

## Article

# Properties and Microcosmic Mechanism of Coral Powder Modified Asphalt in Offshore Islands and Reefs Construction

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**Abstract:** The application of waste coral fragments from natural weathering, harbor construction and channel excavation to infrastructure construction on offshore islands can help alleviate the problems of shortage of traditional materials, land use of waste materials, and long-distances transport. In order to promote the comprehensive application of coral materials in road engineering construction on offshore islands, and to develop road pavement materials with good service performances and economic and environmental benefits, this paper studies the base properties, high-temperature rheological properties, and microstructure of coral powder (CP) modified asphalt through indoor experiments. The base properties tests (penetration, softening point and ductility) showed that the incorporation of CP increased the stiffness and high-temperature stability of the asphalt, but decreased the ductility of the asphalt. The optimal dosing of CP in virgin asphalt (VA) and styrene-butadiene-styrene-modified asphalt (SA) is 12% and 15%, respectively. The results of viscosity and high-temperature rheology tests showed that the right amount of CP could improve the high-temperature rheological properties and resistance to permanent deformation of asphalt, but superfluous CP tends to have a negative effect. Microscopic test results show that in the recommended dosage, the combination effect of CP and asphalt is better. CP-modified asphalt is mainly based on physical modification.

**Keywords:** asphalt modifier; coral powder; properties; modification mechanism



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## 1. Introduction

As human society develops and land resources are consumed, the oceans, with rich energy, mineral and chemical resources are attracting more and more attention. In recent years, countries with maritime rights and interests are actively promoting the construction of offshore islands in order to improve the capacity of marine resources development [1]. Coral is formed by the long-term deposition of calcium secretions of coral polyps; the main component is the presence of calcium carbonate ( $\text{CaCO}_3$ ) in the form of calcite [2]. With excellent biocompatibility and mechanical properties, coral can be used as a biomaterial in bone repair engineering [3]. Calcined coral with membrane activity and species specificity can be used as an environmentally friendly antibacterial agent [4]. In the construction of roads, airports, dams and other infrastructure on islands [5], replacing or partially replacing traditional construction materials with coral can make extensive use of waste coral fragments produced by natural weathering, port construction and channel excavation, and reduce the occupation of scarce island space [6,7]. By fully utilizing local marine resources, it is possible to effectively alleviate the shortage of traditional building materials

in island and atoll areas, and reduce the impact of long-distance transportation of materials on project costs and schedules [8,9].

Due to the special pore structure of coral aggregate and the presence of chloride ions, many scholars have studied the static mechanical properties and durability of coral aggregate concrete [10]. Zhang et al. [11] used alkali-activated materials instead of ordinary Portland cement to prepare alkali-activated seawater coral aggregate concrete, which effectively improved the cubic compressive strength, axial compressive strength and elastic modulus of coral aggregate concrete under corrosive environment. Li et al. [12] demonstrated that glass fiber reinforced polymer interlayer can effectively improve the ultimate strength and axial deformation capacity of coral aggregate concrete and alkali-activated seawater coral aggregate concrete barrels, and the enhancement increases with the increase in interlayer thickness. Da et al. [13] used the “slow-release effect of micropump” of coral aggregate to pre-absorb and incorporate the amino alcohols inhibitor, which could significantly reduce steel bars corrosion of coral aggregate seawater concrete structures. Based on the special application environment of coral aggregate concrete in island infrastructure construction, some scholars have conducted research on the impact resistance of coral aggregate concrete. Cai et al. [14] found that there was a significant brittle–ductile transition in coral aggregate concrete material. Compared with ordinary Portland cement materials, the impact toughness and energy absorption of coral aggregate concrete were significantly lower. Ma et al. [15] found that sisal fiber could significantly enhance the absorption capacity of coral aggregate concrete. Wang et al. [16] improved the brittleness and dynamic mechanical properties of coral aggregate concrete by adding with hybrid fibers. In the field of road engineering, coral aggregate is recommended for the construction of permeable pavements and pavement subgrades. He et al. [17] designed seawater coral aggregate permeable concrete with compressive strength and permeability coefficient at 28 days to meet the values recommended by ACI 522R for permeable concrete suitable for sidewalk areas. Lu et al. [18] found that using 3–6% cement for solidification to stabilize coral aggregate can meet the requirements for the pavement properties of the base material. Zeng et al. [19] suggested that in the design of cement-stabilized coral aggregate semi-rigid pavement base, the upper limit of coral aggregate particle size should be 53 mm, and the optimal content of fine aggregate and cement should be 45% and 8%, respectively. Geng et al. [20] added 6% cement and 8% calcium sulphoaluminate expansion agent (accounting for cement) to the cement-stabilized coral sand, and obtained good mechanical and drying shrinkage performance. The above studies mainly focus on using coral aggregates to replace traditional aggregates in cementitious materials, and there are fewer reports on the application of coral in asphalt materials.

As an excellent binder material, asphalt is widely used in pavement construction. However, under the combined action of environment and traffic loads, asphalt mixtures with insufficient high-temperature stability can lead to pavement diseases such as rutting, shoving, corrugation, and potholes [21,22], and scholars have studied the use of asphalt with superior high-temperature performance for 3D printing to repair pavement damage [23]. Some biobased materials with good performance, economic and ecological benefits have been used to improve the performance of asphalt materials. Bio-oil extracted from animal and plant waste can improve the workability, fatigue resistance, and low-temperature cracking resistance of asphalt, but it may affect the viscosity and resistance to rutting of the asphalt material [24–26]. In addition, some plant fibers and animal bone meal have been studied and proven to enhance the high-temperature performance of asphalt. Gao et al. [27] improved the ability of asphalt binder to resist permanent deformation by adding lignin to increase the elastic component of the virgin asphalt. Lv et al. [28] ground waste crayfish shells into powder for modified asphalt and obtained a clean material with good high-temperature stability, rheology, and stiffness. Nciri et al. [29] investigated the effect of different proportions of oyster shell powder on the performance of asphalt, and the results showed that the addition of oyster shell powder increased the content of the binder in the asphalt and reduced the content of aromatic compounds, thereby improving the thermal stability, rutting resistance, and fatigue performance of the asphalt. Both coral and biological

shells are calcium-based solid wastes and are widely used as aggregate substitutes [30,31]. By exploring the use of CP in modified asphalt binders, it is expected to develop road pavement materials with good performance and economic and environmental benefits, which can be widely used in the construction of offshore island infrastructure in this special circumstances.

In order to investigate the effects of CP on the base properties, high-temperature rheological properties, and microstructure of asphalt materials, the CP-modified asphalt was prepared with different CP content (9%, 12%, 15%, and 18%). The base properties of the materials were evaluated selecting penetration, ductility, and softening point tests. Based on rotational viscometer (RV), temperature sweep, and multiple stress creep recovery tests (MSCR), the flow resistance and high-temperature rheological properties of the materials were evaluated. Scanning electron microscopy (SEM) and Fourier transform infrared (FTIR) spectroscopy tests were used to study the microstructure of the materials. Application of coral powder in asphalt could provide a new method for cleaner production of asphalt [32]. This study creatively explored the material properties of CP-modified asphalt, laying a theoretical foundation for optimizing the application of coral materials in the construction of asphalt pavement on offshore islands.

## 2. Materials and Methods

### 2.1. Raw Materials

The Shell's virgin asphalt (VA) and SBS-modified asphalt (SA) were selected and their technical specifications were shown in Tables 1 and 2. The corals used in this study were collected from the South China Sea, as shown in Figure 1.

**Table 1.** Technical specifications of VA.

| Test Items                     | Penetration<br>25 °C/0.1 mm | Softening<br>Point/°C | Ductility<br>(5 cm/min, 10 °C)/cm |
|--------------------------------|-----------------------------|-----------------------|-----------------------------------|
| Technical indicators (Grade A) | 60–80                       | ≥45                   | ≥15                               |
| VA                             | 75.8                        | 47.9                  | 36.1                              |

**Table 2.** Technical specifications of SA.

| Test Items                     | Penetration<br>25 °C/0.1 mm | Softening<br>Point/°C | Ductility<br>5 cm/min, 5 °C/cm |
|--------------------------------|-----------------------------|-----------------------|--------------------------------|
| Technical indicators (Class I) | ≥40                         | ≥60                   | ≥20                            |
| SA                             | 64.10                       | 77.7                  | 58.6                           |



**Figure 1.** Physical appearance of coral.

## 2.2. Preparation and Characteristic of Coral Powder

### 2.2.1. Preparation of Coral Powder

The main steps of preparing process for CP are shown in Figure 2: (1) Wash the coral with tap water and dry it in the sun; (2) Break the coral into small pieces with a hammer; (3) Put the coral fragments evenly into the ball mill; (4) Add stainless steel beads and seal the ball mill jar; (5) Start the ball mill and grind for 30 min; (6) Screen the coral powder using a sieve with a pore size of 0.125 mm; (7) Obtain coral powder with a particle size of above 120 mesh.

