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Research Article

Preparation and Properties of an Active Cooling Antirutting Asphalt Mixture

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To reduce the temperature of asphalt pavements in summer and improve their high-temperature stability, tourmaline anion powder (TAP) was used as a modifier to prepare modified asphalt, which actively cools the pavement. The effects of different TAP contents on the high- and low-temperature performance of modified asphalt and its pavement cooling performance were studied based on the dynamic shear rheometer, low-temperature bending beam rheometer, and indoor rutting plate temperature difference tests; subsequently, the optimum TAP content was determined. Modified asphalt was used to prepare an active cooling antirutting asphalt mixture, and its pavement cooling performance was verified via outdoor lighting tests. High- and low-temperature dynamic modulus and low-temperature semicircular splitting tests were used to evaluate the high- and low-temperature performance; further, freeze-thaw splitting and immersion Marshall tests were performed to evaluate the water stability of the active cooling antirutting asphalt mixture. The results denote that TAP is useful for improving the rutting factor of asphalt. When the TAP content is 16% of the asphalt material, the maximum cooling value of the surface in laboratory tests becomes 5.9°C. When compared with an ordinary asphalt mixture, the dynamic stability of the active cooling antirutting asphalt mixture at medium and high temperatures increased by 18%–22%. The fracture energy can be increased by 12% at low temperatures. The maximum cooling value of the surfaces in outdoor tests is 7.2°C, and the water stability slightly decreases; however, it still satisfies the specification requirements.

1. Introduction

Asphalt pavement is black and thus can easily absorb heat. Excessive pavement heat in the hot season not only accelerates the development of rutting at high temperature but also aggravates the urban heat island effect. Because of the increasing awareness about environmental protection, constant efforts are being targeted toward finding high-performance materials for building roads and making road engineering a low-carbon and environment-friendly process. Therefore, new environment-friendly pavement materials are being studied. To remedy the issue of the high-temperature stability of asphalt pavement, measures, such as the optimization of gradation [1, 2], addition of fiber [3], and addition of an antirutting agent [4, 5], have been adopted to improve the high-temperature stability of the asphalt mixture. Further, a pavement cooling coating or thermal resistive aggregate can be used to reduce the temperature of asphalt pavements in hot weather [6–8]. However, the aforementioned technical methods usually make the road construction process more complicated and expensive, and majority of the modified materials and coatings are toxic, which may cause environmental pollution.

Hu et al. [9] proposed that the tourmaline anion powder (TAP) contains Al, Na, Fe, and Lu ring-shaped silicate materials and exhibits the characteristics of Be, including good piezoelectric [10], spontaneous polarization, and thermoelectric properties [11]; TAP is extensively used in the environmental protection, electrical, healthcare, and decoration industries. Wang et al. [12] used tourmaline to treat contaminated soil, where the observed material effects were obvious. Zhong and Wang [13] and Cao et al. [14] used the negative ion release function of tourmaline to purify sewage. TAP releases negative ions and exhibits thermoelectric property and spontaneous polarization; therefore, it absorbs the external heat and its pyroelectric properties and spontaneous polarization are significantly enhanced with an increase in the external temperature; further, the thermal energy is transformed into static energy to reduce the temperature of the asphalt pavement. Based on the aforementioned principle, Mckinley et al. [15], Navid and Pilon [16], and Nguyen et al. [17] used TAP for absorbing waste heat. Although Wang et al. [18–22] have conducted detailed studies with respect to the usage of TAP as a construction material, it is not widely used in highway construction at present. TAP is used as an inorganic asphalt modifier to prepare modified asphalt that exhibits flame-retardant and smoke-suppression properties. It has also been observed that TAP can reduce the temperature of the asphalt pavement. Li et al. [23] and Zhang et al. [24] prepared a cooling asphalt mixture by adding a negative ion powder into an asphalt mixture. However, based on the literature, we can conclude that a comprehensive and in-depth study on the road performance of the TAP-modified asphalt or an asphalt mixture mixed with TAP has not yet been conducted.

Therefore, to resolve the issues that are associated with the asphalt pavements at high temperatures, including rutting and congestion, which are easily caused by the high temperature of the asphalt pavement in summer, this study focuses on the application of TAP to modify asphalt by utilizing the negative ion release, thermoelectric, and spontaneous polarization properties of TAP and prepare modified asphalt that can provide the asphalt pavement with an active cooling function. Hence, an active cooling anti-rutting asphalt mixture (APC-AC) has been developed. Subsequently, the influence of the TAP content on the high- and low-temperature performances and the cooling performance of the modified asphalt was investigated. Finally, the cooling effect and paving performance of APC-AC were comprehensively studied and compared with those of an ordinary asphalt mixture.

2. Materials

2.1. TAP. TAP is a silicate mineral exhibiting negative ion release as well as piezoelectric and thermoelectric properties. The modification of asphalt using TAP not only endows the asphalt pavement with a cooling function, reducing its temperature in hot weather and rutting, but also improves the high-temperature performance of asphalt to a certain extent. The TAP used in this study was manufactured in the Lingshou County, Hebei Province, China, and its structure is presented in Figure 1; its main physical parameters are presented in Table 1, whereas its main chemical components are presented in Table 2.

Figure 1: The physical appearance of TAP.

2.2. Asphalt. AH-70# petroleum asphalt was used in this study, and its relevant performance parameters were verified according to *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011) of China* and are shown in Table 3.

2.3. Aggregate. Herein, coarse aggregates having sizes of 3–5, 5–10, and 10–18 mm and fine aggregate in the form of limestone manufactured sand were used. The aggregates were divided into single-stage aggregates and tested; the performance parameters and densities of the aggregates are presented in Tables 4 and 5. Further, the sieving results and apparent relative density of the mineral powder are presented in Table 6.

