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Research Article

Preparation, Structure, and Properties of Modified Asphalt with Waste Packaging Polypropylene and Organic Rectorite

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The modified asphalt with waste packaging polypropylene (WPP) and WPP/organic rectorite (OREC) was prepared by the melt blending method. The effects of OREC on the physical and aging properties of WPP-modified asphalt were studied. The morphologies, microstructure, and thermal properties of WPP-modified asphalt and WPP/OREC-modified asphalt were characterized by fluorescence microscopy, Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), and thermogravimetry (TG). The results show that the composite-modified asphalt exhibits excellent ductility and plasticity when the contents of WPP and OREC are 4 wt. % and 1.5 wt. %, respectively. The deformation ability, softening point, ductility, and high-temperature storage stability of WPP-modified asphalt can be improved by adding the appropriate content of OREC. It is demonstrated that the composite-modified asphalt has an outstanding operational performance when the content of OREC is in the range of 1.5–2 wt. %. Compared with base asphalt, the high temperature performance of WPP-modified asphalt and WPP/OREC-modified asphalt is also improved significantly.

1. Introduction

The asphalt as an important kind of road construction material has held a large proportion in worldwide paved roads [1, 2], which is the complex containing many kinds of molecules and functional groups. Due to the complex and changeable structures of asphalt [3], we hardly guarantee the stability of the indicators when it is applied in road traffic. Asphalt pavement can be prone to produce some early damage phenomena, such as high temperature rutting, cold cracking, fatigue cracking, loose aggregate, pit, and aging, which decrease the road performances and service life [4–8]. Moreover, the asphalt in China contains the high content of paraffin, which is negative for dry resistance, ductility, temperature stability, aging, and fatigue resistance. Then, pavement is easily subjected to deformation, network crack, upheaval, shrinkage cracking or breaking at low temperature, and so on. The poor cohesiveness between asphalt and mineral material will cause the peeling damage and fatigue cracking [9–11]. Consequently, it is necessary to improve the road performances of the asphalt.

Nowadays, the packaging plastic products have the significant contributions to mankind for decades while also bringing serious environment problem. Therefore, handling the packaging waste has changed to be imperative. Thus, utilizing these waste packaging materials in the field of modifying asphalt will turn the waste to be valuable and then can relieve the environment pollution. According to previous research studies, the asphalt is usually modified by the polymers, especially, the waste polymers have been used as the modifier to modify the asphalt [12–17]. It can be found that modified asphalt with the sole polymer is instable due to the obvious phase separation between the asphalt matrix and polymer modifier, and the modified asphalt shows a poor adhesion. Therefore, some nanomaterials have been used as the modifier of the asphalt. Zhang and coworkers reported that the organic rectorite (OREC) could improve the thermal storage stability of the asphalt [18]. Iskender and coworkers investigated the performance of nanoclay-modified asphalt mixtures, and the obtained modified asphalt presented a better stability and greater rutting resistance [19]. Moreover, some researchers found that nanomaterials combining with polymers as the composite modifier could improve the comprehensive properties of the asphalt. Lu and coworkers reported that the nano-MMT/SBS-modified asphalt had a good storage stability and high temperature property [20]. Bala and coworkers investigated the influence of nanosilica particles on the performance of polypropylene- (PP-) modified asphalt, and the nanosilica particles with PP as the composite modifier could improve the durability of modified asphalt [21].

In this work, waste packaging polypropylene (WPP) was used to modify asphalt. However, the present research studies focused on improving the performances of PP-modified asphalt for prolonging the service life of roads. It is worth noting that OREC with special lamellar structures can make the polymer molecules to enter its interlayer structures and form intercalated or exfoliated composite. The layer spacing, adsorption capacity, and internal and external surface area of modified asphalt can be increased after OREC modifying [18]. The modification using polymer/nanoparticles can improve the mechanical, thermal, and antiaging properties of the asphalt. Therefore, the asphalt was modified by WPP and the blending of OREC and WPP in order to improve its high temperature stability and comprehensive performances except for recycling the WPP in this paper.

2. Materials and Methods

2.1. Materials. NO.90A petroleum pitch was purchased from Xi'an Petrochemical Company as the base asphalt. Waste food packaging bag (the main constituent is PP) was retrieved, cleaned, dried, and then extruded to form granules by an extruder. Nano OREC was provided by the College of Science of Northwestern Polytechnical University. The properties of petroleum pitch, WPP, and OREC are shown in Table 1.

2.2. Preparation of WPP-Modified Asphalt and WPP/OREC-Modified Asphalt. The preparation of modified asphalt was carried out using high-speed shearing method. 600 g base asphalt was heated and melted in the iron container by using universal resistance furnace and then poured into the high-speed shearing machine at the shearing speed of 4000 rpm. WPP was rapidly added into base asphalt within 5 min at 170°C. After the above mixtures were stirred for 1.5 h at 170°C, WPP-modified asphalt was obtained. The ration of WPP-adding content to base asphalt was 2 wt. % (12 g), 4 wt. % (24 g), 6 wt. % (36 g), and 8 wt. % (48 g), respectively.

