Research Article

Laboratory Performance Evaluation of High Modulus Asphalt Concrete Modified with Different Additives

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Received 24 January 2017; Accepted 24 April 2017; Published 21 May 2017

Academic Editor: Meor Othman Hamzah

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The objective of this study is to evaluate comprehensive performance of high modulus asphalt concrete (HMAC) and propose common values for establishing evaluation system. Three gradations with different modifiers were conducted to study the high and low temperature performance, shearing behavior, and water stability. The laboratory tests for HMAC included static and dynamic modulus tests, rutting test, uniaxial penetration test, bending test, and immersion Marshall test. Dynamic modulus test results showed that modifier can improve the static modulus and the improvements were remarkable at higher temperature. Moreover, modulus of HMAC-20 was better than those of HMAC-16 and HMAC-25. The results of performance test indicated that HMAC has good performance to resist high temperature rutting, and the resistances of the HMAC-20 and HMAC-25 against rutting were better than that of HMAC-16. Then, the common values of dynamic stability were recommended. Furthermore, common values of HMAC performance were established based on pavement performance tests.

1. Introduction

High modulus asphalt concrete (HMAC) is one of attracting alternatives to enhance load-bearing capacity of pavement structure against conventional structural distresses, such as rutting and fatigue crack [1]. Rutting resistance of conventional mixture is improved by adding special additives such as antirutting additive or using hard grade asphalt binder in the mixture [2]. One of the most controversial issues concerning HMAC is systematic performance evaluation. Many researches have been conducted regarding high and low temperature performance and water stability. Lee et al. evaluated the high temperature performance and fatigue performance of HMAC based on dynamic modulus, moisture susceptibility, wheel tracking, and fatigue tests [3]. Geng et al. studied stiffness, elastic recovery, workability, and thermal

cracking resistance of HMAC and found that the asphalt layers thickness could be significantly reduced by replacing neat binder with HMABs. [4]. Espersson studied dynamic modulus of HMAC at different temperatures to obtain the reduction in thickness depending on the temperature and the use of HMAC, getting that HMAC and conventional bitumen behaved differently in terms of stiffness and elasticity. HMAC in the study had higher complex modulus at all the evaluated temperatures and viscosity was also higher [5]. Laboratory tests, including dynamic modulus, creep compliance, fatigue, moisture damage, and rutting, were conducted to evaluate the performance of different types of WMA mixes [6]. Han chose two kinds of aggregates (basalt and limestone) with obvious differences to study the impact of aggregates on the high modulus mixture properties of hard asphalt (such as high temperature properties, modulus, and fatigue resistance),

TABLE 1: Properties of Zhonghai A-70 asphalt.

Test indexes	Measured value
Penetration (1/10 mm) 100 g, 25°C, 5 S	67
Penetration index	-0.7
Ductility (cm), 10°C	23
Ductility (cm), 15°C	104
Softening point (°C)	48
Dynamic viscosity (Pa/s), 60°C	183
Wax content (%)	2
Flash point (°C)	276
Solubility (%)	99.8
Density (g/cm ³), 15°C	1.0029
TFOT	
Quality change (%)	0.1
Residual penetration ratio (%)	64
Residual ductility 10°C (cm)	10
Residual ductility 15°C (cm)	17

showing that a balanced design of high temperature performance, modulus, and fatigue resistance properties can be achieved on the mixture through the gradation and the hard asphalt dosage adjustment, for different properties aggregate [7]. Wu et al. evaluated performance of several kinds of additives for high modulus asphalt mixture by tests. The testing results in the article had proved that the existing China-made additives can also meet the requirement of high modulus asphalt concrete (HMAC) [8]. Sun and Li tested fatigue properties of high modulus asphalt using Dynamic Shear Rheometer (DSR) and showing that the fatigue performance of PR-Plasts is better than rock asphalt and 15/25# is the worst at given conditions [9]. However, little research results have been reported concerning static and dynamic modulus at different temperatures, relation of static and dynamic modulus, and reasonable evaluation indicators of rut. In addition, research about common values for HMAC performances should be recommended, and then comprehensive performance evaluation system of HMAC needs to be further conducted from performance test [2–5, 7].

