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Effects of surface modified phosphate slag powder on performance of asphalt and asphalt mixture

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HIGHLIGHTS

- The application of phosphorus slag powder (PSD) is environmental friendly.
- The PSD modified by TM-P has good dispersibility and stability in asphalt.
- Phosphorus slag modified asphalt (PSMA) has excellent anti-aging property.

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ABSTRACT

Phosphate type single alkyl oxygen base titanates TM-P was used to modify the surface of phosphorus slag powder in this paper. The surface characteristics and modification mechanism of phosphorus slag particles were characterized by using Scanning Electronic Microscopy (SEM). The effects and mechanism of the surface modified phosphorus slag powder to the asphalt and asphalt mixtures were analyzed by Fourier Transform Infrared Spectroscopy (FTIR), dynamic shear rheological test (DSR), Marshall test, rutting test and freeze-thaw splitting test. The results show that phosphorus slag powder modified by TM-P (10% by weight of the powder) enhance the compatibility with asphalt, resulting in the increase of anti-aging, rutting resistance and water damage resistance of asphalt mixture.

1. Introduction

China is full of phosphate and the total storage is only after Morocco in in the world [1]. According to statistics, 8–10 tons of phosphate slag will be produced with the average production of 1 ton of yellow phosphorus. China produces nearly 900 million tons of phosphate slag every year, resulting in serious waste of land resources and groundwater pollution [2,3]. Hence, the application of phosphate slag into highway construction is not only conducive to environmental protection and resources conservation but also beneficial to economic development.

Due to the superior characteristics of powder material, inorganic micro powder has been selected as one of the optimal choice to improve the performance of asphalt and mixture [4]. As one of the inorganic micro powder, phosphorus slag powder has great specific surface area and high surface energy because its particle size is too small to micron or even nanometer level. Under the Coulomb force and van der Waals force, the powder particles will be reunited, contributing to performance degradation [5,6].

At present, phosphate slag is mainly used in the field of building materials. As a raw material or modifier for cement, phosphorus slag powder can significantly enhance the strength, workability and durability of cement and cement concrete [7–11]. Furthermore, it can also be used as the raw material to produce phosphorus slag Brick and self-leveling material [12]. In addition, due to full of Si, P, Ca and other necessary elements for the growth of crops, phosphate slag is commonly processed to produce agricultural fertilizer [13]. However, there are few studies on the phosphate slag powder selected as asphalt or asphalt mixture modifier. Paul T. Foxworthy et al. have shown that phosphate slag-based slag aggregates can be successfully applied to asphalt concrete [14]. Our research team have found that the addition of phosphorus slag powder can improve anti-aging, rutting resistance, flame retardant of asphalt mixture [15–17]. Due to the nature characteristic of inorganic, polar and surface hydrophobic of phosphorus slag powder, the compatibility difference between phosphorus slag powder and asphalt will exist, which will lead to separation between the two materials and phos-

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phorus slag powder disperse uneven and is easy to segregation, thereby decreasing some aspects of road performance.

Therefore, how to reduce the agglomeration of the ultrafine particles of phosphorus slag and improve the interface compatibility between the slag powder and asphalt to improve performance have become the key factor to affect the application of the slag powder in asphalt.

2. Materials and methods

2.1. Surface modification of phosphorus slag powder

Due to the nature characteristic of inorganic, polar and surface hydrophobic and oleophobic, phosphorus slag powder is incompatible with asphalt, which will lead phosphorus slag powder to uneven dispersion and easy segregation, so separation between the two materials will occur. Thus, it is necessary to modify the phosphorus slag powder before adding to asphalt.

Determination of the best modified materials: in order to solving the reunion phenomenon and improving the dispersion and stability of the slag powder in the asphalt, phosphate type single alkyl oxygen base titanates TM-P and TM-931, composite aluminum titanium coupling agent A4, silane coupling agent KH-550 and KH-570 were selected as surface modifiers to modify phosphorus slag powder respectively. The reaction continued with 3% (by weight of the phosphorus slag powder) modifier at 80 ± 1 °C for 30 min. The effect of modified phosphorus slag powder was evaluated by wetting test, oil absorption and dispersibility test. The results show that TM-P has the best effect on surface modification of phosphorus slag powder, so it was selected as the optimal surface modifier for further study.

The optimal conditions for the modification can be defined as below: to improve the modification effects of the phosphorus slag powder, it is necessary to determine the modification conditions. To determine the optimum modification conditions, different reaction time, different temperature and different content of modifier were discussed by wetting and oil absorption test in this paper. The result shows that it is effective to modify the phosphorus slag powder with 2.5% (weight by asphalt) TM-P reacting for 35 min under 70 °C. A layer of TM-P was formed on the surface of the phosphorus slag powder particles and the dispersibility of the modified slag powder in asphalt was better according to SEM results.

The morphology of the phosphorus slag powder modified by TM-P and unmodified was comparative analyzed by S-3000N scanning electron microscope made by HITACHI (Hitachi) Company in Japan. The results were shown in Figs. 1 and 2.

Figs. 1 and 2 show that the agglomeration of the non-surface-modified phosphate slag powder is more serious, and the agglomerated particles range from several micrometers to about ten micrometers, while the TM-P modified phosphate slag powder can be dispersed evenly. This is mainly because that the unmodified phosphate slag powder too small to have a great deal of specific surface area and lots of surface energy. And the powder particles have a tendency to agglomerate and reunite under the Coulomb force and van der Waals force.

2.2. Preparation of modified asphalt of phosphorus slag powder

70# (based on Penetration) petroleum asphalts for heavy traffic road pavement (AH-70) was used as base asphalts to blend with TM-P by colloid mill for preparing the TM-P modified asphalts. The results show that with the 10% (weight by asphalt) addition of phosphate slag powder, the modified asphalt has better rutting resistance and anti-aging performance [13]. Therefore, the asphalt modified by phosphorus slag powder was prepared in a content of 10%. The preparation device is shown in Fig. 3 and the sample is shown in Fig. 4.