3. Methodology

3.1. Preparation Method

3.1.1. Preparation of the TAP-Modified Asphalt. To improve the dispersion and compatibility of TAP in the base asphalt, sodium stearate was used to treat the TAP surface. Asphalt was initially heated to 135°C and moved into a high-speed shear machine for preparing TAP-modified asphalt. Subsequently, the surface-modified TAP was added into the hot-melt asphalt in batches, and the high-speed shear machine was dispersed for 5 min at a shear rate of 1000 rpm. A glass rod was used to assist stirring during TAP shearing. By maintaining the temperature constant, the shear rate was increased to 3500 rpm, and high-speed shearing was performed for 35 min, resulting in the full dispersion of TAP to produce a uniform cross-linked structure with asphalt. By maintaining the temperature constant, the shear rate was reduced to 1000 rpm; after a shearing time of 10 min, the air bubbles in the asphalt were fully discharged and the finished product was obtained.

Four types of modified asphalt samples containing different TAP contents (8%, 12%, 16%, 20%, and 24%) added to base asphalt were prepared according to the above method. The morphologies of the base and TAP-modified asphalt were observed using a fluorescence microscope, as shown in Figure 2.

Table 1: The main physical parameters of TAP.

Product	Color	Appearance	Amount of negative ion released/ions·cm^3	Particle size/mesh	Mons' hardness scale
Tourmaline anion powder	Yellow	Powder	>8000	2000	7.0–7.2

Table 2: The main chemical components of TAP.

Components	Al_2O_3	SiO_2	B_2O_3	Fe_2O_3	MgO	FeO	Na_2O	Other
Content (%)	35.1	34.8	11.0	10.2	4.7	1.4	0.9	Trace

Table 3: The main performance parameters of asphalt.

Index	25°C penetration (0.1 mm)	15°C ductility (cm)	10°C ductility (cm)	Softening point (°C)	15°C density (g/cm^3)	Penetration index
Testing result	62	>150	32.1	48.5	1.032	−1.32
Normative requirements	60–80	>100	>20	>46	—	−1.5–1.0

Table 4: Performance parameters of the aggregates.

Aggregate type	Project	Normative requirements	Testing result
Coarse aggregate	Crushing value (%)	≤26	17.2
	Los Angeles abrasion value (%)	≤28	16.7
	Needle flake (%)	≤12	8.6
	Adhesiveness (stage)	≥4	5
	Ruggedness (%)	≤12	7.4
	BPN	≥38	52
Fine aggregate	Angularity (s)	≥30	37.5
	Ruggedness (%)	≤12	5.8

Table 5: Densities of the aggregates.

Particle size (mm)	Apparent relative density	Bulk relative density
19-16	2.942	2.907
16-13.2	2.882	2.835
13.2-9.5	2.96	2.899
9.5-4.75	2.938	2.867
4.75-2.36	2.923	2.818
2.36-1.18	2.767	2.687
1.18-0.6	2.764	—
0.6-0.3	2.766	—
0.3–0.15	2.75	—
0.15–0.075	2.751	—
<0.075	2.771	—

Table 6: The sieving and apparent relative density test results of filling.

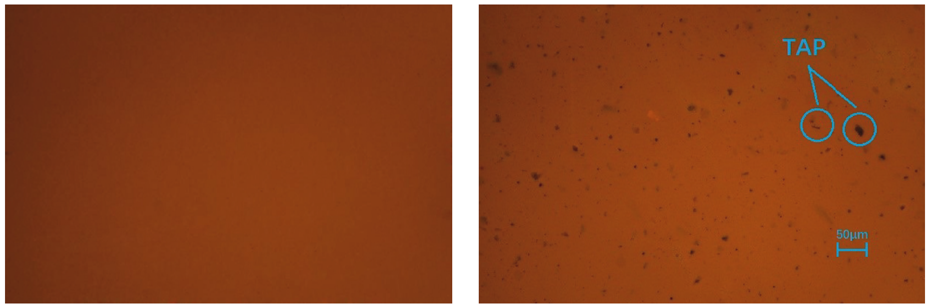
Apparent relative density	The mass percentage of aggregate passing through the following sieve holes (%)			
	0.6 mm	0.3 mm	0.15 mm	0.075 mm
2.771	100.0	100.0	100.0	98.6

3.1.2. Preparation of the APC-AC Samples. The APC-AC samples were prepared using the TAP-modified asphalt containing different TAP contents, and the samples required for conducting the asphalt mixture tests, such as the rutting plate and Marshall samples, were obtained. The specific preparation steps were conducted in accordance with the JTG E20-2011 regulations. AC-16 was the asphalt mixture that was used, and its gradation is presented in Table 7. When the TAP content is 0%, the optimum oil-stone ratio determined using the Marshall test method is 4.8%. The ratio of asphalt to stone was increased by 0.1%–0.3% when the TAP-modified asphalt was used to prepare the active cooling asphalt mixture because the TAP particles contribute a certain proportion of the modified asphalt quality in the TAP-modified asphalt.

3.2. Test Methods

3.2.1. Dynamic Shear Rheometer and Bending Beam Rheometer Tests

(1) Dynamic Shear Rheometer Tests. In this study, dynamic shear rheometer (DSR) was used to test the rheological parameters of the TAP-modified and base asphalt materials containing different TAP contents at 58°C, 64°C, and 70°C. The phase angle (δ) and rutting factor ($G*/\sin\,\delta$) were used to evaluate the high-temperature performances of the asphalt samples at a test load of 100 Pa and a frequency of 1.59 Hz (with a corresponding angular velocity of 10 rad/s) for samples with a diameter of 25 mm and a thickness of 1 mm. A Malvine DSR was used in the experiments.



(a) (b)

Figure 2: Morphologies of the (a) base asphalt and (b) TAP-modified asphalt.

Table 7: Requirements of the aggregate gradation range and synthetic gradation of the AC-16 mixture.

