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Relationship between repeated triaxial test and Hamburg wheel tracking test on asphalt mixtures

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Abstract: Both the repeated triaxial test (RTT) and the Hamburg wheel tracking test (HWTT) are adopted to evaluate the high temperature performance of the stone mastic asphalt (SMA) and the mastic asphalt (MA). The correlation of the permanent deformations of the MA and the correlation of the deformation developments of the SMA between the two tests are analyzed, respectively. Results show that both the two tests can effectively identify the high temperature performance of mixtures, and the correlation between the final results of the two tests as well as that between the deformation developments of the two tests are excellent with $R^2 > 0.9$. In order to further prove the correlation, viscoelastic parameters estimated from the RTT results is used to simulate the rutting development in the HWTT slabs by the finite element method (FEM). Results indicate that the correlation between the two tests is significant with errors less than 10%. It is suitable to predict the rutting development with the viscoelastic parameters obtained from the RTT.

Key words: asphalt mixture; repeated triaxial test; Hamburg wheel tracking test; correlation; high temperature performance; finite element method

In this paper, some test data obtained from the performance examination on the actual steel deck bridge pavement on Hong Kong-Shenzhen Western Corridor during the process of quality control are deeply analyzed, and some valuable conclusions are achieved. Previous researches indicate that the repeated triaxial test (RTT) and the Hamburg wheel tracking test (HWTT) can well simulate the actual pavement conditions and evaluate the high temperature performance of asphalt mixtures[1-4]. And many relationships among other tests on asphalt mixtures have been analyzed. Carpenter and Vavrik[5] evaluated the correlation between the repeated triaxial test and the asphalt pavement analyzer (APA). Zhang et al.[6] observed a significant correlation between the APA rut test and the repeated simple shear test at constant height (RSST-CH) and the significant correlation between the APA rut test and the repeated load confined creep test. Martin and Park[7] proposed the relationship between the APA rut depth and the RSST-CH permanent shear strain. Pellinen and Xiao[8] concentrated on the relationship between triaxial shear strength and indirect tensile strength of hot mix asphalts. However, there is little study on the relationship between the two test methods of the RTT and the HWTT. This paper introduces some recent research that evaluates the correlation between the results from the two tests, which is useful to recommend the most suitable test method and to predict the rut depth of asphalt mixtures with simple tests.

1 Proportion Design

1.1 Materials

Two mixtures, the stone mastic asphalt (SMA) and the mastic asphalt (MA), which are often used for the steel deck bridge pavement in European countries and Hong Kong, are adopted in this study. Granite aggregates are used as the sources in both mixtures. The polymer-modified-binder (PMB) is used in the SMA, while a mixed binder (30% Shell 60/70 asphalt and 70% lake asphalt) is used in the MA[9]. Properties of aggregates and binders are shown in Tabs. 1 and 2.

Tab. 1 Properties of PMB used in SMA

Properties	Results	Specification	Test method
Penetration at 25 ℃/(0.1 mm)	53	50 to 70	BSEN-1426
Softening point(R&B)/℃	80	≥70	BSEN-1427
Viscosity at 135 ℃/(Pa·s)	1.6		AASHTO T201
RTFOT mass loss/%	0.045	≤1.0	BSEN 12607-1
Elastic recovery at 10 ℃/%	81	≥65	ASTM D6084-97

Tab. 2 Properties of composite asphalt used in MA

Properties	Test results			Test method
	Shell asphalt	Lake asphalt	Composite asphalt	
Specific gravity at 25 ℃/(g·cm^{-3})	1.033	1.40	1.29	ASTM D70
Softening point(R&B)/℃	49.2	93.0	68	IP58
Penetration at 25 ℃/(0.1 mm)	63	0	13	ASTM D5
RTFOT mass loss/%	<0.05	0.24	0.5	ASTM D2872
Viscosity at 100 ℃/(Pa·s)	4.438			ASTM D2171
Viscosity at 135 ℃/(Pa·s)	0.490			ASTM D2171
Mineral matter/%		36.29	26	BS 2000-223

1.2 Gradation design

Gradations of the SMA and the MA, as shown in Tabs. 3 and 4, are consulted from the related technical standards in Denmark and Britain, respectively[10], when used for the actual steel bridge deck pavement. The optimal asphalt

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Tab. 3 Gradation of SMA

Gradation	Percent passing of the sieve size/%						
	14 mm	11. 2 mm	8 mm	5. 6 mm	2 mm	1 mm	0. 075 mm
Target	100	94	44	29	22	19	13
Limit	100	86 to 98	38 to 50	22 to 34	16 to 24	13 to 21	9 to 13

Tab. 4 Gradation of MA

Gradation	Percent passing of the sieve size/%						
	14 mm	10 mm	6. 3 mm	2. 36 mm	0. 6 mm	0. 212 mm	0. 075 mm
Target	100	100	51	51	46	36	24
Limit	100	95 to 100	46 to 56	46 to 56	43 to 49	33 to 39	22 to 26

content of the SMA and the asphalt content in asphalt mastic of the MA are 6. 5% and 14. 5%, respectively.

