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The Effectiviness of Warm Mix Asphalt (WMA) Additives Affected by The Type of Aggregate and Binder

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Abstract: The objective of this research was to select the most effective Warm Mix Asphalt (WMA) additives for WMA 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 WMA mixtures included the use of three commonly-used WMA additives (Sasobit, Rediset and Evotherm), two types of aggregate (Basalt and limestone), and two types of asphalt (unmodified and SBS modified). Results showed that: (1) Most of WMA with Sasobit had the higher mechanical strength, whereas all WMA with Evotherm had the lowest. (2)When basalt Aggregate was used, Sasobit additive was the more effective on IDT and TSR. For all WMA, Evotherm additive was the less effective on IDT. (3) Sasobit additive had better effectiveness on resistance to rutting among all WMA. (4) When basalt aggregate was used, Rediset additive was more effective on bending failure strain. When limestone aggregate was used, Sasobit and Evotherm additive was more effective.

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***Key words**: Aggregate; Properties; Warm Mix Asphalt; WMA Additives.*

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 decreases energy consumption, carbon dioxide emission, and asphalt oxidation but also extends paving season and increases distance for a better working environment [1-4].

There are many WMA technologies widely used including foaming (i.e. Double Barrel Green and Asphamin), organic technology (i.e. Sasobit) and chemical technology (i.e. Evotherm and Rediset). Sasobit is 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℃ to 116℃ [5]. 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 [6, 7)]. Rediset is a chemical additive free of water that has been recently developed by Akzo Nobel. It is a combination of cationic surface-active agents (called surfactants) and rheology modifiers (organic additives) 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 [3, 4, 8].

Gandhi [2] reported that Asphamin ® reduced the resilient modulus values of the mixes, Sasobit ® reduced the rut depths of the mixes, and both the additives improved the tensile strength ratio (TSR) of the mixes. Akisetty [9] evaluated the effect of WMA additives on compaction temperature of the Crumb Rubber Modified (CRM) mixtures. The results indicated that WMA technologies have no negative effect on the CRM mixture's engineering properties such as rutting, moisture susceptibility and resilient modulus. Sheth [10] 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 [11] 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 [12] 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. Hurley and Prowell [13-15] 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. Biro et al. [16] reported that Sasobit significantly reduced a permanent deformation based on the repeated creep recovery test. Xiao et al. [17] reported that TSR values of WMA mixtures with Sasobit and Aspha-min additives were lower than 85% but increased above 85% when 1.0% of hydrated lime was added.

It is noted that these results are binder-type dependent, aggregate

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type dependent. In addition, comparative study about the properties of the mixtures with various different additives is limited. So, further investigation of the effectiveness of various WMA additives on the properties of WMA is needed for the various types of aggregate and aggregate gradation and the environmental conditions in China.

The main objectives of the research project were 1) to evaluate the effectiveness of the WMA additives on the properties of WMA with different aggregates and binders. All results will be compared with traditional HMA; 2) to examine and compare the properties of the WMA mixtures with the three different additives when they are made by different aggregates and binders.

Test Program, Materials and Test Methods

Typical pavement materials used in asphalt pavement construction in Suzhou, China were selected. Two different aggregates of crushed basalt and limestone, two different asphalts of SBS modified asphalt and SK-70 unmodified asphalt, and three WMA additives of Rediset, Evotherm and Sasobit were used. Fig. 1 showed the combination of the experimental design used in this 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.

A typical continuous aggregate gradation of AC-13 popularly-used in the region was adopted (Table 2 and Fig. 2). The nominal maximum aggregate size of AC-13 was 13.2 mm. Marshall mixture design method was used in the determination of the optimum asphalt binder content (OAC) for both HMA and WMA mixtures. Table 3 presents the adopted mixing and compaction temperature of both HMA and WMA mixtures. A reduction of 25℃ for mixing and compaction WMA were actually recommended by the producers of WMA additives. The OAC for AC-13 mixtures were 4.8%, respectively.