Gradation type	Mass percentage of aggregate passing through the following sieve holes (%)										
	19 mm	16 mm	13.2 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	0.6 mm	0.3 mm	0.15 mm	0.075 mm
Normative requirements (%)	100	90–100	76–92	60–80	34–62	20–48	13–36	9–26	7–18	5–14	4–8
Synthetic gradation (%)	100.0	95.1	81.3	65.6	40.0	27.9	19.5	13.8	9.7	6.8	4.7

(2) Bending Beam Rheometer Tests. Based on the existing research on the cooling and rutting resistances of modified asphalt, its low-temperature performance can be improved by adding a certain amount of TAP. Therefore, bending beam rheometer (BBR) tests were conducted using a Cannon low-temperature bending rheometer to evaluate the low-temperature stability of modified asphalt containing different amounts of TAP, and the creep stiffness S and creep rate m were selected as evaluation parameters at a test temperature of −6°C.

3.2.2. Temperature Difference Tests in Indoor Rutting Plate and Outdoor Illumination

(1) Temperature Difference Testing with Respect to the Indoor Rutting Plate. In this study, the temperature difference testing of indoor rutting plate was used to study the effects of different TAP contents on the cooling of the APC-AC pavement materials. First, rutting slab samples with a thickness of 10 cm were prepared using APC-AC and divided into two layers comprising a 5 cm ordinary asphalt mixture bottom layer and an APC-AC upper layer, as shown in Figure 3. Next, a common rutting plate was prepared using a rutting plate test model with a depth of 5 cm. Then, this rutting plate was put into a rutting plate test model with a depth of 10 cm. The probe of the temperature sensor was subsequently placed in the center of the rutting plate surface, covered with APC-AC, and compacted using a wheel roll forming instrument to obtain 10 cm thick rutting plate samples.

After demolding the rutting plate specimens, a temperature sensor is introduced along with asphalt mortar onto the upper and lower surfaces at the central position. The temperature sensors were placed on the surface at a depth of 5 cm and at the bottom of the rutting plate samples. Then, the test samples were moved onto the test platform

Figure 3: Photograph of a laboratory test sample.

(Figure 4). The test chamber comprises a high-density foam insulation board and glass cylinder to prevent heat exchange between the samples and their surrounding environment. A 500 W tungsten iodide lamp placed on the upper part of the test platform was used to simulate the solar light source. This light source was turned on to irradiate the samples, and the temperature of the sensor was read using an Ulide UT325 contact thermometer every 10 min.

(2) Outdoor Illumination Tests. To verify the actual cooling effects of the APC-AC, the test platform was placed outdoors in direct sunlight, and the temperature changes on the top and bottom surfaces of the 5 mm thick single layer APC-AC and asphalt mixture rutting plate samples were recorded using a thermometer every 3 min.

3.2.3. Dynamic Modulus, Semicircular Splitting, and Water Stability Testing

(1) Dynamic Modulus Tests at Medium and High Temperature. Static test methods are usually used to test the modulus of the pavement materials, but the loading times of these methods are generally long and the loading speeds are

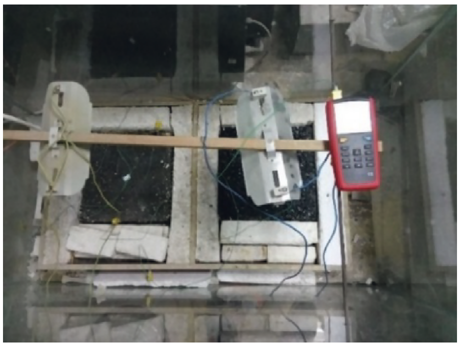


Figure 4: Photograph of the test platform.

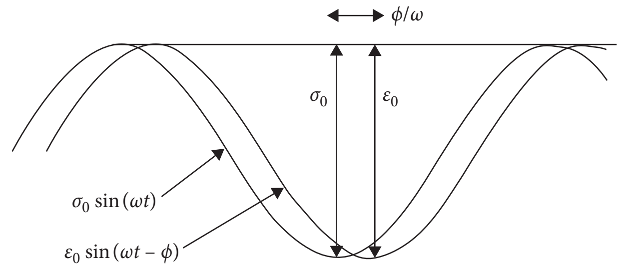


Figure 5: Schematic of the sine wave associated with the loading of the samples.

slow. Under this type of loading method, the samples have sufficient time to deform, which is obviously inconsistent with the real loading conditions on a road. To better simulate the effects of driving load on the asphalt mixtures and more accurately evaluate their rutting resistance, dynamic modulus tests were conducted at medium and high temperatures according to T0738 in the JTG E20-2011 regulations. The dynamic modulus and phase angles of the APC-AC and ordinary asphalt mixtures at 40°C and 60°C and at 25, 10, 5, 1, 0.5, and 0.1 Hz were used to evaluate their high-temperature stability. In the dynamic modulus testing of the asphalt mixtures, the load applied to the samples was in the form of periodic sine waves, as shown in Figure 5, where the relation between the stress and strain of the asphalt mixture can be expressed using the dynamic modulus under continuous sine wave loading.

The dynamic modulus is defined as the ratio of the stress mode (amplitude) to the strain mode (amplitude) of the material for a given waveform and period of dynamic loading, as shown in the following equation:

$$E^{*} = \frac{|\sigma(t)|}{|\varepsilon(t)|} = \frac{|\sigma_0 \sin(\omega t)|}{|\varepsilon_0 \sin(\omega t - \phi)|}, \quad (1)$$

where E^{*} denotes the dynamic modulus, Φ denotes the phase angle, σ_0 denotes the peak stress, ε_0 denotes the peak strain, ω denotes the angular momentum, and t denotes the time.

In accordance with T0738 in the JTG E20-2011 regulations, the height and diameter of the dynamic modulus asphalt mixture samples were 150 and 100 mm, respectively. In this study, the APC-AC and ordinary asphalt mixture samples were formed using an SGC rotary compactor, where the SGC-formed samples were controlled based on the rotation times. The compaction parameters used in the tests were as follows: pressure = 0.6 MPa; number of rotations = 100; speed of rotation = 30 revolutions per min; angle of rotation = 1.160°; and molding temperature = 150°C–160°C. A sample is shown in Figure 6.