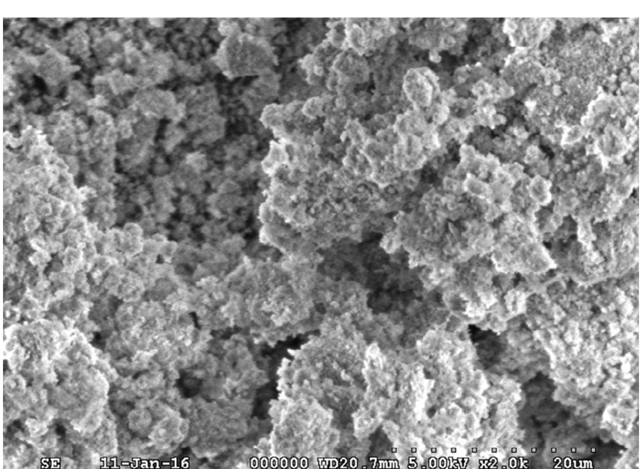

Fig. 1. Unmodified phosphorus slag powder.

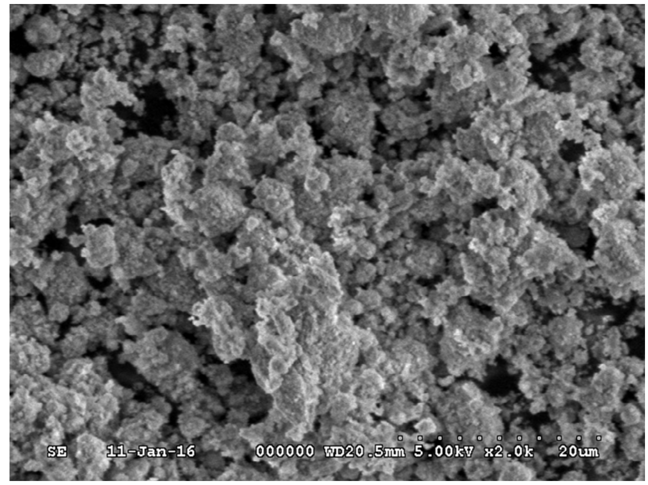

Fig. 2. Modified phosphorus slag powder.

Fig. 3. Reaction device.

Specific experimental steps are depicted as follows:

1) Add 10% of the prepared phosphorus slag powder after being dried in an oven at 130 °C for 4 h to the asphalt and keep stirring, and then put the modified asphalt in an oven of 130 °C to swollen for about 10 min.
2) The colloid mill was preheated for two hours at 130 °C before the test.
3) Open the colloid mill and pour the asphalt from the inlet to cut in the colloid mill for about 30 min to prepare the asphalt modified by phosphorus slag powder.

2.3. Preparation of asphalt mixture specimen

2.3.1. Physical properties test

On the basis of "Asphalt & Asphalt Mixture Test Code" (JTG E20-2011). The physical characteristics of the virgin asphalts and modified asphalts were detected, for instance the penetration, ductility and softening point, respectively. The test results are shown in Table 3.

2.3.2. Mineral grade design

According to the results of aggregate screening, AC-16 asphalt mixture gradation designing by Marshall method was selected in this paper. The synthetic gradation is shown in Fig. 5.

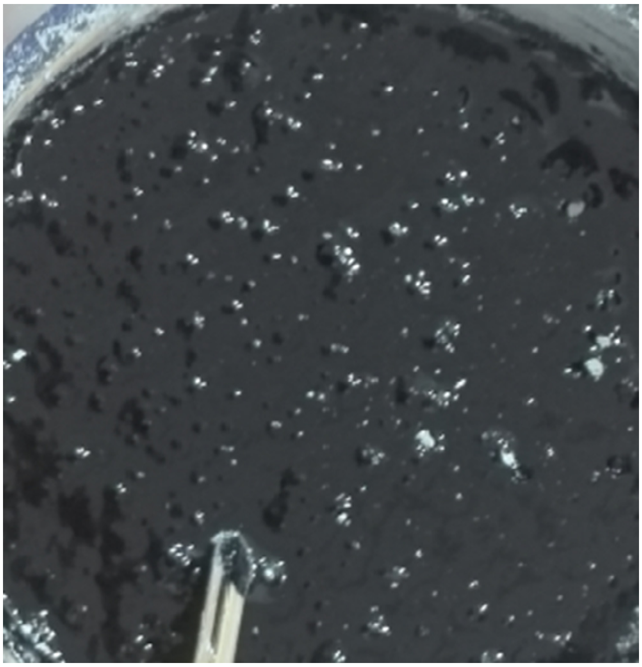

Fig. 4. Modified asphalt.

2.3.3. Determination of the optimum asphalt content

According to the "Asphalt & Asphalt Mixture Test Code" (JTG E20-2011) and combining with engineering actual situation, five modified and unmodified asphalt content (3.9%, 4.3%, 4.7%, 5.1%, 5.5%) were carried out respectively to determine the optimum asphalt content with the same standard Marshall test conditions (150 ± 5 °C, double-sided compaction of 75 times). Based on the physical and mechanical indexes of the specimen, it is recommended that the optimum asphalt aggregate ratio for virgin asphalt mixture is 4.6% and 4.7% for the slag powder modified asphalt one. The specific results are shown in Tables 1 and 2.

3. Test methods and analysis

3.1. Asphalt performance tests

The slag powder modified by TM-P was added into the virgin asphalt mixing with colloid mill to prepare the slag powder modified asphalt. Under the same experimental conditions, the performance indexes of three asphalts namely 70# asphalt, unmodified phosphate slag powder modified asphalt and TM-P modified phosphorus slag powder asphalt were tested respectively.

3.1.1. Physical properties test

The routine performance of the three asphalts were tested in accordance with the specification, respectively. The results are summarized in Table 3.

Table 4 shows that addition of TM-P in asphalt shows increase in softening point while decrease in penetration value. The softening point of TM-P modified phosphorus slag powder asphalt was increased by 1.7 °C and the penetration rate was decreased by 0.31 mm compared with the virgin asphalt, and the unmodified phosphorus slag powder asphalt 0.9 °C and 0.26 mm. It shows that the addition of TM-P modified phosphorus slag powder has a favourable effect on the viscosity and high temperature properties of virgin asphalt.

