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SELECTING WARM MIX ASPHALT ADDITIVES BY THE PROPERTIES OF WARM MIX ASPHALT MIXTURES – CHINA EXPERIENCE

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Abstract. The objective of this research was to select the most effective warm asphalt additives for mix practice based on a series of laboratory testing programs such as density, Marshall stability, freeze-thaw splitting strength, dynamic stability, and bending beam strain. The experimental design of warm mix asphalt included the use of three commonly-used additives, two typical aggregate gradations, one crushed aggregate, and one modified asphalt. Results showed that: (1) the bulk specific gravity and air voids of all the mix specimens were similar to those of controls; (2) the Marshall stability and flow values of the warm stone mastic asphalt were 6.8%–26.6% and 3.5%–10.3%% higher than those of controls, respectively, and those of the warm asphalt concrete were 6.1%–15.6% and 6.5%–9.7% higher than those of controls, respectively; (3) the indirect tensile strength of two types of mixtures was 1.7%–14.4% lower than that of controls, and the average tensile strength ratio of the warm stone mastic asphalt and asphalt concrete was 4.3% and 1.3% higher than that of controls, respectively; (4) the dynamic stability of warm mix specimens was 10.8%–16.6% lower than that of the controls; (5) the average bending failure strain of warm stone mastic asphalt was 7.6% higher than that of the controls, and that of warm asphalt concrete was 12.8% lower than that of the controls; (6) Overall, warm asphalt mixtures with Sasobit and Rediset had relatively best performances required in Southeast China, where rutting and stripping are the main failures of asphalt pavements.

Keywords: warm mix asphalt, additives, aggregate gradation, properties, comparative investigation.

1. Introduction

In the recent years, the asphalt industry has investigated the warm asphalt technology as a means to reduce the mixing and compaction temperatures of asphalt mixes. Warm mix asphalt (WMA) is an asphalt mixture which is mixed at temperatures lower than conventional hot mix asphalt (HMA). WMA technology not only reduces the mixing and compaction temperatures and decreases energy consumption, carbon dioxide emission, and asphalt oxidation but also extends paving season and increases distance for a better working environment (Alossta 2011; Carbonneau *et al.* 2008; Čygas *et al.* 2009; Gandhi 2008).

There are many WMA technologies widely used including foaming (i.e., Double Barrel Green and Aspha-min), organic technology (i.e., Sasobit) and chemical technology (i.e., Evotherm and Rediset). The foamed asphalt technology relies on the fact that when the water is dispersed into hot asphalt binder and turns into steam, this results in expansion of the binder and a corresponding reduction in the mix viscosity (Kavussi, Hashemian 2011; Xiao *et al.* 2011). Sasobit is a long chain aliphatic hydrocarbon obtained from coal gasification. After crystallization, Sasobit forms a lattice structure in the binder, which is the basis of the structural stability of the binder containing Sasobit. The melting point of Sasobit1 is around 85 °C to 116 °C. Evotherm is a product developed by MeadWestvaco Asphalt Innovations. Evotherm uses a chemical additive technology and a "Dispersed Asphalt Technology" delivery system. By using this technology a unique chemistry customized for aggregate compatibility is delivered into a dispersed asphalt phase (emulsion). The emulsion provides aggregate coating, workability, adhesion, and improved compaction with no change in materials or job mix formula required. Rediset is a chemical additive free of water that has been recently developed by AkzoNobel. It is a combination of cationic surface-active agents (called surfactants) and rheology modifiers (organic additives)

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in a solid form. The product typically comes in the form of beads also known as free-flowing pastilles for ease of handling and incorporation into the asphalt mixture production process (Kasozi 2010; Rogers 2011).

The properties of WMA mixes were influenced by WMA additives to some extent (Akisetty 2008; Biro *et al.* 2009; Cooper III *et al.* 2011; Gandhi 2008; Goh, You 2012; Hanz 2012; Kim *et al.* 2012; Sampath 2010; Shang *et al.* 2011; Sheth 2010; Xiao *et al.* 2010; You *et al.* 2008). For example, Sasobit® can reduce the rut depths of the mixes, and improve the tensile strength ratio (TSR) of the mixes (Biro *et al.* 2009; Gandhi 2008; Liu *et al.* 2011). Kim *et al.* (2012) reported the polymer-modified asphalt (PMA) mixtures containing the additives can satisfy the current Superpave mixture requirements and no statistical differences existed between the control and the warm PMA mixtures for the properties. Sheth (2010) reported that the WMA specimens exhibited similar air voids as HMA specimens at a lower temperature; the Indirect Tensile Strengths (IDT) and TSR values of all WMA specimens were lower than that of HMA specimens. Hanz (2012) investigated the impacts of warm mix asphalt on constructability and performance. The results showed that WMA reduced wet bond strength, but did not affect dry bond strength. In addition, the proper dosages of WMA additives should be selected based on the gradation used. Sampath (2010) evaluated the properties of four warm asphalt mixtures. The results indicated that the IDT and TSR values of the WMA specimens were higher than the controls; the WMA specimen with Sasobit® additive exhibited the lowest permanent deformation. Goh, You (2012) reported that a slight decrease in dynamic modulus was found when 0.25% Advera® WMA additive was added to the porous asphalt mixture containing reclaimed asphalt pavement (RAP) and WMA containing RAP was found to have the highest tensile strength among all of the mixtures tested. Hurley and Prowell (2005a, 2005b) evaluated three different WMA additives and concluded that all three technologies improved the compatibility of the asphalt mixtures and resulted in lower air voids compared to HMA. TSR values of WMA mixtures increased significantly when antistripping additives and hydrated lime was added in WMA mix (Hossain *et al.* 2012; Xiao *et al.* 2009, 2010).