Performance tests (including static modulus and dynamic modulus, high and low temperature, water stability, and shear behavior tests) were conducted on three different mixtures (HMAC-16, HMAC-20, and HMAC-25) in this study and the test temperatures were 15, 20, and 60°C. Based on the performance tests, common values of HMAC were proposed which can be a reference for establishing evaluation system of HMAC performance.

2. Materials and Test Scheme

2.1. Materials

2.1.1. Asphalt and Aggregate. In this study, Zhonghai A-70 asphalt with high consistency and viscosity at 60°C was chosen to ensure the resistance to permanent deformation. The physical and mechanical features of the asphalt are shown in Table 1.

Rutting resistance of HMAC is affected by the shape and interlock of aggregates. Therefore, clean, hard, wear-resistant, crushed, and nonacidic aggregates were selected in this study to achieve high rutting resistance of asphalt mixtures. Limestone was employed as aggregate. Three types of asphalt mixtures known as HMAC-16, HMAC-20, and HMAC-25 were studied. The gradations of HMAC-16 were chosen following the JTG F40-2004. Different sizes of coarse aggregate were naturally filled, tamped, compacted, and detected by maximum skeleton strength (CBR) test, in order to get the minimum VCA (voids in coarse aggregates), CBR, and best proportion of each single particle size of coarse aggregate for HMAC-20 and HMAC-25. Talbol formula was adopted to guide the design for fine aggregate gradation and the mass ratio of fine aggregates with different size was determined. Talbol formula is one of the grading formulas and is used to design the grading curve of aggregate, showing the fluctuation range of gradation. The detailed formula is as follows:

$$P = 100 \left(\frac{d}{D} \right)^n, \quad (1)$$

where P is passing percentage of aggregate, %, d is mesh size of particles, mm, D is the maximum particle size of aggregate, mm, and n is grading index.

The gradations of HMAC-20 and HMAC-25 were determined after optimization [10, 11]. Aggregate gradations and optimum bitumen-aggregate ratio are shown in Tables 2 and 3.

2.1.2. Additives. Pavement deformation under the vehicle load is reduced by increasing the modulus of asphalt concrete, which means the rutting resistance is improved. The high modulus additive, antirutting additive, and hard asphalt can be used as additives to increase the modulus of asphalt concrete. In this paper, PR-Module (PRM), PR-Plasts (PRS), and Resin Alloy (RA) additives were adopted, and Zengqiang (ZQ) additive was for contrastive study.

PRM and PRS additives, originated in France, were applied to pavement structure of heavy traffic as shown in Figures 1(a) and 1(b). RA was asphalt compound modifier used as antirutting agent and had stability properties as shown in Figure 1(c). ZQ additive [12], originated in China, was a high modulus additive aimed at reducing rutting, as shown in Figure 1(d). The additives were used according to dry process, meaning that additive was dry-mixed with hot aggregate and then fixed with asphalt.

Mass ratio between additives (PRS, PRM, ZQ, and RA) and matrix asphalt is 0.7%, 0.4%, 0.8%, and 0.4%, respectively. The main characteristics of these materials are shown in Table 4.

2.2. Laboratory Testing

2.2.1. Static Modulus Test. Modulus is the main structural design parameter due to its prominent influence on the deformation of asphalt pavement. The uniaxial compression test was conducted in the universal material testing machine

TABLE 2: Aggregate gradations of HMAC.

Sieves (mm)	Percent passing (%)											
	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
HMAC-16	100	100	93.2	82.9	70.4	39.7	27.3	21.4	15.8	11.4	8.8	6.1
HMAC-20	100	95.3	85.6	73.3	59.1	39.1	28	21.9	16.1	11.6	9.1	6.2
HMAC-25	97.3	82.2	73.4	64.9	55	31.8	22.3	17.7	13.3	9.9	8	5.6

TABLE 3: Optimum bitumen-aggregate ratio of mixtures.

Asphalt Mixture	Optimum bitumen-aggregate ratio (%)			
	Matrix asphalt mix	Mixture with PRM-Module	Mixture with PR-Plasts	Mixture with ZQ
HMAC-16	4.5	4.7	4.8	4.7
HMAC-20	4.2	4.4	4.3	4.4
HMAC-25	3.9	4.1	4.1	4.2

TABLE 4: Additives properties.