3.1.2. Dynamic Shear Rheometer (DSR) test

Based on the idea of rheology, extensive experimental researches were carried out on the high and low temperature performance of the asphalt binder and SHRP proposed the new rheological performance test method of the asphalt binder [18]. According to the SHRP asphalt test specification requirements, the rheological properties of the asphalt binder were measured using DSR on three kinds of specimens namely initial asphalt specimen, short-term aged specimen and long-term aged specimen. The results are shown in Figs. 6–8.

(M-TM-P means modified phosphate type single alkyl oxygen base titanates and U-TM-P means unmodified phosphate type single alkyl oxygen base titanates)

The experimental analysis shows that:

(1) The $G^*/\sin\delta$ of the three asphalts after short-term aging through the rotating film oven test (RTFOT) have the same trend contrasting with the original ones, both decrease along with the temperature increment. The anti-rutting factors of asphalt modified by TM-P modified phosphate slag power and non-modified phosphate slag power were increased by 61.76% and 21.41% under 50 °C comparing with that of virgin asphalt, while the phase angle δ decreased. Studies conducted by numerous researchers showed that the anti-rutting factor reflects the anti-permanent deformation ability of the asphalt binder, the larger the value, the smaller the flow deformation and the better the rutting resistance

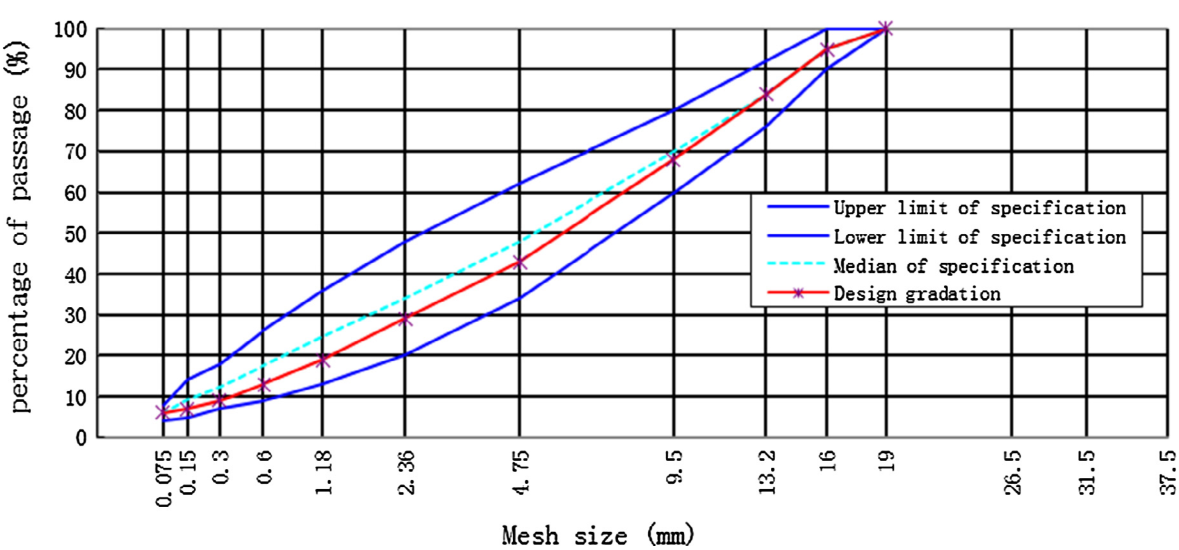

Fig. 5. Aggregate of AC-16C asphalt mixture.

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Table 1
The results of Marshall test of the best slag ratio of 70 # asphalt mixture.

Bitumen aggregate ratio (%)	Bulk density (g/cm^3)	Porosity VV (%)	Mineral gap rate VMA (%)	Asphalt saturation VFA (%)	Stability (kN)	Flow value (mm)
4.6	2.441	4.72	14.5	68.3	17.92	28.9

Table 2
The results of Marshall test of the best slag ratio of phosphate slag powder asphalt mixture.

Bitumen aggregate ratio (%)	Bulk density (g/cm^3)	Porosity VV (%)	Mineral gap rate VMA (%)	Asphalt saturation VFA (%)	Stability (kN)	Flow value (mm)
4.7	2.444	4.56	14.4	68.1	20.21	29.1

Table 3
Asphalt test results.

Test index		AH-70 virgin asphalt	Unmodified phosphate slag powder asphalt	Modified phosphate slag powder asphalt	Technical requirements
Softening point TR&B (°C)		51.4	52.3	53.1	44–54
Ductility (10 cm/min, 15 °C) (cm)		126	115	116	≥100
Penetration (25 °C,100 g, 5 s) (0.1 mm)		69.7	67.12	66.63	60–80
Solubility (%)		99.91	99.92	99.54	≥99
The remains after RTFOT	Quality change (%)	−0.1	−0.31	−0.35	≤±1.0
	Residual penetration ratio 25 °C(%)	73	74	74	≥55

Table 4
Asphalt Aged Index·

Asphalt species	UIA
Virgin asphalt	2.8175
Unmodified Phosphate Slag Powder Asphalt	2.3795
TM-P modified phosphorus slag powder asphalt	2.3701

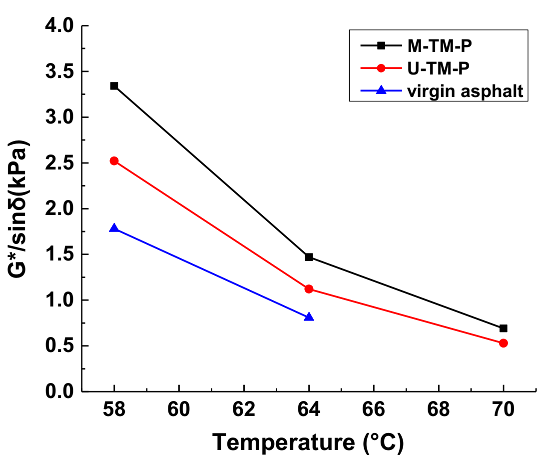

Fig. 6. Initial asphalt ($G^*/\sin\delta$).