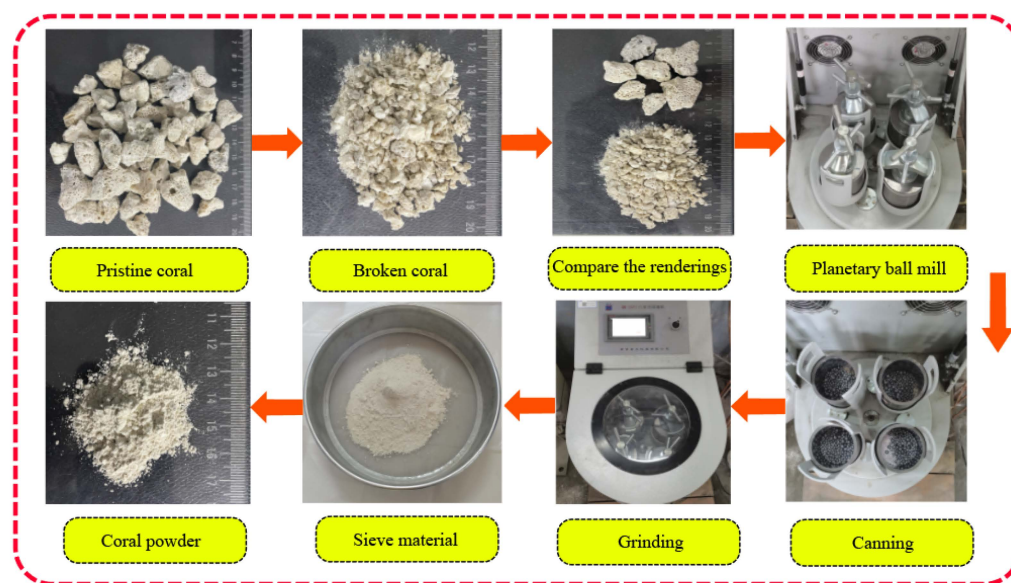


Figure 2. Preparation process of coral powder.

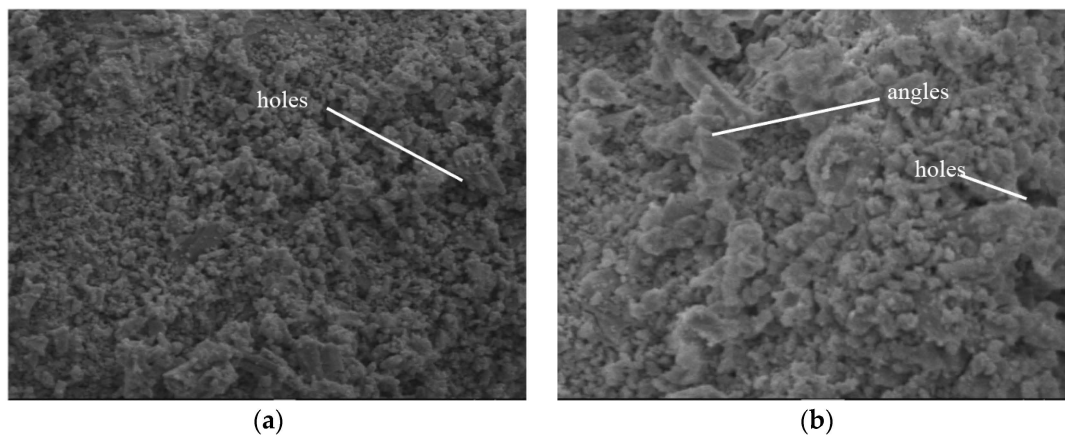
### 2.2.2. Characteristic of Coral Powder

Observed that the color of the CP was white. The CP was placed in a container of a certain volume, and its weight was measured to obtain a bulk density of  $1.14 \text{ g/cm}^3$  for the CP. A small amount of CP was taken and put into water, and it was found that the aqueous solution was weakly alkaline. This is because the main components of CP include aragonite and magnesium-enriched calcite [33].

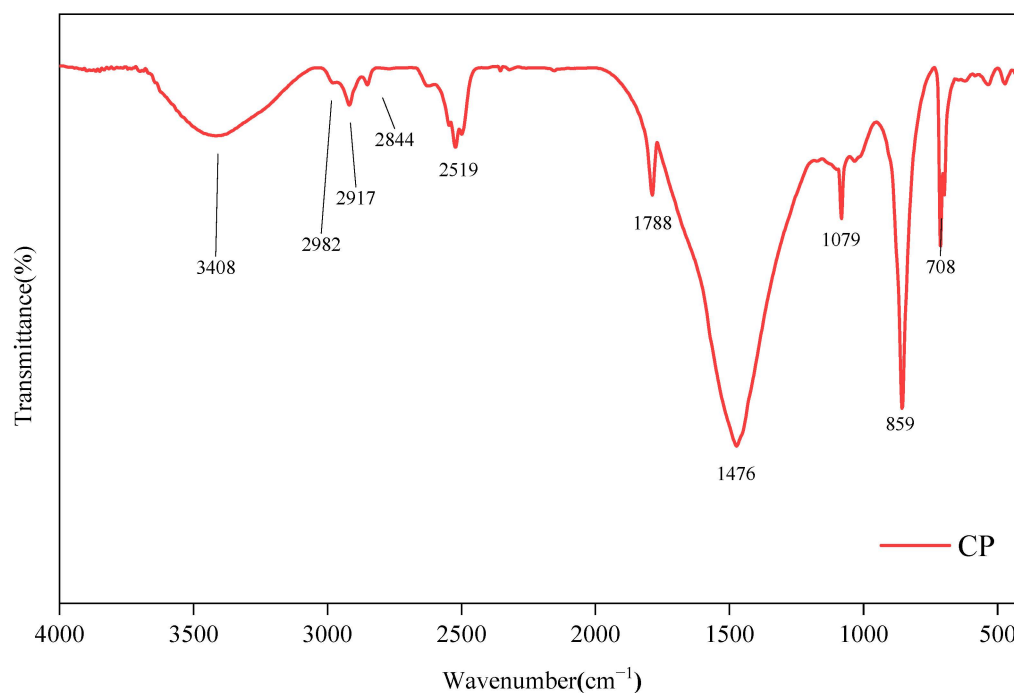
To explore the bonding mechanism between CP and asphalt, the microstructure of CP was analyzed in this study. As shown in Figure 3, microscopic characterization images of the CP obtained by magnifying 5000 and 10,000 times, respectively. From the figure, it could be observed that the CP has an overall irregular state, with many holes and voids between the powder. At  $10,000\times$  magnification, some angular crystal particles appear, which are identified as crystalline calcite ( $\text{CaCO}_3$ ) [2]. As mentioned above, the large number of voids, pores, and angular particles between CP will increase the contact area with the asphalt, forming a more stable bonding structure and allowing for a more complete combination with the asphalt.

Further investigation of the constituent properties of CP was carried out by FTIR, as shown in Figure 4. The strong absorption peak at  $1476 \text{ cm}^{-1}$  is due to the anti-symmetric stretching vibration of the carbonate; The absorption peak located at  $1079 \text{ cm}^{-1}$  is due to the symmetric stretching vibration of the carbonate; The peak change at  $859 \text{ cm}^{-1}$  is attributed to the out-of-plane bending vibration of the carbonate, and the peak at  $708 \text{ cm}^{-1}$  is identified as the in-plane bending vibration of the carbonate [34,35]. The absorption peak at  $3408 \text{ cm}^{-1}$  is assigned to the stretching vibration of hydroxyl ( $-\text{OH}$ ); The two successive peaks at  $2982 \text{ cm}^{-1}$  and  $2917 \text{ cm}^{-1}$  are due to the anti-symmetric stretching vibration of methyl ( $-\text{CH}_3$ ) and the anti-symmetric stretching vibration of methylene ( $-\text{CH}_2$ ), respectively; The weak absorption peak at  $2844 \text{ cm}^{-1}$  is attributed to the symmetric stretching vibration of methylene ( $-\text{CH}_2$ ); The obviously peak at  $2519 \text{ cm}^{-1}$  is the combination frequency of

anti-symmetric and symmetric stretching vibrations, and the peak locked at  $1788\text{ cm}^{-1}$  is attributed to the stretching vibration of  $\text{C}=\text{O}$  [29,36,37]. The above results indicate that the coral used in this study is composed of inorganic substances (mainly containing carbonate ions) and organic substances (possibly proteins) [38].



**Figure 3.** SEM images of CP. (a) CP images  $\times 5000$ ; (b) CP images  $\times 10,000$ .

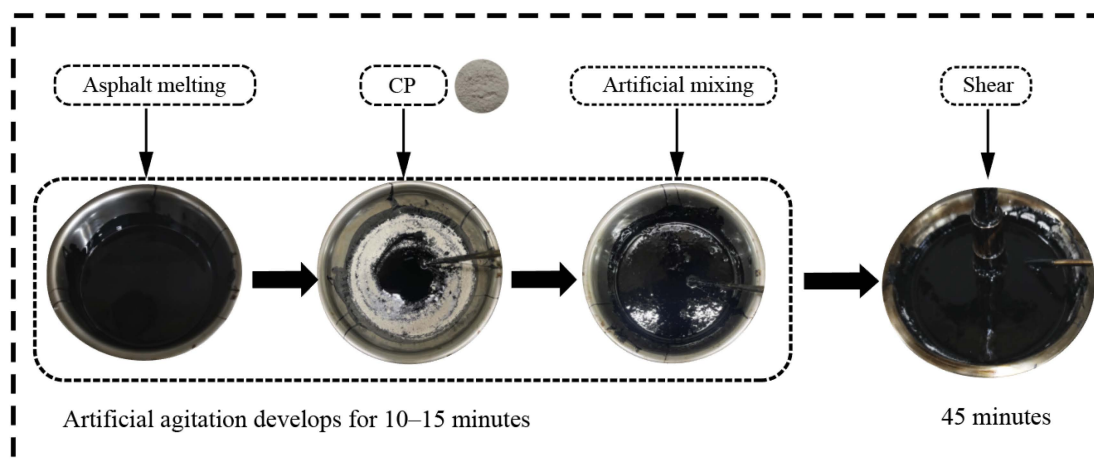


**Figure 4.** FTIR analysis of CP.

### 2.3. Preparation of Modified Asphalts

In this study, a high shear mixer was used to shear the mixture of CP and asphalt binder at a speed of 3000 rpm, to ensure that CP and asphalt binder were completely fused under the same experimental conditions.