Materials	Appearance	Size (mm)	Melting point (°C)	Density (g/cm ³)	Ingredient
PRM	Grey	5	175	0.93~0.965	—
PRS	Cylinder black	2~4	140~150	0.91~0.965	Plastic > 95%, filling < 5%
RA	Granular black	2~4	150	0.96	Rock asphalt, low density polyethylene
ZQ	Black solid	3	≥160	1~1.2	—

(a) PRM particle

(b) PRS particle

(c) RA particle

(d) ZQ particle

FIGURE 1

TABLE 5: Static modulus test scheme.

Parameter type	Parameter values
Additive	PRM, PRS, RA, and base asphalt
Gradation	HMAC-16, HMAC-20, and HMAC-25
Asphalt	A-70
Aggregate	Limestone
Asphalt-aggregate ratio	Determined by Marshall test
Bulk density	Determined by Marshall test
Temperature	15, 20, and 60°C
Loading rate	2 mm/min
Loading method	First, determine the compressive strength (P) and then stepping loading
Compressive strength test	Failure load
Compression resilient modulus test	Compression resilient modulus

at 20°C and a test rate of 2 mm/min was applied to the 100 mm × 100 mm × 100 mm cylinder specimens (HMAC-16, HMAC-20, and HMAC-25) according to ASTM D1074. The additives (PRM, PRS, and RA) were also used to modify the mechanical properties of conventional asphalt mixture [13, 14]. Details of the testing scheme are shown in Table 5.

2.2.2. Dynamic Modulus Test (DMT). The dynamic modulus test was evaluated according to the test procedure described in ASTM D3497-79. Dynamic modulus test was conducted in the simple performance tester at three different temperatures (15, 20, and 60°C). At each temperature, the test was performed at eight different frequencies (25, 10, 5, 1, 0.5, 0.2, 0.1, and 0.01 Hz). The tests specimens used in the dynamic modulus tests were directly obtained from the gyratory compactor with a diameter of 100 mm and height of 150 mm as depicted in Figures 2(a) and 2(b).

2.2.3. Wheel Tracking Test

(1) Conventional Wheel Tracking Test. The conventional wheel tracking test was conducted to evaluate the high temperature stability of asphalt mixtures. A contact pressure of 700 kPa was applied to the 300 mm × 300 mm × 50 mm slab specimens at 60°C according to the test procedure described in JTJ T0719.

(2) Unconventional Wheel Tracking Test. Contact pressures (800, 900, and 1000 kPa) were applied to the 300 mm × 300 mm × 50 mm slab specimens, respectively. The unconventional wheel tracking tests were conducted at 70°C to evaluate the permanent deformation characteristics of asphalt mixtures.

2.2.4. Uniaxial Penetration Test. The uniaxial penetration test is similar to the CBR test in soil test method. A cylindrical steel pressure head was loaded on a cylinder specimen at a fixed loading rate, to simulate the actual stress state of the road. In this study, the uniaxial penetration method was used for evaluating the shear performance of asphalt mixture.

The uniaxial penetration test was conducted to evaluate the shear behavior of asphalt mixtures according to the test

procedure described in JTGE40-2007-T0134. A test rate of 1 mm/min as well as head size of 28.5 mm was applied to the 100 mm × 100 mm cylinder specimens at three different temperatures (15, 20, and 60°C). During the constant temperature process, the temperature will be controlled automatically by the temperature controller with heat preservation for at least 6 h. Figure 3 shows the test instruments and specimen of uniaxial penetration test.

2.2.5. Bending Test at Low Temperature. The bending test was conducted according to the test procedure described in JTJ T0715-2011 to evaluate the low temperature performance of asphalt mixtures. A test rate of 50 mm/min was applied to the 250 mm × 30 mm × 35 mm slab specimens at temperature of −10°C.

2.2.6. Water Stability Test. Freeze-thaw splitting strength test and immersion Marshall test were conducted to study the water stability of mixture after freeze-thaw cycles on specimens. Three groups of specimens (HMAC-16, HMAC-20, and HMAC-25) were compacted in a Marshall compactor according to the test procedure described in JTJ T0709-2011 and AASHTO T-283-98.

Marshall samples were first water-conditioned by vacuum saturation for 15 minutes with distilled water, then were placed in water under atmospheric pressure for 0.5 hours, and finally subjected to successive cycles of freezing and thawing. Each cycle consisted of freezing at −20°C for 16 hours followed by soaking in distilled water at 60°C for 24 hours [13–16].