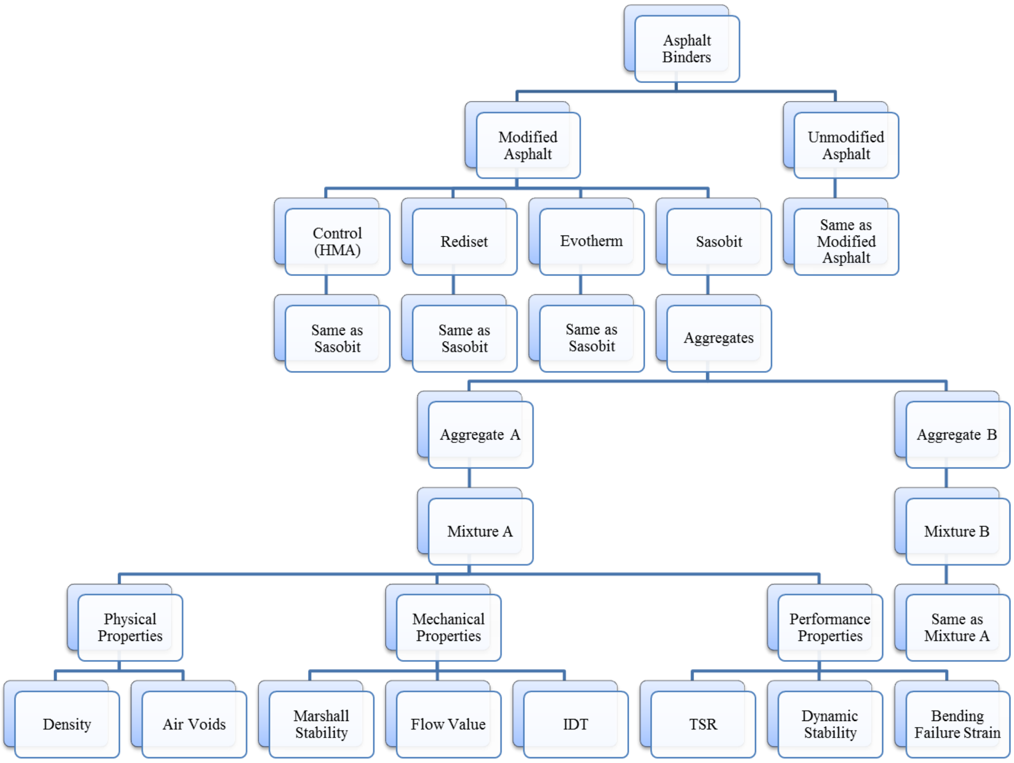

Fig. 1. Flowchart of Experimental Design.

Table 1. Properties of Asphalt Binders.

Asphalt Binder Types	Penetration at 25℃ (0.1mm)	Softening Point (℃)	Ductility at 15℃ (cm)	Ductility at 5℃ (cm)	Dynamic Viscosity* at 60℃ (Pa·S)	Kinematic Viscosity* at 135℃ (Pa•S)
Unmodified Asphalt	66	49	□100	17	294	---
Modified Asphalt	64	75	□100	38	---	1.8

* Dynamic viscosity is suitable to the asphalt that has the low viscosity, while kinematic viscosity for the high viscosity asphalt. The viscosity of modified asphalt is significantly higher than that of the unmodified asphalt. So the unmodified asphalt was measured by dynamic viscosity, while the modified asphalt was measured using kinematic viscosity.

Table 2. Aggregate Gradation.

Sieve (mm)	16.0	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Percentage Passing (%)	100	96.2	71.3	43.4	28.7	21.5	15.9	12.2	9.7	7.3

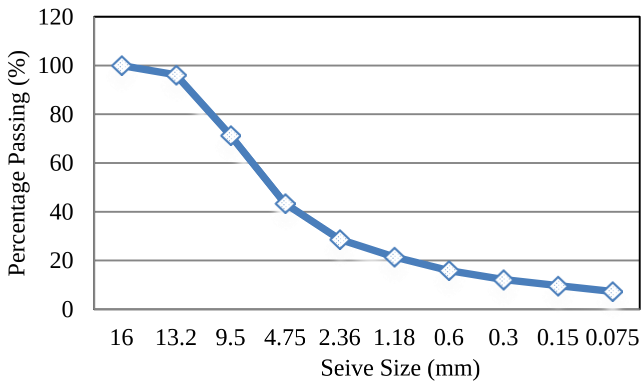

Fig. 2. Particle Size Distribution of the Aggregate.