The preparation process of the samples is shown in Figure 5. Firstly, the asphalt was heated and melted (the melting temperature of VA is  $140\text{--}150\text{ }^{\circ}\text{C}$ , and the melting temperature of SA is  $160\text{--}170\text{ }^{\circ}\text{C}$ ). Then, the CP was added in batches and stirred manually for 10–15 min to ensure no obvious free coral particles. Finally, the asphalt sample was obtained by high-speed shearing at 3000 rpm for 40 min [39,40], as shown in Table 3.



**Figure 5.** Preparation process of sample.

**Table 3.** Prepared sample groups.

| CP Content (%)       | 0  | 9    | 12    | 15    | 18    |
|----------------------|----|------|-------|-------|-------|
| virgin asphalt       | VA | VAC9 | VAC12 | VAC15 | VAC18 |
| SBS-modified asphalt | SA | SAC9 | SAC12 | SAC15 | SAC18 |

#### 2.4. Test Method

##### 2.4.1. Base Properties Testing

To evaluate the base properties of the CP-modified asphalt, the penetration, softening point, and ductility tests of the asphalt binder were designed according to AASHTO T 49 [41], AASHTO T 53 [42] and AASHTO T 300 [43] test methods.

##### 2.4.2. Storage Stability

According to the test method T0661-2011 (JTG E20-2011) [44], about 50 g of asphalt was taken and poured into an aluminum tube. Seal the upper end of the aluminum tube and place it vertically in a  $163 \pm 5$  °C oven for 48 h. Afterwards, place the aluminum tube in a  $-5$  °C refrigerator for 4 h to solidify. Divide the completely solidified sample into three parts: top, middle, and bottom. Test the softening point of the samples from the top and bottom portions, and calculate the difference to evaluate the storage stability of coral-powder-modified asphalt.

##### 2.4.3. Rotational Viscometer (RV)

Viscosity is one of the important indicators of asphalt flowability. According to the test method of AASHTO T 316 [45], the viscosity of the sample was tested using a No. 27 rotor at 135 °C.

##### 2.4.4. Temperature Sweep of DSR

To evaluate the viscoelastic properties of the asphalt binder, a temperature sweep test was carried out using a Dynamic Shear Rheometer (DSR) according to the AASHTO T 315 [46]. Prepared a circular specimen of one to two gram of asphalt binder and let it cool at room temperature for 30 min before demolding. The specimens were placed between two parallel plates with a diameter of 25 mm and the gap between the two plates was controlled at 1 mm. A sinusoidal shear load was applied to the specimen at a testing frequency of 10 rad/s using a controlled strain method. The initial sweep temperature was 46 °C, and the test was conducted at 6 °C intervals with a heating rate of 1.5 °C/min. The dynamic shear modulus ( $G^*$ ) and rutting indexes ( $G^*/\sin\delta$ ) were used as the evaluation indices for the high-temperature properties of the asphalt binder.

#### 2.4.5. Multiple Stress Creep and Recovery Test (MSCR)

Meanwhile, according to AASHTO T 350 [47] test specification, MSCR tests were conducted using the Anton Paar smart Pave 102 to evaluate the high-temperature properties of the asphalt. After short-term aging through Rolling Thin Film Oven Test (RTFOT), one to two gram of asphalt binder was taken to make a circular specimen. According to the MSCR test specification, the asphalt was tested at two stresses of 0.1 kPa and 3.2 kPa, with the first second being the creep stage and the subsequent nine seconds being the recovery stage. The DSR performed “load-unload” cyclic tests on the asphalt, with one cycle lasting 10 s, and ten cycles were tested at each of the three temperatures (52 °C, 58 °C, and 64 °C) in this study to evaluate the high-temperature properties of the asphalt. The calculation methods of R and  $J_{nr}$  are shown as follows.

$$R = \frac{\varepsilon_1 - \varepsilon_{10}}{\varepsilon_1} \times 100\% \quad (1)$$

$$J_{nr} = \frac{\varepsilon_{10}}{\delta} \quad (2)$$

where: R is the percent recovery of asphalt material;  $J_{nr}$  is the non-recoverable compliance of asphalt material;  $\varepsilon_i$  is the non-recovered strain after i cycles;  $\delta$  is the stress level applied to the asphalt material (0.1 kPa or 3.2 kPa).

#### 2.4.6. Scanning Electron Microscope (SEM)

SEM is a technique that uses a high-energy electron beam to scan a sample, excite various physical information, and obtain surface morphology images of the sample by receiving, amplifying, and displaying the information. In this study, a Japanese field emission scanning electron microscope JSM-7800F was used to observe the micro-morphological characteristics of asphalt binders. Since asphalt is an insulator, the surface of the asphalt sample should be sprayed with gold to increase its conductivity prior to testing.

#### 2.4.7. Fourier Transform Infrared (FTIR) Spectroscopy

An FTIR spectrometer was used to further investigate the interaction mechanism between CP and asphalt. Firstly, the asphalt sample to be tested was dissolved in dichloromethane solution, then the fully dissolved solution was dropped onto a potassium bromide pellet and placed in an oven to dry. Finally, the sample was tested using the FTIR spectrometer.

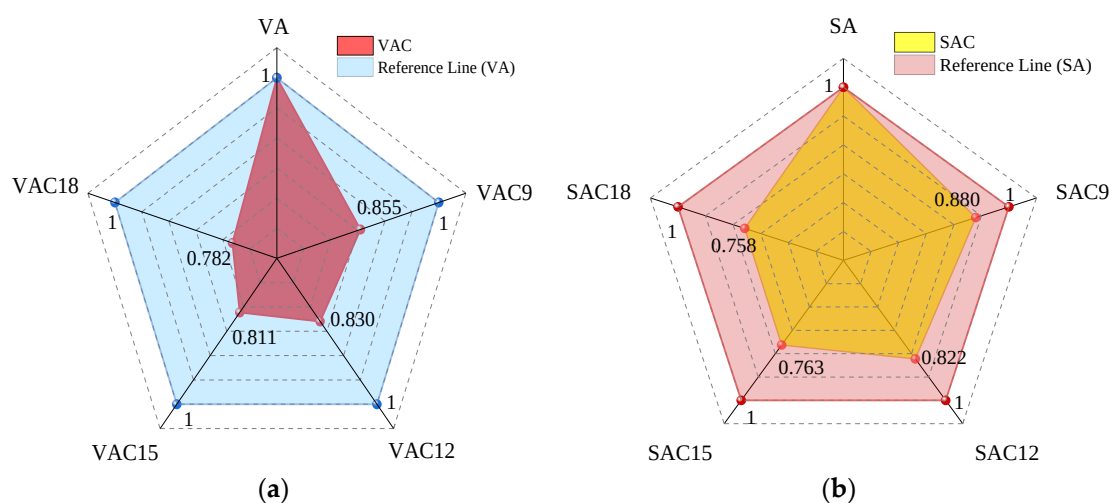
### 3. Results and Discussion

#### 3.1. Base Properties Analysis

The modification characteristics of CP as a modifier in both VA (coral-powder-modified virgin asphalt is represented by VAC) and SA (CP-modified styrene-butadiene-styrene-modified asphalt is represented by SAC) were investigated in this paper. Taking VA and SA as control groups, the conventional properties and optimal content of CP-modified asphalt were preliminarily analyzed by penetration, softening point and ductility tests.

##### 3.1.1. Penetration

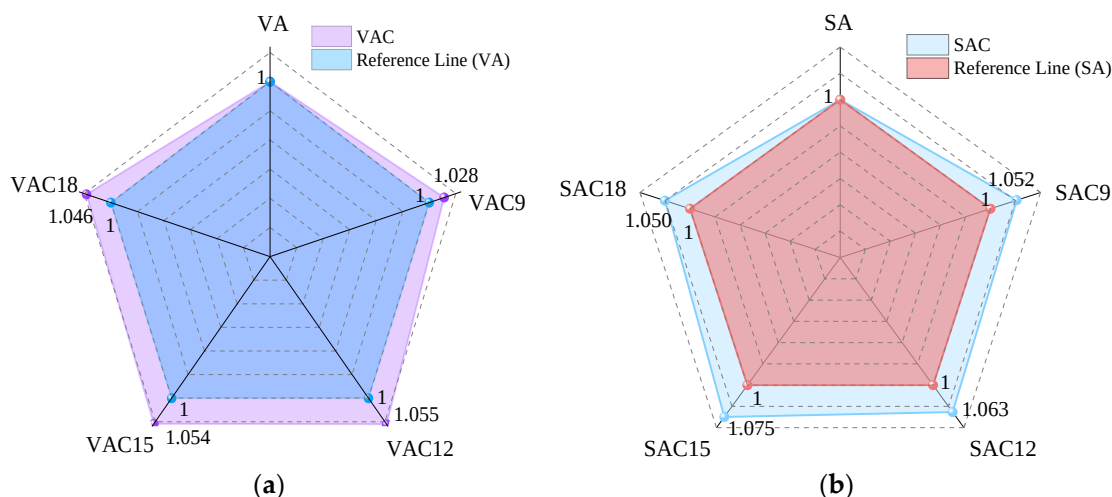
Selecting the 25 °C penetration test as the evaluation index, which can directly reflect the stiffness of the asphalt. Figure 6 shows the ratio of penetration values between CP-modified asphalt and the control asphalt. Obviously, the penetration of asphalt decreases with the increase in CP content. When the CP content in the VA is 9%, 12%, 15%, and 18%, the penetration of the asphalt binder is reduced by 14.5%, 17.0%, 18.1%, and 21.8%, respectively. When the content of CP in SA reached 9%, 12%, 15%, and 18%, the ductility decreased by 8.9%, 17.8%, 23.7%, and 24.2%, respectively. It can be seen that CP has a more significant effect on the ductility of both VA and SA, mainly by increasing the CP content to enhance the hardness and consistency of the asphalt to improve its deformation resistance.



