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Evaluation of Material Composition on the Shear Performance of Asphalt Mixtures under Different Test Conditions

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Abstract: Although shear strength plays an important role in the performance of asphalt mixtures, it is still not adopted as a control index in traditional asphalt pavement structure design. Among most shear strength tests, the shape of specimen damage in the uniaxial penetration test and circle shear test proved to be more accurate in reflecting the practical asphalt pavement damage shape. To explore the impact of material composition on the shear performance of asphalt mixtures under different test conditions, uniaxial penetration tests, circle shear tests, and unconfined compressive strength tests were conducted to evaluate shear strength with considerations of asphalt mixture composition (asphalt binders, aggregate, and mineral powder). Experimental results demonstrate that the SBS-modified asphalt mixtures have a higher shear strength than conventional 70# asphalt mixtures, and the shear performance of mixtures is positively correlated with softening point of asphalt binder. For the same gradation, the shear strength of asphalt mixtures increases with the asphalt-aggregate ratio first, then decreases with the ratio increases. The shear performance of mixtures can be increased by properly increasing the maximum nominal aggregate size and reasonably adjusting the aggregate gradation. Mineral powder replaced by 20% cement or 10% PSP (phosphorus slag powder) can also satisfy the requirement. Both coarse aggregate and fine aggregate containing silt impact the shear performance of mixtures; it is recommended that the silt content of coarse aggregates is controlled within 3%, and that of fine aggregate should be within 1%.

Keywords: asphalt mixture; shear strength; uniaxial penetration: circle shear; aggregate containing silt

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1. Introduction

Rutting is one of the most critical damages among all kinds of damage types of asphalt pavement, which reduces pavement performance, endangers driving safety, and shortens the service life of asphalt pavement. Rutting can be caused by the high-temperature permanent deformation of asphalt pavement under traffic load, which includes the compaction deformation of asphalt mixtures in the primary stage and flow deformation under repeated load and stress, and research found that the flow deformation played a leading role in the total deformation [1].

Semi-rigid base with high base strength is generally used in Chinese asphalt pavement design. However, lacking shear strength on the surface would lead to permanent deformation accumulation and cause rutting [2,3]. Furthermore, some researchers [4–6] have shown that some top-down cracks, and early diseases, such as flow rutting, slippage, and wrapping, were connected with the shear performance of asphalt mixtures.

In traditional pavement mechanics calculation and pavement structure design, the surface deflection and the bottom tensile stress of the structure were generally used as design -control indexes. The surface deflection reflected the overall strength of the pavement, and the tensile stress at the bottom of the control layer was mainly to prevent the fatigue cracking of the corresponding structural layer. Although the shear strength of the pavement surface structure was very important, it was not selected as the control parameter in the design standards. Therefore, selecting the appropriate shear test method and evaluating the shear performance is of great significance to preventing rutting disease, prolonging the service life of asphalt pavement, and improving vehicle driving safety.

Research has been carried out on evaluations of the shear strength of asphalt mixtures and their test methods. Smith [7] proposed the triaxial test and put forward the failure standard of asphalt mixture after systematically studying the shear stress state of roads by elastic theory. Hoyos et al. [8,9] further improved the triaxial test and developed a true triaxial test with two independent pore air and pore water pressure control systems, improving stress control accuracy. Huang et al. [10,11] devoted a self-developed triaxial test method and gave the asphalt mixtures' shear strength nonlinear evolutional laws. Fan et al. [12] evaluated the volume expansion of asphalt pavement under shear action through triaxial testing and numerical simulation. Based on the triaxial test, researchers [13] have done a series of studies on the factors affecting the strength of asphalt mixtures, such as temperature, loading speed, confining pressure, etc.

However, the triaxial test is usually very complicated, and the specimen confining pressure has difficulties in simulating the real pavement stress environment, etc. Based on the California Bearing Ratio (CBR) test method, Bi and Sun [14] developed the uniaxial penetration test method, tested the method's feasibility using three-dimensional finite element simulation, and determined the standard indenter, specimen size and shape, and molding method. Yan et al. [15] further evaluated the feasibility of the uniaxial penetration test theoretically and revealed the uniaxial penetration test mechanism from the mesoscopic level, and put forward suggestions on the specimen, indenter size, and loading speed of the uniaxial penetration test. Zhang et al. [16] proposed that the penetration strength and displacement of the uniaxial penetration test could characterize the high-temperature performance of asphalt mixtures well. Ren et al. [17] investigated the shear deformation characteristics of the asphalt mixture and proposed a repeated uniaxial penetrating test (RUPT) based on flow number and uniaxial penetration tests to evaluate the shear fatigue life of the asphalt mixture. As a result, a prediction equation of the shear fatigue life of asphalt mixtures was proposed. Zhou et al. [18] provided a new idea for anti-rutting technology innovation of asphalt pavement in the civil airport field based on the uniaxial penetration test results. The uniaxial penetration test was proved to correspond well with the strength performance of asphalt mixtures [19]. Overall, the above research found that the uniaxial penetration test was not only easy to operate but also solved the problem of confining pressure imposed by experience in the triaxial test. Besides, the test equipment was cheap and easy to popularize.

