there is no significant difference in flow values amongst any mixtures regardless of HMA or WMA mixtures.

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