The process for preparing WPP/OREC-modified asphalt was the same to that of WPP-modified asphalt. Instead of WPP, the modifiers (WPP and nano OREC) were rapidly added into base asphalt within 5 min at 170°C. After the above mixtures were stirred for 1.5 h at 170°C, WPP/OREC-modified asphalt was obtained. The ration of WPP content to base asphalt was fixed at 4 wt. % (24 g) and nano OREC content was 0.5 wt. %, 1 wt. %, 1.5 wt. %, 2 wt. %, and 2.5 wt. % (3 g, 6 g, 9 g, 12 g, and 15 g), respectively. As-prepared composite-modified asphalt was denoted as WPP/OREC-0.5-modified asphalt, WPP/OREC-1-modified asphalt, WPP/OREC-1.5-modified asphalt, WPP/OREC-2-modified asphalt, and WPP/OREC-2.5-modified asphalt, respectively.

Table 1: The properties of petroleum pitch, WPP, and OREC.

Raw materials	Properties			
Asphalt	C/H 0.73	TI (wt. %) 13.6	QI (wt. %) 0.1	SP (°C) 51.3
WPP	Basis PP	Purity 93%	Density (g/cm^3) 0.91	SP (°C) 134.5
OREC	$d_{(001)}$ (nm) 3.2	Purity 85%	Specific surface area (m^2/g) 87	Average diameter (nm) 180

Note. C/H: atomic ration; TI: toluene insoluble; QI: quinolone insoluble; SP: softening point; $d_{(001)}$: interlayer spacing of (001).

2.3. Characterization

2.3.1. Conventional Physical Performance Test. The penetration (25°C), softening point, and ductility (5°C) of modified asphalts were measured according to highway engineering asphalt and asphalt test procedures of T 0604-2000, T 0606-2000, T 0605-1993, and T 0625-2000 standard, respectively. The penetration of modified asphalts was tested by a GS-IV automatic asphalt penetrometer supplied by Shuyang Highway Instrument Co., Ltd., China. The softening point of modified asphalts was tested by a SLR-C digital softening point tester supplied by Shuyang Highway Instrument Co., Ltd., China. The ductility was tested by a STYD-3 digital ductility testing machine (Shanghai Luda Instrument Co., Ltd., China).

2.3.2. Thermogravimetric Analysis (TG). The thermal stability and the composition change of modified asphalt were studied by using TG to accurately measure the mass change of the sample. The samples were heated from 100°C to 700°C at a heating rate of 15°C/min by using a Mettler Toledo TGA/DSC 1 TGA instrument under a N_2 flow.

2.3.3. Differential Scanning Calorimetry (DSC). The DSC curve was used to describe the high temperature stability of modified asphalt by measuring the characteristic temperature and the peak value (endothermic peak and/or exothermic peak) during the reaction. The samples were heated from 25°C to 200°C at a heating rate of 10°C/min by using a Mettler Toledo DSC823e instrument under a N_2 flow.

2.3.4. Fluorescence Analysis. The particle size and distribution of polymer in the asphalt matrix were observed by using a NIKON 80i fluorescent microscope instrument. The hot asphalt drop on the glass slide was covered by the coverslip (the asphalt drop forming the thin sheet) and then placed under the fluorescence microscope with the laser.

2.3.5. Fourier Transform Infrared (FTIR) Analysis. The FTIR spectra were used to reflect the change of functional groups in the modified asphalt before and after aging. The FTIR spectra of samples were obtained by using a FTIR-8400S spectrometer (Shimadzu Corporation, Japan) in the range of 400–4000 cm^{-1} with the resolution of 16.0 cm^{-1}. The drying KBr powder was pressed into a uniform and transparent sheet, and the modified asphalt sample was coated with a thin layer on the thin sheet for testing.

2.3.6. Aging of the Modified Asphalt. The rotating thin film oven was utilized to simulate the short-term aging property of modified asphalt and study the influence of OREC on the aging resistance of WPP-modified asphalt. The modified asphalt aging test was as follows: each aging tank was loaded with 35 g as-prepared modified asphalt in the rolling thin film oven turntable at 163°C for 85 min as the simulative aging. The speed of turntable was 15 rpm with a hot air flow of 4 L/min by using a SBX-85 type asphalt rotating film aging box (Zhejiang Chen Xin Machinery Co., Ltd., China).

2.3.7. High-Temperature Storage Stability. The prepared modified asphalt was poured into a glass tube, and it was sealed and stored vertically in an oven at 163°C for 48 h. Then, the tube was taken out and cooled to room temperature. Subsequently, the treated sample was cut into three equal sections horizontally. The top and bottom sections of samples were used to evaluate the storage stability of the modified asphalts by measuring their softening point difference.

3. Results and Discussion

3.1. The Influence of WPP Content on the Penetration and SP of WPP-Modified Asphalt. The softening point and penetration of WPP-modified asphalt with different contents of WPP are shown in Figure 1. It can be found that the softening point of WPP-modified asphalt increases with increasing of the WPP content, and the increasing trend changes to be slow when it exceeded 4 wt. %. Moreover, the penetration of WPP-modified asphalt decreases, and the downtrend also changes to be slow when the WPP content exceeds 4 wt. %. The trend for the softening point and penetration of WPP-modified asphalt with the increasing of WPP content is in accordance with that of PP-modified asphalt in the previous report [21]. This result indicates that as-prepared WPP-modified asphalt with 4 wt. % WPP can exhibit better physical properties compared with other WPP-modified asphalt samples. Considering the comprehensive physical properties of WPP-modified asphalt and the cost of WPP, the content of WPP was fixed at 4 wt. % during the preparation of WPP/OREC-modified asphalt.