It should be noted that these results are binder-type dependent and aggregate type dependent. In addition, comparative study about the properties of the mixtures with various different additives is limited. Thus, further investigation of the effect of various WMA additives on the properties of WMA is needed since the types of aggregate and aggregate gradation used and the environmental conditions in China are different from those of other countries.

The main objectives of the research project were 1) to examine and compare the properties of various WMA mixtures with different types of aggregate gradation; 2) to evaluate the effects of the WMA additives on the properties of WMA with different types of aggregate gradation. All results were compared with traditional HMA.

The WMA mixtures were manufactured with three most commonly-used WMA additives of Sasobit, Evotherm and Rediset, styrene butadiene styrene (SBS) modified asphalt binder and crushed basalt aggregate. Selected physical, mechanical and performance properties of the WMA and control HMA were measured and evaluated.

2. Test program, materials and test methods

Typical pavement materials used in asphalt pavement construction in Suzhou, China were selected. Crushed basalt aggregate, SBS modified asphalt, and three WMA additives of Rediset, Evotherm and Sasobit were used. Fig. 1 showed the combination of the experimental design used in this

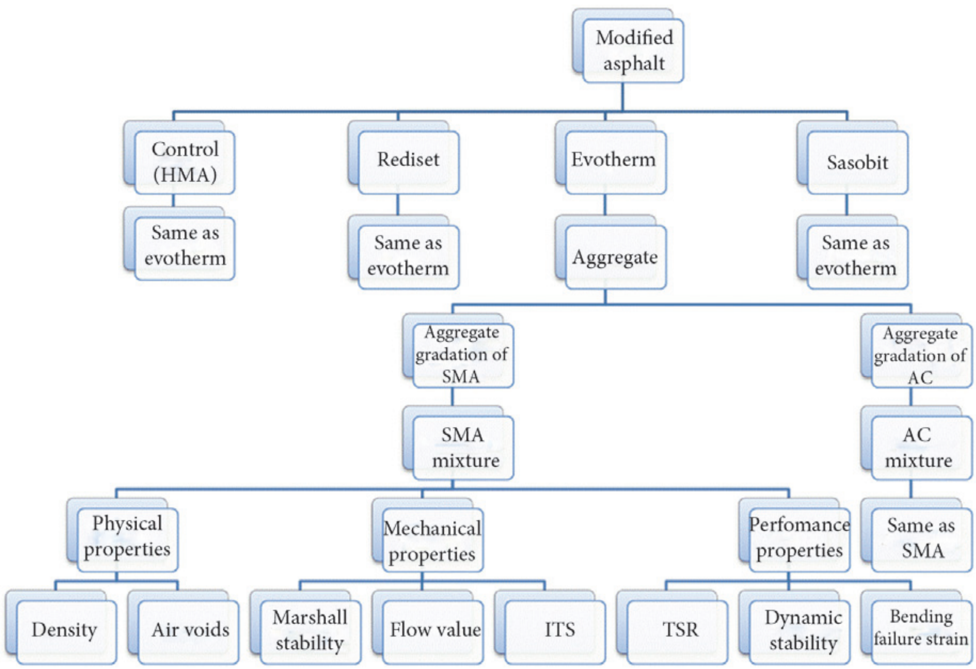

Fig. 1. Flowchart of experimental design

study. Table 1 presents the properties of SBS unmodified asphalt. Rediset, Evotherm and Sasobit were added at the rate of 2.0%, 0.6% and 2.0% by weight of asphalt binder according to the recommendation by the producers of the WMA additives. The rates are currently used as the optimum content for the corresponding additive in China, and thus accepted in the research.

Marshall mixture design method was used in the determination of the optimum asphalt content (OAC) for both HMA and WMA mixtures according to the asphalt mixture design standard methods of China (*JTG E20-2011*). Table 2 presents the adopted mixing and compaction temperature of both HMA and WMA mixtures. A reduction of 25 °C for mixing and compaction WMA were used which was actually recommended by the producers of WMA additives. Two typical aggregate gradations popularly used in the region, i.e., a continuous gradation (Asphalt Concrete (AC)-13) and a gap gradation (Stone Mastic Asphalt (SMA)-13), were adopted (Table 3 and Fig. 2). They are AC-13 and SMA-13 with a nominal maximum aggregate size of 13.2 mm, which are popularly used as the surface layer. The OAC for SMA-13 and AC-13 mixtures were 5.6% and 4.8%, respectively. Cellulose fibers were added into SMA at the rate of 0.3% by weight of the mixture.