3. Results and Discussion

3.1. Modulus

3.1.1. Static Modulus. Modulus of asphalt mixture, the main indicator characterizing antideformation performance of HMAC, is the key parameter of comprehensive evaluation system. Details of the static compressive modulus test are shown in Figures 4(a)–4(c).

FIGURE 2

FIGURE 3: Uniaxial penetration test.

(1) *The Effect of Temperature on Modulus.* Static modulus of asphalt mixture decreased when the temperature increased from 15°C to 60°C, meaning that asphalt mixture is sensitive to temperature. Compressive moduli of HMAC at 15, 20, and 60°C were 46%, 58%, and 72% more than those of conventional mixture, and the improving effect was more striking with the increasing temperature.

Figure 4 shows that compressive modulus of asphalt mixture decreases with the increase of temperature. Asphalt mixture is a typical complex viscoelastic plasticity indicating that the mechanical properties are very sensitive to temperature. Along with the increase of temperature, the physical characteristics manifest as being soft whereas strength and stiffness decrease resulting in the decrease of modulus.

In general, the high temperature stability of asphalt mixture increases along with increase of modulus. At the temperature of 15, 20, and 60°C, compressive moduli of high modulus asphalt concrete are 1.3~1.5, 1.4~1.6, and 1.8~2.1 times the value of matrix asphalt mixture, respectively. The following can be indicated: compressive moduli of high modulus asphalt concrete are far bigger than that of ordinary asphalt mixture, and the higher the temperature, the more apparent the improving effect.

At the temperature of 15, 20, and 60°C, moduli of HMAC-PRM were 13% ~18%, 1% ~7%, and 4% ~7% bigger than those of HMAC-PRS and moduli of HMAC-PRS were 4%~7%, 10%~20%, and 4%~7% greater than that of HMAC-RA, respectively, which means that PRM has the most significant effect on improving modulus of asphalt mixture. The ranking among the three mixes is HMAC-PRM, HMAC-RA, and HMAC-PRS from superior to inferior.

(2) *The Effect of Nominal Maximum Aggregate Size on Modulus.* The compressive moduli of HMAC-16 were 2300~2900 MPa, 1600~2000 MPa, and 490~560 MPa at the temperature of 15, 20, and 60°C, and those of HMAC-20 were 2600~3300 MPa, 1700~2300 MPa, and 520~610 MPa and those for HMAC-25 were 2200~2900 MPa, 1500~2000 MPa, and 490~590 MPa, respectively. On the whole, the modulus of HMAC-20 was bigger than those of HMAC-16 and HMAC-25.

Generally speaking, static moduli of HMAC-16 are better than those of HMAC-25 and HMAC-20. However, results obtained from 15°C, 20°C, and 60°C showed that static modulus of HMAC-20 is the best. The reasons for the phenomenon are simply that grading of HMAC-20 is better than those of HMAC-16 and HMAC-25, and additives for

FIGURE 4

TABLE 6: Technical index of static modulus.

Mixture	Compressive modulus (MPa)		
	15°C	20°C	60°C
HMAC-16, HMAC-20	2600~3000	2000~2400	450~650
HMAC-25	2300~2700	1800~2200	400~600

improving modulus of HMAC-20 are better than those for HMAC-16 and HMAC-25.

In conclusion, the recommended common values of static modulus used as a reference for road design are shown in Table 6.

3.1.2. Dynamic Modulus. As a typical viscoelastic material, mechanical characteristics of asphalt mixture are closely related to loading frequency and temperature. Modulus and stiffness of the asphalt mixture decreased when loading rate decreased or temperature was risen, which are shown in Figures 5(a)–5(d) and Table 7.

Growth rate of dynamic modulus was larger when the frequency increased from 0.01 Hz to 2 Hz and it gradually reduced when the frequency increased from 2 Hz to 25 Hz. In addition, the dynamic modulus of HMAC was bigger than that of conventional mixture regardless of frequency and temperature condition.