Physical, mechanical and performance properties were selected for evaluation. The density and air void were used to evaluate the physical properties. Marshall Stability, flow value, and IDT were used to evaluate the mechanical properties of asphalt mixtures. 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 minutes. Apply the load to the specimen with a constant rate of movement for the testing machine head of 50.8 mm per minute until the maximum 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 six to eight 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 per minute. The load continued until the specimen cracks, and the maximum load is recorded. The indirect tensile strength is calculated using the following equation:

$$S_{t} = \frac{2000 \times P}{\pi \times t \times D} \quad (1)$$

where:
St = indirect tensile strength, kPa
P = maximum load, Newtons
t = specimen thickness, mm
D = specimen diameter, mm

The TSR is calculated as follows:

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

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 via 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℃. A wheel pressure of 0.7 MPa ± 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:

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

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 per minute

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℃. 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 maximum deflection of the mid-span was recorded.

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

$$\varepsilon = \frac{6 \times h \times d}{L^2} \quad (4)$$

where:
ε = bending failure strain, $\mu\varepsilon$
L = span length, mm
h = beam height, mm
d= maximum deflection of the mid-span, mm

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

Table 3. Mixing and Compaction Temperature.

Asphalt Type	HMA		WMA	
	Mixing Temperature	Compaction Temperature	Mixing Temperature	Compaction Temperature
Unmodified Asphalt	155℃	145℃	130℃	120℃
Modified Asphalt	165℃	155℃	140℃	130℃

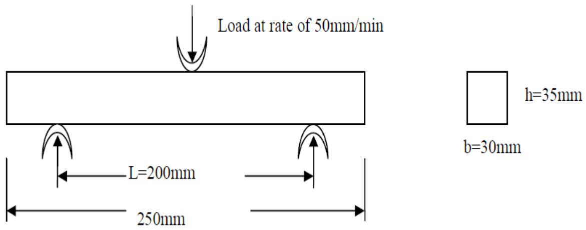

Fig. 3. Sketch of Bending Beam Test.

freeze-thaw splitting test; three rut-resistance specimen slabs with a size of 300 mm ×300 mm ×40 mm, were prepared for the wheel tracking test; six specimens with a size of 30 mm ×250 mm ×35 mm, were prepared for the bending beam test. A total of 400 samples were used in this study.

Results and Discussions

Bulk Specific Gravity and Air Void

Table 4 showed the test results of bulk specific gravity and air void of all the specimens. In general, among twelve WMA in Table 4, ten WMA had 0.04 % - 0.32 % lower bulk specific gravity and 0.77 % - 6.25 % higher air voids than the controls, respectively; while only two WMA had 0.04 % and 0.08 % higher lower bulk specific gravity and 0.77 % and 1.56 % lower air voids than the controls, respectively. The results indicated that most of WMA specimens may have a little bit tougher compaction than the controls after the compaction temperature being reduced by 25℃ for WMA, regardless of the types of aggregate and asphalt.

For three different WMA additives, the difference of air voids of three WMA is not significant. Therefore, three WMA additives have the similar effectiveness on compaction property.

For WMA with unmodified asphalt, the average bulk specific gravity and air voids of WMA specimens with basalt were 4.4 %, and 10.4 % higher than those with limestone, respectively. For WMA with modified asphalt, the average bulk specific gravity and air voids of WMA specimens with basalt were 4.6 % and 9.3 % higher than those with limestone, respectively. It was indicated that the WMA with limestone had easier compaction than that with basalt, regardless the types of asphalt.

For WMA with basalt, the average bulk specific gravity and air voids of WMA specimens with modified asphalt were 0.24 % higher and 0.95 % lower than those with unmodified asphalt, respectively. For WMA with limestone, the average bulk specific gravity and air voids of WMA specimens with modified asphalt were the same as those with unmodified asphalt. The finding indicated that WMA with unmodified asphalt had a little bit easier or similar compaction, compared with those with modified asphalt.

Overall, three WMA additives had the similar effectiveness on air voids. Most of WMA specimens had a little bit tougher compaction than the controls after the compaction temperature being reduced by 25℃ for WMA, regardless of the types of aggregate and asphalt; WMA with limestone had easier compaction than that with basalt, regardless the types of asphalt.