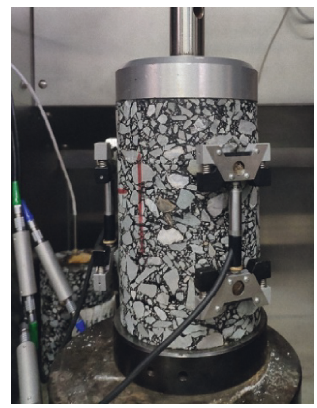


Figure 6: Photograph of a dynamic modulus sample (installed sensors).

(2) Semicircular Splitting Tests at Low Temperature. In this study, semicircular bending tests were conducted. The fracture energy G_f of the APC-AC and common asphalt mixture at 0°C was used as a parameter to evaluate the low-temperature crack resistance of the materials. G_f considers the flexibility and strength of the samples, leading to a better evaluation of the low-temperature performance of the asphalt mixtures. According to AASHTO TP124, the semicircular splitting test G_f value can be calculated from the fracture work W_f and ductile zone area A_{lig}, as shown in the following equation:

$$G_f = \frac{W_f}{A_{\text{lig}}} \times 10^6, \quad (2)$$

where G_f is the fracture energy in J/m^2, W_f is the fracture work in J, and A_{lig} is the area of the ductile zone in mm^2. The fracture work W_f can be calculated according to the load-displacement curve of the sample that is being tested. As shown in Figure 7, the area under the load-displacement curve can be directly integrated using the Origin program.

The area of the ductile zone can be calculated based on the diameter, thickness, and length of the slit of the sample, as shown in the following equation:

$$A_{\text{lig}} = W \times (D - l), \quad (3)$$

where l is the length of the slit in mm, W is the thickness of the sample in mm (here, 30 ± 0.5 mm), and D is the diameter of the sample in mm (here, 100 mm).

In this experiment, the method used to prepare the samples is identical to that used for the dynamic modulus samples, and the specific parameters can be found in Table 8, whereas the samples are shown in Figures 8 and 9.

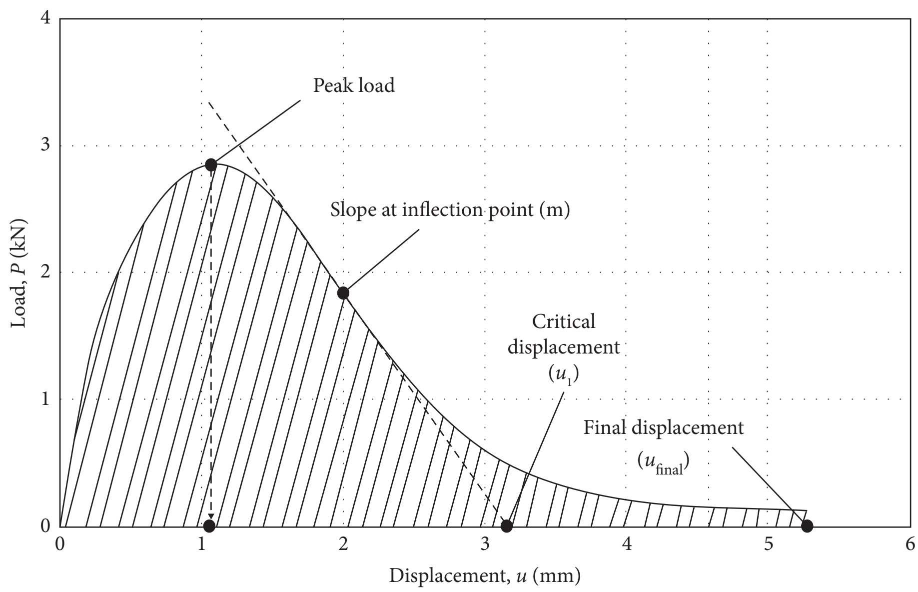


Figure 7: Calculation of the fracture work region.

Table 8: Parameters of the semicircular splitting tests.

Maximum nominal diameter (mm)	Diameter (mm)	Thickness (mm)	Length of slit (mm)	Diameter of roller shaft (mm)	Spacing between supporting rollers	Temperature (°C)	Loading rate (mm\min)	Waveform
16	150	50	15; 25	12	0.8D	0	5	Linear wave

Figure 8: Photograph of the failed semicircular split samples.

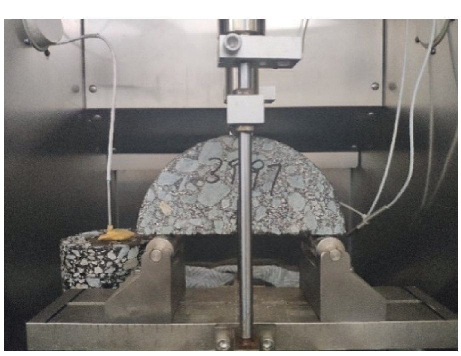


Figure 9: Photograph of the assembly of semicircular split samples.

(3) Water Stability Tests. In this study, the water stabilities of two types of asphalt mixtures were investigated via the water immersion Marshall stability and freeze-thaw splitting tests according to the JTG E20-2011 regulations. The Marshall compaction method was used to form the samples, and the APC-AC and ordinary asphalt mixture were used to prepare Marshall samples with a standard height of 63.5 mm and a diameter of 101.6 mm. Equations (4) and (5) were used to calculate the residual stabilities and tensile strength ratios of the freeze-thaw splitting of the samples:

$$MS_0 = \frac{MS_1}{MS} \times 100, \quad (4)$$

where MS_0 is the residual stability in %, MS_1 is the stability after 48 h of immersion in kN, and MS is the Marshall stability in kN.

$$TSR = \frac{\overline{R}_{T2}}{\overline{R}_{T1}} \times 100, \quad (5)$$

where TSR is the tensile strength ratio of freeze-thaw splitting in %, $\overline{R}_{T1}$ is the average value of the splitting tensile strength of the first group of effective samples without a freeze-thaw cycle in MPa, and $\overline{R}_{T2}$ is the average value of the splitting tensile strength of the second group of effective samples with a freeze-thaw cycle in MPa.