3.2. Conventional Physical Properties Analysis of WPP/OREC-Modified Asphalt

3.2.1. Penetration. The penetration of road asphalt represents the consistency of asphalt, indicating the viscosity of asphalt at the test temperature in essence. Furthermore, the

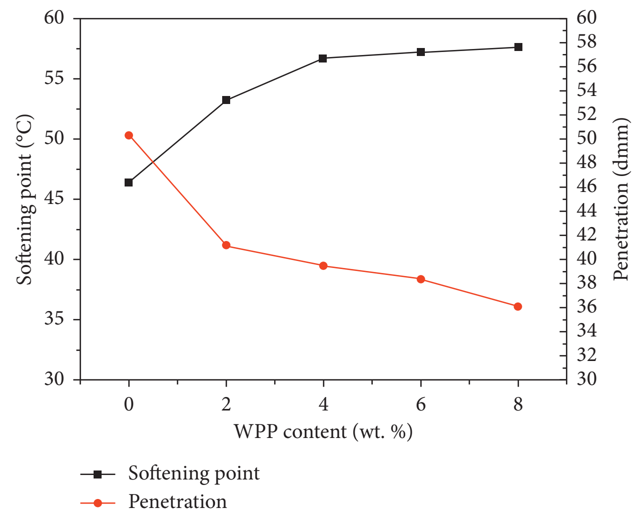

Figure 1: The softening point and penetration of WPP-modified asphalt.

penetration reflects the deformation ability of the asphalt under a certain load. In previous research studies, it is mentioned that the viscosity of asphalt is high, and then the deformation ability changes to be poor when the penetration is low. Moreover, the penetration will decrease with increase of the polymer modifier dosage [22], which is consistent with the result of the penetration of as-prepared WPP-modified asphalt in this paper. For the as-prepared WPP/OREC-modified asphalt, the penetration also decreases compared with that of base asphalt (as shown in Figure 2). It is because that the viscosity of WPP/OREC-modified asphalt increases with the increasing of WPP/OREC content. It is interesting that the penetration of all as-prepared WPP/OREC-modified asphalt samples is higher than that of WPP-modified asphalt with 4 wt. % WPP, and it decreases slowly in the range of 0.5–2.5 wt. % OREC. It can be concluded that the appropriate content of OREC is benefit to improve the deformation ability of WPP-modified asphalt. Compared with some previous research studies, the penetration of WPP/OREC-modified asphalt is comparable to that. Ren and coworkers [23] reported that the penetration of gilsonite-modified asphalt was 4.46 mm when the gilsonite content was 20 wt. %, and the penetration of SBR-modified asphalt was 4.1 mm when the SBR content was 7.5 wt. %. Gama and coworkers [24] found that the penetration of modified asphalt was 4.35 mm when the elastomer content was 0.5 wt. %. Ali and coworkers [25] investigated the physical properties of acrylate-styrene-acrylonitrile-modified asphalt, and they found that the penetration of modified asphalt was 4.76 mm when the acrylate-styrene-acrylonitrile content was 3 wt. %. In this paper, the penetration of WPP/OREC-modified asphalt is 4.95 mm when the OREC content is 0.5 wt. %, which is better than that of polymer-modified asphalt, demonstrating that nano OREC can improve the viscosity of polymer-modified asphalt.

3.2.2. Softening Point. The softening point represents the plastic flow of asphalt, which can be used to evaluate the high

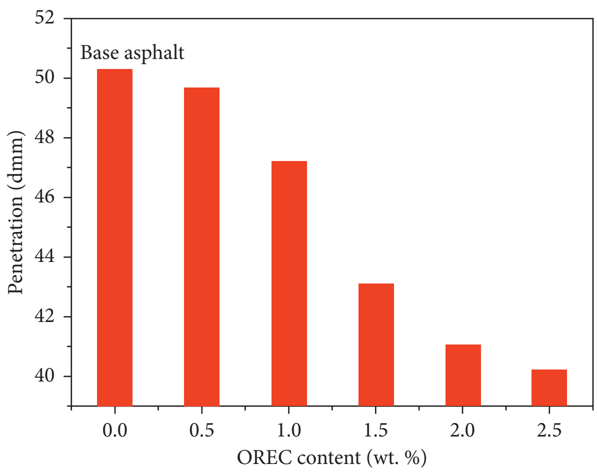

Figure 2: The penetration of WPP/OREC-modified asphalt.

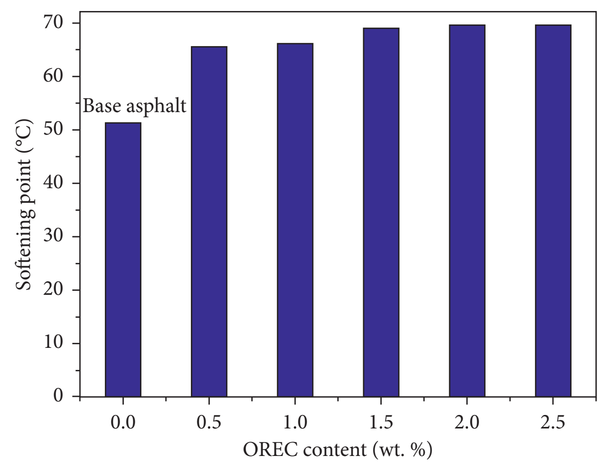

Figure 3: The softening point of WPP/OREC-modified asphalt.