Physical, mechanical and performance properties were selected for evaluation. The density and air voids were used to evaluate the physical properties. Marshall stability, flow value, and Indirect Tensile Strength (IDT) were used to evaluate the mechanical properties of asphalt mixtures. Tensile strength ratio (TSR), dynamic stability at high temperature and bending beam failure strain at low temperature were used to evaluate the performance properties such as the resistances to moisture damage, rutting and cracking, respectively.

Bulk specific gravity of asphalt mixtures was measured by surface dry method (*T 0705-2011*) of standard test methods of bitumen and bituminous mixtures for highway engineering of China (*JTG E20-2011*). Theoretical maximum specific gravity test of asphalt mixtures was conducted by vacuum method (*T 0711-2011*).

Marshall stability and flow test was performed by the standard test method (*T 0709-2011*). In this test, Marshall specimens were immersed in the water of 60±1 °C for 30° min. The load was applied to the specimen with a constant rate of movement for the testing machine head of 50.8 mm/min until the max load is reached. The maximum load and the maximum deformation were determined.

IDT and TSR were obtained by freeze-thaw splitting test of bituminous mixtures (*T0729-2000*) of standard test methods of bitumen and bituminous mixtures for highway engineering of China (*JTG E20-2011*). All specimens had the air void level of 6 to 8 percent in this test. During this testing, a load is applied to the specimen by forcing the bearing plates together at a constant rate of 50 mm/min. The load continued until the specimen cracks, and the maximum load is recorded. The indirect tensile strength is calculated using the Eq (1):

$$S_t = \frac{2000P}{\pi t D}, \quad (1)$$

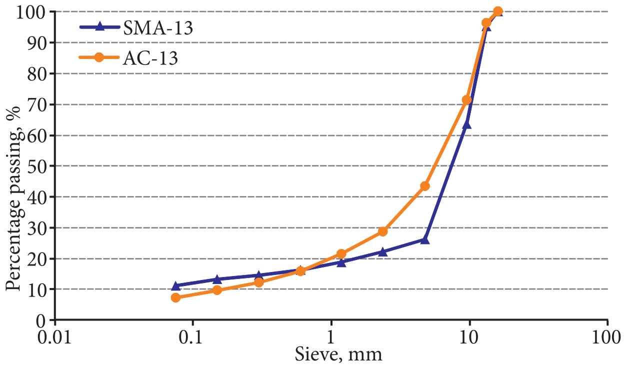

Fig. 2. Particle size distribution of the aggregate

Table 1. Properties of SBS modified asphalt binders

Penetration at 25 °C, 0.1 mm	Softening point, °C	Ductility at 15 °C, cm	Ductility at 5 °C, cm	Kinematic viscosity at 135 °C, PaS)
64	75	>100	38	1.8

Table 2. Mixing and compaction temperature

Mixture type	HMA		WMA	
	Mixing temperature, °C	Compaction temperature, °C	Mixing temperature, °C	Compaction temperature, °C
SMA-13	170	160	145	135
AC-13	165	155	140	130

Table 3. Aggregate gradation

Sieve, mm	Mixture type	16.0	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Percentage passing, %	SMA-13	100	95.2	63.6	26.2	22.2	18.8	16.3	14.6	13.3	11.2
	AC-13	100	96.2	71.3	43.4	28.7	21.5	15.9	12.2	9.7	7.3

where S_t – indirect tensile strength, kPa; P – maximum load, Newtons; t = specimen thickness, mm; D – specimen diameter, mm.

The TSR is calculated as follows:

$$\text{TSR} = \frac{S_2}{S_1}, \quad (2)$$

where S_1 – average indirect tensile strength of the dry condition, MPa; S_2 – average indirect tensile strength of the wet condition, MPa.

The dynamic stability was measured by the wheel tracking test of bituminous mixtures (*T 0719-2011*) of standard test methods of bitumen and bituminous mixtures for highway engineering of China (*JTG E20-2011*). In the dynamic stability test, the size of specimen is 300 mm long, 300 mm wide and 50 mm thick, and testing temperature is 60±0.5 °C. A wheel pressure of 0.7±0.05 MPa was applied onto the specimens. The traveling distance of the wheel was 230±10 mm. The traveling speed of the wheel was 42±1 times/min. The wheel was loaded for 60 minutes. The dynamic stability was determined as follows:

$$\text{DS} = \frac{(t_2 - t_1)42}{d_2 - d_1}, \quad (3)$$

where DS – dynamic stability, times/mm; d_1 – rut depth after 45 min loading, mm; d_2 – rut depth after 60 min loading, mm; t_1, t_2 – loading time, 45 min and 60 min, respectively; N – loading frequency, typically 42 times/min.

Bending beam test at low temperature was conducted by the bending test of bituminous mixtures (*T 0715-2011*) of standard test methods of bitumen and bituminous mixtures for highway engineering of China (*JTG E20-2011*). In the this test, the size of specimen is 250 mm long, 30 mm wide and 35 mm thick, and testing temperature is −10 °C. The concentrated center load was applied on top at the mid-span, and the loading rate was 50 mm/min (Fig. 3). The load continued until the specimen failed, and the max deflection of the mid-span was recorded.