[19]. It can be seen that the addition of TM-P modified phosphorus slag powder improves the anti-rutting performance of asphalt even more effective than the unmodified one. It is due to that the phosphorus slag powder in asphalt has a better dispersion after surface modification, and the surface of the hydrophobic base is more easily compatible with asphalt to form a stable polymer. Therefore, the elasticity of asphalt can be enhanced. In short, TM-P modified slag powder can improve the anti-rutting performance and anti-aging properties of asphalt effectively.

(2) The anti-fatigue factors of the three selected asphalts all increased with the decrease of temperature. The fatigue resistance of asphalt modified by TM-P modified phosphate

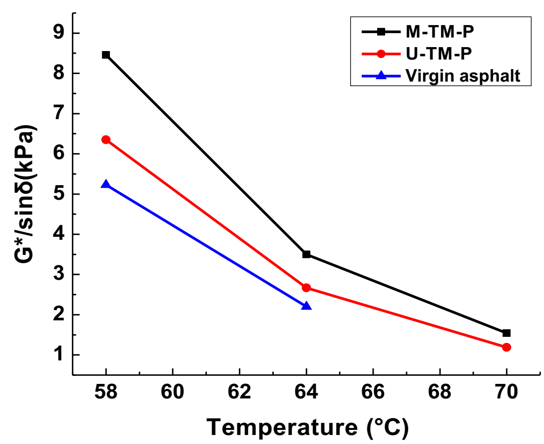

Fig. 7. Short-term aged asphalt ($G^*/\sin\delta$).

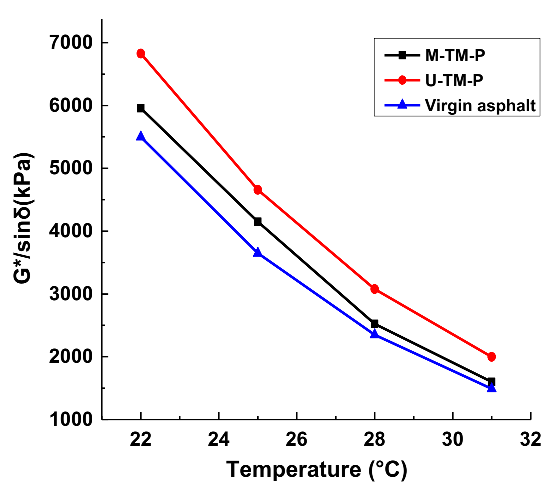

Fig. 8. Fatigue factor with temperature change. (M-TM-P means modified phosphate type single alkyl oxygen base titanates and U-TM-P means unmodified phosphate type single alkyl oxygen base titanates.)

slag powder increased slightly comparing with that of virgin asphalt, but less obvious than that of unmodified phosphate slag powder. Meanwhile, both meet the specification requirements. It indicates that the addition of slag powder to the asphalt have a slight negative effect on the fatigue resistance.

3.1.3. Aging performance test based on rheological performance

The three selected asphalt were subjected to aged treatment by RTFOT method. The rheological properties of the asphalt after aging were analyzed by DSR. The results are shown in Figs. 9 and 10.

The components of the asphalt will change as the asphalt ages, resulting in the changes of G^*. Thus, Ultraviolet Ageing Index (UAI) is used to describe the changes of the G^* of the asphalt, and the calculation of the UAI is shown as follows:

$$UIA = \frac{G_1^*}{G_0^*} \quad (1)$$

G_0^*—The complex shear modulus of the asphalt sample before UV aging

G_1^*—The complex shear modulus of the asphalt sample after UV aging

Figs. 9–12 illustrate that the complex shear modulus of the three asphalts after aging increase comparing with the initial ones, and all decrease with the increase of temperature, which indicates that aging has a significant influence on the viscoelasticity .The increase of G^* at the same temperature indicate the asphalt becomes more elastic and brittle, related to the decrease in the light components of asphalt and the decrease in viscosity after aging. Table 4 shows that the UIA of the two kinds of phosphorus slag powder modified asphalt decrease compared with the virgin asphalt, indicating that the addition of phosphorus slag powder can improve the anti-aging properties of asphalt.

3.1.4. Low temperature performance test

The Bending beam rheometer test was carried out on the three selected asphalts. The results are shown in Figs. 13 and 14.

The experimental results show that the variation rule of the stiffness S and the *m*-value of the three asphalts are basically the same as the temperature changes. As the temperature decreases, the stiffness modulus S increases gradually, while the creep rate m decreases. The stiffness modulus curves of the three asphalts are as follow: unmodified phosphate slag asphalt > TM-P modified phosphorus slag asphalt > virgin asphalt, while the creep rate m of the three asphalt are in contrary. It is indicates that the addition of slag powder has a slight negative impact on the low temperature performance of asphalt.

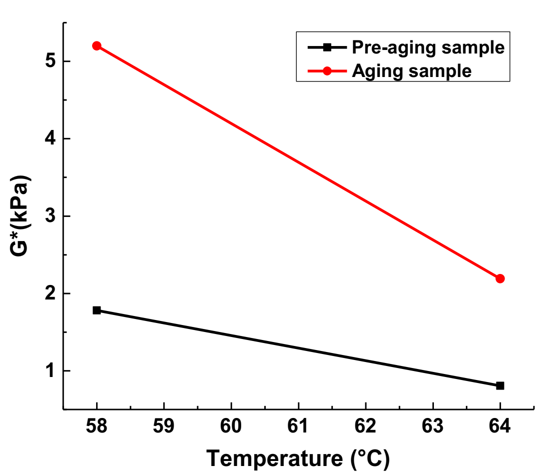

Fig. 9. Aged virgin asphalt (G^*).

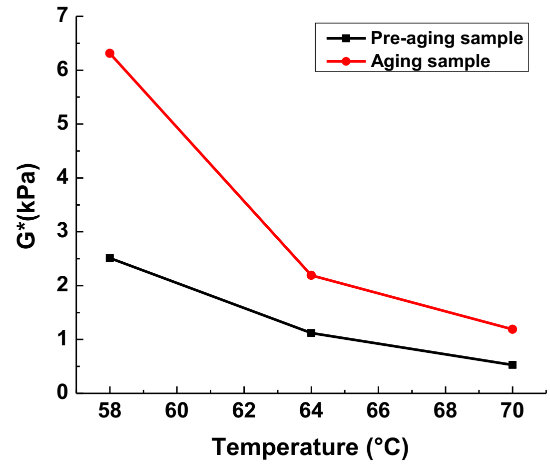

Fig. 10. Aged U-TM-P asphalt (G^*).