For the uniaxial penetration tests, Huang et al. [20] found it difficult to have a conical failure surface when uniaxial penetration test specimens were damaged, so the uniaxial penetration test was further improved to put forward the circle shear test. The research found that the variability of the shear test data obtained by the second test was smaller, and the cone surface unique to shear failure can appear when the specimen is damaged. Even though the circle shear test has been shown to be a useful method of evaluating asphalt mixture shear performance well, systematic research on the influence of affecting asphalt mixture shear performance based on this test is still lacking.

Asphalt mixture consists of asphalt binder, aggregate, and mineral powder [21], and the shear performance of asphalt mixtures was determined by a variety of factors. Asphalt binder was considered a primary factor affecting the maximum shear strength of its mixture [22], and asphalt modification could efficiently enhance the high-temperature performance of asphalt pavement [23]. Liu et al. [24] selected asphalt grade as a key design parameter to study its effect on the high-temperature performance of asphalt mixtures. Therefore, it is necessary to study how the content and properties of asphalt binders affect the strength properties of asphalt mixtures.

In addition, the shear performance of asphalt mixtures depends largely on aggregates. Cheng and Kong [25] proposed the adhesion principle between asphalt binder and aggregates based on surface energy theory and found that different types of aggregate with different surface energy could lead to varying strengths of asphalt mixture. Selinah and James [21] have shown that aggregate microstructure can also impact the mechanical performance of asphalt mixtures. Based on the digital image processing technology method and indoor tests, Cai et al. [26] studied the impacts of aggregate angularity and its interlocking on asphalt mixture rutting resistance and found that both factors significantly affected rutting performance. Peng and Sun [27] found that aggregate physical properties greatly affected the aggregate homogeneity in asphalt mixtures and further affected test results of uniaxial penetration. Research [28–30] has also shown that the high-temperature performance of asphalt mixtures was greatly influenced by aggregate gradation based on Particle Flow Code 2D (PFC 2D) simulation analysis, rutting test, and uniaxial penetration test. The interface between aggregates and asphalt binders could be one of the weakest parts of mixtures. Su et al. [31] found that the interface interaction between aggregates and asphalt was a key factor affecting the strength formation and deterioration of asphalt mixtures. Kuang et al. [32] further proposed the asphalt mixture pavement performance index according to the correlation between asphalt-aggregate interfacial strength and asphalt mixture performance. In practical engineering, it is more convenient and direct to improve the shear strength of the mixture by improving the gradation and aggregate silt content. However, most current research on aggregate silt content focuses on water damage [33]. The research on the influence of aggregate silt content on the strength of the mixture is of great significance for engineering.

As a key component of asphalt mixture, mineral powder also plays a key role in the performance of asphalt mixtures. Research [34] has found that replacing the typical mineral powder with other materials could improve the performance of the asphalt mixture. Qian et al. [35] also found that replacing a certain content of mineral powder with Phosphorus Slag Powder (PSP) could enhance the rutting resistance of mixtures since it is hydrophobic and stable at high temperatures. Yu et al. [36] further evaluated the impacts of the specific surface area of PSP with the physical blending method on the rutting resistance of asphalt mixtures. Also, researchers found that cement material tended to have a chemical adsorption process with asphalt components [37] and found that asphalt mixture containing cement filler had improved the rutting resistance [38]. The bonding behavior between aggregate and asphalt directly influences the performance of the asphalt mixture. Alkaline fillers were normally used to modify asphalt binders to improve the engineering performances of asphalt mixture [39].