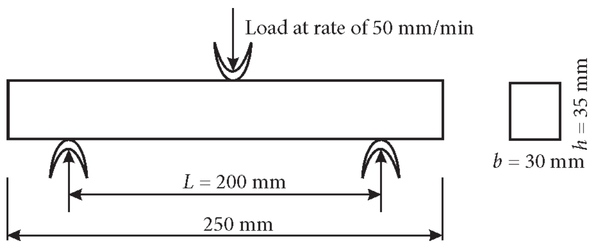

Fig. 3. Sketch of bending beam test

Bending failure strain was adopted to evaluate the low temperature performance. The bending failure strain was determined as follows:

$$\varepsilon = \frac{6hd}{L^2}, \quad (4)$$

where ε – bending failure strain, με; h – beam height, mm; d – maximum deflection of the mid-span, mm; L – span length, mm.

3. Experimental specimen preparation

All specimens were prepared at the OAC obtained from mix design with the same compaction level. For each type of asphalt mixtures, three Marshall specimens were prepared for density test; five Marshall specimens were prepared for the Marshall stability and flow test; eight Marshall specimens were prepared for the freeze-thaw splitting test; three rut-resistance specimen slabs with a size of 300×300×40 mm, were prepared for the wheel tracking test; six specimens with a size of 30×250×35 mm, were prepared for the bending beam test. A total of 200 samples were used in this study.

4. Results and discussions

4.1. Bulk specific gravity and air void

Table 4 shows the test results of bulk specific gravity and air void of all the specimens. In general, the bulk specific gravity and air void of all the WMA specimens were similar to those of the controls for either SMA-13 or AC-1, illustrating that WMA specimens had a similar compaction property with the controls after the mixing and compaction temperature being reduced by 25 °C for WMA, regardless of the types of aggregate gradation.

Table 4. Bulk specific gravity and air voids

Mixture type			Bulk specific gravity	Standard deviation	Maximum specific gravity	Air voids, %	Standard deviation
SMA-13	HMA (Control)		2.495	0.007	2.604	4.19	0.28
	WMA	Rediset additive	2.494	0.009	2.604	4.22	0.34
		Evotherm additive	2.497	0.004		4.11	0.16
		Sasobit additive	2.496	0.011		4.15	0.41
		Average	2.496	–		4.16	–
AC-13	HMA (Control)		2.503	0.009	2.633	4.94	0.33
	WMA	Rediset additive	2.501	0.007	2.633	5.01	0.27
		Evotherm additive	2.502	0.007		4.98	0.25
		Sasobit additive	2.504	0.004		4.90	0.15
		Average	2.502	–		4.96	–

The results indicated that the air voids of the WMA specimens with Rediset additive were the maximum, while the specific gravities are the minimum, regardless of the types of aggregate gradation. This finding showed WMA mixtures with Rediset additive may be not compacted as easily as the WMAs with other two WMA additives regardless of the types of aggregate gradation.

In addition, all SMA-13 mixtures had lower bulk specific gravity and air void than AC-13. It may partially be contributed to a higher OAC adopted in SMA-13 than AC-13 used in this study. The density of asphalt binder was significantly less than the aggregate, and more asphalt in the mixtures meant lower density of the mixtures. In addition, more asphalt in the mixtures made the compaction easier, and resulted in lower air voids of SMA-13.

4.2. Marshall stability and flow value

The Marshall stability and flow value are used to evaluate the mechanical strength and resistance to plastic flow at 60 °C. Table 5 showed the Marshall stability and flow value of the specimens.

In general, the average values of the Marshall stability and flow value of all the WMA specimens of SMA-13 are 18.1% and 6.9% higher than those of the controls, respectively, while those of all the WMA specimens of AC-13 are 10.4% and 9.7% higher than those of controls, respectively. A higher stability means a high strength, while a large flow means a low stiffness. This illustrated that all the WMA specimens had higher mechanical strength and a little bit low stiffness at 60 °C, compared with the controls no matter which aggregate gradation is used. In addition, all the WMA samples of SMA-13 and AC-13 had higher Marshall stability than 6.0 kN and 8.0 kN required by Technical Specification for Construction of Highway Asphalt Pavements (*JTG F40-2004*) for SMA-13 and AC-13, respectively. The flow values of all the WMA specimens of SMA-13 and AC-13 met the requirements of the specification (*JTG F40-2004*), 2–5 mm for SMA mixtures and 1.5–4 mm for AC mixtures.

For SMA-13, WMA specimens with Rediset, Evotherm and Sasobit additives had 6.8%, 20.7%, and 26.6% higher Marshall stability than the controls, respectively, and had 10.3%, 3.5%, and 10.3% higher flow value than the controls, respectively. These results illustrated that WMA specimens with Sasobit additive had the highest Marshall stability and flow value among three WMA. For AC-13, WMA specimens with Rediset, Evotherm and Sasobit additives had 9.5%, 6.1%, and 15.6% higher Marshall stability than the controls, respectively, and had 6.5%, 9.7%, and 9.7% higher flow value than the controls, respectively. These results showed WMA specimens with Sasobit additive had the highest Marshall stability and flow value among three WMA, as found for SMA-13. The increase in the Marshall stability and flow value is generally higher for SMA-13 over AC-13. At the same time, WMA specimens with Sasobit additive had the highest Marshall stability and flow value regardless of the types of aggregate gradation.