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℃. A higher stability means a high strength, while a large flow means low stiffness. Table 5 showed the Marshall stability and flow value of

Table 4. Bulk Specific Gravity and Air Voids.

Mixture Types				Maximum Specific Gravity	Bulk Specific Gravity	Air Voids (%)
Unmodified Asphalt	Basalt	HMA (Control)		2.628	2.500	4.9
		WMA	Rediset	2.628	2.495	5.1
			Evotherm		2.502	4.8
			Sasobit		2.492	5.2
			Average		2.496	5.0
	Limestone	HMA (Control)		2.505	2.395	4.4
		WMA	Rediset	2.505	2.394	4.4
			Evotherm		2.388	4.7
			Sasobit		2.392	4.5
			Average		2.391	4.5
Modified Asphalt	Basalt	HMA (Control)		2.633	2.503	4.9
		WMA	Rediset	2.633	2.501	5.0
			Evotherm		2.502	5.0
			Sasobit		2.504	4.9
			Average		2.502	5.0
	Limestone	HMA (Control)		2.505	2.396	4.4
		WMA	Rediset	2.505	2.394	4.4
			Evotherm		2.391	4.6
			Sasobit		2.389	4.6
			Average		2.391	4.5

Table 5. Marshall Stability and Flow Value.

Mixture Types				Marshall Stability (kN)	Flow (mm)
Unmodified Asphalt	Basalt	HMA (Control)		9.32	2.8
		WMA	Rediset	9.98	2.9
			Evotherm	8.19	3.1
			Sasobit	10.56	2.9
			Average	9.58	3.0
	Limestone	HMA (Control)		9.71	3.0
		WMA	Rediset	8.80	2.8
			Evotherm	8.11	2.9
			Sasobit	8.23	2.7
			Average	8.38	2.8
Modified Asphalt	Basalt	HMA (Control)		10.95	3.1
		WMA	Rediset	11.99	3.3
			Evotherm	11.62	3.4
			Sasobit	12.66	3.4
			Average	12.09	3.4
	Limestone	HMA (Control)		9.17	2.6
		WMA	Rediset	8.18	3.0
			Evotherm	8.13	3.0
			Sasobit	8.59	2.6
			Average	8.30	2.9

the specimens.

Generally, for WMA with basalt, five of six WMA had 6.1 % -15.6 % higher Marshall stability than the controls, while only one WMA had 12.1% lower Marshall stability than the control. However, for WMA with limestone, all WMA had 6.3 % -16.5 % lower Marshall stability than the controls. It illustrated that for WMA with basalt, most of WMA additives increased the mechanical strength of WMA, while for WMA with limestone, and all WMA additives reduced the mechanical strength of WMA. For WMA with basalt, all WMA had 3.6 % -10.7 % higher flow than the controls; for WMA with limestone, all WMA with unmodified asphalt had 0.03 % - 0.1% lower flow and WMA with modified asphalt had 15.4 higher or equal flows, compared to the controls. It illustrated that for WMA with basalt, all WMA additives reduced the stiffness of WMA, while for WMA with limestone, and all WMA additives increased the stiffness of WMA with unmodified asphalt and most of WMA additives reduced the stiffness of WMA with modified asphalt.

For three different WMA additives, most of WMA with Sasobit had the highest Marshall stability, followed by the WMA with Rediset, whereas all WMA with Evotherm had the lowest. It was indicated that all WMA with Sasobit had the higher mechanical strength, whereas all WMA with Evotherm had the lowest. All WMA with Evotherm had the highest flow, whereas most of WMA with Sasobit had the lowest flow. It was illustrated that All WMA with Evotherm had the lowest stiffness, while most of WMA with Sasobit had the highest.

For WMA with unmodified asphalt, the average Marshall stability and flow of WMA specimens with basalt were 14.3%, and 7.1% higher than those with limestone, respectively. For WMA with modified asphalt, the average Marshall stability and flow of WMA specimens with basalt were 45.7% and 17.2% higher than those with limestone, respectively. It was indicated that the WMA with basalt had higher mechanical strength and lower stiffness than that with limestone, regardless the types of asphalt.