Overall, the previous research found that the uniaxial penetration and circle shear tests both can effectively figure out the shear performance of asphalt mixtures. Therefore, the two test methods mentioned above were both selected to evaluate the influencing factors of the shear performance of asphalt mixtures. Different types, properties, and contents of asphalt binder were adopted to study the influence of asphalt binder on the shear performance of the mixtures. Aggregates containing silt and different gradations of asphalt mixture were chosen to evaluate the impacts of the aggregates used in asphalt mixtures on the shear strength of the mixtures. Cement and PSP replacing minerals were also selected to investigate the improvement in the shear performance of mixtures. The specific research plan was as Figure 1.

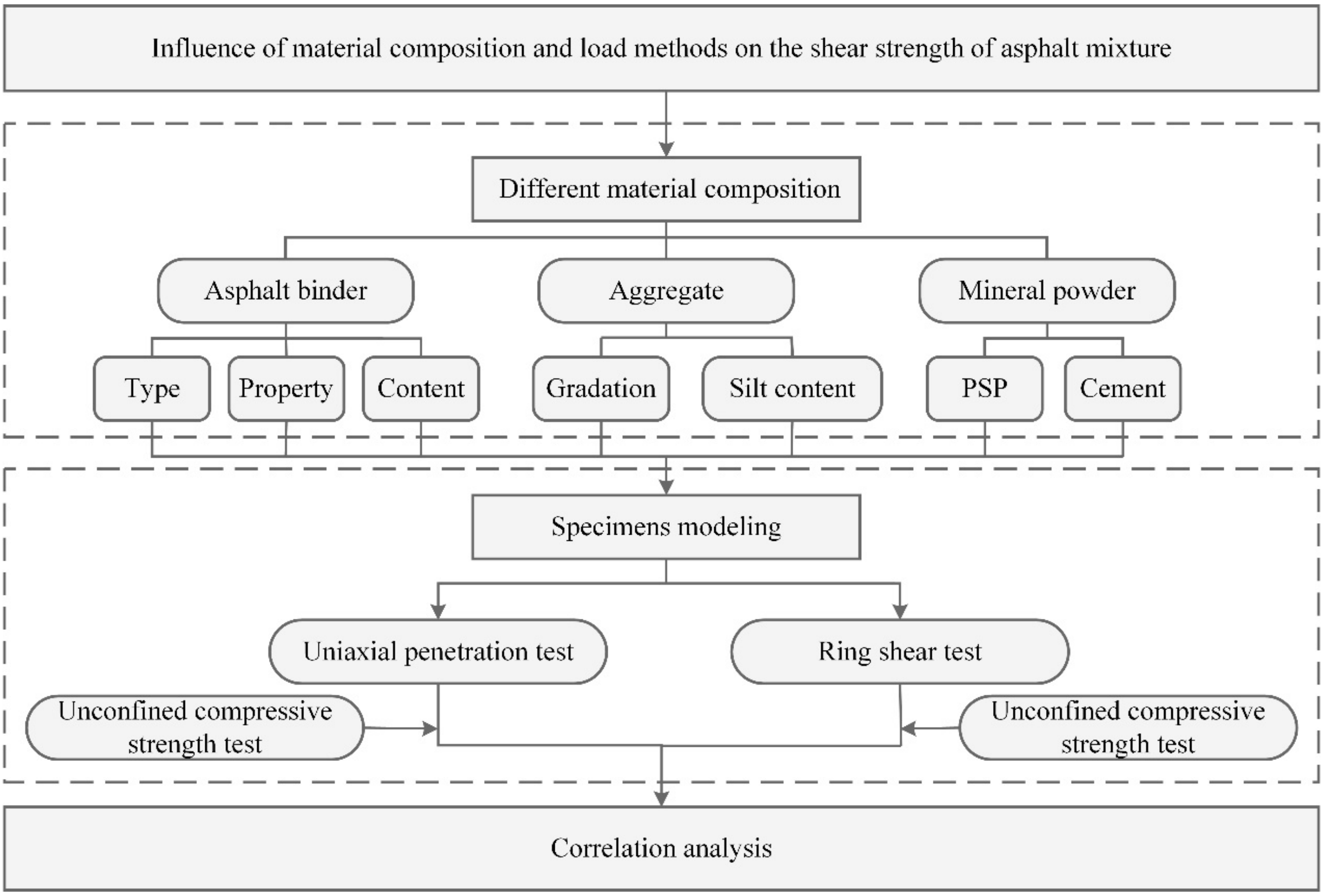


Figure 1. Research plan.