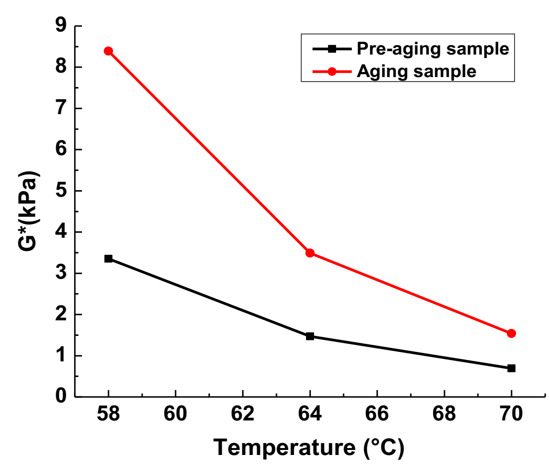

Fig. 11. Aged M-TM-P asphalt (G^*).

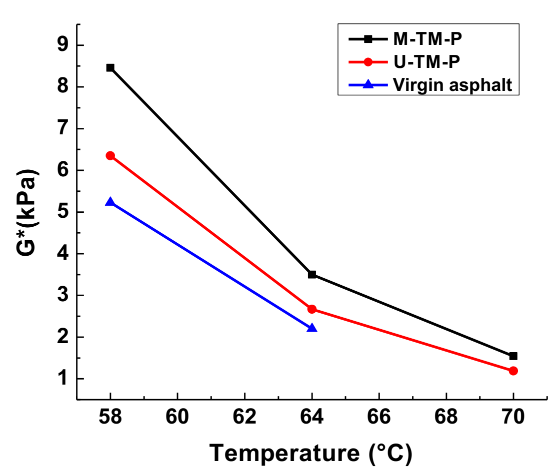

Fig. 12. Relationship of G^* and temperature.

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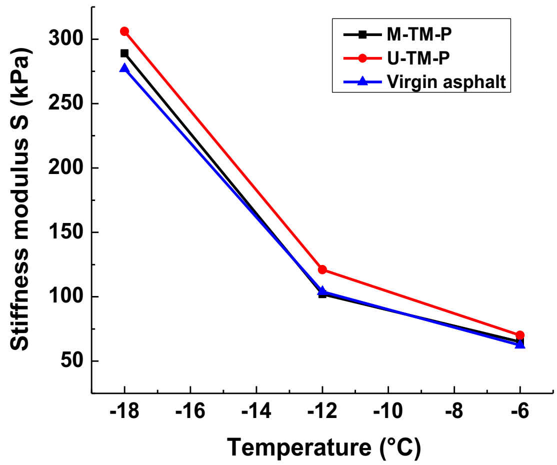

Fig. 13. Relationship of the S and temperature.

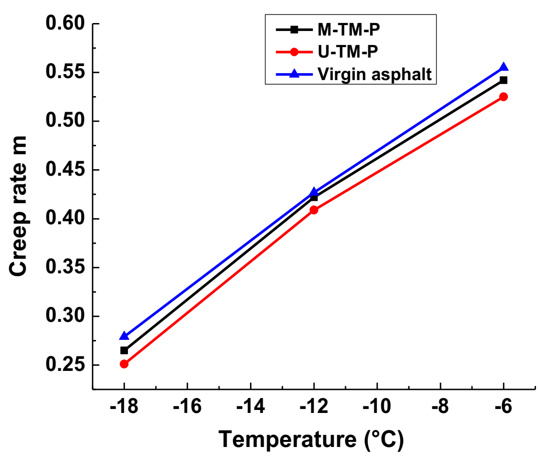

Fig. 14. Relationship of the m and temperature.

3.1.5. Infrared Spectroscopy test

Fourier Transform Infrared Spectroscopy (FTIR) is a technique used to analyze samples qualitatively and quantitatively. Based on the assignments and positions of FTIR spectra main bands, molecular-level interactions and chemical bonding of asphalt binder can be obtained. So FTIR was regarded as a powerful tool to investigate the structure, characteristics and chemical compositions of modified asphalt [20–22]. In this study, the aging mechanism of asphalt and the anti-aging impacts of the phosphate slag power modified asphalt were explored by the FTIR test. The main band assignments and positions are summarized in Table 5, and the FTIR images of the three asphalts before and after short (RTFOT) and long term aging (PAV) are shown in Fig. 15.

It can be seen from Fig. 15 that two kinds of phosphorus slag modified asphalt have a new absorption peak caused by Si-O-Si antisymmetric vibrations near 1040 cm^{-1} compared with the virgin asphalt, and the peak value of the TM-P modified phosphorus slag powder asphalt is higher than that of the unmodified one. It indicates that the surface modification of the phosphorus slag powder has a better dispersibility in asphalt and is not easy to reunite and segregation.

Figs. 16 and 17 show that the characteristics of the peak of the virgin asphalt before and after short-term aging and long-term aging are basically the same, just only slightly different in intensity. The absorption peak at 1700 cm^{-1} is the carbonyl characteristic, which can characterize the aging of the asphalt [23]. The peaks of the two kinds of phosphorus slag powder modified asphalt were significantly smaller than the virgin asphalt, especially the TM-P modified phosphorus slag powder one. It shows that the addition of phosphorus slag powder reduces the aging sensitivity to improve the anti-aging properties of asphalt, which is consistent with the previous results of DSR test.

3.2. Experimental study on road performance

The specimens were fabricated with a design of AC-16, and the optimum asphalt dosage determined by the Marshall method was 4.6% for the AH-70 asphalt, and 4.7% the modified slag powder asphalt. A series of experiments were carried out to detect the rutting resistance, water stability and thermal cracking resistance of asphalt mixtures. The results are shown in Table 3.