For WMA with basalt, the average Marshall stability and flow of WMA specimens with modified asphalt were 26.2% and 13.3% higher than those with unmodified asphalt, respectively. For WMA with limestone, the average Marshall stability and flow of WMA specimens with modified asphalt were 1.0% lower and 3.6% higher than those with unmodified asphalt, respectively. The finding indicated that WMA with modified asphalt had higher flow than that with unmodified asphalt, regardless the types of aggregate, and the influence of three WMA additives on Marshall stability was aggregate-dependent.

In addition, all the WMA samples had higher Marshall stability than 8.0 kN, the requirement of the specification (JTG F40—2004). The flow values of all the WMA specimens met the requirement of the specification (JTG F40—2004), 1.5-4 mm.

Overall, most of WMA with Sasobit had the higher mechanical strength, whereas all WMA with Evotherm had the lowest; all WMA with Evotherm had the lowest stiffness, while most of WMA with Sasobit had the highest; WMA with basalt had higher mechanical strength and lower stiffness than that with limestone, regardless the types of asphalt.

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 shows the IDT and

TSR results of the WMA and control samples.

In General, among twelve WMA in Table 8, eight WMA had 0.1 % - 14.4 % lower IDT in dry condition and 2.8% - 13.9 % lower IDT in wet condition than the controls, while four WMA had 0.1 % - 4.5 % higher IDT in dry condition and 9.4 % - 28.2 % higher IDT in dry condition than the controls. Eight of twelve WMA had 0.4 % - 7.8 % higher TSR than the controls, while four WMA had 0.1 % - 6.5 % lower TSR than the controls. The results indicated that most of WMA specimens had lower potential for rutting or cracking and higher resistance to moisture damage than the controls. In addition, the TSR of all the WMA and control mixtures was higher than 80%, the requirement of the specification (JTG F40—2004).

For three different WMA additives, WMA with Sasobit had the highest IDT in wet condition and TSR, except WMA with modified asphalt and limestone. It indicated that most of WMA with Sasobit had higher potential for rutting or cracking and resistance to moisture damage than other two additives. In addition, for WMA with basalt, WMA with Sasobit had the highest IDT in dry condition, and for WMA with limestone, WMA with Rediset had the highest IDT in dry condition. The finding indicated that the influence of three WMA additives on IDT was aggregate-dependent.

For WMA with unmodified asphalt, the average IDT in dry condition, IDT in wet condition and TSR of WMA specimens with basalt were 2.4 %, 3.1 %, and 0.8 % higher than those with limestone, respectively. For WMA with modified asphalt, the average IDT in dry condition, IDT in wet condition and TSR of WMA specimens with basalt were 11.7 % lower, 7.9 % lower, and 4.2 % higher than those with limestone, respectively.

For WMA with basalt, the average IDT in dry condition, IDT in wet condition and TSR of WMA specimens with modified asphalt were 11.7 % lower, 8.9 % lower, and 3.2 % higher than those with unmodified asphalt, respectively. For WMA with limestone, the average IDT in dry condition, IDT in wet condition and TSR of WMA specimens with modified asphalt were 2.4 % higher, 1.9 % higher, and 0.1% lower than those with unmodified asphalt, respectively. The finding indicated that the influence of three WMA additives on IDT and TSR was aggregate-dependent.

Overall, when basalt Aggregate was used, Sasobit additive was the most effective on IDT and TSR. For all WMA, Evotherm additive was the worst effective on IDT, but it had the similar effective on TSR to Rediset additive.

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 shows the dynamic stability of WMA and control HMA samples. In general, the average dynamic stability of the WMA specimens with unmodified asphalt and basalt was 4.8 % lower than that of the controls, while that of the WMA specimens with unmodified asphalt and limestone was 26.8 % higher than that of the control; the average dynamic stability of the WMA specimens with modified asphalt and basalt was 15.3 % lower than that of the controls, and that of the WMA specimens with modified asphalt and limestone was 26.8 % lower than that of the control. It illustrated that all the WMA with modified asphalt had lower resistance to rutting than the controls, while the WMA with unmodified asphalt had lower or higher resistance to rutting than the control, which depends on the type of aggregate. Furthermore, the dynamic stability of all the WMA and control with modified asphalt was significantly higher than 2,400 times/mm, the requirement of the specification (JTG F40—2004), while that of most of WMA and control with unmodified asphalt was lower than 800 times/mm, the requirement of the specification (JTG F40—2004).

