Study on low-temperature crack resistance of zirconium tungstate modified asphalt mastic and asphalt mixtures

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ABSTRACT: During the service time of asphalt pavement, low-temperature cracking is one of the main deteriorations which could influence the performance of pavement and shorten the service life of the pavement. One of the main causes of low-temperature cracking is that the thermal stress inside the asphalt mixture cannot well relax along with time and then accumulate continuously until exceeding the tensile strength when the temperature drops suddenly in winter. To improve the thermal cracking resistance of asphalt mixture, zirconium tungstate (ZT) with a negative expansion property was introduced to partly replace the mineral powder in asphalt mortar and asphalt mixtures in this study. From the thermal contraction test, it was conducted that the ZT could reduce the low-temperature contraction coefficient of asphalt mortar as well as asphalt mixture. Besides, the contraction coefficient of mortar had a good positive correlation with the contraction coefficient of mixtures under different ZT content conditions. Results of the Thermal Stress Restrained Specimen Test showed that the cracking temperature and transition temperature of asphalt mixtures reduced with the increase of ZT contents. The research of this subject can provide a new idea for solving the low-temperature contraction cracking and design of asphalt pavement.

Keywords: Asphalt mortar, asphalt mixtures, zirconium tungstate, low-temperature cracking

1 INTRODUCTION

In the course of pavement service, low-temperature cracking is one of the main failure modes, which has appeared in many countries in the world (Das et al. 2013, Son et al. 2019). Because most of the materials have the characteristics of thermal expansion and cold contraction, it is difficult to avoid temperature shrinkage cracks in the pavement under extreme temperature (Park et al. 2016, Judycki, 2016). For example, in China, the technical index of asphalt pavement design specification for the high-grade highway is that no more than three low-temperature cracks can be allowed within 100 meters after completion acceptance. However, low-temperature cracking not only affects the driving comfort of the road surface but also has a greater impact on the continuity and safety of the road surface, which will increase the fuel cost and time cost of driving (Aflaki and Hajikarimi 2012, Sun et al. 2018). Besides, water and impurities could corrode the pavement structure through

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cracks, and the water remaining in the pores will cause further damage to the pavement structure when it is frozen at low temperatures (Ren and Sun 2017, Ahmad and Khawaja 2018).

To improve the ability of pavement structure to resist low-temperature cracking, scholars have carried out a lot of related research. Results indicate that the asphalt binder has a significant influence on the low-temperature performance of asphalt mixture (Judycki, 2014). However, asphalt binders show “hard” and “brittle” mechanical properties in the low-temperature environment. Besides, with the aging process, the asphalt becomes more “hard” and “brittle”, which brings adverse impact on the low-temperature performance of asphalt mixture (Wu et al. 2012, Wang et al. 2013). Therefore, many researches focus on improving the performance of asphalt binders to improve the ability of asphalt mixture to resist low temperature cracking. The modification of asphalt has aroused great interest of researchers. The results show that styrene-butadiene-styrene (SBS) or rubber powder can improve the low-temperature performance of asphalt binder and reduce the low-temperature cracking of the asphalt mixture (Nam and Bahia 2009, Hajikarimi et al. 2013). Besides, the addition of 0.2 ~ 0.4% lignin fiber can also improve the low-temperature performance of asphalt mixture (Luo et al. 2019, Yue et al. 2019). The thermal conductivity of the asphalt mixture can be reduced by adding expanded polypropylene (EPP) microspheres to the asphalt mixture, to change its thermodynamic performance (Shi et al. 2019). Besides, the use of lightweight aggregate can reduce the thermal conductivity of asphalt mixture, to improve its mechanical properties at low temperatures (Khan and Mrawira 2008). Open-graded friction course (OGFC) has a lower thermal shrinkage coefficient and is more potential to resist low temperature cracking than asphalt concrete (AC) (Islam et al. 2018). Although researchers have carried out a lot of research on asphalt binder, aggregate, and mixture gradation to improve the low-temperature cracking performance of asphalt mixture, the effect is still not particularly obvious. The main reason is that the contraction stress of the asphalt mixture in the low-temperature environment is difficult to avoid. If the thermal stress in the low-temperature environment can be greatly reduced, the low-temperature cracking resistance of asphalt mixture will be greatly improved. Negative thermal expansion materials can be tried to achieve this function.