4. Results and Discussion

4.1. Evaluation of the High- and Low-Temperature Performance of the TAP-Modified Asphalt

4.1.1. DSR Results. The rutting factor $G*/\sin\delta$ and phase angle *d* of the surface-modified asphalt samples with different TAP contents are shown in Figures 10 and 11, respectively.

Figure 10 shows that the $G*/\sin\delta$ values of the TAP-modified asphalt samples increase with an increase in the TAP content at the same temperature; however, with an increase in the test temperature, the trend of the $G*/\sin\delta$ values of the TAP-modified asphalt samples continuously decrease with an increase in the modified TAP content, with the greatest changes being observed at 58°C. When the temperature is low, increasing the amount of modified TAP can significantly improve the high-temperature stability of the modified asphalt. When the modified TAP content is 0%–12%, the $G*/\sin\delta$ values of the modified asphalt samples rapidly increase. When the modified TAP content is 12%–16%, the $G*/\sin\delta$ values of the modified asphalt samples gradually increase and increase rapidly again when the modified TAP content is greater than 16%.

The reasons for the above phenomena are mainly the small particle size, large specific surface area, and uniform dispersion of the TAP, which exhibit a strong absorption effect on the light components in the base asphalt. After the surface modification of TAP with sodium stearate, the hydrophilic end of the surface modifier molecule reacts with the surface of TAP and adheres to the powder. The other end combines with asphalt, playing a bridging role, significantly enhancing the adhesion between TAP and asphalt, significantly increasing the consistency of the modified asphalt, and effectively improving the high-temperature performance of the asphalt.

As shown in Figure 11, the curves of the variation in the *d* values of the TAP-modified asphalt samples with different powder-to-oil ratios shows that at the same temperature, the *d* values of the modified asphalt samples show little changes with an increase in modified TAP, with a variation range of approximately 0.7°. This shows that the increase in modified TAP content does not alter the proportion of viscoelastic components in the asphalt. The phase angle of the modified asphalt at the same temperature is a property of the asphalt system itself, which is not related to the modified TAP. Furthermore, the modified asphalt with the same amount of TAP exhibits better elastic properties at low temperature because of its smaller *d* value. With an increase in temperature, the *d* value gradually increases, and, at this point, the viscous properties of the modified asphalt play a major role. Based on the analysis of the above test results, it is recommended that the TAP content should be 12%–16% of the asphalt quality, where the $G*/\sin\delta$ values exhibit little change.

4.1.2. BBR Results. The creep stiffness *S* and creep rate *m* of the surface-modified asphalt with different TAP contents are shown in Figures 12 and 13, respectively.

Figure 12 shows that with an increase in the TAP content, the *S* value of the modified asphalt first increases,

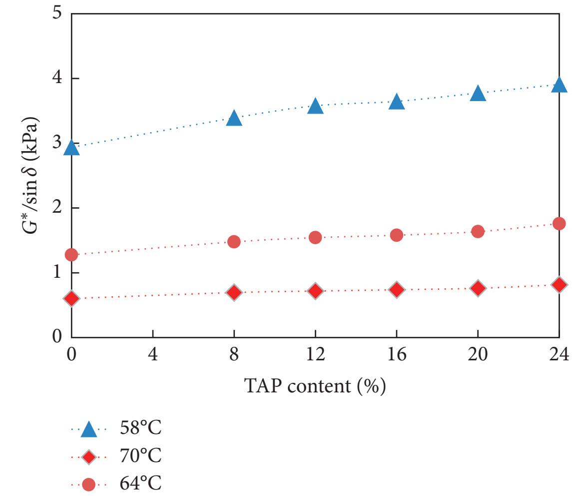


FIGURE 10: Variation in the $G*/\sin\delta$ value of TAP-modified asphalt with TAP content.

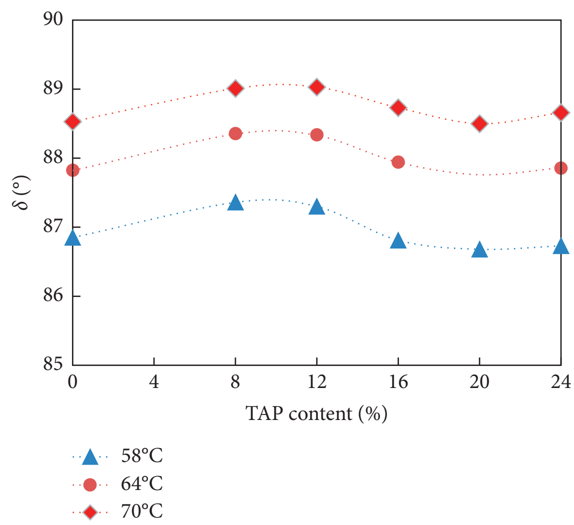


FIGURE 11: Variation in the *d* values of TAP-modified asphalt with TAP content.

then decreases, and increases again, indicating that the low-temperature performance of asphalt can be improved if the TAP content is appropriate. Based on the related research on tourmaline-modified asphalt, this study shows that this phenomenon is caused because TAP is piezoelectric; when the asphalt mixture is loaded, TAP releases charges and the attraction between the charges enhances the connection between the internal structures of the asphalt. However, when the TAP content exceeds a certain value, the consistency of the asphalt increases; furthermore, the presence of too much TAP hardens the asphalt. At this time, the binding force of charge on the asphalt structure is not superior to the stiffness of the asphalt, and the stress relaxation ability of the asphalt is weakened, which reduces the low-temperature crack resistance of the modified asphalt. From the 60 s creep stiffness *S* test results of the modified asphalt samples with different TAP contents, the TAP content should be controlled at 8%–20% to endow modified asphalt with good low-temperature