(1) A high frequency of loading was initially applied on HMAC in dynamic modulus test and then applied with low frequency loading. As seen in Figure 5, the dynamic

modulus of asphalt mixture increases along with the increase of loading frequency. This is due to the fact that asphalt mixture is a typical viscoelastic material and mechanical properties related to the loading speed, material strength, and stiffness increased with the increase of loading rate. Asphalt mixture will not be instantaneously compressed under dynamic loading, nor will it be completely spring back after unloading. Mechanical properties of asphalt mixtures are as follows: strength and modulus under dynamic loading are bigger than those under static load. With the increase of loading frequency, the load response lag phenomenon is more obvious, indicating the strength and modulus of asphalt mixture increase with the increase of loading frequency.

(2) As shown in Figure 5, the dynamic modulus of asphalt mixture sharply increased at frequency ranging from 0.01 to 2 Hz, and the increasing trend reduced ranging from 2 to 25 Hz. This is because, at high load frequency, asphalt mixture is mainly characterized by elasticity; the influence of frequency on dynamic modulus is less than that of material property.

With dynamic loading at high and low frequencies, moduli of high modulus asphalt concrete are much bigger than those of common asphalt mixture. It is well known that the mechanical properties are better with higher modulus, meaning that high modulus additives can effectively improve the mechanical properties of asphalt mixture.

The mechanical properties of asphalt mixture are significantly correlated with loading rate, and loading frequency of 10 Hz is equivalent to the driving speed of 72~80 km/h that

TABLE 7: Values of dynamic modulus.

Mixture	Additive	Temp (°C)	25 Hz	20 Hz	10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.01 Hz
HMAC-16	Base asphalt	15	19472	18689	16934	14819	12450	10635	8657	6860	5308	2727
		20	15321	14323	13091	11657	8672	7054	6278	4006	3381	1476
		60	2798	2087	1583	1222	890	729	623	536	523	314
	PRM	15	25475	24621	22639	20680	17305	15690	13695	12042	10988	6914
		20	22577	21223	17340	15779	14010	12815	11643	9230	8297	4844
		60	4635	3741	3243	2281	1549	1388	1015	826	781	608
	PRS	15	24072	23521	21087	19009	16505	14630	12765	10490	8934	4698
		20	18275	17059	15011	13302	11196	9676	8190	6410	5204	2671
		60	4053	3462	2617	2012	1413	1119	926	758	713	526
	RA	15	24773.5	24071	21863	19844.5	16905	15160	13230	11266	9961	5806
HMAC-20	Base asphalt	20	20426	19141	16175	14540	12603	11245	9916	7820	6750	3757
		60	4344	3601	2930	2146	1481	1253	970	792	747	567
	PRM	15	19370	18318	16782	14746	12354	10523	8620	6782	5283	2693
		20	15256	14210	12979	11523	8340	6675	5899	3892	2951	1227
		60	2925	2632	1971	1421	884	668	502	370	321	235
	PRS	15	24976	23982	22370	20010	17245	15599	13545	11804	10603	6780
		20	21116	20087	17175	15501	13676	12710	11299	9075	8160	4757
		60	4057	3784	3068	2487	1882	1522	1254	998	859	560
	RA	15	23880	23247	20984	18872	15631	14502	12344	10201	8638	4368
		20	17948	16064	14915	13028	11042	9426	8023	6157	4820	2160
HMAC-25	Base asphalt	60	3998	3398	2571	1919	1388	1021	909	738	706	515
		15	24428	23614	21677	19441	16438	15050	12944	11002	9620	5574
		20	19532	18075	16045	14264	12359	11068	9661	7616	6490	3458
	PRM	60	4027	3591	2819	2203	1635	1271	1081	868	782	537
		15	19279	18099	16697	14695	12129	10354	8594	6501	5215	2590
		20	15080	13931	12580	11106	8297	6438	5685	3576	2609	1096
	PRS	60	2009	1199	865	638	430	337	278	230	223	183
		15	24498	23598	21974	19651	16967	15112	13434	11523	10301	6566
		20	20734	19020	16775	15216	13284	11927	10594	8962	7903	4711
	RA	60	2945	2390	1990	1600	1338	1147	964	806	778	518
HMAC-25	Base asphalt	15	23643	23011	20714	18479	15402	14354	12067	10006	8425	4157
		20	17347	15902	14789	12948	10697	9201	7930	5900	4436	2101
		60	2591	2259	1884	1578	1224	1017	879	744	710	501
	PRM	15	24070	23304	21344	19065	16184	14733	12750	10764	9363	5361
		20	19040	17461	15782	14082	11990	10564	9262	7431	6169	3406
		60	2768	2324.5	1937	1589	1281	1082	921.5	775	744	509.5

FIGURE 5

is close to the normal speed. Therefore, dynamic modulus of HMAC at frequency of 10 Hz was systematically analyzed as shown in Figures 6(a)–6(c) [17], and then the corresponding evaluation index was put forward.