**Figure 6.** Penetration results. (a) VAC; (b) SAC.

### 3.1.2. Softening Point

Softening point is an important indicator for measuring the high-temperature properties of asphalt. It shows that the ratio of softening points between CP-modified asphalt and the control asphalt, in Figure 7. When the content of CP in the VA was 9%, 12%, 15%, and 18%, the corresponding softening points were increased by 2.8%, 5.5%, 5.4%, and 4.6%, respectively. When the content of CP in SA was 9%, 12%, 15%, and 18%, the corresponding softening points were increased by 5.3%, 6.3%, 7.5%, and 5.0%, respectively. From the softening point curve in Figure 7a, it can be seen that the softening point increased with the increase in CP content and reached its highest point at VAC12 before showing a downward trend. In Figure 7b, the softening point increased with the increase in CP content and reached its highest point at SAC15 before showing a downward trend. Therefore, it could be preliminarily observed through softening point testing that CP would improve the high-temperature stability of VA and SA, but excessive CP will gradually have negative influence on the high-temperature property.

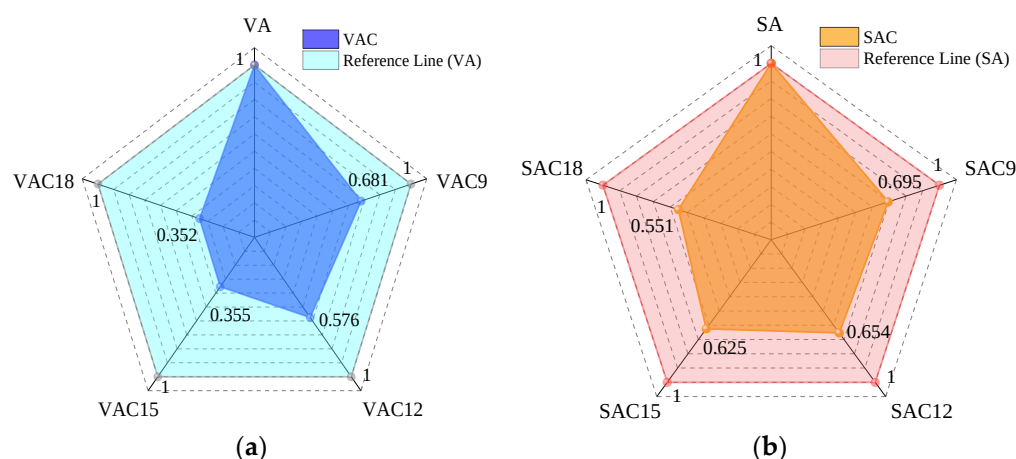


**Figure 7.** Softening point results. (a) VAC; (b) SAC.

### 3.1.3. Ductility

To facilitate the comparison of the effect of CP on the ductility of VA and SA, the ductility test at a temperature of 10 °C is chosen as the evaluation index in this study. The ductility reflects the plasticity of the asphalt, that is, the ability of the asphalt to bear deformation under external force without damage. As shown in Figure 8, the ratio of the

ductility values of CP-modified asphalt to the control asphalt is given. It could be observed from the figure that with the increase in CP content, the ductility of both VAC and SAC asphalt binders decreases. When the content of CP in VA was 9%, 12%, 15%, and 18%, the corresponding ductility decreased by 31.9%, 42.4%, 64.5%, and 64.8%, respectively. In the VA, when the CP content exceeded 12%, the ductility of the asphalt binder showed a “cliff-like” drop, meaning that the ductility experiences a significant drop. When the content of CP in SA was 9%, 12%, 15%, and 18%, the corresponding ductility decreased by 30.5%, 34.6%, 37.5%, and 44.9%, respectively. The downward trend of SA with the increase in CP content was relatively slow. The testing results demonstrated that the addition of CP would decrease the ductility of the asphalt, and the impact on the ductility of VA was more significant.

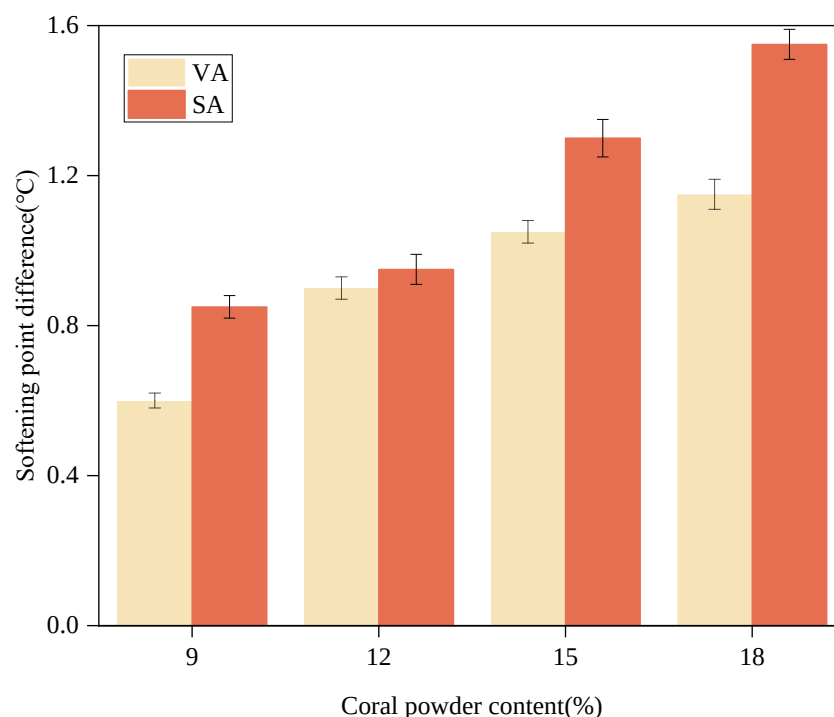


**Figure 8.** Ductility results. (a) VAC; (b) SAC.

The results of the penetration, softening point and ductility showed that adding a certain amount of CP can effectively improve the high-temperature stability and deformation resistance of 88 °C. However, excessive CP not only has a significant impact on the ductility but also leads to a decrease in the high-temperature properties of the asphalt binder. Based on a comprehensive analysis of the base properties of VAC and SAC, the optimal modification dosage of CP for VA and SA is preliminarily selected as 12% and 15%, respectively.

### 3.2. Storage Stability Analysis

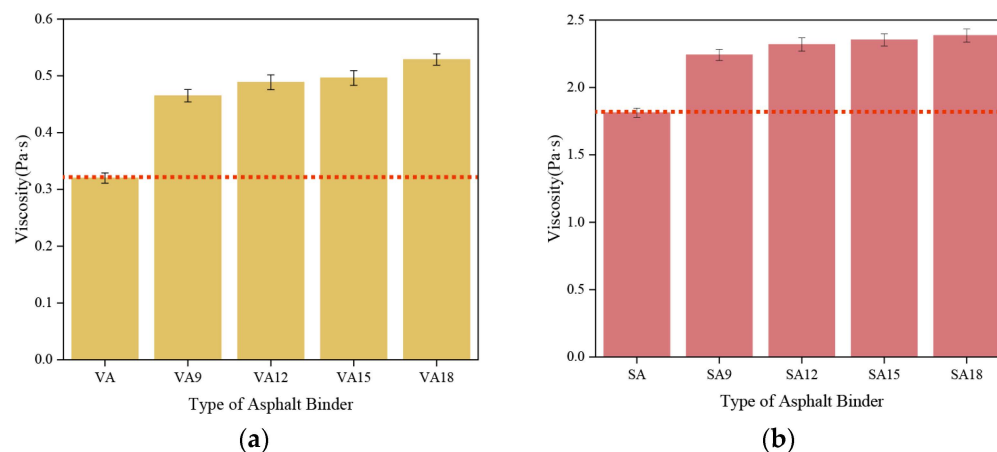
Evaluate the storage stability of VAC and SAC by comparing the difference in softening points between the upper and lower parts of the separated asphalt. Generally, the smaller the difference in softening points, the better the storage stability of the asphalt, indicating better compatibility between the asphalt and the polymer. Figure 9 displays the softening point difference at different CP contents in both VA and SA. Among them, the softening point differences for VAC9, VAC12, VAC15, and VAC18 are 0.6 °C, 0.9 °C, 1.05 °C, and 1.15 °C, respectively, while the softening point differences for SAC9, SAC12, SAC15, and SAC18 are 0.85 °C, 0.95 °C, 1.3 °C, and 1.55 °C, respectively. This suggests that the softening point difference increases with the growing content of CP in both VA and SA. This could be attributed to the sedimentation of CP under the influence of gravity. According to the specifications, when the softening point difference of polymer-modified asphalt is no more than 2.5 °C, it is considered to have good storage stability. The results indicate that with the addition of CP, the compatibility between asphalt particles is weakened. However, the storage stability of both VAC and SAC remains within the permissible range according to the specifications.