2 Experiment

2. 1 Test method

MA specimens are trial mixed at the same binder content, but on different days. Variations among specimens prepared on different days are expected due to the influence of change in mixing temperatures, construction sequence and other factors. SMA specimens are fabricated at three binder contents: 6. 5% (optimal) and (6. 5 ± 0. 3)%. By comparing the deformations after the same loading cycles in the RTT and the HWTT both at 60 ℃, the relationship between the two tests can be analyzed. The test conditions are listed in Tab. 5.

Using the criteria developed by NCHRP-report-465[11], the subjective classification of the goodness-of-fit is shown in Tab. 6.

Tab. 5 Test conditions

Test condition	Test method	Sample size	Test equipment	Load condition					
				Deviatoric stress/kPa	Confining pressure/kPa	Square pulse load	Tire load/N	Rolling distance/mm	Frequency/ (pass·min^{-1})
RTT	BSEN 12697-52b	ϕ101. 6mm × 63. 5 mm	Universal test machine	100	25	1 s loading, 1 s rest			
HWTT	BS EN 12697-22	290 mm × 290 mm × 40 mm	Hamburg WTT machine				700	230	52

Tab. 6 Subjective classification of the goodness-of-fit statistical parameters

Rank	R^2	S_e/S_y
Excellent	>0. 90	<0. 35
Good	0. 70 to 0. 89	0. 36 to 0. 55
Fair	0. 40 to 0. 69	0. 56 to 0. 75
Poor	0. 20 to 0. 39	0. 76 to 0. 90
Very Poor	<0. 19	>0. 90

2. 2 Test results

The MA mixture shows very poor high-temperature performance. The deformation of specimens reaches large values or even exceeds the range of the LVDT capability after only a few thousand load cycles. The deformations after 10^3 cycles in the two tests, therefore, are selected as the parameter for analysis, and the relationship between the deformation in the RTT and the rut depth in the HWTT is shown in Fig. 1.

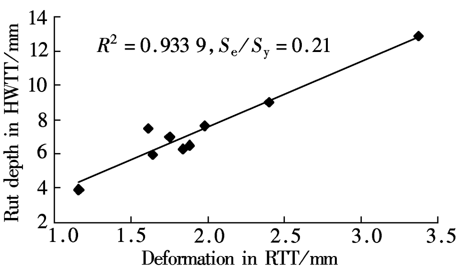

Fig. 1 Relationship between deformation of RTT and HWTT of MA

Comparatively, the SMA with the PMB binder has good deformation resistance performance. Fig. 2 shows the deformation of the SMA at three binder contents in both the RTT and the HWTT. So the values of every 10^3 load cycles from 10^3 to 10^4 cycles can be taken into account, and the relationships between the deformation development features of the two tests are obtained, as shown in Fig. 3.

The goodness-of-fit parameters are shown in Tab. 7.