In addition, the average Marshall stability and flow value of WMA SMA-13 mixtures were a little bit lower than those of WMA AC-13, implying that WMA SMA-13 had slightly lower strength and better resistance to deform compared with WMA AC-13. It may partially be contributed to the higher OAC in SMA-13 and the difference of aggregate gradation between two asphalt mixtures used in this study.

4.3. Resistance to moisture damage

IDT strength may be used to evaluate the relative quality of bituminous mixtures in conjunction with laboratory mix design testing and the potential for rutting or cracking (*ASTM D6931-12*). The TSR value is used to evaluate the resistance to moisture damage of an asphalt mixture. Higher values of IDT and/or TSR imply better resistance to rutting or cracking. Table 6 and Figs 4 and 5 shows the IDT and TSR results of the WMA and control samples.

Generally, the average values of the IDT for WMA SMA-13 were 9.9% and 5.2% lower than those of the controls in dry and wet, respectively, and for WMA AC-13 specimens were 9.6% and 9.1% lower than those of the controls, respectively. The average values of TSR for the WMA SMA-13 and AC-13 were 4.3% and 1.3% higher than those of the controls, respectively. This indicated that most of the WMA used in this study may have slightly lower potential for rutting or cracking and better resistance

Table 5. Marshall stability and flow value

Mixture type			Marshall stability, kN	Standard deviation	Flow, 0.1 mm	Standard deviation
SMA-13	HMA (Control)		9.75	0.71	29	1.53
	WMA	Rediset additive	10.41	0.76	32	1.73
		Evotherm additive	11.77	0.91	30	2.08
		Sasobit additive	12.34	0.33	32	0.58
		Average	11.51	–	31	–
AC-13	HMA (Control)		10.95	0.91	31	3.06
	WMA	Rediset additive	11.99	0.75	33	2.08
		Evotherm additive	11.62	0.69	34	2.52
		Sasobit additive	12.66	0.38	34	1.53
		Average	12.09	–	34	–

to moisture damage than the control. In addition, the TSR of all the WMA and control mixtures was higher than 80%, the requirement of the specification (*JTG F40-2004*).

For SMA-13, WMA specimens with Rediset, Evotherm and Sasobit additives had 13.7%, 10.0%, and 2.8% lower IDT values in dry condition than the control, respectively, and had 6.3%, 10.9% lower and 1.7% higher IDT in wet condition than the control, respectively, consequently, had 8.9% higher, 1.1% lower and 5.0% higher TSR than the control, respectively. This illustrated that the WMA specimens with Rediset additive may have the best resistance to moisture damage, and the WMA specimens with Sasobit additive may have the best potential for rutting or cracking, compared to the other two additives.

For AC-13, WMA specimens with Rediset, Evotherm and Sasobit additives had 7.2%, 14.4%, and 6.6% lower IDT in dry condition than the control, respectively, and had 6.3%, 13.9%, 4.2% lower IDT in wet condition than the control, respectively, as a result, had 0.8%, 0.6% and 2.3% higher TSR than the control, respectively. This illustrated that the WMA specimens with Sasobit additive may have the best resistance to moisture damage and potential for rutting or cracking, compared to other two additives.

The decrease in the IDT of WMA depended on the state of curing (i.e., in both dry and wet condition) and the aggregate gradation. The WMA specimens with Sasobit additive had the best potential for rutting or cracking regardless of the types of aggregate gradation. However,

Table 6. IDT and TSR

Mixture type			IDT in dry condition, MPa	Standard deviation	IDT in wet condition, MPa	Standard deviation	TSR, %	Standard deviation
SMA-13	HMA (Control)		2.11	0.16	1.74	0.10	82.3	2.56
	WMA	Rediset additive	1.82	0.15	1.63	0.13	89.6	1.33
		Evotherm additive	1.90	0.19	1.55	0.13	81.4	2.24
		Sasobit additive	2.05	0.12	1.77	0.11	86.4	0.78
		Average	1.92	–	1.65	–	85.8	–
AC-13	HMA (Control)		1.67	0.12	1.44	0.10	86.4	1.82
	WMA	Rediset additive	1.55	0.11	1.35	0.10	87.1	0.95
		Evotherm additive	1.43	0.21	1.24	0.18	86.9	0.19
		Sasobit additive	1.56	0.08	1.38	0.08	88.4	0.63
		Average	1.51	–	1.32	–	87.5	–