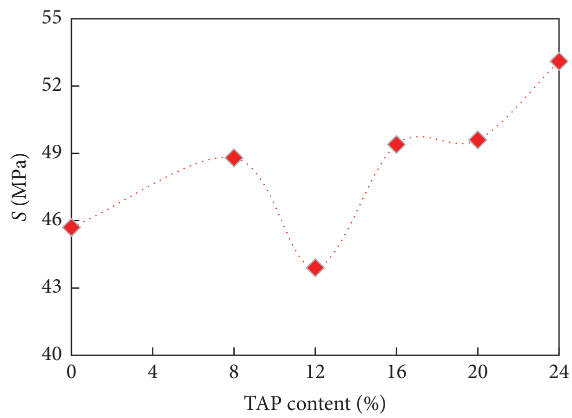


Figure 12: Creep stiffness of modified asphalt with different TAP contents.

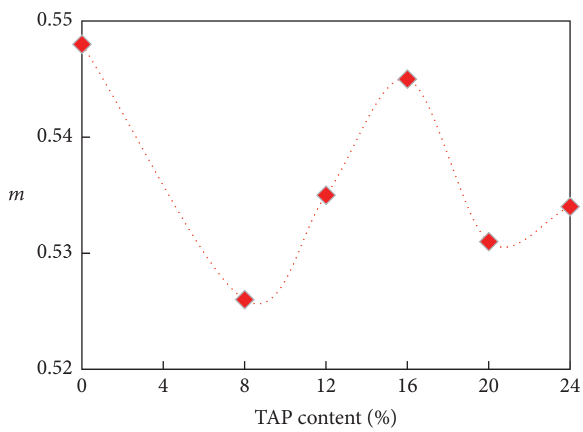


Figure 13: Creep rate of modified asphalt with different TAP contents.

performance. It can be seen from Figure 13 that the creep rate m of the modified asphalt samples does not significantly change with change in the TAP content.

4.2. Evaluation of the Indoor Cooling Effect. The temperature difference test results of the APC-AC indoor rutting slabs with different TAP contents are shown in Figure 14, where the samples are irradiated using a tungsten iodide lamp for 3 hours.

From Figure 14, the temperatures of the rutting slabs prepared using APC-AC are lower than those of the ordinary asphalt concrete rutting slabs; further, the greater the TAP content is, the more obvious will be the cooling effect. TAP can reduce the pavement material temperature mainly due to its spontaneous polarization, thermoelectric, and negative ion release properties. In terms of the spontaneous polarization effects, when the temperature of TAP increases, the stress inside the powder particles changes and the polarization effect is enhanced. Under the action of temperature stress, the [SiO_4] tetrahedra inside the structure promote the expansion vibrations of the Si–O–Si, B–O, and O–H bonds. During the transition of polar molecules from the low level

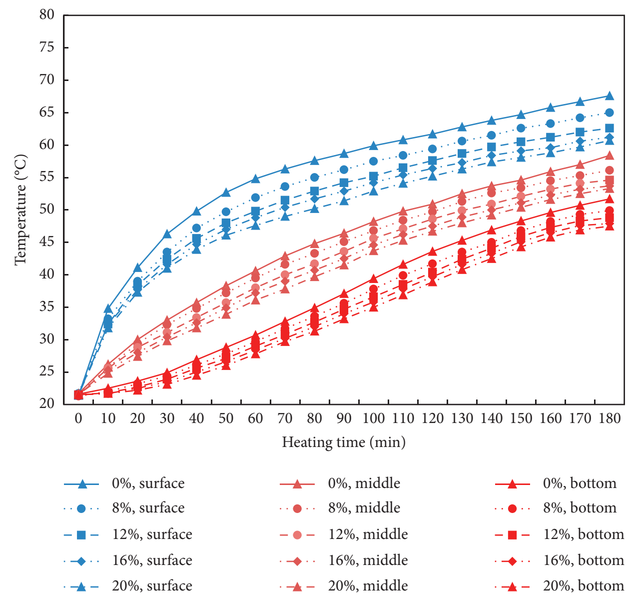


Figure 14: Temperature difference results of tests on the APC-AC indoor rutting slabs.

to the high level, some energy is released in the form of an electromagnetic wave, reducing the temperature of the APC-AC material. In terms of the thermoelectric properties, TAP will release charge to form an electrostatic field when the temperature changes, which will absorb heat for the APC-AC and convert it into electrical energy, reducing the temperature of the asphalt paving material and alleviating the urban heat island effect. In terms of the negative ion release, when the surface thickness of TAP particles is more than ten microns, a high-strength electrostatic field that is not covered by asphalt can be observed. When this comes into contact with the electrostatic field in the atmosphere, direct current electrostatic energy is generated, which causes instantaneous discharge, decomposing the water molecules into HO^- and H^+, when it comes into contact with the surrounding water molecules. At the same time, this process also consumes some of the heat from the APC-AC material.

The optimum content of TAP in the TAP-modified asphalt can be determined from its high- and low-temperature performance and cooling effect data. Considering the high-temperature performance of the material, the TAP content should be 12%–16% of the asphalt quantity; with respect to the low-temperature performance; a content of 8%–20% is optimal. The temperatures of the rutting plate samples with different TAP contents were judged after 3 h of exposure to a tungsten iodide lamp, as shown in Figure 15. The rutting plate samples show the greatest cooling range on the surface, followed by the middle and bottom parts of the materials. The surface temperatures of the ordinary asphalt concrete rutting slab samples can reach 67.3°C after being heated by a tungsten iodide lamp for 3 h. When the TAP content reaches 20% of the asphalt material, the surface temperatures of the rutting slab samples decrease by 6.6°C, the middle temperatures decrease by 4.4°C, and the bottom temperatures decrease by 3.4°C. When the TAP content is