temperature stability of asphalt. When the softening point is high, the high temperature stability of asphalt is excellent and the high temperature antideformation capacity of asphalt pavement changes to be high. As shown in Figure 3, we can infer that the OREC content has a slight effect on the softening point of WPP/OREC-modified asphalt. However, the softening point of composite-modified asphalt is greatly improved compared with that of base asphalt (the softening point of 51.3°C). Furthermore, the softening point of all as-prepared composite-modified asphalt samples is higher than that of WPP-modified asphalt with 4 wt. % WPP, and OREC can increase the softening point of WPP-modified asphalt. Therefore, the high temperature stability of WPP/OREC-modified asphalt is also improved obviously, indicating that the polymer modifier and nanomaterials play an important role in the high temperature performance of asphalt mixture. In addition, the results indicate that the WPP/OREC-modified asphalt shows a better high temperature stability compared with the previous research studies. Padhan and coworkers [26] reported that the softening point of modified asphalt was 56.2°C when the PE/TPOR content was 0.5 wt. %. Ming and coworkers [27] found that the softening point of SBR/PF-modified asphalt was 54°C when the SBR content was 4 wt. % and the PF content was 3 wt. %. Zhang and coworkers [28] investigated the properties of water-borne epoxy resin-modified asphalt, and they found that the softening point of modified asphalt was 62.2°C when the content of water-borne epoxy resin was 4 wt. %. In this paper, the softening point of as-prepared WPP/OREC-modified asphalt is in the range of 65.6–69.8°C, revealing that the composite-modified asphalt has an excellent high temperature performance.

3.2.3. Ductility. The ductility is used to evaluate the expansion or elongation of the asphalt before breaking. When the ductility is high, the durability of the paved road is good. The low temperature anticracking performance of asphalt is usually characterized by the low temperature ductility (5°C). Furthermore, the high ductility of the asphalt predicts its excellent performance at low temperature. Due to the high wax content of domestic asphalt, the low temperature ductility of base asphalt is high. However, the low temperature ductility becomes extremely low after the modification with polymer, and then the low temperature performance becomes poor. Importantly, the ductility of composite-modified asphalt shows a rising trend after adding OREC into WPP-modified asphalt (as shown in Figure 4), indicating that the low temperature anticrack performance of WPP/OREC-modified asphalt has been improved compared with that of WPP-modified asphalt. The ductility of composite-modified asphalt reaches the highest when the OREC content is 1.5 wt. % and then decreases with further increasing the OREC content. Thus, the as-prepared WPP/OREC-modified asphalt shows an excellent anticracking performance at low temperature when the OREC content is 1.5 wt. %. This result is comparable to that reported by Bai [15]. They investigated the low temperature properties of recycling of aged SBS-modified asphalt, and the ductility at 5°C was 24.6 cm when adding 5 wt. % aged SBS and 3 wt. % rejuvenator. Moreover, Yu and coworkers [29] found that the ductility of modified asphalt with 3 wt. % OMMT was 5.2 cm at 5°C. The above ductility is smaller than our results, indicating that the WPP/OREC-modified asphalt exhibits a better expansion.

Based on the analysis of the penetration, softening point, and ductility, we find that the results obtained in our experiment are comparable to that in many previous research studies. The comparisons of conventional physical properties obtained in previous reports are shown in Table 2.

3.3. High-Temperature Storage Stability of Modified Asphalt. For evaluating the high-temperature storage stability of modified asphalt, the softening point difference values were tested, and the results are shown in Figure 5. It can be found that the softening point difference values of modified asphalt are low, and the values of WPP/OREC-modified asphalt are lower than those of WPP-modified asphalt, indicating that WPP/OREC-modified asphalt has a better high-temperature storage stability. Furthermore, there is no obvious phase separation in the WPP/OREC-modified asphalt during the

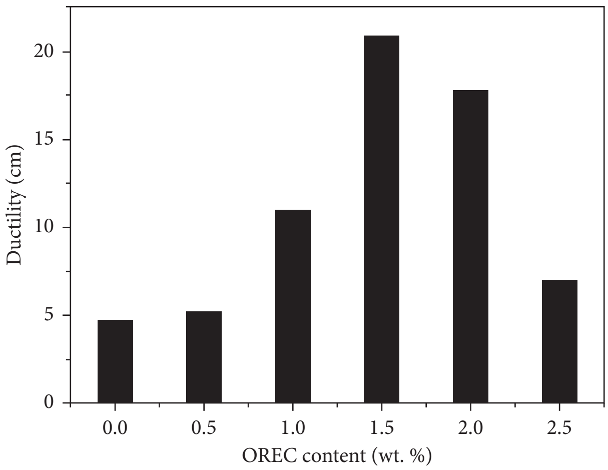

Figure 4: The ductility of WPP/OREC-modified asphalt.

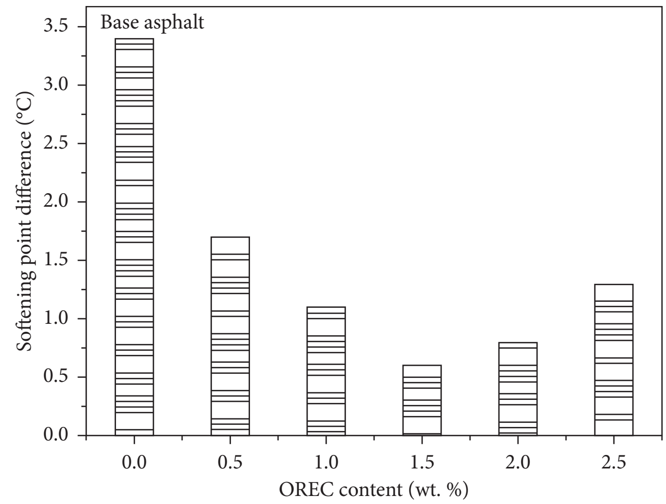

Figure 5: The softening point difference of WPP/OREC-modified asphalt with different contents of OREC.