**Figure 9.** Softening point differences of VAC and SAC.

### 3.3. Rotational Viscometer Analysis

In Figure 10, VAC and SAC were tested using the Brookfield viscosity test at 135 °C, with VA and SA as reference groups. The results showed that the viscosity of asphalt binders modified with CP was significantly improved compared to the original asphalt. When the content of CP in VA was 9%, 12%, 15%, and 18%, the viscosity increased by 45.3%, 52.7%, 55.1%, and 65.2%, respectively. Similarly, when the content of CP in SA was 9%, 12%, 15%, and 18%, the viscosity increased by 23.7%, 27.9%, 29.8%, and 31.6%, respectively. Therefore, CP can increase the viscosity of asphalt, thereby improving the stiffness of asphalt binders. As the content of CP increases, the viscosity gradually increases because the CP particles increase the cohesion force of the asphalt, thereby enhancing its resistance to flow. In addition, it was worth noting that CP has a more significant effect on improving the viscosity of VA, with a larger increase in viscosity. It might be due to the fact that a relatively simple structure was possessed by VA.

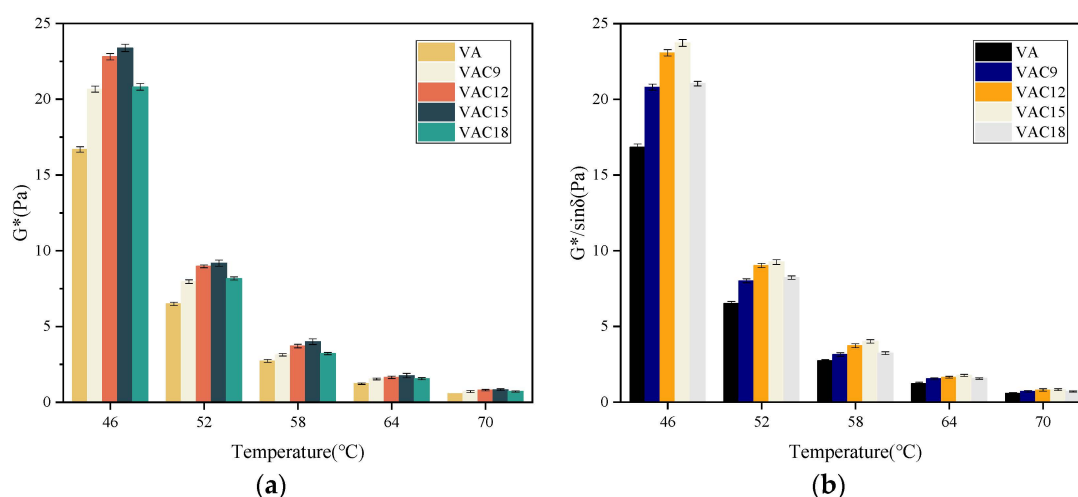


**Figure 10.** Viscosities results. (a) VAC; (b) SAC.

### 3.4. Temperature Sweep

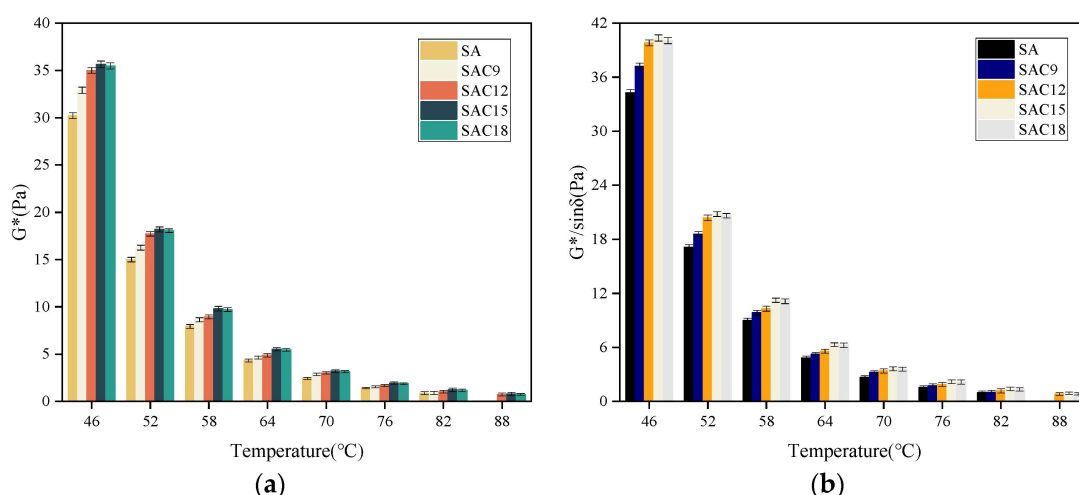
The VAC and SAC samples were conducted by temperature sweep tests, using  $G^*$  and  $G^*/\sin\delta$  as evaluation indicators. The anti-shear deformation ability of asphalt binders is usually characterized by the  $G^*$ , and the larger value of  $G^*$ , the greater stiffness of asphalt. The  $G^*/\sin\delta$  is usually consistent with the trend of dynamic shear modulus changes, and the better high-temperature stability of asphalt binder, the larger value of  $G^*/\sin\delta$ .

In Figure 11,  $G^*$  and  $G^*/\sin\delta$  of the same asphalt binder decreased with increasing temperature, indicating that temperature has a significant effect on the properties of asphalt binders. At lower temperatures, the characteristics of asphalt were dominated by its elastic properties. Conversely, as temperature increased, asphalt gradually changed from an elastic material to a non-Newtonian fluid, and its viscous properties became more prominent with higher temperatures. At the same temperature, when the content of CP in virgin asphalt was 9%, 12%, 15%, and 18%, the  $G^*$  and  $G^*/\sin\delta$  first increased and then decreased, with the highest values achieved by VAC15. Furthermore, the  $G^*$  and  $G^*/\sin\delta$  of VAC were both higher than those of VA at the same temperature, indicating that CP effectively enhanced the high-temperature rheological properties of VA. However, with the continuous increase in CP content, it may have caused CP to form agglomerated structures in the asphalt, which may have had a negative effect on the high-temperature stability of the asphalt.



**Figure 11.** Temperature sweep results of VA and VAC. (a)  $G^*$ ; (b)  $G^*/\sin\delta$ .

The high-temperature rheological properties of SAC and VAC exhibited consistency: both  $G^*$  and  $G^*/\sin\delta$  decreased with increasing temperature, as shown in Figure 12. At the same temperature, when the content of CP in SA was 9%, 12%, 15%, and 18%, respectively, the  $G^*$  and  $G^*/\sin\delta$  firstly increased and then decreased and the highest values achieved in SAC15. Moreover, the  $G^*$  and  $G^*/\sin\delta$  of SAC were also higher than that of SA, which also indicated that CP could improve the high-temperature rheological properties of SA. However, excessive CP content could also cause a deterioration in the high-temperature properties of SA. It might be due to the agglomeration of CP in SA. Unlike VA, SA had high elasticity and high-temperature stability due to the uniform dispersion of SBS in the asphalt and the formation of physical cross-linking and fixed segments, which created a stable three-dimensional spatial network structure. Therefore, the improvement of high-temperature rheology of asphalt by CP could be clearly observed in Figure 12. In particular, the temperature of three asphalt binders (SAC12, SAC15 and SAC18) in temperature sweep test could reach 88 °C, indicating better high-temperature properties.



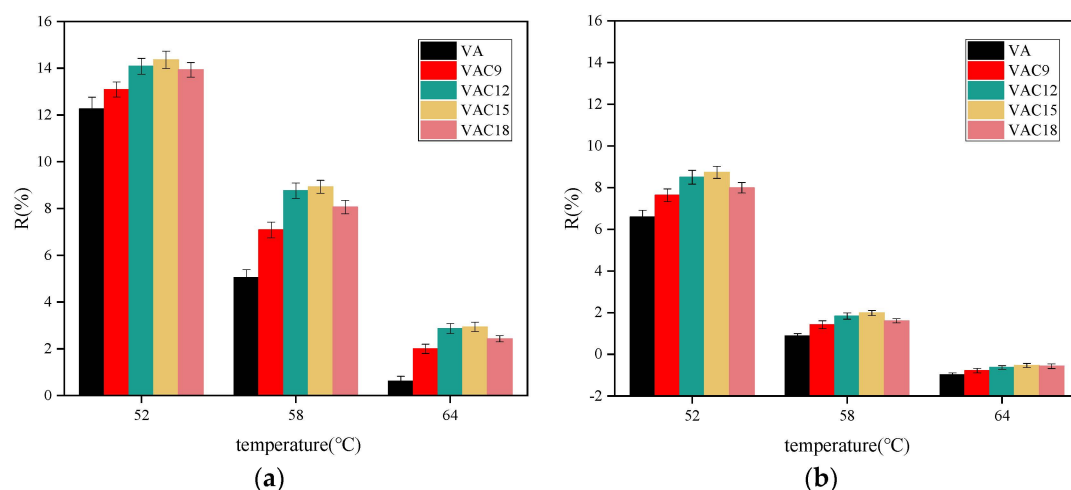
**Figure 12.** Temperature sweep results of SA and SAC. (a)  $G^*$ ; (b)  $G^*/\sin\delta$ .