As shown in Figure 6, the dynamic modulus of asphalt mixture decreases along with the rise of temperature, and this is mainly because asphalt mixture is sensitive to temperature. When the temperature is higher, asphalt characteristics become physically soft, with strength and stiffness decreasing; thus dynamic modulus decreases. Under the low temperature and high temperature conditions, the dynamic modulus of high modulus asphalt concrete is far greater than that of the ordinary asphalt mixture.

At the frequency of 10 Hz, dynamic modulus of HMAC decreased by 26% from 15°C to 20°C and 91% from 20°C to 60°C, respectively. At the temperature of 60°C, decreasing tendency of HMAC-25 was more striking than that of HMAC-20, which means dynamic modulus of HMAC-20 is superior to that of HMAC-25.

Based on analysis of the above test results and relevant analysis, common values of dynamic modulus were recommended which can be used as road design reference, as shown in Table 8.

3.1.3. Correlation between Dynamic Modulus and Static Modulus of HMAC. In this study, correlations between dynamic modulus and static modulus of high modulus asphalt mixture

were studied to obtain approximate value of dynamic modulus from static modulus. At the frequency of 10 Hz, comparative analyses of the dynamic modulus and static modulus of high modulus asphalt mixture (PRS) are shown in Figures 7(a)–7(c).

At frequency of 10 Hz, the dynamic moduli at 15, 20, and 60°C are 8~10, 8~10, and 1.5~2.5 times as much as static modulus, respectively. This phenomenon shows that dynamic modulus of asphalt mixture is far higher than the static modulus at normal temperature; however, change range of dynamic modulus is less than that of static modulus at high temperature. The mechanical properties of asphalt mixture are mainly viscous when test temperature increases or frequency decreases, whereas the mechanical properties are mainly elastic when test temperature decreases or frequency increases.

As seen from Figures 7(a)–7(c), dynamic modulus was correlated with static modulus and correlation coefficient (R^2) of HMAC-16, HMAC-20, and HMAC-25 was 0.9735, 0.9735, and 0.9702, respectively, meaning that dynamic modulus of HMAC can be obtained from static modulus.

3.2. High Temperature Performance Evaluation

3.2.1. The Evaluation Standard for Dynamic Stability. Conformed to actual response of the pavement, wheel tracking test (60°C, 0.7 MPa) can reflect the change process of

FIGURE 6

TABLE 8: Common values of dynamic modulus at 10 Hz.

Mixture	Dynamic modulus (MPa)		
	15°C	20°C	60°C
HMAC-16, HMAC-20	18000~23000	14000~18000	2600~3200
HMAC-25	16000~20000	14000~16000	1800~2400

permanent deformation. Figures 8(a)–8(c) show the wheel tracking test results (dynamic stability, relative deformation parameters, and comprehensive stability index [18]) for the conventional asphalt mixture and HMAC.

As seen from Figures 8(a)–8(c), dynamic stability and complex stability index of HMAC were bigger than those of conventional mix. Meanwhile, relative deformation of HMAC was much smaller than that of conventional mixture, which means that HMAC is a fine pavement material with good high temperature performance. Moreover, dynamic stability of HMAC-20 and HMAC-25 was larger than that of HMAC-16.

(1) Dynamic stability of high modulus asphalt concrete (PRM, PRS, and RA) has greatly improved, far larger than that of matrix asphalt mixture, almost 3~4 times that of ordinary asphalt mixture; dynamic stability of HMAC (RA) has also

improved, but the improving effect is less obvious than those of high modulus asphalt concrete (PRM, PRS).

(2) Similarly, the comprehensive stability index of high modulus asphalt concrete (PRM, PRS, and RA) is also greatly improved compared with ordinary asphalt mixture. However, the improving effect of RA is not obvious as that of high modulus asphalt concrete (PRM, PRS).