Table 2: The comparisons of conventional physical properties shown in previous reports.

Modified asphalt	Penetration (dmm)	Softening point (°C)	Ductility (cm)
[18] OREC-1831	69.8	50	74.7 (15°C)
[23] Gilsonite	44.6	65.4	12.5(10°C)
[24] Elastomer	43.45	78.5	/
[25] Acrylate-styrene-acrylonitrile	47.6	50	53(25°C)
[26] PE/TPOR	56.4	56.2	/
[15] SBS/rejuvenator	29.5 (5°C)	62.4	24.6 (5°C)
[13] CRMA/BHETA	35.2	63.4	/
[30] SBS/$CaCO_3$	70.2	73.4	26.6(5°C)
[31] Sasobit/PPA	43.5	78.8	127.3 (15°C)
[32] SEBS/MMNC	24.4	78.75	/
WPP/OREC (this work)	**42.4**	**66.8**	**20.9 (5°C)**

high-temperature storage test. Due to the swelling of PP in the asphalt matrix and the intercalation of the PP and asphalt molecules into OREC lamella, the asphalt-polymer interphase will improve the compatibility between these materials. However, the softening point difference value of WPP/OREC-modified asphalt increases when the content of OREC exceeds 1.5 wt. %. This is because that excess OREC will agglomerate in asphalt matrix, and it goes against the intercalation of the PP and asphalt molecules into the OREC lamella. In addition, the storage stability of WPP/OREC-modified asphalt is better than that of single nanomaterials and polymer-modified asphalt. Lu and coworkers [20] investigated the storage stability of nano MMT modified asphalt, and the softening difference of modified asphalt with 3 wt. % nano MMT was 2.3°C. Padhan and coworkers [26] evaluated the PE-modified asphalt using the storage stability tests, and they found that the softening point difference of modified asphalt with 0.5 wt. % PE was 2.5°C. Moreover, Castillo and coworkers found that the SEBS/nano clay-modified asphalt had a good storage stability, and the softening difference was 1°C when the SEBS/nano clay content was 4 wt. % [32]. Compared with other polymer/nanomaterial composite-modified asphalt, the storage stability of as-prepared WPP/OREC asphalt in this paper is reasonable.

3.4. *Thermal Performance of WPP-Modified Asphalt and WPP/OREC-Modified Asphalt*

3.4.1. TG Analysis. The TG curves of WPP-modified asphalt with 4 wt. % WPP and WPP/OREC-1.5-modified asphalt before and after aging are shown in Figure 6 and 7, respectively. It can be seen that the weight loss of WPP-modified asphalt is divided into two stages, and the curve of weight loss is a basically horizontal line in the range of 100°C–300°C, indicating that the weight of WPP-modified asphalt is relatively stable in this temperature range. The WPP-modified asphalt initially shows the weight loss in the range of 300–450°C, which may be due to the removal of light components in asphalt and the polycondensation of the asphalt molecules. The volatilization of light components will occur during the aging test, and the weight loss of asphalt after aging decreases in this stage. In addition, WPP-modified asphalt has the second stage of weight loss in the range of 450–480°C, which is due to the decomposition of heavy components in asphalt. Moreover, the weight loss change for WPP-modified asphalt before and after aging is not obvious in this stage, and the total weight loss in the range of 100–700°C is about 80 wt. %. According to Figure 7, we can find that OREC can improve the thermal performance of WPP-modified asphalt, the weight loss of WPP/OREC-1.5-modified asphalt is delayed (the initial weight loss temperature of about 320°C), and the heat stability of the asphalt is improved.

3.4.2. DSC Analysis. Due to the complexity of the composition, the endothermic peak in the DSC curve of the asphalt changes to be wide compared with that of the model polymers having a single composition. In fact, this endothermic peak is the set of many different phase transition

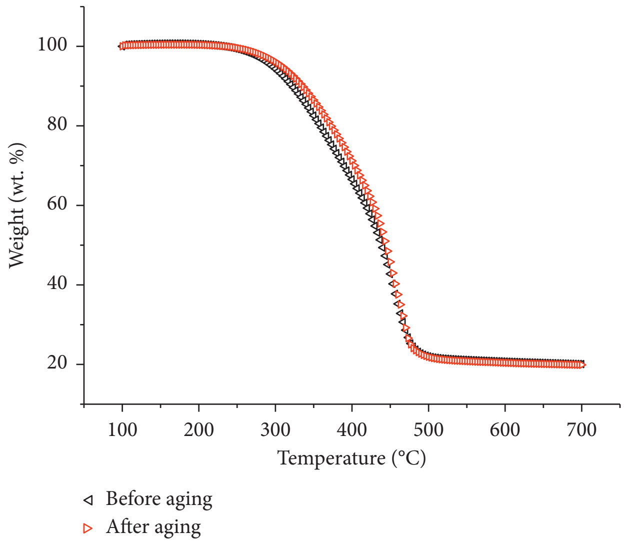

Figure 6: TG curves of WPP-modified asphalt before and after aging.