Zirconium tungstate (ZT) was successfully prepared in 1996 by Mary et al (Mary et al. 1996). They found that the negative thermal expansion temperature range of zirconium tungstate is - 273 °C ~ 777 °C, and the isotropic properties of ZT was good. This discovery makes it possible for the practical application of negative thermal expansion materials. ZT has been widely used in the preparation of composite materials due to its wide range of reverse expansion temperature range and isotropy. ZT was combined with aluminum alloy to make the alloy. When the volume of ZT was three times that of aluminum alloy, the contraction coefficient of the alloy could reach 0 (Matsumoto et al. 2003). ZT and zirconia were used to produce composite materials, and the expansion coefficient of the composites was close to 0 when the mass of zirconia was twice that of ZT (Niwa et al. 2004). Also, ZT was used to improve the performance of cement concrete, and the results show that the contraction coefficient of cement concrete was close to 0 when the mass fraction of ZT reaches 60% (Kofteros et al. 2001). If the thermal contraction coefficient of asphalt mixture can be improved by using ZT, it will greatly change the anti-cracking ability of asphalt mixture at low temperatures.

Based on the above analysis, ZT with a negative expansion property was introduced to partly replace the mineral powder in asphalt mastic and asphalt mixtures in this study. Through the performance changes of asphalt mortar and asphalt mixture, the influence of zirconium tungstate on the low-temperature crack resistance of asphalt mixture was explored and evaluated. The research of this subject can provide a new idea for solving the low-temperature contraction cracking and design of asphalt pavement.

2 MATERIALS

2.1 Asphalt

The 70 base asphalt selected in this project is the asphalt binder commonly used in northern China, and its technical indicators are shown in Table 1. The test method refers to “Standard test methods of bitumen and bituminous mixtures for highway engineering” (JTG E20-2011).

Table 1. Technical index of 70 base asphalt.

Technical indexes	Test result	Criteria	Testing method
Penetration (25 °C, 100 g, 5 s)/0.1 mm	69	60-80	JTG T0604-2011
Penetration index	-0.15	1.5 ~+ 1.0	
Extension (10 °C)/(cm)	31	≥ 15	JTG T0605-2011
Extension (15 °C)/(cm)	>100	≥ 100	
Softening point (R&B)/°C	51	≥ 45	JTG T0606-2011
Density (15°C)/kg/m ³	1.003	-	JTG T0603-2011
Residue after RTFOT			
Quality change/%	0.53	± 0.8	JTG T0610-2011
Residual penetration ratio (25°C)/%	63	≥ 61	JTG T0604-2011
Extension (10 °C)/(cm)	11	≥ 6	JTG T0605-2011

2.2 Fillers

ZT is introduced to partly replace the mineral powder in asphalt mastic and asphalt mixtures. The appearance of ZT used in this study is a bright green powder, and the purity is above 99.5%. The mineral powder is made of limestone, and its technical indicators are shown in Table 2, and the test method refers to “Test methods of aggregate for highway engineering” (JTG E42-2005). In this study, the fillers are divided into five kinds, and the mass ratio of ZT to the total filler is 0%, 20%, 40%, 60%, and 80%, respectively.

Table 2. Technical index of mineral powder.