For three different WMA additives, WMA with Sasobit had the highest dynamic stability, except the WMA with modified asphalt

Table 6. IDT and TSR.

Mixture Types				IDT in Dry Condition (MPa)	IDT in Wet Condition (MPa)	TSR (%)
Unmodified Asphalt	Basalt	HMA (Control)		1.77	1.43	80.9
		WMA	Rediset	1.68	1.36	81.2
			Evotherm	1.61	1.39	86.1
			Sasobit	1.85	1.61	87.2
			Average	1.71	1.45	84.8
	Limestone	HMA (Control)		1.43	1.17	82.0
		WMA	Rediset	1.75	1.45	82.6
			Evotherm	1.56	1.28	81.9
			Sasobit	1.71	1.50	87.7
			Average	1.67	1.41	84.1
Modified Asphalt	Basalt	HMA (Control)		1.67	1.44	86.4
		WMA	Rediset	1.55	1.35	87.1
			Evotherm	1.43	1.24	86.9
			Sasobit	1.56	1.38	88.4
			Average	1.51	1.32	87.5
	Limestone	HMA (Control)		1.86	1.64	88.2
		WMA	Rediset	1.76	1.45	82.5
			Evotherm	1.67	1.42	85.1
			Sasobit	1.71	1.44	84.3
			Average	1.71	1.44	84.0

Table 7. Dynamic Stability.

Mixture Types				Dynamic Stability (Times/mm)
Unmodified Asphalt	Basalt	HMA (Control)		925
		WMA	Rediset	778
			Evotherm	906
			Sasobit	957
			Average	880
	Limestone	HMA (Control)		325
		WMA	Rediset	364
			Evotherm	386
			Sasobit	486
			Average	412
Modified Asphalt	Basalt	HMA (Control)		4768
		WMA	Rediset	4147
			Evotherm	3977
			Sasobit	3987
			Average	4037
	Limestone	HMA (Control)		4772
		WMA	Rediset	3424
			Evotherm	3124
			Sasobit	3927
			Average	3492

Table 8. Bending Failure Strain.

Mixture Types				Bending Failure Strain (μ ε)
Unmodified Asphalt	Basalt	HMA (Control)		2660
		WMA	Rediset	2748
			Evotherm	2533
			Sasobit	2340
			Average	2540
	Limestone	HMA (Control)		2110
		WMA	Rediset	2048
			Evotherm	2293
			Sasobit	2170
			Average	2170
Modified Asphalt	Basalt	HMA (Control)		3325
		WMA	Rediset	3045
			Evotherm	2794
			Sasobit	2855
			Average	2898
	Limestone	HMA (Control)		2730
		WMA	Rediset	2512
			Evotherm	2543
			Sasobit	2668
			Average	2574

and basalt. It indicated that most of WMA with Sasobit had higher resistance to rutting than those of other two additives. By comparing Evotherm with Rediset additive, it was noted that the dynamic stability of WMA with Evotherm was higher than that of WMA with Rediset when unmodified asphalt was used; an inverse relationship between Evotherm and Rediset existed when modified asphalt was used: the dynamic stability of WMA with Rediset additive was higher. Therefore, the influence of three WMA additives on dynamic stability is asphalt-dependent.

For WMA with unmodified asphalt, the average dynamic stability of WMA specimens with basalt was 113.7 % higher than those with limestone. For WMA with modified asphalt, the average dynamic stability of WMA specimens with basalt was 15.6 % higher than those with limestone. The finding indicated that the WMA with basalt had higher resistance to rutting than that with limestone, regardless the types of asphalt. It might be contributed to higher compression strength of basalt than limestone.

For WMA with basalt, the average dynamic stability of WMA specimens with modified asphalt was 358.6 % higher than that of WMA specimens with unmodified asphalt. For WMA with limestone, the average dynamic stability of WMA specimens with modified asphalt was 747.5 % higher than that of WMA specimens with unmodified asphalt. The finding indicated that the WMA with modified asphalt had significant higher resistance to rutting than that with unmodified asphalt, regardless the types of aggregate.