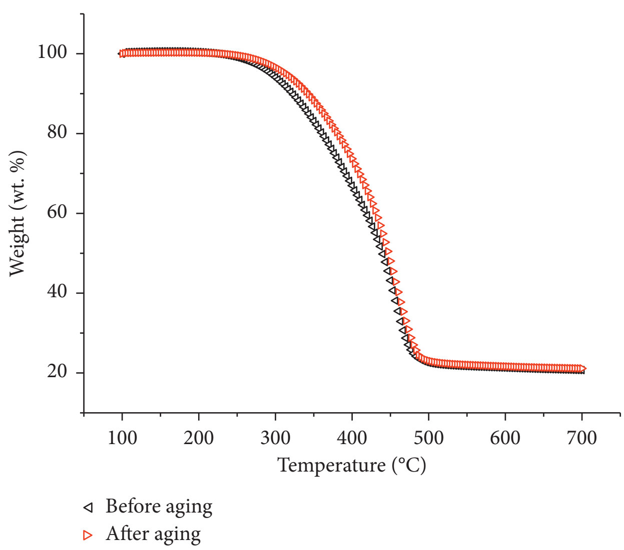

Figure 7: TG curves of WPP/OREC-1.5-modified asphalt before and after aging.

peaks, and the broad peak indicates that the phase transition of the material has more types [33, 34]. The peak in the low temperature region is a phase transition peak of small molecules, and that at the high temperature is the phase transition peak of the molecules with a high molecular weight. The DSC curve of WPP/OREC-modified asphalt before and after aging is shown in Figure 8. The as-prepared WPP/OREC-1.5-modified asphalt without aging has an endothermic peak at around 65°C, corresponding to the softening point where the phase transition of WPP/OREC-1.5-modified asphalt with complicated components occurred. In addition, a large endothermic peak generated by melting WPP emerges at around 120°C. A small endothermic peak appears at around 150°C in the DSC curve of the sample before aging, indicating that some components

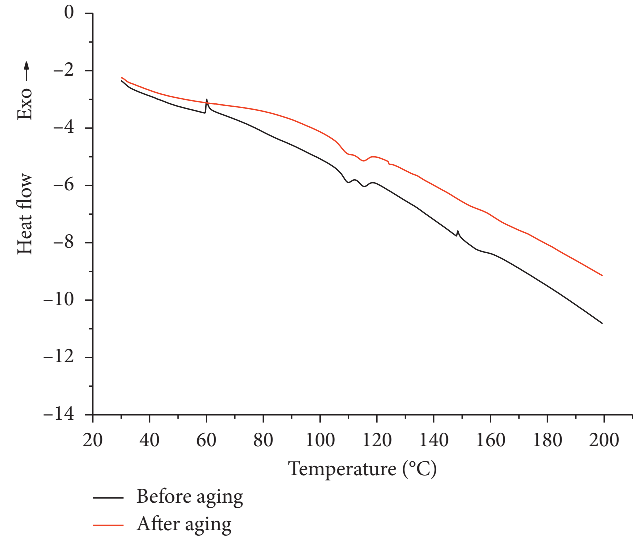

Figure 8: DSC curves of WPP/OREC-1.5-modified asphalt before and after aging.

have volatilized during the heating process. Compared with the sample before aging, the two endothermic peaks (at around 65° C and 150°C) of WPP/OREC-1.5-modified asphalt after aging disappear, indicating that some components of the asphalt have changed in the aging process. There are two possible changes for the components in asphalt during the aging of the sample. Some components have evaporated and other components have transformed into macromolecules via the chemical reaction, which can be attributed to adequate oxygen and a suitable aging temperature. According to the DSC result, it can be inferred that the macromolecular components have been generated during the aging process of WPP/OREC-1.5-modified asphalt, and its phase transition temperature will be in the range of 100–110°C.

3.5. Micromorphology of WPP-Modified Asphalt and WPP/OREC-Modified Asphalt. The morphology and dispersion of WPP in the asphalt can be observed by fluorescence microscope, and the fluorescence microscope images of the samples are shown in Figure 9. The WPP after absorbing the light components of asphalt can display the color under the fluorescence, and it shows the distribution of WPP in asphalt matrix clearly [35, 36]. The bright part in the fluorescent images is the polymer modifier, while the black is the asphalt matrix (as shown in Figure 9(a)). The polymer is formed by the granular morphology in base asphalt during the modification with WPP, and the bright WPP and the black asphalt phase regions can be easily distinguished (as shown in Figure 9(b)). However, the difference in the composite-modified asphalt is not obvious, and the floc materials can be observed (as shown in Figure 9(c)–9(g)). This is due to the rich active groups in OREC and the aggregation of OREC particles. In the previous papers of our group [12, 14, 37, 38], we found that the nano OMMT could aggregate when the content of OMMT was high. Castillo and coworkers [32] reported that the aggregation of SEBS