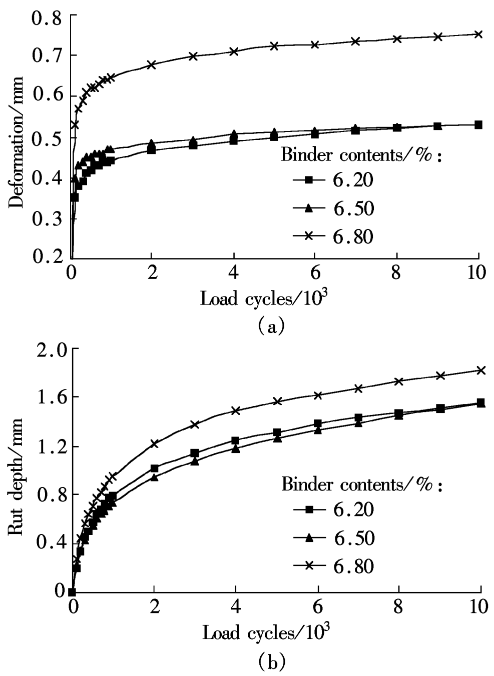

Fig. 2 Test results of SMA. (a) RTT; (b) HWTT

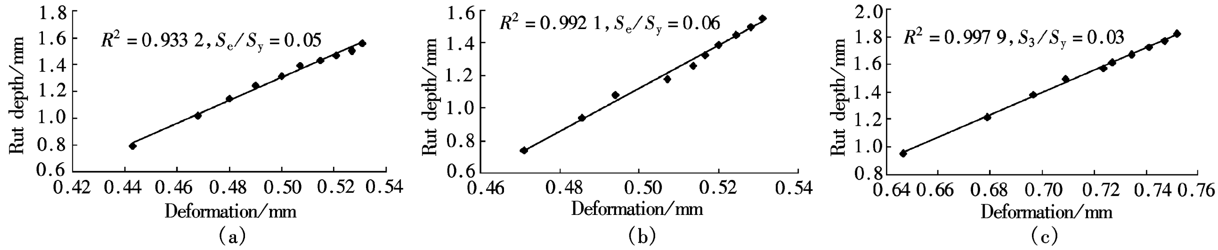

Fig. 3 Relationship between deformation of RTT and rut depth of HWTT. (a) SMA-6.2; (b) SMA-6.5; (c) SMA-6.8

Tab. 7 Results of goodness-of-fit parameters

Type of asphalt mixture	R^2	S_e/S_y	Rank
MA	0.934	0.21	Excellent
SMA-6.2	0.993	0.05	Excellent
SMA-6.5	0.992	0.06	Excellent
SMA-6.8	0.998	0.03	Excellent

The following conclusions can be obtained from the test results. Based on the goodness-of-fit criteria developed by the NCHRP, the results of the MA and the SMA show the excellent correlation between the final deformations from the RTT and the HWTT; furthermore, the results of the SMA indicate that the deformation development of the two tests is also highly correlated. Besides, in both the RTT and the HWTT, the deformation of the SMA with 6.8% binder content is the largest, which indicates that the high temperature performance of the SMA with high binder contents is poor. So it can be proved that both tests can identify mixtures with different high temperature properties. In order to further prove the correlation between the two tests, creep parameters obtained from the RTT are used to simulate the rut development in the HWTT by the finite element analysis method.

3 Finite Element Analysis

3.1 Creep parameters of mixtures

In this paper, the creep model embedded in ABAQUS is adopted to simulate the asphalt mixture, which is described as[4]

$$\dot{\varepsilon}_c = A\sigma^m t^n \tag{1}$$

where $\dot{\varepsilon}_c$ is the slope of strain; σ is the equivalent deviatoric stress, and $\sigma = 0.7$ MPa is used in this paper as the standard stress; t is the accumulative loading time; A, m, and n are the creep parameters related to material properties.

Integrate Eq. (1) and substitute the boundary condition that the strain $\varepsilon_c = 0$ when $t = 0$, and then Eq. (1) is transformed into the following one:

$$\varepsilon_c = \frac{A}{m+1}\sigma^n t^{m+1} \tag{2}$$

The logarithmic transformation is

$$\log\varepsilon_c = n\log\sigma + (m+1)\log t + \log\left(\frac{A}{m+1}\right) \tag{3}$$

In the square pulse load condition of the RTT, with 1 s loading time and 1 s rest, the accumulative loading time t of load cycles N is $1 \times N$ s.

Based on Eq. (3), the parameters (i. e., A, m, n) are obtained from the test results under three different levels of deviatoric stresses (0.3, 0.5, and 0.7 MPa) in the RTT through the linear multi-analysis regression, as shown in Tab. 8.

Tab. 8 Creep parameters of asphalt mixture used in FEM analysis

Asphalt mixture type	Test condition			Creep parameter		
	Deviatoric stress/MPa	Confining pressure/kPa	Temperature/℃	A	m	n
SMA	0.3, 0.5, 0.7	138	60	3.54×10^{-10}	−0.643	1.148
MA				1.08×10^{-9}	−0.215	1.154

3.2 Finite element modeling

In accordance with the actual size of the rut slab, the finite element modeling is built up in 290 mm × 290 mm × 40 mm. The contact pressure of the tire wheel is 0.7 MPa; the rolling distance is 230 mm; the width of the tire wheel is 50 mm. The loading pressure is distributed in the area of 230 mm × 50 mm. The finite element model in ABAQUS is shown in Fig. 4.

If the contact length of the tire wheel is defined as l and the distance of rolling as D, then the loading time per rolling pass is l/D, so the total loading time in the HWTT can be calculated according to the following equation:

$$t = \frac{N}{f}\frac{l}{D} \tag{4}$$

where the contact length l is 20 mm, which is calculated by dividing the weight of single wheel 700 N by the contact pressure 0.7 MPa; N is the rolling pass; f is the frequency, 52 pass/min. For example, if the loading pass is 10^4, then the total loading time is $10^4/52 \times 60 \times 1/230 = 1\ 003$ s.