(3) Relative deformation of matrix asphalt mixture and RA mixture is much larger than that of high modulus asphalt concrete (PRM, PRS), and the relative deformation of matrix asphalt mixture is basically the same as that of RA mixture.

(4) Dynamic stability of HMAC-20 and HMAC-25 is greater than that of HMAC-16, whereas comprehensive stability index is smaller than that of HMAC-16, suggesting that rutting resistance of HMAC-25 and HMAC-20 is better than that of HMAC-16.

FIGURE 7

FIGURE 8

To sum up, high modulus asphalt concrete has better dynamic stability, with larger comprehensive stability index and smaller relative deformation, indicating that HMAC has good rutting resistance at high temperature. This is mainly because both asphalt and mixture are modified by additives. Shearing force of dry mixed aggregate will make

high modulus additives dispersed evenly in the mixture, mechanical embedded crowded, reinforced, and cemented, and road performance improved. The improvement effect is more obvious with the increase of dosage.

In addition, dynamic stability and the comprehensive stability index of HMAC (HMAC-20, HMAC-25) are bigger

FIGURE 9

than those of HMAC-16, whereas relative deformation is much smaller than that of HMAC-16, concluding that proposed gradation design for HMAC-20 and HMAC-25 can improve the high temperature rutting resistance of asphalt mixture.

Combined with the experimental results, HMAC common values for dynamic stability (≥ 8000 N/mm) are recommended.

3.2.2. Shear Strength Evaluation Standard. Shear strengths of mixture with different additives were determined at three different temperatures (15, 20, and 60°C), as shown in Figures 9(a)–9(c).

Shear strengths of specimen with additives increased by 19%, 51%, and 67% at 15, 20, and 60°C compared to conventional mixture without additives, which means additives can improve the shear behavior of asphalt mixture.

What is more, shear strengths decrease with the increase of temperature. Shear strengths of specimen with additives increased by 15%~23%, 38%~64%, and 76%~97% at 15, 20, and 60°C compared to conventional mixture without additives, suggesting that the higher the temperature, the larger the shear strength.

Figures 9(a)–9(c) also show that shear strengths among HMAC-16, HMAC-20, and HMAC-25 are almost the same, which means that nominal maximum aggregate size has limited influences on shear behavior of HMAC.

Combined with performance index of dense gradation mixture, uniaxial shear test at 60°C was recommended to evaluate the shear behavior of HMAC and the common values for shear behavior at different temperatures (15, 20, and 60°C) were proposed as shown in Table 9.

TABLE 9: Common values of shear strength.

Temperature	Shear strength (MPa)
15°C	7.5~9.0
20°C	5.5~7.0
60°C	0.8~1.2

3.3. Low Temperature Performance Evaluation. As can be seen from Figure 10, maximum bending strain of HMAC-16 is greater than those of HMAC-20 and HMAC-25, suggesting that nominal maximum aggregate size has evident influences on low temperature performance. Effects of additive dosage on low temperature performance are shown in Figure 11.

Figure 12 shows that the maximum failure strain of HMAC decreased when dosage of additive increased. Maximum failure strain decreased by 34.9% when the percentage of PRS was 0.8% (mass ratio between PRS and mixture) and it decreased by 25.4% when the percentages of RA was 0.8% (mass ratio between RA and mixture), which means that modifier of mixture can reduce the low temperature crack resistance. Thus, dosage or type of the modifier can be chosen based on high temperature stability, and low temperature anticracking performance can just meet the basic requirements.

It is hard to take both high and low temperature performance of asphalt mixture into account. Therefore, performance of modified asphalt mixture should be examined according to the modifying purpose, meaning that the low temperature performance can just meet conventional standard as the main modifying purpose is to improve the high temperature performance.

FIGURE 10: The maximum flexure tensile strain of asphalt mixture.

FIGURE 11: The maximum flexure tensile strain of asphalt mixture with different dosage of additive.

FIGURE 12: Residual stability of HMAC.

3.4. *Water Stability Evaluation.* Results for immersing Marshall test and freeze-thaw splitting strength are shown in Figures 12 and 13. The change trend of residual stability was in accordance with that of freeze-thaw split intensity ratio.