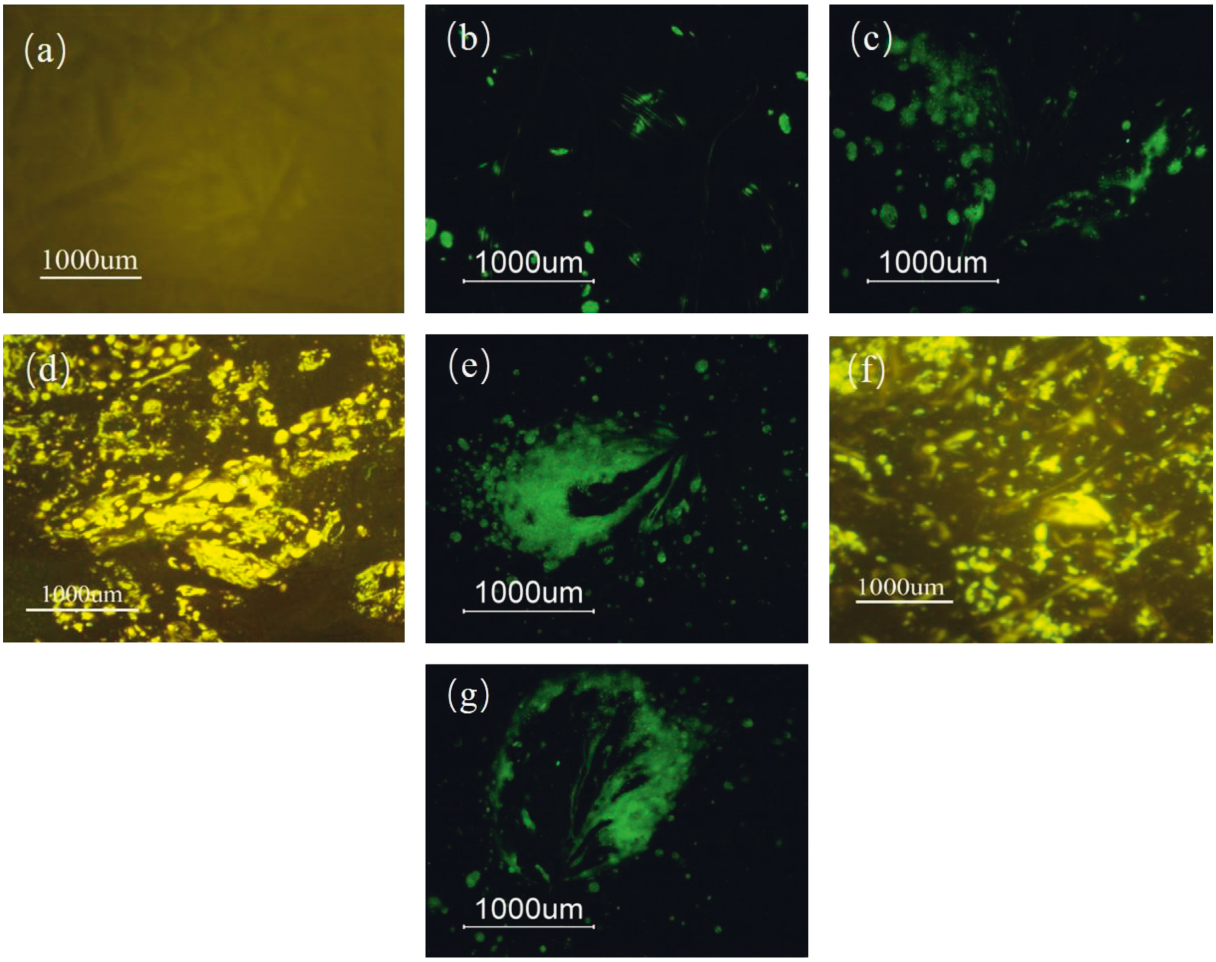

FIGURE 9: Fluorescence microscope images of the samples: (a) basic asphalt, (b) WPP-modified asphalt with 4 wt. % WPP, (c) WPP/OREC-0.5-modified asphalt, (d) WPP/OREC-1-modified asphalt, (e) WPP/OREC-1.5-modified asphalt, (f) WPP/OREC-2-modified asphalt, and (g) WPP/OREC-2.5-modified asphalt.

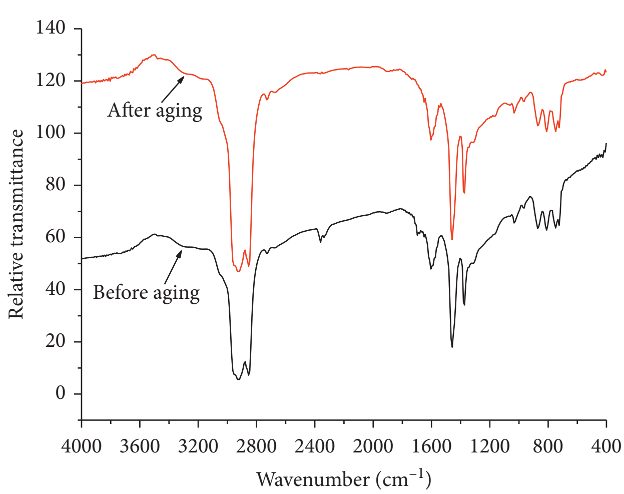

FIGURE 10: FTIR spectra of WPP/OREC-1.5-modified asphalt before and after aging.

appeared in the modified asphalt when the SEBS/nano clay was 6 wt. %. The phenomenon in this paper is similar with those in the previous studies. In a conclusion, when the OREC content is low (as shown in Figure 9(c)), OREC can be dispersed in WPP-modified asphalt, and the uniform dispersion of WPP in the asphalt also can be realized. When the OREC content increases (as shown in Figure 9(d)–9(g)), the OREC particles aggregate and adsorb the polymer in the asphalt, and it shows the uneven dispersion.