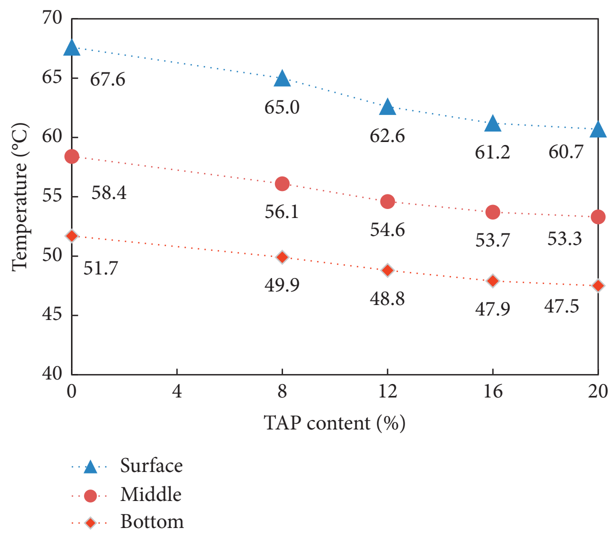


FIGURE 15: Temperature change of the rutting plate samples with different TAP contents after irradiation using a tungsten iodide lamp for 3 h.

more than 16% of the asphalt material, it is difficult to improve the cooling effect of the paving material by increasing the TAP content. At the same time, too much TAP only serves to increase the engineering costs of making pavements and negatively impacts the low-temperature performance of the asphalt. Therefore, considering the cooling effect and other factors, the optimum TAP content was found to be 16%.

4.3. Road Performance Evaluation of APC-AC. APC-AC was prepared from the TAP-modified asphalt, where the TAP content of the material was 16% and an ordinary asphalt mixture was prepared from the 70# base asphalt. The samples required for each test were prepared according to the requirements of Chinese specifications.

4.3.1. Dynamic Modulus Test Results at High Temperature. The results of the dynamic modulus tests using two types of asphalt mixtures at different test temperatures are shown in Figures 16 and 17.

The results of the dynamic modulus tests at medium and high temperatures show that the dynamic modulus of APC-AC is obviously higher than that of an ordinary asphalt mixture. When the test temperature is 40°C, the dynamic modulus increases by approximately 22%, whereas it increases by 18% when the test temperature is 60°C. This is mainly because the TAP particle size is very small and its specific surface is positive, which is conducive to the conversion of free asphalt into structural asphalt. Free asphalt is not conducive to maintain the stability of an asphalt mixture at high temperature. At the same time, due to the piezoelectric properties of TAP, the TAP in APC-AC will release charge when loaded. The attraction between the charges enhances the connection between the internal structures of the asphalt and improves the high-temperature stability of

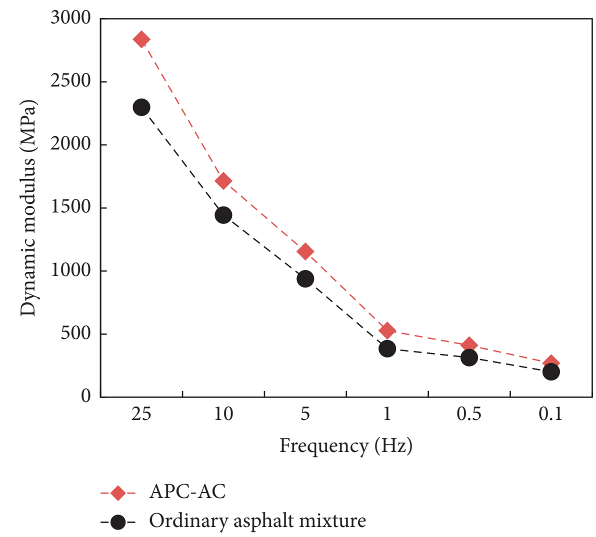


FIGURE 16: Results of dynamic modulus tests at 40°C.

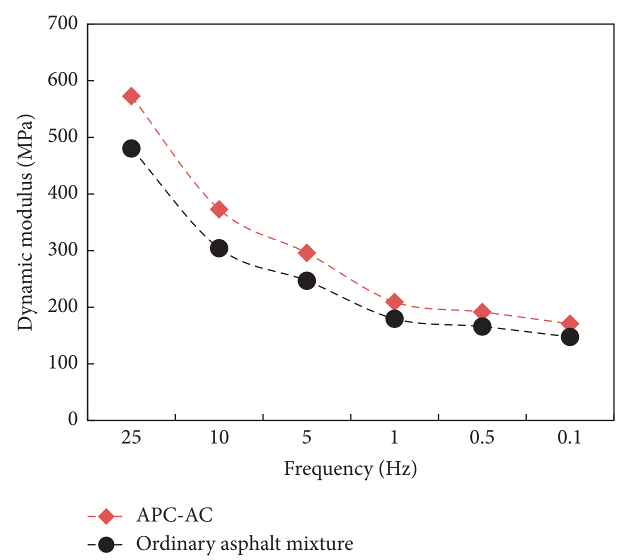


FIGURE 17: Results of dynamic modulus tests at 60°C.

the asphalt mixture to a certain extent, reflected in an increase in the dynamic modulus.

4.3.2. Results of the Semicircular Splitting Tests at Low Temperature. The results of the low-temperature semicircular splitting tests on different asphalt mixtures are shown in Table 9. When the slit depth is 15 mm, the G_f values of the APC-AC are 11.8% higher than those of the ordinary asphalt mixture and 12.6% higher than those obtained when the slit depth is 25 mm. This can be mainly attributed to the fact that the small TAP particles can strongly absorb the light components in the base asphalt material and that the large specific surface area of the material is beneficial for the formation of structural asphalt. Therefore, the low-temperature fracture energies of the APC-AC samples are higher than those of the ordinary asphalt mixtures, and their low-temperature crack resistance is also better.

Table 9: Results of the semicircular splitting tests.