Technical indexes	Test result	Criteria	Testing method
Density/kg/m ³	2.63	≥ 2.50	JTG E42-T0352-2005
Moisture content/%	0.61	≤ 1	JTG E42-T0103-2005
Hydrophilic coefficient	0.6	< 1	JTG E42-T0353-2005
Appearance	No agglomeration	No agglomeration	-

2.3 Asphalt concrete

The asphalt concrete (AC-13) is used as the test object, and the aggregate and gradation are carried out according to the requirements of “Technical specification for construction of highway asphalt pavement” (JTG F40-2004). The optimum asphalt content is determined to be 4.9% through the mixture proportion design. Besides, the mixing ratio of asphalt mortar is selected as the mass ratio of asphalt and filler in AC-13.

3 TEST METHODS

3.1 Thermal contraction test of asphalt mortar

The coefficient of thermal contraction of asphalt mortar refers to the volume change value with the change of unit temperature, which could well characterize the low-temperature performance of asphalt mortar (Islam and Tarefder 2015). The low-temperature performance of asphalt mortar deteriorates with the increase of temperature contraction coefficient.

To measure the volume deformation of the mortar more accurately, the contraction coefficient test device developed by the research group is used to carry out the test, as shown in Figure 1. During the test, the prepared asphalt mortar specimen is put into the metal chamber of the equipment, and then the top cover is covered. The fixed bolts are tightened, and the base is adjusted to make the measuring instrument in a horizontal state. Then ethanol is injected into the glass calibration tube, and the device is placed in the environment of different temperatures. Finally, the change value of the mortar volume is calculated according to the change of ethanol liquid scale.

Figure 1. Device of asphalt mortar contraction coefficient.

During the test, constant temperature equipment is used for temperature control. Firstly, the initial temperature is set, and the test device is put into the temperature control equipment for 4 hours to read the initial value of the calibration tube. Then the temperature is adjusted to the next setting value and the value of the calibration tube is read after 4 hours of heat preservation. In this way, the volume changes of asphalt mortar at - 20 °C, - 10 °C, and 0 °C are measured. In the process of temperature change, the volume of the test device and ethanol will change as well, resulting in system errors. Therefore, the metal specimen with a known volume contraction coefficient and the same volume as the standard asphalt mortar specimen is used to calibrate the system errors. The calibration process is also carried out at - 20 °C, - 10 °C, and 0 °C. Finally, the thermal contraction coefficient of asphalt mortar is calculated according to formula (1).

$$\beta_i = \frac{(L_{i+1} - L_i) - \Delta V_{system-errors}}{(T_i - T_{i+1}) \times V_{specimen}} \quad (1)$$

where β_i is the coefficient of thermal contraction of asphalt mortar, L_i is the value of calibration tube at time T_i , $\Delta V_{system-errors}$ is the system errors calibrated by the metal specimen, $\Delta V_{specimen}$ is the volume of asphalt mortar specimen.

3.2 Thermal contraction test of asphalt mixture

The contraction capacity of asphalt mixture can well reflect its low-temperature performance. Many parameters affect the thermal contraction coefficient of asphalt mixture, including mineral aggregate gradation of asphalt mixture, asphalt properties, and asphalt dosage. The thermal contraction coefficient of the asphalt mixture is about $2.21 \times 10^{-5} \sim 3.33 \times 10^{-5}$ ($/^{\circ}\text{C}$) in several studies (Zeng and Shields 1999, Akentuna et al. 2018). To verify the low-temperature performance of ZT modified asphalt mixture, a test on the thermal contraction coefficient of the asphalt mixture is carried out.

The test system includes an incubator for temperature control, a test chamber for holding test pieces, a displacement sensor system, and a temperature sensor system. The asphalt concrete specimens are formed by the method of the wheel rolling and cut into $200 \text{ mm} \times 35 \text{ mm} \times 30 \text{ mm}$ prisms.