### 3.5. MSCR

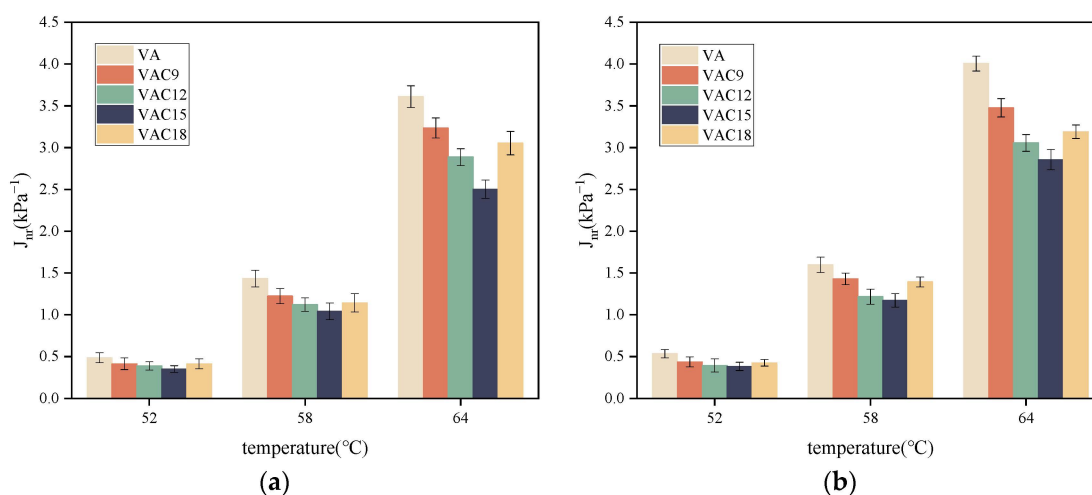
Through the MSCR test, all samples of VAC and SAC were tested at two stresses of 0.1 kPa and 3.2 kPa to obtain two evaluation indicators: the strain recovery rate (R) and the non-recoverable creep compliance ( $J_{nr}$ ). The R represents the proportion of recoverable strain to total strain, while  $J_{nr}$  represents non-recoverable residual deformation.

As shown in Figure 13, under the same loading conditions, the R value of the same asphalt binder decreased with increasing temperature, indicating that the elastic properties of asphalt binder deteriorated with increasing temperature. It was further explained that asphalt exhibited predominantly viscous behavior under high-temperature conditions, and therefore deformation recovery deteriorated with increasing temperature. Taking VA as the control group, under the same temperature and stress, the R value of VAC was higher than that of the control asphalt, indicating that the added CP could improve the elastic recovery ability of the asphalt binder and enhance its resistance to rutting. At the same temperature, the elastic recovery rate of the CP-modified asphalt first increased and then decreased with the increase in CP content. The elastic recovery rate of VAC15 reached the highest point, indicating that CP could improve the elastic recovery ability of the asphalt binder, but excessive CP will have a negative effect on the elastic recovery ability of the binder. Meanwhile, at the same temperature, it was observed that R value of the same asphalt binder under 3.2 kPa was smaller than that of 0.1 kPa, indicating that the larger the load, the deeper the rutting, and the worse the elastic recovery ability. At a temperature of 64 °C, the elastic recovery rate of VAC and VA under a stress of 3.2 kPa was less than 0, indicating that the elastic properties of the asphalt binder were basically lost under heavy load and high-temperature conditions [28].

In Figure 14, under the same load, the  $J_{nr}$  of the same asphalt binder increased with the temperature, indicating that the resistance to permanent deformation of the asphalt binder decreased with the temperature. Moreover, the larger the temperature, the greater the difference in  $J_{nr}$  between the different asphalt binders, indicating that temperature had a significant impact on  $J_{nr}$ . At the same temperature and load, the  $J_{nr}$  of VAC was lower than VA and it decreased first and then increased with the increase in CP content. It indicated that CP at a certain amount could improve the resistance to permanent deformation of the asphalt binder, while excessive CP would lead to decreased resistance to permanent deformation. In this study, the VAC15 presented the optimal resistance to permanent deformation.



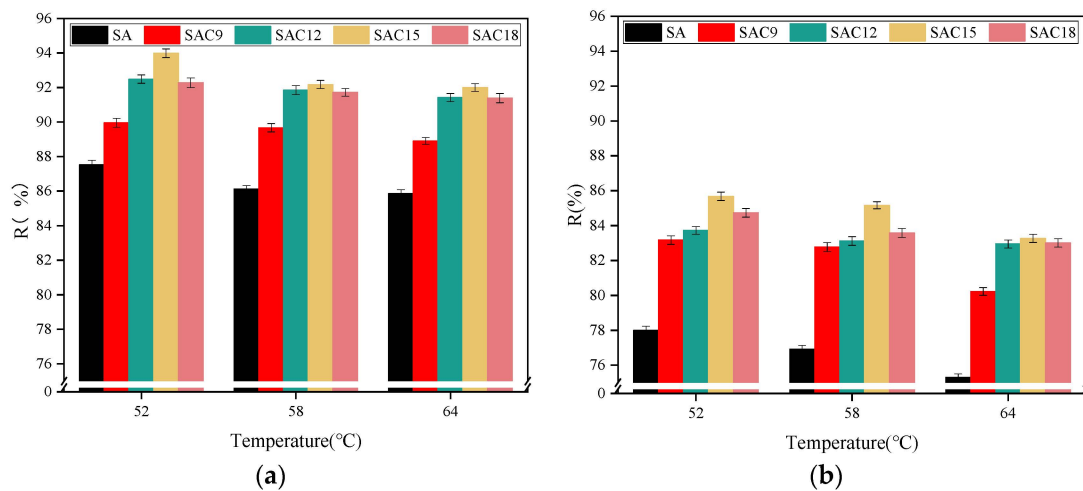
**Figure 13.** R of VA and VAC. (a) R value under 0.1 kPa; (b) R value under 3.2 kPa.



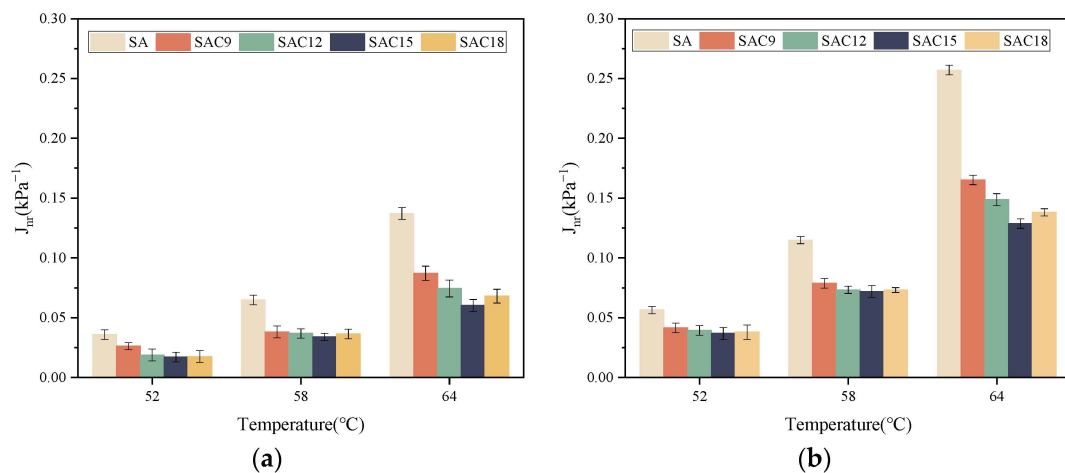
**Figure 14.**  $J_{nr}$  of VA and VAC. (a)  $J_{nr}$  value under 0.1 kPa; (b)  $J_{nr}$  value under 3.2 kPa.

As shown in Figure 15, taking SA as the control asphalt, under the same load, the R value of SAC at the same temperature was higher than SA, indicating that the addition of a certain amount of CP could improve the rutting resistance of SA. Different from VAC, the R value of SAC did not increase significantly with the increasing temperature. It might be due to the relatively stable spatial network structure of SA. At the same temperature and stress, the R value of SAC showed a trend of first increasing and then decreasing with the increase in CP content, indicating that excessive CP content would induce an adverse effect on the rutting resistance of the binder. Under the same temperature, the R of the same type of asphalt binder decreased with the increase in stress, and the rutting resistance decreased, which conformed to the actual law of general asphalt binders.

As shown in Figure 16, the  $J_{nr}$  of the same asphalt binder increased with temperature, similar to VAC, indicating that the permanent deformation resistance of SAC would decrease at high-temperatures. The difference in  $J_{nr}$  between SAC samples increased as temperature increased, indicating that temperature has a more significant impact on the permanent deformation resistance of asphalt binders. Comparing the same temperature and stress, SAC showed a trend of decreasing, then increasing  $J_{nr}$  with increasing CP content, indicating that an appropriate amount of CP could enhance the permanent deformation resistance of SA, but excessive CP will still weaken its permanent deformation resistance. The experiment showed that SAC15 was the best asphalt binder for strain recovery rate and permanent deformation resistance in SAC.