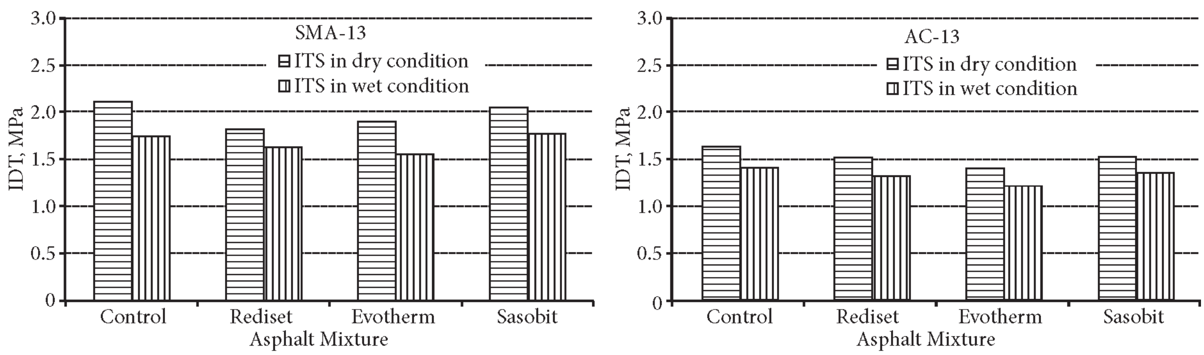

Fig. 4. Average IDT

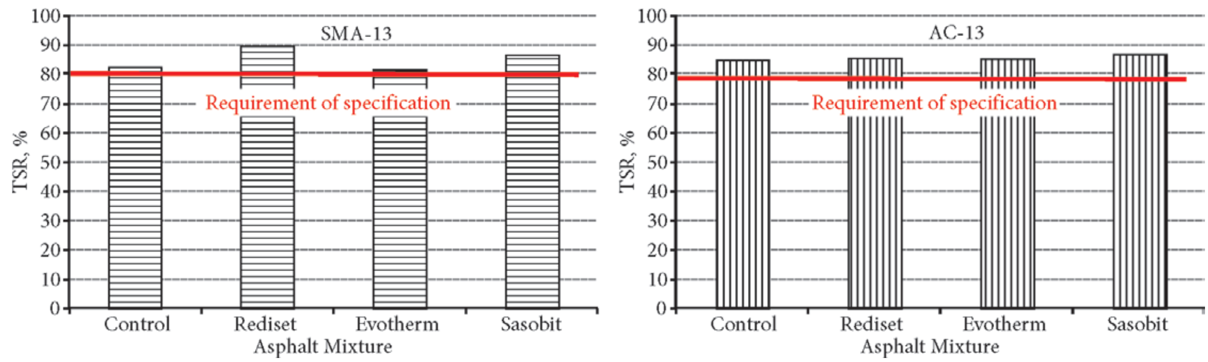

Fig. 5. Average TSR

the influence of WMA additives on the resistance to moisture damage of WMA seem be partly aggregate gradation-dependent, i.e. for the gap aggregate gradation (SMA-13), WMA with Rediset additive had the best resistance to moisture damage; for the continuous aggregate gradation (AC-13), WMA with Sasobit additive had the best resistance to moisture damage.

In addition, the average of TSR of WMA SMA-13 mixtures was 1.9% lower than that of WMA AC-13, while the average of IDT in dry condition and wet condition of WMA SMA-13 mixtures was 27.2% and 25% higher than that of the WMA AC-13, respectively. This implied that WMA SMA-13 had slightly lower resistance to moisture damage and significantly better potential for rutting or cracking, compared to WMA AC-13. It may partially be contributed to the difference of aggregate gradation between two asphalt mixtures, and the use of cellulose fibers and high percentage of mineral filler in SMA-13.

4.4. Resistance to rutting

The dynamic stability is widely used to evaluate the resistance to rutting of asphalt mixtures. The higher value of dynamic stability means the better resistance to rutting. Table 7 and Fig. 6 shows the dynamic stability of WMA and control HMA samples. In general, the average o dynamic stability of WMA SMA-13 specimens was 12.3% lower than that of the control, and that of WMA AC-13 specimens was 15.3% lower than that of the control. It illustrated that all the WMA for SMA-13 and AC-13 had lower resistance to rutting than the control. Furthermore, the dynamic stability of all WMA and control was significantly higher 2400 times/mm, the requirement of the specification (*JTG F40−2004*).

For SMA-13, WMA specimens with Rediset, Evotherm and Sasobit additives had 14.1%, 12.0%, and 10.8% lower dynamic stability than the control, respectively. This showed that WMA with Sasobit additive had the best resistance to rutting, compared to the mixtures with other two additives. For AC-13, WMA specimens with Rediset, Evotherm and Sasobit additives had 13.0%, 16.6%, and 16.4% lower dynamic stability than the control, respectively. This illustrated that WMA with Rediset additive had the best resistance to rutting, compared to those with other two additives.

The influence of WMA additives on the resistance to rutting of WMA is partly aggregate gradation-dependent, i.e. for the gap aggregate gradation (SMA-13), WMA with Sasobit additive had the best resistance to rutting; however, for the continuous aggregate gradation (AC-13), WMA with Rediset additive had the best resistance to rutting.

In addition, the average of dynamic stability of WMA SMA-13 mixtures was 3.7% higher than that of WMA AC-13. This implied that WMA SMA-13 had slightly better resistance to rutting, compared to WMA AC-13. This tendency was proved by the results of IDT and flow value too. It may partially be contributed to the difference of aggregate gradation between two asphalt mixtures, and the use of cellulose fibers and high percentage of mineral filler in SMA-13.

4.5. Resistance to cracking

The bending failure strain is widely used to evaluate the resistance to cracking at low temperature of asphalt mixtures. The higher value of bending failure strain means better resistance to cracking. Table 8 and Fig. 7 showed the bending failure strain at low temperature (−10 °C) of WMA and control samples.