The initial temperature was set at 20°C with a cooling rate of $5^{\circ}\text{C}/\text{h}$. The temperature range is set at $-20^{\circ}\text{C} \sim 20^{\circ}\text{C}$. Because the measurement system will shrink due to the change of temperature, the instrument without the test piece is calibrated, and the calibration temperature range is $-20^{\circ}\text{C} \sim 20^{\circ}\text{C}$. Finally, the thermal contraction coefficient of the asphalt mixture is calculated according to formula (2).

$$\alpha = \frac{(L_{i+1} - L_i) - L_{\text{system-errors}}}{L_{\text{specimen}} \times (T_{m+1} - T_m)} \quad (2)$$

where α is the thermal contraction coefficient of asphalt mixture, L_i is the value of displacement sensor at time T_i (mm), $L_{\text{system-errors}}$ is the system errors calibrated by standard test, L_{specimen} is the height of test piece (mm).

3.3 The thermal stress restrained specimen test

The device of thermal stress restrained specimen test is composed of a temperature control system, loading system, data acquisition system, and measurement system, as shown in Figure 2. The device can accurately control the length variation of the specimen with an accuracy of $3 \mu\text{m}$. The maximum allowable deformation of asphalt mixture is 4 cm. The temperature sensor is used to measure the test temperature, and the accuracy is 0.25°C . The accuracy of the stress measuring device is 10N.

Figure 2. Test of thermal stress restrained specimen.

4 RESULTS AND DISCUSSIONS

4.1 Coefficient of thermal contraction asphalt mortar

The contraction coefficient of asphalt mortar containing 0%, 20%, 40%, 60%, and 80% ZT was tested. At least 3 parallel tests were conducted for each group. Finally, the contraction coefficient of asphalt mortar is obtained, as shown in Table 3.

It can be seen from Table 3 that the thermal contraction coefficient of asphalt mortar is not completely the same in different temperature ranges. However, with the addition of ZT, the thermal contraction coefficient of asphalt mortar decreases gradually. The results show that the negative expansion of zirconium tungstate can reduce the thermal contraction coefficient of asphalt mortar. The average contraction coefficient of 80% group is 60.55% lower than that of the 0% group. The addition of zirconium tungstate can effectively slow down the contraction trend of asphalt mortar in the low-temperature environment.

Table 3. Test results of volume contraction of asphalt mortar.

Content of ZT in filler	T_i (°C)	Contraction coefficient ($/^{\circ}\text{C}\times 10^{-4}$)			Average contraction coefficient ($/^{\circ}\text{C}\times 10^{-4}$)
0%	0	7.24	8.44	7.52	6.92
	-10	5.89	5.65	6.75	
	-20				
20%	0	6.69	5.94	6.95	6.12
	-10	6.03	5.62	5.46	
	-20				
40%	0	6.77	5.96	5.68	5.32
	-10	4.36	4.87	4.26	
	-20				
60%	0	3.48	4.1	3.67	4.33
	-10	5.2	4.44	5.06	
	-20				
80%	0	2.29	1.98	2.19	2.73
	-10	3.18	3.2	3.54	
	-20				

4.2 Coefficient of thermal contraction asphalt mixture

The displacement variation under unit temperature is taken as the index of the contraction coefficient of the asphalt mixture. In the experiment, the cooling rate was 5 °C/h, and the data were collected every 1 hour. The contraction of asphalt mixture with different content of ZT is obtained, as shown in Figure 3. According to formula (2), the thermal contraction coefficient of the asphalt mixture is calculated, as shown in Table 4.

Table 4. Thermal contraction coefficient of asphalt mixture.

Content of ZT in filler	Contraction coefficient ($\times 10^{-5}/^{\circ}\text{C}$)	Correlation coefficient
0%	3.34	0.9884
20%	3.08	0.9817
40%	2.83	0.9645
60%	2.78	0.9598
80%	2.51	0.9489

The contraction coefficient of asphalt mixture (0% group) without ZT is 3.34×10^{-5} ($/^{\circ}\text{C}$) in the range from -20°C to 20°C , which is very close to the contraction coefficient of asphalt mixture measured by other scholars (Dong et al. 2012, Akentuna et al. 2018). It can be seen from Table 4 that the contraction coefficient of the asphalt mixture gradually decreases with the increase of ZT content. The contraction coefficient of 80% group was 24.85% lower than that of the 0% group. Compared with the contraction coefficient test of asphalt mortar, the decrease range of the contraction coefficient of the asphalt mixture with ZT is smaller. The main reason is that the stone accounts for the majority of the asphalt mixture, and the contraction coefficient of the mixture is affected by the properties of the stone. On the whole, the low-temperature contraction trend of asphalt mixture is weakened by adding ZT.