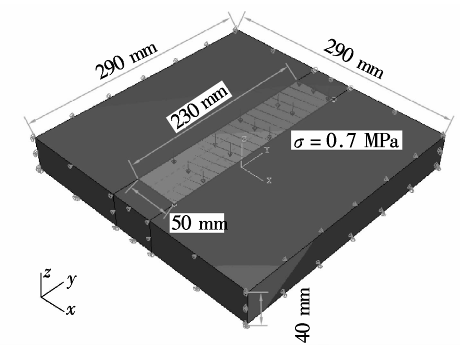

Fig. 4 Model of rut slab in the HWTT

3.3 Calculated results

On the basis of all the above analysis, the rut depth can be calculated by ABAQUS. The calculated values are compared with the measured values in the HWTT as shown in Fig. 5.

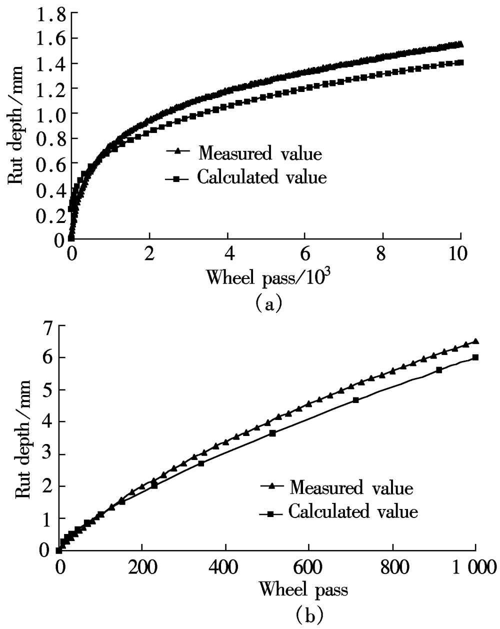

Fig. 5 Comparison of measured and calculated rut depths in HWTT. (a) SMA; (b) MA

It can be seen that the feature of the rut depth development in the HWTT test is similar to that of the rut depth calculated with numerical simulation by ABAQUS using the creep parameters obtained from the RTT. The difference between the measured and the calculated rut depth is less than 10%. This further proves the excellent correlation between the RTT and the HWTT. It also shows that prediction of the rut depth with creep parameters obtained from the RTT is applicable.

4 Conclusions

Some test data obtained from the performance examination on the actual steel deck bridge pavement materials during the process of quality control are deeply analyzed in this paper, and some valuable conclusions are achieved as follows:

1) From the test on SMA, it is found that the features of rut depth development from the RTT and the HWTT are highly correlated. The coefficients of determination R^2 are greater than 0.99, and the standard error ratio S_e/S_y is less than 0.03. From the test on the MA, the R^2 and S_e/S_y values for the correlation of the deformations between the two tests after the same number of loading cycles are 0.934 and 0.21, respectively, so the goodness-of-fit between the two tests is excellent according to the criteria developed by NCHRP.

2) When using the creep parameters obtained from the RTT to simulate the rutting development in the HWTT by ABAQUS, the development trend of the calculated rut depths is close to that of the measured values. The difference between the measured and the calculated rut depths is less than 10%. This further proves the excellent correlation between the RTT and the HWTT. It also shows that prediction of the rut depth with creep parameters obtained from the RTT is applicable.

3) Both the RTT and the HWTT can discriminate mixtures with different properties in terms of rutting potential, so both the two test procedures can be adopted to evaluate the high temperature performance of asphalt mixtures.

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沥青混合料重复三轴试验和汉堡车辙试验的相关性分析

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摘要：采用重复三轴试验和汉堡车辙试验对 SMA 和 MA 两种沥青混合料的高温性能进行评价，并分别分析了这 2 种试验之间的 MA 最终变形的相关性及 SMA 变形发展过程的相关性. 结果显示,2 种试验方法均能够有效区分混合料高温性能的优劣，且两者的最终变形及变形发展过程均呈现极好的线性相关关系，相关性系数均大于 0. 9. 为了更进一步验证相关性，利用重复三轴试验获得混合料的粘弹性参数，对车辙试验进行有限元模拟，结果表明 2 种试验方法具有显著的相关关系，误差小于 10%. 将采用重复三轴试验获得沥青混合料的粘弹性参数用于预测车辙的发展是合理有效的.

关键词：沥青混合料；重复三轴试验；汉堡车辙试验；相关性；高温性能；有限元法
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