In general, the average bending failure strain of WMA SMA-13 specimens was 7.6% higher than that of the control, and that of WMA AC-13 specimens was

Table 7. Dynamic stability

Mixture types			Dynamic stability, times/mm	Standard deviation
SMA-13	HMA (Control)		4773	116
	WMA	Rediset additive	4098	150
		Evotherm additive	4200	178
		Sasobit additive	4257	138
		Average	4185	–
AC-13	HMA (Control)		4768	146
	WMA	Rediset additive	4147	140
		Evotherm additive	3977	177
		Sasobit additive	3987	155
		Average	4037	–

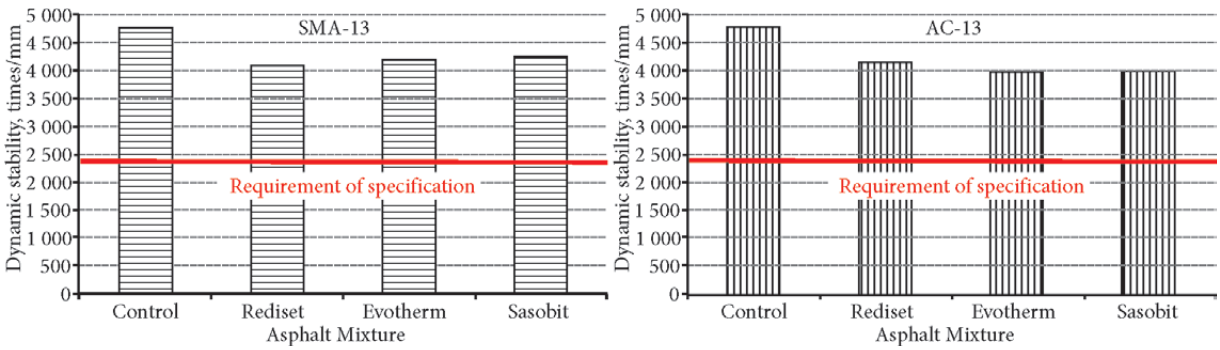

Fig. 6. Average dynamic stability

12.8% lower than that of the control. It indicated that all the WMA SMA-13 had higher resistance to cracking than the control, while the WMA AC-13 had lower resistance to cracking than the control. Furthermore, the bending failure strain of all WMA and control were higher than 2500 με, the requirement of the specification (*JTG F40–2004*).

For SMA-13, WMA specimens with Rediset, Evotherm and Sasobit additives had 1.4%, 12.7%, and 8.7% higher bending failure strain than the control, respectively. This illustrated that WMA with Evotherm additive had the best resistance to cracking, compared to the other two additives. For AC-13 WMA specimens with Rediset, Evotherm and Sasobit additives had 8.4%, 16.0%, and 14.1% lower bending failure strain than the control, respectively. This indicated that WMA with Rediset additive had the best resistance to cracking among three WMA.

The above results showed the influence of WMA additives on the resistance to cracking of WMA is aggregate gradation-dependent, i.e. all the WMA additives improved the resistance to cracking of WMA mixtures with gap aggregate gradation (SMA-13); on the contrary, all the WMA additives reduced the resistance to cracking of WMA mixtures with continuous aggregate gradation (AC-13). Furthermore, for the gap aggregate gradation (SMA-13), Evotherm additive had the most positive effect on the resistance to cracking of WMA; on the contrary, for the continuous aggregate gradation (AC-13), Evotherm additive had the most negative effect on the resistance to cracking of WMA.

Table 8. Bending failure strain

Mixture type			Bending failure strain, με	Standard deviation
SMA-13	HMA (Control)		2657	143
	WMA	Rediset additive	2695	165
		Evotherm additive	2993	118
		Sasobit additive	2888	166
		Average	2859	–
AC-13	HMA (Control)		3325	160
	WMA	Rediset additive	3045	154
		Evotherm additive	2794	118
		Sasobit additive	2855	107
		Average	2898	–

In addition, WMA SMA-13 mixtures with Evotherm and Sasobit had 7.1% and 1.2% higher bending failure strain than corresponding WMA AC-13, respectively. This implied that WMA SMA-13 with Evotherm and Sasobit had slightly better resistance to cracking, compared to WMA AC-13. This regulation was proved by the results of IDT. It may partially be contributed to the use of cellulose fibers in SMA-13. However, WMA SMA-13 mixtures with Rediset had 11.5% lower bending failure strain than corresponding WMA AC-13. The cause of the result needs more research.

5. Conclusions

From the results obtained from the study the following conclusions can be made:

1. Warm asphalt mix of stone mastic asphalt and asphalt concrete had similar densities and air voids with the controls after the compaction temperature for warm mix was reduced by 25 °C, indicating warm asphalt mix had similar compaction property with the controls regardless of the types of aggregate gradation. The three warm asphalt mix additives performed equally in regard to the compaction property.

2. Marshall stability and flow of all the warm asphalt mix samples met the requirement of the specification for both stone mastic asphalt and asphalt concrete. All the warm mix specimens had higher Marshall stability and flow value than the controls. Warm mix of both stone mastic asphalt and asphalt concrete with Sasobit additive had the highest Marshall stability and highest flow value among the three additives. For stone mastic asphalt, the Sasobit additive performed best, Evotherm additive was the second in regard to Marshall stability; for asphalt concrete, the Sasobit additive performed best, Rediset additive was the second in regard to Marshall stability.