3.6. FTIR Analysis of WPP/OREC-Modified Asphalt. The FTIR spectra of WPP/OREC-modified asphalt before and after aging are shown in Figure 10. The absorption peaks at 1690 cm^{-1} and 1025 cm^{-1} are ascribed to the carbonyl and sulfoxide functional groups, respectively. After the aging, the absorption intensity of carbonyl group in WPP/OREC-1.5-modified asphalt increases. According to FTIR spectra, we find that there are no extra functional groups appearing in the WPP/OREC-1.5-modified asphalt after aging. In addition, the sulfur ether or thiol groups are very rare. Therefore, it can be inferred that the active functional groups of the molecules in the asphalt will react with the oxygen in the air, and the polar molecules with carbonyl functional groups can be formed during the asphalt aging. The absorption peaks of phenyl substituents at 750 cm^{-1}, 815 cm^{-1}, and 870 cm^{-1} basically keep consistent after the aging, and the absorption band of C-H for the alkane at 2960–2850 cm^{-1} is also enhanced after the aging. It can be concluded that the functional groups in WPP/OREC-modified asphalt have no obvious changes before and after aging. This result manifests that some active components will change, but there are no new functional groups generating during the aging of WPP/OREC-modified asphalt.

4. Conclusions

The combined modification with WPP and OREC is an effective method to improve the comprehensive performance of the base asphalt. When the content of OREC in the composite-modified asphalt is 1.5–2 wt. %, its comprehensive performance is excellent. When the content of WPP is 4 wt. % and the content of OREC is 1.5 wt. %, the ductility of the composite-modified asphalt is the highest. When the OREC content is low, the synergy of WPP and active groups of OREC can promote the homogeneous dispersion of WPP in base asphalt. When the OREC content is high, nano OREC will agglomerate significantly and cannot play the role of nanomaterial modifier entirely. There are no new functional groups generating but some polar components can be formed during the aging of composite-modified asphalt.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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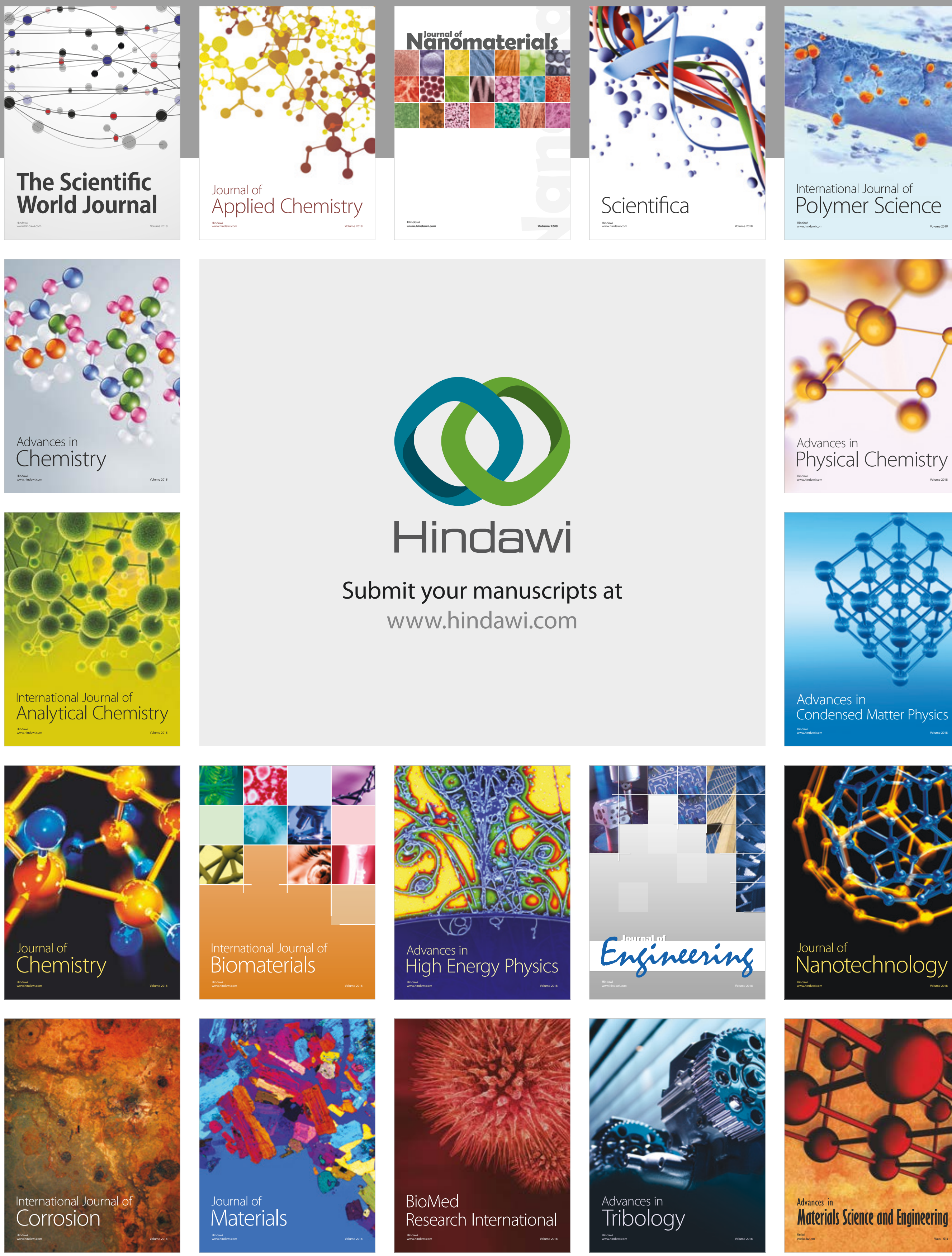
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