Overall, Sasobit additive had the best effectiveness on resistance to rutting for most of WMA. When unmodified asphalt was used, Rediset additive was the least effective on dynamic stability. When modified asphalt was used, Evotherm additive was the least effective. WMA with basalt had higher resistance to rutting than that with limestone, regardless the types of asphalt; WMA with modified asphalt had significant higher resistance to rutting than that with unmodified asphalt, regardless the types of aggregate.

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 shows the bending failure strain at low temperature (-10℃) of WMA and control samples.

In general, among twelve WMA in Table 8, nine WMA had 2.3 % - 16.0 % lower bending failure strain than the controls, while only three WMA had 2.8 % - 8.7 % higher bending failure strain than the controls. It indicated that most of the WMA specimens had lower resistance to cracking than the controls. Furthermore, for mixtures with modified asphalt, the bending failure strain of all WMA and control were higher than 2,500 μ ε , the requirement of the (JTG F40—2004); for mixtures with unmodified asphalt, only two of six WMA mixtures were slightly higher (1.3 % and 9.9 %) than 2,500 μ ε . The finding illustrated that the mixtures with modified asphalt had higher resistance to cracking than those with unmodified asphalt, no matter the mixtures were HMA or WMA.

For three different WMA additives, the influence of three WMA additives on bending failure strain of WMA specimens were related with the types of aggregate and asphalt. For example, for WMA with unmodified asphalt and basalt, WMA with Rediset had the highest bending failure strain; for WMA with unmodified asphalt and limestone, WMA with Evotherm had the highest bending failure strain, and for WMA with modified asphalt and limestone, WMA with Sasobit had the highest bending failure strain. Therefore, the influence of three different WMA additives on bending failure strain was aggregate-dependent.

For WMA with unmodified asphalt, the average bending failure strain of WMA specimens with basalt was 17.1 % higher than that of WMA with limestone. For WMA with modified asphalt, the average bending failure strain of WMA specimens with basalt was 12.6 % higher than that of WMA with limestone. The finding indicated that the WMA with basalt had higher resistance to cracking than that with limestone, regardless the types of asphalt. It might be contributed to higher compression strength of basalt than limestone and less broken particles in asphalt mix with basalt .

For WMA with basalt, the average bending failure strain of WMA with modified asphalt was 14.1 % higher than that of WMA specimens with unmodified asphalt. For WMA with limestone, the average bending failure strain of WMA specimens with modified asphalt was 18.6 % higher than that of WMA with unmodified asphalt. The finding indicated that the WMA with modified asphalt had significant higher resistance to cracking than that with unmodified asphalt, regardless the types of aggregate.

Overall, when basalt aggregate was used, Rediset additive was the most effective on bending failure strain. When limestone aggregate was used, Sasobit and Evotherm additive was the more effective than Rediset. The WMA with basalt had higher resistance to cracking than that with limestone, regardless the types of asphalt.

Summary and Conclusions

A series of lab tests including density test, Marshall stability test, freeze-thaw splitting test, dynamic stability, and bending beam test were performed on WMA mixtures with three WMA additives to investigate the effect of the WMA additives on the properties of WMA made from different aggregate and asphalt. The following conclusions can be obtained from the research:

(1) Three WMA additives had the similar effectiveness on air voids. WMA with limestone had easier compaction than that with basalt, regardless the types of asphalt.

(2) Most of WMA with Sasobit had the higher mechanical strength, whereas all WMA with Evotherm had the lowest; all WMA with Evotherm had less stiffness, while most of WMA with Sasobit had the highest; WMA with basalt had higher mechanical strength and lower stiffness than that with limestone, regardless the types of asphalt.

(3) When basalt Aggregate was used, Sasobit additive was the most effective on IDT and TSR. For all WMA, Evotherm additive was less effective on IDT, but it had the similar effective on TSR to Rediset additive.

(4) Sasobit additive had more effectiveness on resistance to rutting for most of WMA. When unmodified asphalt was used, Rediset additive was less effective on dynamic stability. When modified asphalt was used, Evotherm additive was less effective. WMA with basalt had higher resistance to rutting than that with limestone, regardless the types of asphalt.

(5) When basalt aggregate was used, Rediset additive was more effective on bending failure strain. When limestone aggregate was used, Sasobit and Evotherm additive was more effective than Rediset. The WMA with basalt had higher resistance to cracking than that with limestone, regardless the types of asphalt.

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