3. The indirect tensile strength of the warm mix specimens was 1.7%–14.4% lower than that of controls for either

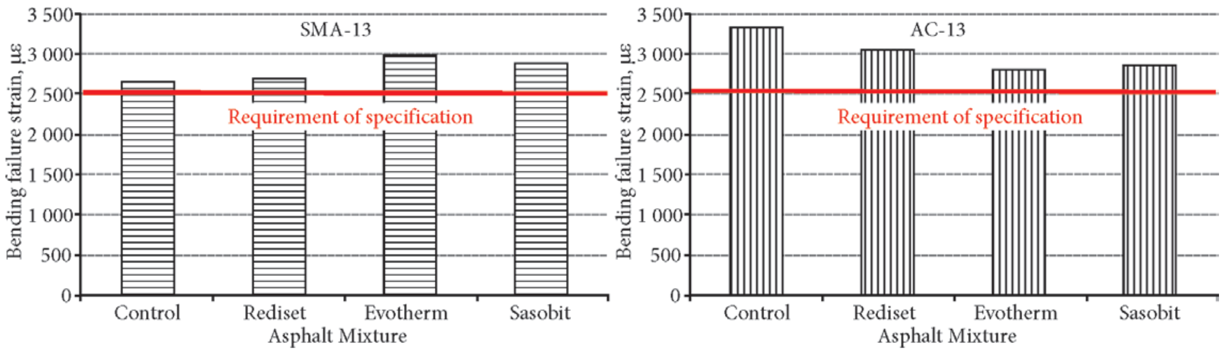

Fig. 7. Average bending failure strain

stone mastic asphalt or asphalt concrete, the illustrating warm mix specimens had lower potential for rutting or cracking. Both stone mastic asphalt and asphalt concrete with Sasobit additive had the highest indirect tensile strength.

4. For stone mastic asphalt, the Sasobit additive performed best, Evotherm additive was the second in regard to indirect tensile strength in dry condition; for asphalt concrete, the Sasobit additive performed best, Rediset additive was the second in regard to indirect tensile strength in dry condition. For stone mastic asphalt, the Sasobit additive performed best, Rediset additive was the second in regard to indirect tensile strength in wet condition; for asphalt concrete, the Sasobit additive performed best, Rediset additive was the second in regard to indirect tensile strength in wet condition.

5. Most of the warm mix specimens had slightly higher tensile strength ratio than the controls, indicating better resistance to moisture damage. Warm stone mastic asphalt with Rediset additive had the highest tensile strength ratio, while warm asphalt concrete with Sasobit additive had the highest tensile strength ratio. The influence of the warm mix additives on tensile strength ratio is gradation-dependent. For stone mastic asphalt, the Rediset additive performed better in regard to tensile strength ratio than other two warm mix additives; for asphalt concrete, the Sasobit additive performed better in regard to tensile strength ratio than other two warm mix additives. Tensile strength ratio of all the warm mix samples met the requirement of the specification.

6. All the warm mix for stone mastic asphalt and asphalt concrete had lower dynamic stability than the controls, indicating a lower resistance to rutting than the controls. Among three warm mixes, stone mastic asphalt specimens with Sasobit additive had the highest dynamic stability, while warm asphalt concrete specimens with Rediset additive had the highest dynamic stability. Therefore, the influence of the warm mix additives on dynamic stability is gradation-dependent.

7. For stone mastic asphalt, the Sasobit additive performed best, Evotherm additive was the second in regard to dynamic stability; for asphalt concrete, the Rediset additive performed best, Sasobit additive was the second in regard to dynamic stability. Stone mastic asphalt specimens had slightly higher dynamic stability than asphalt concrete. Dynamic stability of all the warm mix samples met the requirement of the specification.

8. All the stone mastic asphalt specimens had higher bending failure strain than the controls, indicating higher resistance to cracking than the controls, while the warm asphalt concrete specimens had lower resistance to cracking than the controls. Among three warm mixes, stone mastic asphalt with Sasobit had the highest bending failure strain, while warm asphalt concrete with Rediset additive had the highest bending failure strain. Therefore, the influence of the warm mix additives on bending failure strain is gradation-dependent.

9. For stone mastic asphalt, the Evotherm additive performed best, Sasobit additive was the second in regard to bending failure strain; for asphalt concrete, the Rediset additive performed best, Sasobit additive was the second in regard to bending failure strain. Warm stone mastic asphalt with Evotherm and Sasobit had slightly higher bending failure strain than corresponding warm asphalt concrete. Bending failure strain of all the warm asphalt mix samples met the requirement of the specification.

10. Overall, warm mix with Rediset had the best performance in anti-stripping for stone mastic asphalt, while that with Sasobit had the best for asphalt concrete. Warm mix with Sasobit had the relative best performance in rutting resistant for stone mastic asphalt, while that with Rediset had the best for asphalt concrete. Warm mix with Evotherm had the best performance in low temperature shrinkage resistant for stone mastic asphalt, while that with Rediset had the best for asphalt concrete.

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