Cutting depth (mm)	Fracture energy G_f (J/m^2)	
	Ordinary AC	APC-AC
15	1060	1186
25	875	980

Table 10: Results of the Marshall stability tests and freeze-thaw splitting tests for different asphalt mixtures.

Residual stability MS (%)		Tensile strength ratio of freeze-thaw splitting TSR (%)	
APC-AC	Ordinary AC	APC-AC	Ordinary AC
87.9	88.6	85.4	86.0

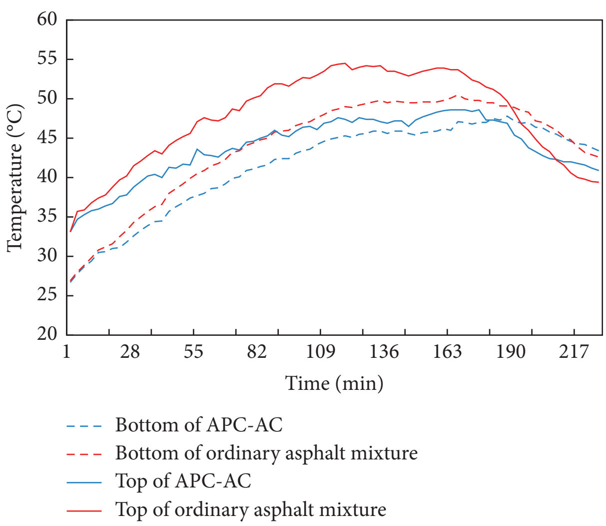


Figure 18: Temperature variation in the rutting plate samples at different positions.

4.3.3. Results of the Water Stability Tests. The results of immersion Marshall stability and freeze-thaw splitting tests using different asphalt mixtures are shown in Table 10. From the test results, it can be concluded that the water stability of the asphalt mixture is slightly affected by the addition of TAP, which may be due to the fact that TAP constitutes a proportion of the quality of modified asphalt material; therefore, the actual amount of asphalt in the material is effectively reduced, which leads to the thinning of the asphalt film thickness of the asphalt mixture. In the water stability tests, the asphalt-aggregate interface in APC-AC is more easily destroyed by the water content, and the water stability is reduced when the samples are affected by the combination of cold-hot pressure water.

4.4. Evaluation of the Outdoor Cooling Effect. APC-AC asphalt with a TAP content of 16% was prepared, and 5 cm rutting slab samples were fabricated. Light tests were performed outdoors in direct sunlight, where the daytime temperature was 18°C–29°C, the weather was clear, and the test time was between 11:30 and 15:18. The temperature changes of the APC-AC rutting and common rutting plates

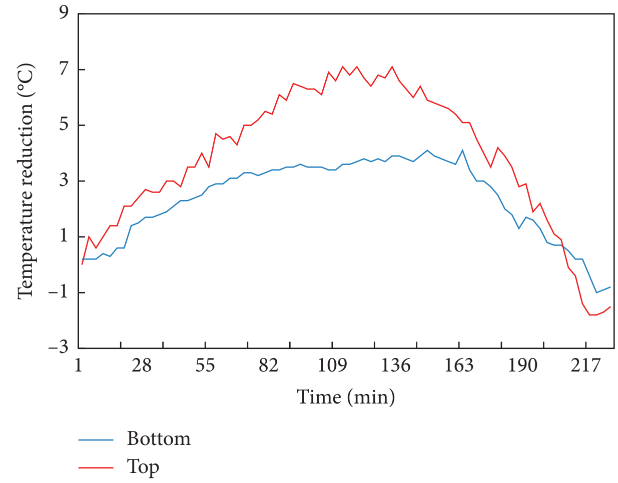


Figure 19: Change in the temperature reduction range on the upper and lower surfaces of the rutting plate samples.

are shown in Figure 18, and the range of cooling is shown in Figure 19.

From the outdoor light test results, it can be concluded that when the TAP content is 16% of the asphalt material, the maximum cooling value of the 5 cm thick APC-AC rutting slab samples can reach 7.2°C and the maximum cooling value of bottom can reach 4.3°C. The cooling effect observed in the outdoor tests is slightly higher than that observed in the indoor tests, and the surface temperatures of the samples fluctuate considerably, which may be due to the influence of wind gusts, clouds, and other environmental factors on the temperatures of the outdoor specimens, making the temperature changes of the samples unstable in outdoor light tests. Figures 18 and 19 show that the time corresponding to the maximum instantaneous cooling value is 13:30 when the daytime outdoor temperature is at its highest and the surface temperature of the rutting plate samples reaches its maximum. At an ambient temperature or when the asphalt concrete temperature is higher, the spontaneous polarization, thermoelectric, and negative ion release properties of the TAP are enhanced, conducive to improving the pavement cooling effect of the APC-AC.

5. Conclusions

In this paper, the effect of TAP on the properties of asphalt and asphalt mixture was investigated comprehensively, and some useful conclusions were summarized as follows:

(1) With an increase in TAP content, the high-temperature stability of the TAP-modified asphalt increases, whereas the low-temperature crack resistance initially fluctuates and subsequently decreases; further, the cooling effect of the pavement continuously improves.

(2) According to the variation in the high- and low-temperature stability and cooling performance of the TAP-modified asphalt, an appropriate TAP content of 16% is recommended.

(3) TAP can improve the high-temperature stability and low-temperature crack resistance of the asphalt mixture. When compared with the ordinary asphalt mixtures, the dynamic modulus of the APC-AC at medium and high temperatures is 18%–22% higher than that of the base asphalt, the fracture energy at low temperature is 12% higher than that of the base asphalt, and TAP has a slightly adverse effect on the water stability of the asphalt mixtures.

(4) The APC-AC shows an obvious pavement cooling effect. The maximum cooling value of the pavement surface in the indoor tests was 6.6°C and that in the outdoor tests was 7.2°C.

Data Availability

The experimental data used to support the findings of this study are included within the article.

Conflicts of Interest

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

Acknowledgments

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