3.2.1. High temperature stability performance analysis

There are many methods to evaluate the high temperature performance of asphalt mixture. Rutting test, which is simple to operate, widely used in domestic and abroad and the result is intuitive and has good correlation with the actual rutting, can fully simulate the actual situation of asphalt pavement on wheels. According to "Specification for construction of highway asphalt pavement (JTG E20 2011)", the mix design of asphalt mixture for highway by Marshall method must to be detected by the rutting test. So in this paper, the high temperature stability of asphalt mixture was measured using a rutting test. And the results are shown in Table 6.

Table 7 presents the dynamic stability of the modified phosphorus slag powder asphalt mixture is 3005 times/mm (the specification requirement is larger than 2800 times/mm), about 13.5% higher than the one of virgin asphalt mixture. Surface modification makes the phosphorus slag powder better combine with asphalt and improves the adhesion of asphalt and mineral resources, resulting in an improvement of high temperature properties.

Table 5
Phosphate slag powder asphalt infrared spectrum absorption peak.

Asphalt types	Infrared spectral absorption peak (cm^{-1})								
	-OH	Saturated Hydro-carbons	Methy-lene	CO_2	Carbonyl	Aromatic Hydro-carbons	Methylene C-H	Si-O	Aromatic Hydro-carbons
70#-YY	–	2923.77	2857.92	2392.16	–	1597.89	1375.24	–	779.83
70#-RTFOT	3741.70	2924.26	2857.52	–	–	1597.09	1375.04	–	780.53
70#-PAV	3779.33	2923.91	2857.86	2359.95	1697.19	1957.08	1375.13	–	780.78
Mp-YY	3896.74	2923.06	2858.77	2356.23	–	1458.51	1373.41	1041.21	778.22
Mp-RT	–	2923.80	2857.78	2360.01	–	1550.69	1375.42	1042.63	780.98
Up-PAV	–	2923.22	2862.31	2360.02	1698.88	1460.21	1374.56	1039.68	781.10
Up-YY	3768.76	2923.25	2858.79	2358.09	–	1456.68	1373.410	1042.1	778.22
Up-RT	–	2924.73	2858.45	2358.89		1461.23	1375.98	1043.78	789.37
Up-PAV	3741.71	2924.00	2857.87	2359.97	1700.16	1597.72	1375.07	–	778.29

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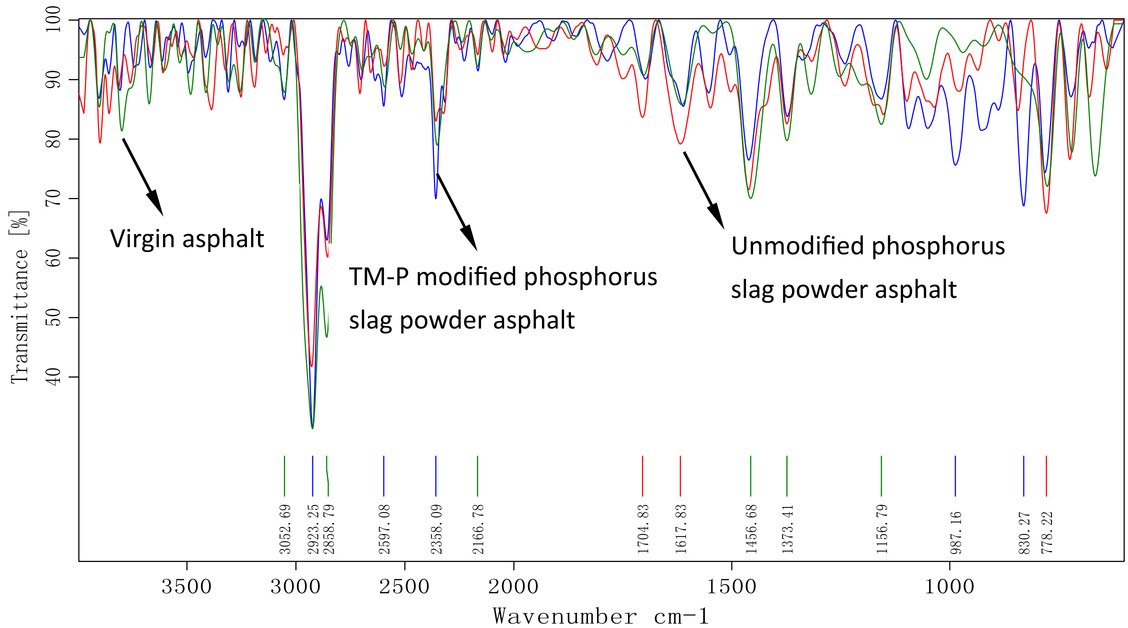

Fig. 15. Infrared spectra of the initial asphalt specimen.

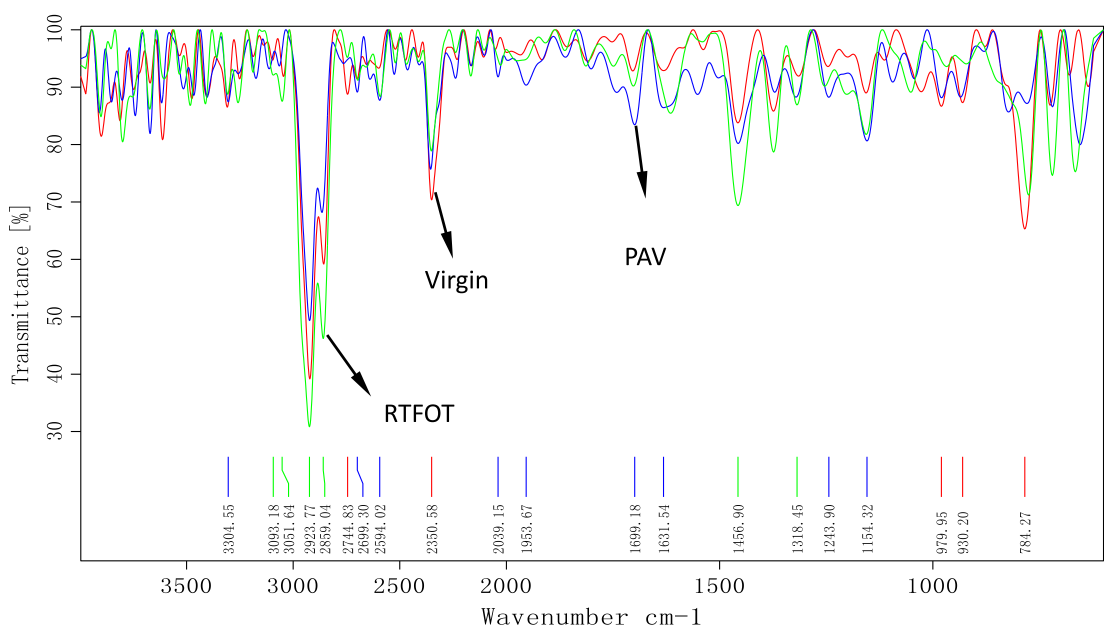

Fig. 16. Infrared spectrum of initial asphalt with different aging levels.