Figure 3. Fitting results of contraction test of asphalt mixture.

Asphalt mixture is composed of asphalt mortar and stone, and there is a close connection on low-temperature performance between asphalt mortar and asphalt mixture. The correlation of contraction coefficient between ZT modified asphalt mortar and asphalt mixture was analyzed. The contraction coefficient of ZT modified asphalt mixture decreases with the decrease of contraction coefficient of the asphalt mortar, and the correlation coefficient reaches to 0.9365, as shown in Figure 4. It shows that the contraction coefficient of the mixture has a good positive correlation with the contraction coefficient of mortar.

4.3 Results of the thermal stress restrained specimen test

The thermal stress restrained specimen test can simulate the stress process of pavement cracking at low temperatures. Among many evaluation indexes, the cracking temperature and the transition temperature have good consistency in evaluating the low-temperature performance of the asphalt mixture. In this study, the low-temperature performance of ZT modified asphalt mixture is evaluated by cracking temperature and transition temperature. The results of the thermal stress restrained specimen test are shown in Figure 5.

Figure 4. Fitting results of contraction coefficient of asphalt mortar and asphalt mixture.

Figure 5. Results of thermal stress restrained specimen test.

It can be seen from Figure 5 that the cracking temperature and transition temperature of asphalt mixture gradually decrease with the increase of ZT content, which shows that the low-temperature performance of asphalt mixture could be improved by adding ZT. And the cracking temperature of the test group added ZT is at least 1.8 °C lower than that of the ordinary asphalt mixture. Besides, the cracking temperature of the 80% group was 10.34% lower than that of the 0% group, and the transition temperature of the 80% group was 15.27% lower than that of the 0% group. It shows that the low-temperature performance of the ZT-modified asphalt mixture is better than that of ordinary asphalt mixture. Moreover, the cracking temperature and transition temperature of the asphalt mixture have a good consistency.

Although the cracking temperature of asphalt mixture only decreases by 2-3 °C after adding ZT, the thermal stress restrained specimen test is also related to the size effect of the specimen, which can not fully represent the real service condition of asphalt pavement. Therefore, the test results mainly show the influence trend of ZT addition on the low-temperature performance of asphalt mixture and provide some new ideas to improve the low-temperature performance.

5 CONCLUSION

- (1) The negative expansion of ZT can reduce the thermal contraction coefficient of asphalt mortar. And the average contraction coefficient of asphalt mortar of 80% group is 60.55% lower than that of 0% group.
- (2) The contraction coefficient of asphalt mixture gradually decreases with the increase of ZT content. And the contraction coefficient of the 80% group was 24.85% lower than that of the 0% group. Besides, the contraction coefficient of the asphalt mixture has a good positive correlation with the contraction coefficient of the asphalt mortar.
- (3) The low-temperature performance of ZT modified asphalt mixture is better than that of ordinary asphalt mixture. The cracking temperature of the asphalt mixture of 80% group is 10.34% lower than that of 0% group, and the transition temperature of the asphalt mixture of 80% group is 15.27% lower than that of 0% group.
- (4) The addition of ZT could improve the cracking resistance of asphalt mixture at low temperatures. Although the cost of ZT is high at present, the unit price of material has been greatly reduced with the improvement of preparation technology in recent years. In the following study, other mechanical properties of asphalt mixtures mixed with ZT will be fully verified. We hope that this research can provide a new idea for solving the low-temperature shrinkage cracking and design of asphalt pavement.

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