2. Materials and Experiments

2.1. Materials

2.1.1. Asphalt Binder

Six groups of asphalts from three different manufacturers were used to form the specimen by AC-13F grading. For the convenience of description, asphalts were numbered, as shown in Table 1.

Table 1. Type of different asphalts.

Asphalt Type	SK AH-70	Donghai Brand 70#A	Walter SK AH-70#	Walter SBS (I-D)	1# SBS (I-D)	2# SBS (I-D)
Number	70#1	70#2	70#3	SBS1	SBS2	SBS3

The technical properties of 70#1 and SBS1 were tested following the requirements of "Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering" (JTG E20-2011) [40]. The material test results are shown in Tables 2 and 3. It can be inferred that the asphalt adopted in this research meets the requirements of the standard. The properties of different asphalt used for evaluating the influence of the shear performance of asphalt mixtures are shown in Table 4.

Table 2. Material properties of 70#1.

Original Sample	SK AH-70	Technical Requirement
Penetration, 25 °C, 100 g, 5 s, 0.1 mm.	67	60–80
Penetration index (PI)	−1.3	−1.5~+1.0
Ductility, 5 cm/min, 15 °C, cm	>100	≥100
Ductility, 5 cm/min, 10 °C, cm	45	≥20
Softening point TR&B, °C	47.5	≥47
Wax content, %	1.8	≤2
Flash point (COC), °C	316	≥260
Solubility, %	99.7	99.5
Density, 15 °C	1.031	measure with instruments
Dynamic viscosity, 60 °C, Pa·s	212	180–240
Mass loss after aging, %	−0.17	≤±0.8
Penetration ratio after aging, 25 °C, %	68	≥61

Table 3. Material properties of SBS1.

Original Sample	SBS (I-D)	Technical Requirement
Penetration, 25 °C, 100 g, 5 s, 0.1 mm	55	40–60
Penetration index (PI)	0.1	≥0
Ductility, 5 cm/min, 5 °C, cm	34	≥25
Softening point, °C	87	≥70
Dynamic viscosity, 135 °C, Pa·s	2.1	≤3
Kinetic viscosity, 60 °C, Pa·s	8000	≥6000
Flash point (COC), °C	318	≥230
Solubility, %	99.7	≥99.0
Segregation test, 48 h softening point difference, 163 °C	0.8	≤1.0
Elastic recovery, 25 °C, 10 cm, 60 min, %	95	≥85
Mass loss after aging, %	0.06	≤±1.0
Penetration ratio after aging, 25 °C, %	80	≥65
Elongation after aging, 5 cm/min, 5 °C, cm	21.0	≥20

Table 4. Three indexes of different asphalt.

Number of Asphalt	70#1	70#2	70#3	SBS1	SBS2	SBS3
Penetration	67	69	67.5	55	51.7	54
Ductility (10 °C, cm)	45	53	45	34	34.5	29
Softening point (°C)	47.5	48	48.7	87	86.2	74.5

The optimal asphalt content of mixtures tested by the Marshall test was 5.0%. To evaluate the influence of asphalt content on shear performance, 4.0%, 4.5%, 5.0%, 5.5%, and 6.0% were selected.

2.1.2. Aggregate

The aggregate used in the test is basalt, and the mineral powder is made by grinding limestone. All indexes of the aggregate meet the requirements of "Test Methods of Aggregate For Highway Engineering" (JTG E42-2005) [41].

In order to explore the impact of different gradations on the shear performance of mixtures, mixtures with five different gradations of AC-13F, AC-13M, AC-13C, SMA-13, and AC-16 were evaluated. The five different gradations are shown in Figure 2.

Also, for evaluating the impact of aggregate silt content on the shear strength of mixtures, six different silt contents (1%, 2%, 3%, 4%, 5%, 6%) of coarse aggregate and four different silt contents (1%, 2%, 3%, 4%) of fine aggregate were evaluated. The silt adopted in this research was clay. Before being mixed with aggregates, it was placed in the oven after removing organic impurities such as roots until dried to constant weight. The method to control a specific silt content in the specimen was to weigh the dried clay at a specific percentage of the weight of coarse or fine aggregate. Mix the weighed clay and coarse or fine aggregate with water; the content of water can slightly wet the surface of the coarse or fine aggregate. Aggregates with silt are shown in Figure 3.