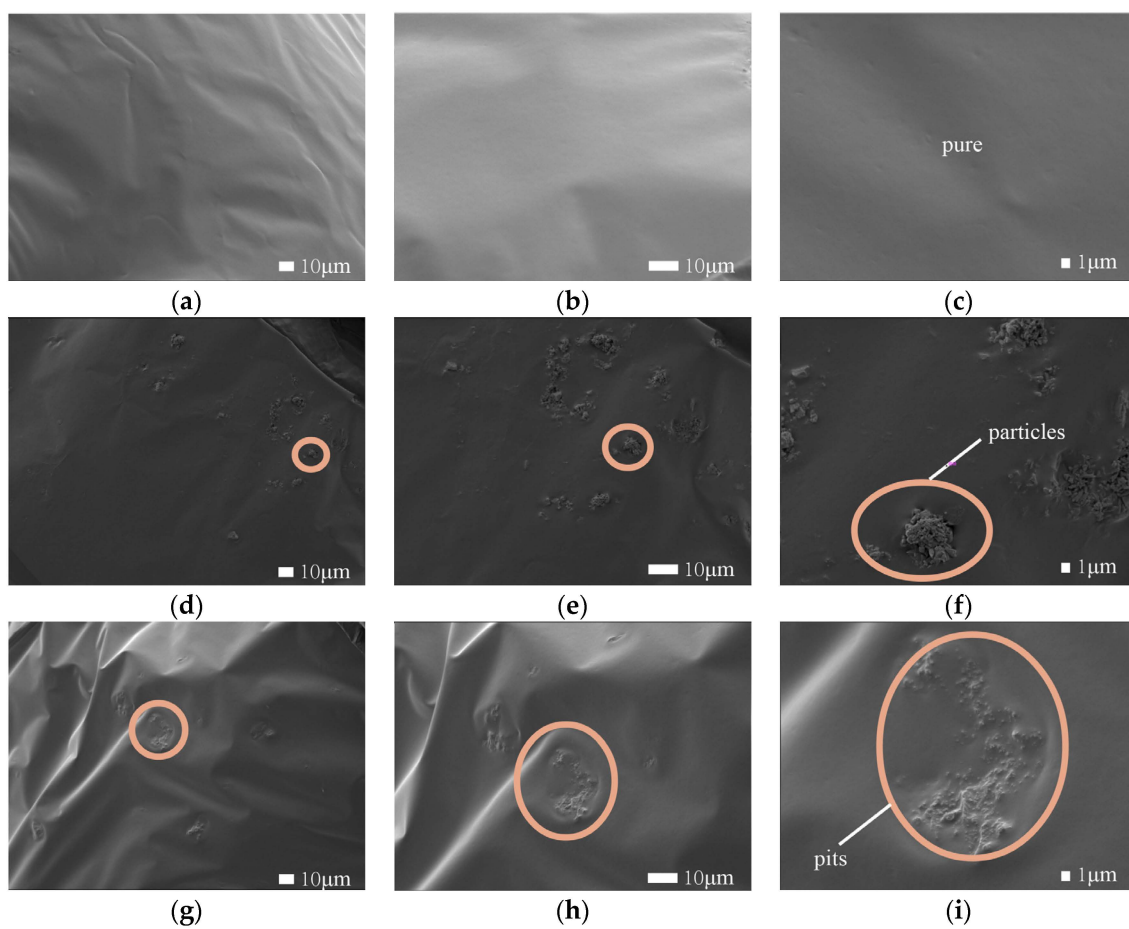
**Figure 15.** R of SA and SAC. (a) R value under 0.1 kPa; (b) R value under 3.2 kPa.



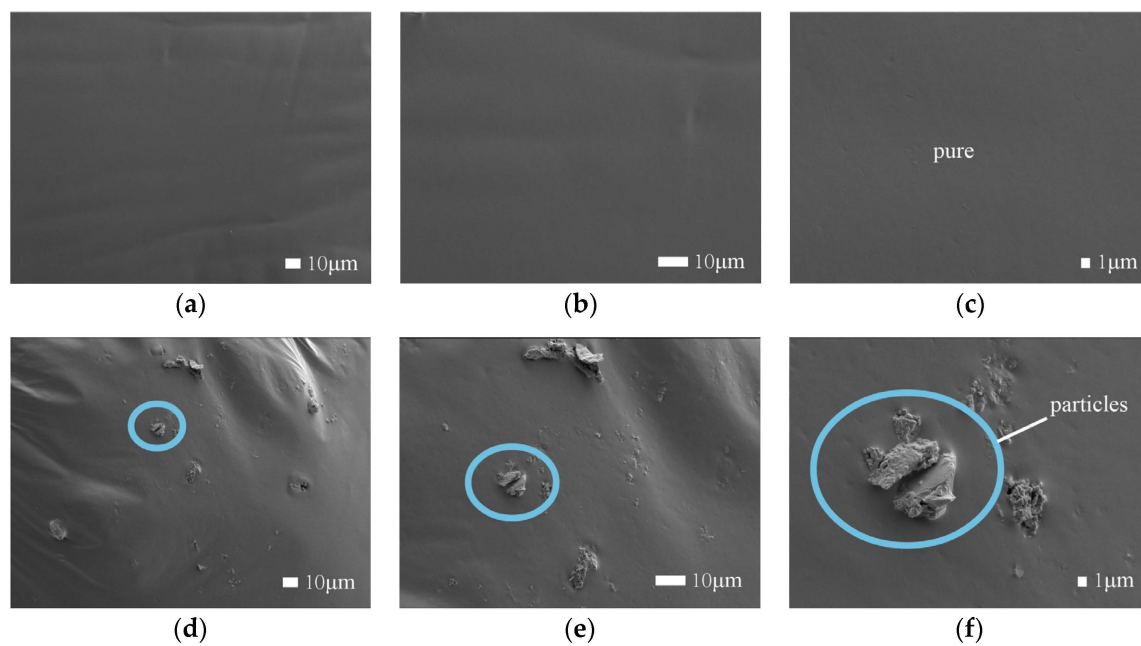
**Figure 16.**  $J_{nr}$  of SA and SAC. (a)  $J_{nr}$  value under 0.1 kPa; (b)  $J_{nr}$  value under 3.2 kPa.

### 3.6. SEM

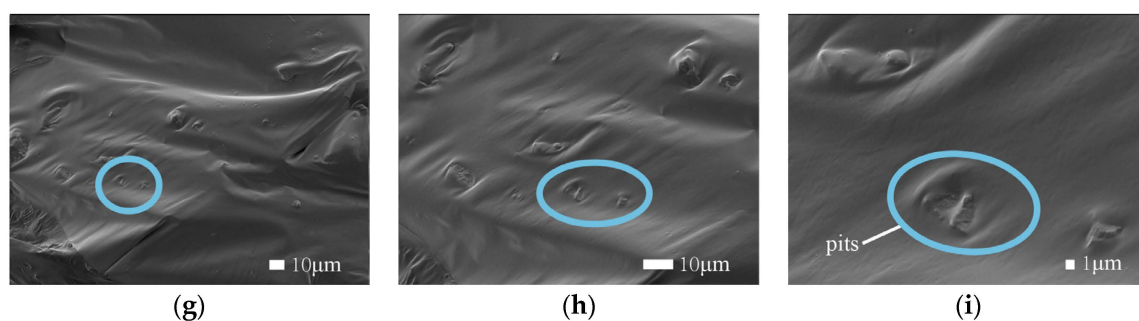
To investigate the modification mechanism of CP on VA and SA, in this study, VA, VAC12, VAC18, SA, SAC15, and SAC18 were selected as samples for SEM tests. Figures 17 and 18, respectively, showed the effect of CP on the microstructure of VA and SA before and after modification. From Figures 17a–c and 18a–c, it could be seen that the surface of VA and SA was relatively pure, smooth, and flat at different magnifications. Figures 17d–f and 18d–f showed the distribution of CP in VAC12 and SAC15, and it could be seen that CP was well embedded in the asphalt to form a stable bonding structure. At the same time, SEM images showed that CP was not homogeneously distributed in asphalt, and it cannot dissolve in asphalt. Instead, it filled the asphalt in the form of elastic particles, and the complex structure formed by CP and asphalt confirmed that CP can improve the high-temperature properties of asphalt. From Figures 17g–i and 18g–i, it could be seen that as the content of CP becomes too high, the micrograph of the asphalt binder shows pits and grooves of various sizes. It might be due to the excessive content of CP, which led to the agglomerate structure and reduced the contact area between filler and binder. Therefore, the agglomerated CP had a negative impact on the high-temperature properties of the asphalt, which was consistent with the results of previous high-temperature rheological tests. The higher the agglomeration degree of CP in asphalt, the more concentrated the stress-bearing, and the greater the impact on the low-temperature properties of asphalt. This also explained the trend of decreased ductility after adding CP to VA and SA.



**Figure 17.** SEM image of VA, VAC12 and VAC18. (a) VA image  $\times 500$ ; (b) VA image  $\times 1000$ ; (c) VA image  $\times 3000$ ; (d) VAC12 image  $\times 500$ ; (e) VAC12 image  $\times 1000$ ; (f) VAC12 image  $\times 3000$ ; (g) VAC18 image  $\times 500$ ; (h) VAC18 image  $\times 1000$ ; (i) VAC18 image  $\times 3000$ .