The ranking among the three mixes is HMAC-16, HMAC-20, and HMAC-25 from superior to inferior. HMAC-16 with optimum asphalt content produced larger mineral aggregate surface with the increasing of interacted aggregate superficial

FIGURE 13: Freeze-thaw split intensity ratio of HMAC.

TABLE 10: Comprehensive evaluating system of HMAC performance.

Evaluation index	HMAC-16, HMAC-20		HMAC-25	Test methods
Dynamic stability (N/mm)	≥ 8000		≥ 8000	JTJ T0719
Shear strength (MPa)	15°C	7.5~9.0	7.5~9.0	JTGE40-2007-T0134
	20°C	5.5~7.0	5.5~7.0	
	60°C	0.8~1.2	0.8~1.2	
Static modulus (MPa)	15°C	2600~3000	2300~2700	ASTM D1074 (rate of 2 mm/min)
	20°C	2000~2400	1800~2200	
	60°C	450~650	400~600	
Dynamic modulus (MPa)	15°C	18000~23000	16000~20000	AASHTO TP 62-03
	20°C	14000~18000	14000~16000	
	60°C	2600~3200	1800~2400	

area. Moreover, cohesion of HMAC-16 was higher than those of HMAC-25 and HMAC-20, which means that HMAC-16 has better water stability.

It is believed that the following factors were important and potential to impact water stability of HMAC: (1) additives of asphalt mixture (PRS, PRM, ZQ, and RA); (2) skeleton dense structure of the mixture gradations; (3) alkaline aggregate (limestone). The main purpose of HMAC is to improve the high temperature stability. Thus, there are no special requirements for water stability as long as it meets the standard for conventional mixture.

3.5. HMAC Performance Evaluation System. On the basis of the experimental results and relevant specifications, the HMAC performance evaluation system was put forward as shown in Table 10. Rutting test at the 60°C of temperature is adopted to evaluate high temperature performance, the uniaxial penetration test is adopted to evaluate the shear performance, modulus test is adopted to evaluate the dynamic and static modulus, low temperature bending test is adopted to evaluate low temperature performance, and water stability test is adopted to evaluate retained Marshall stability and freeze-thaw split intensity ratio. On the whole, high temperature performance, shear performance, and modulus refer to evaluation system of HMAC (high modulus asphalt concrete) performance, technical indexes of low temperature performance adopt conventional asphalt mixture standard,

and water stability adopts modified bitumen mixture standard [19, 20].

4. Conclusions

This study provides an experimental investigation on the performance of high modulus asphalt concrete, including the uniaxial compression test, simple performance tests (SPT), wheel tracking test, the uniaxial penetration test, the bending test, freeze-thaw splitting strength test, and immersion Marshall test [21, 22]. The tests were performed on HMAC-16, HMAC-20, and HMAC-25 and the following conclusions can be drawn:

(1) The uniaxial compression results show that temperature has significant effects on static modulus and it is significant at higher temperature. Moreover, modulus of HMAC-20 is superior to those of HMAC-16 and HMAC-25.

(2) The dynamic modulus (E^*) results show that dynamic modulus of HMAC is larger than that of conventional asphalt mixture regardless of load frequency and temperature.

(3) Wheel tracking test shows that high temperature performance of HMAC is better than that of conventional mixture and high temperature performance of HMAC-25 and HMAC-20 is superior to that of HMAC-16. Common values of HMAC dynamic stability (≥ 8000 N/mm) are recommended, and correlation between dynamic modulus and static modulus of HMAC is proposed combined with the

effect of different modifier contents on the dynamic stability of HMAC.

(4) Low temperature anticracking performance and water stability do not need special requirements as long as they meet the specification.

(5) Nominal maximum aggregate size has limited influence on shear behavior of HMAC. Uniaxial shear test is recommended to evaluate the shear behavior of HMAC and the common values of HMAC shear behavior are proposed.

(6) The common values of HMAC performance are proposed based on pavement performance tests. It is expected that further analysis of more samples will be significant in evaluation system of HMAC performance.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

This research was supported by the Transportation Department of Shandong Province (Grant no. 2008Y007), the Fundamental Research Funds for the Central Universities (Grant no. 310821163502), the Transportation Department of Hebei Province (Grant nos. T-2012107, Y-2012014), the National Natural Science Foundation (Grant no. 51008033), and the Transportation Department of Hubei Province of China (Grant no. Ejiaokejiao [2013] 731).

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