3.2.2. Water stability analysis

According to ‘‘Specification for construction of highway asphalt pavement (JTG E20 2011)”, the immersion Marshall test and freeze-thaw splitting test are adopted as the standard test for water stability of asphalt mixture. Therefore, the two tests are used to evaluate the water stability of phosphorus slag powder modified asphalt mixture in this paper.

3.2.2.1. Immersion Marshall test. According to Referring to the requirements of the specification, the virgin asphalt and the TM-P modified phosphorus slag powder modified asphalt were tested by the Marshal method based on the optimum asphalt dosage. The results are shown in Table 7.

Table 7 presents the immersion stability of the TM-P modified phosphorus slag powder modified asphalt mixture was higher by 2.24% compared with the virgin asphalt, and both meet the requirements of JTG F40-2004 (≥85%), indicating that the slag modified asphalt had a better water stability.

3.2.2.2. Freeze-thaw splitting test. The specimens were fabricated on the basis of the optimum asphalt dosage, and the asphalt mixture was subjected to freeze-thaw splitting test. The experimental results are shown in Tables 8 and 9.

Tables 8 and 9 present that the freeze-thaw splitting strength of virgin asphalt and TM-P modified phosphorus slag power modified asphalt mixture meet the requirements (≥75%). The splitting strength of the modified slag powder asphalt mixture is around 60% higher than that of the virgin asphalt before and after freezing and thawing, and the splitting strength ratio is increased by around

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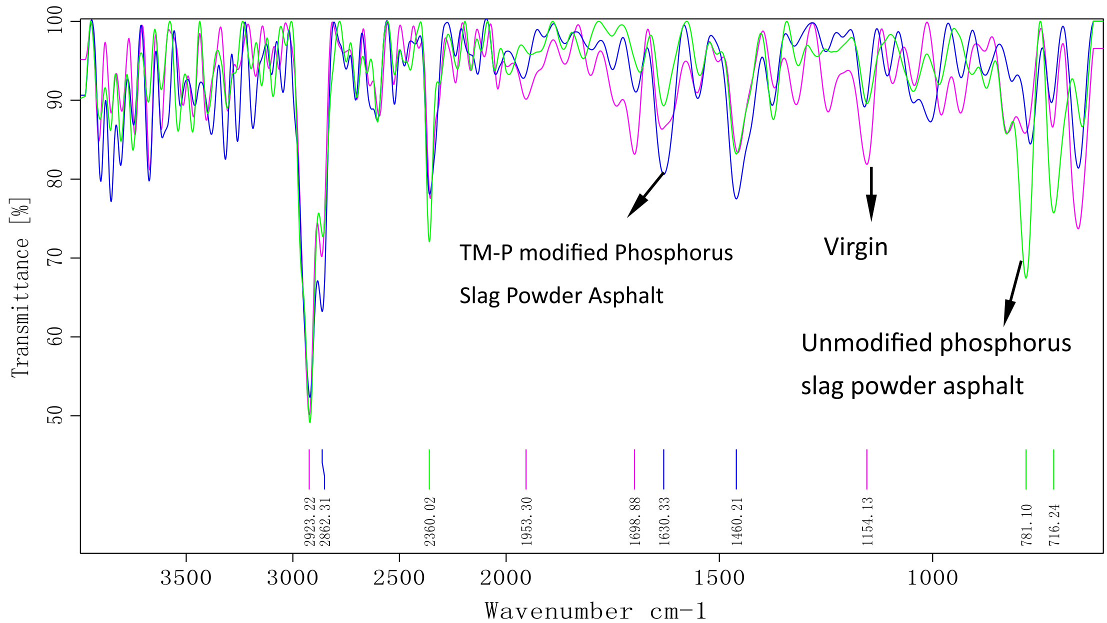

Fig. 17. Infrared spectra of asphalt specimen after long-term aging (PAV).

Table 6
Dynamic stability test results.

Specimen type	Bitumen aggregate ratio (%)	Dynamic stability (times/mm)			Dynamic stability (times/mm)
		1	2	3	
70 # asphalt mixture	4.6	2656	2689	2596	2647
Phosphate slag powder asphalt mixture	4.7	3073	3069	2873	3005

Remarks: 1. Test method: T 0719–2011.
2. Rolling speed: 42 times/min, test temperature 60 °C.
3. Specimen size: (300 × 300 × 50) mm.

Table 7
Immersion Marshall stability values.

Mixture type	Marshall stability (MS1/kN)	Average value MS1/kN	Soaking 48 h stability (MS1/kN)	Average value MS1/kN	Residual stability of immersion MS0 (%)
70 # virgin asphalt mixture	17.72	17.20	15.21	15.13	87.97
	17.87		14.98		
	16.53		15.04		
	16.69		15.29		
Modified phosphorus slag powder asphalt mixture	19.02	18.99	16.96	17.13	90.21
	18.68		17.19		
	19.54		16.65		
	18.71		17.72		

Table 8
Freeze-thaw splitting values of 70# asphalt mix specimens.

Not through the freeze-thaw cycle test pieces				After freezing and thawing the specimen			
Load value PT_1/kN	Specimen height $H_{1/}$mm	Splitting strength RT_1/MPa		Load value PT_2/kN	Specimen height $H_{2/}$mm	Splitting strength RT_2/MPa	
10.85	62.70	1.09	1.05	8.23	63.72	0.81	0.79
10.46	63.18	1.04		8.12	63.20	0.81	
11.02	62.84	1.10		8.96	63.62	0.86	
9.87	63.86	0.97		7.21	64.12	0.71	
Cleavage strength ratio TSR/%	75.238						

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Table 9
Freeze-thaw splitting values of phosphate-slag-modified asphalt mixture.