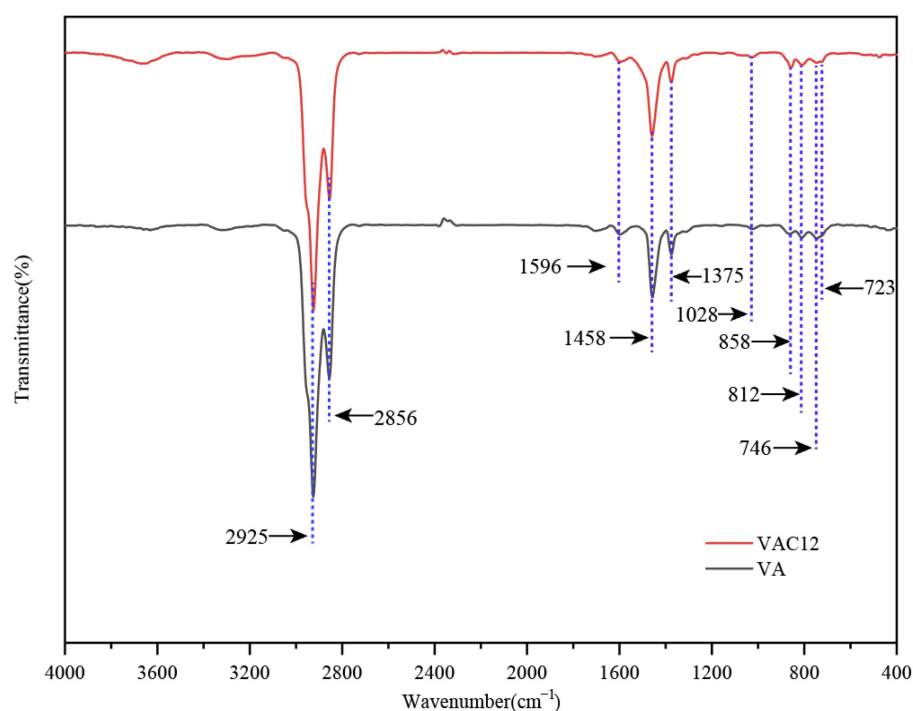
**Figure 18.** Cont.



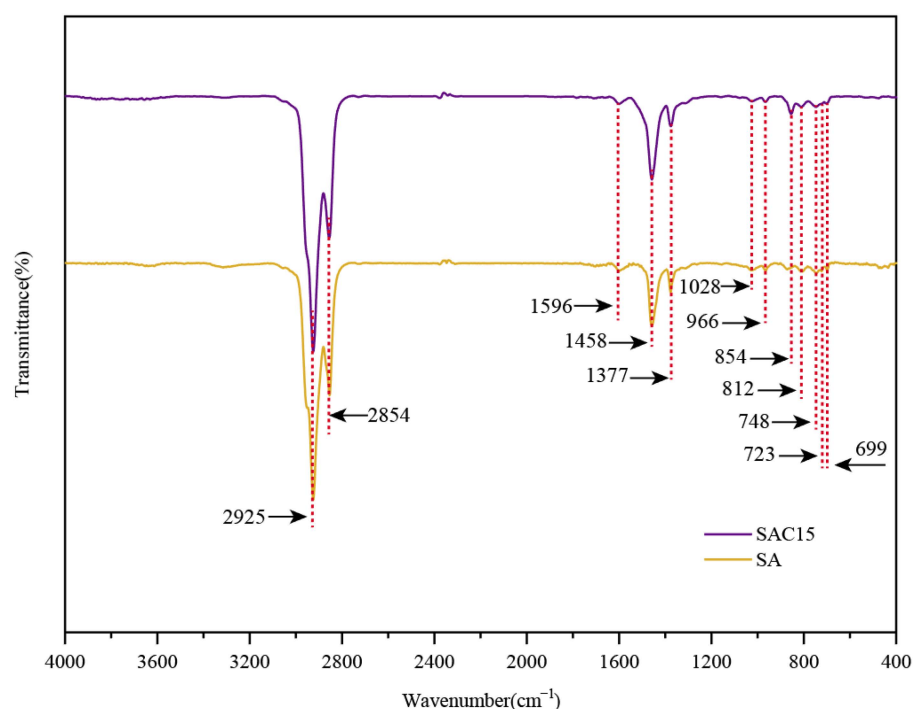
**Figure 18.** SEM image of SA, SAC15 and SAC18. (a) SA image  $\times 500$ ; (b) SA image  $\times 1000$ ; (c) SA image  $\times 3000$ ; (d) SAC15 image  $\times 500$ ; (e) SAC15 image  $\times 1000$ ; (f) SAC15 image  $\times 3000$ ; (g) SAC18 image  $\times 500$ ; (h) SAC18 image  $\times 1000$ ; (i) SAC18 image  $\times 3000$ .

### 3.7. FTIR

To further analyze the interaction mechanism between CP and asphalt, FTIR tests were conducted on four types of asphalt binders, including VA, VAC12, SA, and SAC15. Figures 19 and 20 show the FTIR analysis results of VA and VAC12. The results indicate that the FTIR spectra of VAC12 are similar to VA. The peaks near  $2925\text{ cm}^{-1}$  and  $2856\text{ cm}^{-1}$  are assigned to the asymmetric stretching vibration and symmetric stretching vibrations of C-H in methylene [48,49]. The peak at  $1596\text{ cm}^{-1}$  is attributed to the C=C stretching vibration [50], while the two peaks at  $1458\text{ cm}^{-1}$  and  $1375\text{ cm}^{-1}$  are caused by the vibration of C-H in methyl [51,52]. The S=O bond stretching vibration of sulfoxide groups is observed at  $1028\text{ cm}^{-1}$  [53]. The two peaks locked at  $858\text{ cm}^{-1}$  and  $812\text{ cm}^{-1}$  are attributed to the stretching vibration of the benzene ring [54]. The absorption peak at  $746\text{ cm}^{-1}$  is caused by the bending vibration of the aromatic side chain and the weak peak at  $723\text{ cm}^{-1}$  is associated with the synergistic vibration of  $(\text{CH}_2)_n$  groups, where  $n > 3$  [55]. Figure 20 shows the FTIR test results of SA and SAC15. As expected, the FTIR spectra of SAC15 are similar to VA. All the peaks of the VA and two additional peaks are appeared in SA [56]. The one peak locked at  $966\text{ cm}^{-1}$  is caused by the vibration of double bonds in polybutadiene in SBS [57], while the other peak at  $699\text{ cm}^{-1}$  is generated by the vibration of the polystyrene segment [58].



**Figure 19.** FTIR analysis of VA and VAC.



**Figure 20.** FTIR analysis of SA and SAC.

Through FTIR analysis of CP and asphalt binder, it was found that coral mainly contains inorganic substances (primarily carbonate) and organic matter (possibly including some proteins), making it a composite material. The FTIR spectra of VAC and SAC were similar to VA and SA, indicating that the modification of asphalt by CP was mainly physical. The inorganic substances in CP mainly acted as mineral fillers in the asphalt, and the addition of rigid particles effectively enhanced the stiffness of the asphalt, thereby improving its resistance to deformation [59]. The organic matter in CP had carbon properties, which might have increased the crystallization ability of VA and SA, thus benefiting the high-temperature stability of the asphalt binder [60]. Therefore, CP could effectively improve the high-temperature stability and adhesion of asphalt binder.

#### 4. Conclusions

This article explores the feasibility of using coral powder (CP) as a modifier for asphalt and utilizes abandoned corals that naturally die or are produced by human activities. The aim is to develop pavement materials that offer good road properties and economic and environmental benefits for the construction of offshore island roads. This study investigates the properties and modification mechanism of CP-modified asphalt through indoor experiments, and the following conclusions are mainly obtained:

- (1) Based on the analysis of base properties, it was found that the incorporation of CP reduced the ductility of asphalt but effectively improved the high-temperature properties and rheological properties of the binder. CP was used as a modifier to improve the viscosity of asphalt binder, increase its internal cohesion, and enhance its resistance to flow.
- (2) The results obtained from temperature sweep tests and MSCR testing indicate that CP can enhance the high-temperature rheological properties, elastic recovery capacity, and resistance to permanent deformation of the asphalt binder. However, excessive CP content can have adverse effects on its performance.
- (3) After observing the microstructure of the samples through SEM tests, the results showed that the asphalt and CP were well compatible at the optimal CP content. Furthermore, FTIR results showed that the modification of asphalt with CP was mainly achieved through physical modification. Therefore, based on the fact that

coral powder and asphalt are linked by physical interaction, the article can enhance the performance of coral-powder-modified asphalt by coupling agent in the future.

- (4) Considering the base properties, high-temperature rheological properties and micro-morphological characteristics of asphalt binder, the recommended dosage of CP-modified VA and SA was determined to be 12% and 15%, respectively.

In summary, this study provided a new approach for recycling and utilizing coral waste. By using waste coral as a modifier for asphalt, this method advanced the development and utilization of coral resources in the field of road engineering.

## 5. Future Research

This paper explores the properties and mechanisms of CP-modified asphalt with VA and SA and determines the recommended dosage of CP as a modifier. However, further research is needed to investigate the characteristics of the combined mixture and its application in practical engineering. It is also recommended to focus on physical or chemical treatments of the CP surface to enhance the interaction between the CP and asphalt in the future research.

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