Not through the freeze-thaw cycle test pieces				After freezing and thawing the specimen			
Load value PT_1/kN	Specimen height H_1/mm	Splitting strength RT_1/MPa		Load value PT_1/kN	Specimen height H_1/mm	Splitting strength RT_1/MPa	
17.53	62.70	1.75	1.68	13.58	63.72	1.33	1.31
16.45	63.18	1.64		14.21	64.20	1.39	
17.78	62.84	1.78		13.07	64.62	1.27	
15.88	63.86	1.56		12.91	64.12	1.26	
Cleavage strength ratio TSR/%	78.125						

3%. It shows that the addition of slag powder can improve the water resistance performance of the mixture.

4. Conclusion

(1) TM-P can form a layer coating on the surface of the slag powder particles, showing better surface modification for phosphorus slag powder than other four modifiers. TM-P modification makes the phosphor slag powder difficult to agglomerate and excellent dispersibility and stability in asphalt.

(2) For the virgin asphalt, the addition of TM-P modified phosphorus slag powder in asphalt shows improvement in anti-aging, rutting resistance properties, while decrease in anti-fatigue performance .With the increase of temperature, the anti-rutting factor decreased while the phase angle increased.

(3) For the asphalt mixture, the addition of TM-P modified phosphorus slag powder can improve the high temperature stability and water resistance performance of the mixture. Under the same test conditions, the dynamic stability of the asphalt mixed with modified phosphorus slag powder increased by 358 times/mm, about 13.5% increase compared with the virgin asphalt. The stability of water immersion increased by 2.24%, and the splitting strength ratio increased by 60% and 65% respectively before and after freezing and thawing.

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References

[1] L.Q. Liu, International and domestic phosphate resources development of the optimal marginal grade and its prediction, Central South University, 2013. 1–5.
[2] L.W. Ran, H. Zhu, Y. Lou, Application and application prospect of yellow phosphorus slag, Guangzhou Chem. Ind. 42 (18) (2014) 51–53.
[3] D.M. Liu, K.H. Fang, F.Y. Wu, Study on the development and utilization of phosphorus slag, Mining News 429 (3) (2005) 21–25.
[4] J.G. Wang, Inorganic powder modified asphalt preparation and its modification mechanism, Wuhan Univ. Sci. Technol. (2009) 71–73.
[5] J. Zhao, M. Milanova, M.M.C.G. Warmoeskerken, et al., Surface modification of TiO 2 nanoparticles with silane coupling agents, Colloids Surfaces A: Physicochem. Eng. Aspects 413 (2012) 273–279.
[6] A.S. Golub, I.B. Shumilova, Y.V. Zubavichus, et al., Layered compounds based on molybdenum disulfide and ruthenium arene complexes, J. Mater. Chem. 7 (1) (1997) 163–167.
[7] Z.B. Yan, J. Peng, X.Y. Xie, Application of Phosphorus Slag in Cement Industry, China Non-metallic Mineral Ind. 5 (2013) 19–20.
[8] S.M. Ren, X. Sun, X.Y. Wang, et al., Study on hydraulic cementitious materials of steel slag, phosphate slag and fly ash, Build. Mater. 3 (1995) 16–17.
[9] Y. Wang, Y.S. Gao, Study on properties of modified phosphorus slag powder and concrete, J. Concr. 6 (2014) 92–96.
[10] N.Q. Feng, Y.X. Shi, J.T. Ding, Properties of concrete with ground ultrafine phosphorus slag, Cem. Concr. Aggregates 22 (2) (2000) 128–132.
[11] A. Allahverdi, M. Mahinroosta, Mechanical activation of chemically activated high phosphorous slag content cement, Powder Technol. 245 (2013) 182–188.
[12] X. Xu, L.Y. Wang, L.S. Peng, et al., Preparation of phosphogypsum self-leveling material, Green Build. 4 (2012) 70–72.
[13] W.W. Feng, C.H. Cheng, Comprehensive study and utilization of a phosphorus slag in Guizhou, Journal of Concrete 11 (2005) 95–97.
[14] P.T. Foxworthy, R.S. Nadimpalli, R.K. Seals, Phosphogypsum slag aggregate-based asphaltic concrete, J. Trans. Eng. (1996).
[15] X.H. Nie, Experimental study on performance of phosphorite slag modified asphalt and mixture, Changsha University of Science and Technology, 2014. 73–74.
[16] X.H. Nie, G.P. Qian, Y.Q. Ouyang, Study on asphalt pavement performance based on SHRP, Highway 03 (2014) 145–151.
[17] G.P. Qian, K. Wang, W.F. Zheng, Preparation and performance test of phosphorus slag powder-based tunnel asphalt pavement flame retardant, J. Changsha Univ. Sci. Technol. 13 (1) (2016) 16–21.
[18] G.L. Zou, J. Xu, J.L. Hu, Design principle of low-grade asphalt mixture based on asphalt mortar test, J. Highway Trans. Res. Dev. 31 (10) (2014) 21–25.
[19] W.T. Huang, North American asphalt and its mixture characteristics, South China University of Technology, 2014. 134–139.
[20] N.C. Xu, J.L. Shen, H.Y. Luo, X-ray diffraction and infrared spectroscopy analysis of kaolinite crystallinity, Resour. Invest. Environ. 35 (2) (2014) 152–156.
[21] R. Li, F. Xiao, S. Amirkhanian, Z. You, J. Huang, Developments of nano materials and technologies on asphalt materials – A review, Constr. Build. Mater. 143 (2017) 633–648.
[22] Z.R. Xu, Z.D. Chen, Y.T. Chang, et al., Infrared spectroscopic analysis of SBS content in modified asphalt, J. Chang'an Univ. (Nat. Sci. Ed.) 35 (2) (2015) 7–12.
[23] Q. Wang, Y. Ye, C.F. Ouyang, et al., Research on aging of waste rubber modified asphalt, Acta Metall. Sin. 6 (2015) 19–28.

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