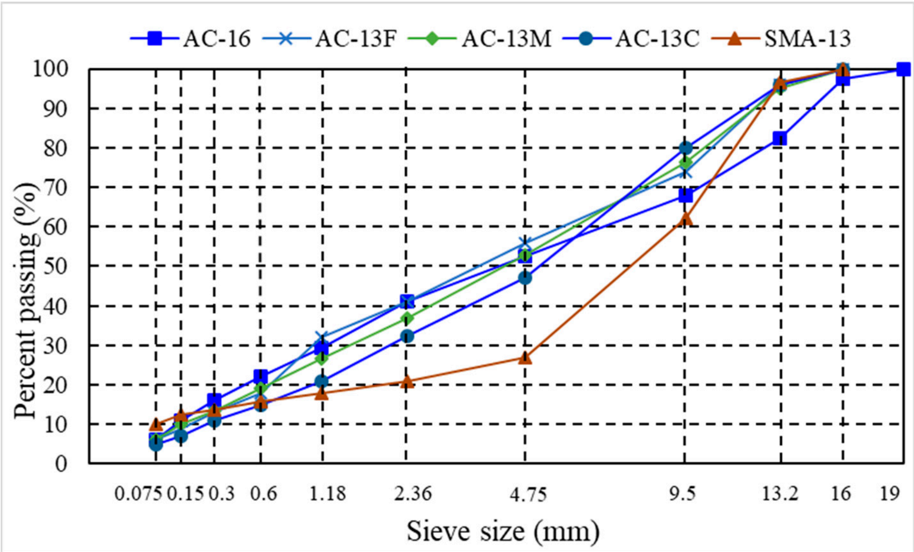


Figure 2. Gradations.

(**a**) (**b**)

Figure 3. Aggregates with silt. (**a**) Fine aggregate with silt; (**b**) Coarse aggregate with silt.

To determine the water damage resistance of asphalt pavement, the Marshall immersion test under high temperatures was conducted.

2.1.3. Mineral Powder

The phosphate slag powder was made by the water quenching method from mechanical grinding of phosphate slag, and the average diameter was about 1 μm. The properties of phosphate slag powder are shown in Tables 5 and 6. The cement adopted to replace the mineral powder was PF32.5 road cement. The properties of cement are shown in Table 7.

Table 5. Material composition of PSP.

Composition	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	P_2O_5	F
Average (%)	39.95	45.84	4.03	1.00	2.82	2.41	2.34

Table 6. Material properties of PSP.

	PSP Adopted	Technical Requirement
Surface density (g/cm^3)	2.897	>2.50
Water content (%)	0.4	≤1
<0.6 mm (%)	100	100
<0.15 mm (%)	100	90–100
<0.075 mm (%)	99.5	75–100
PH	9.9	—-

Table 7. Material properties of cement.

	PF3.25 Cement	Technical Requirement
Fineness (%)	4.7	≤10
Initial setting time (min)	310	≥180
Final setting time (min)	309	≤600
3d flexural strength (MPa)	4	≥2.5
3d compressive strength (MPa)	16.5	≥11
28d flexural strength (MPa)	7.6	≥5.5
28d compressive strength (MPa)	32.8	≥32.5

2.2. Test Method

Uniaxial penetration and circle shear tests were conducted to measure the shear performance of asphalt mixtures. The cohesion and internal friction angle of the asphalt mixture were solved with the help of an unconfined compressive strength test. Specimens used in this research were uniformly formed by rotary compaction, and the number of rotations was 55. Specimens are placed in a 60 °C incubator for 6 h before the tests. The loading speed was 1 mm/min, and the test temperature was 60 °C.

2.2.1. Uniaxial Penetration Test

The uniaxial penetration test specimen size was 100 mm × Φ100 mm, and its indenter diameter was 28.5 mm. The loading speed of this experiment was 1 mm/min. The diagram of uniaxial penetration is shown in Figure 4.

Figure 4. Uniaxial penetration test.

For simplifying the method of solving the shear strength of mixtures by a uniaxial penetration test, Bi proposed a simplified calculation method to solve σ_1, σ_3, τ_{max} by adopting the strength parameter C in formula (1), and the strength parameters are shown in Table 8.

Table 8. Strength parameters of uniaxial penetration.

Parameter Type	C_1	C_3	C_τ
Strength parameter	0.7650	0.0872	0.3390

Through strength parameters and penetration pressure obtained from the uniaxial penetration test, two principal stresses and shear stresses were calculated by Formula (1).

$$S_i = C_i \cdot P \quad (1)$$

where,
S_i represents the required stresses: σ_1, σ_3, τ_{max};
C_i represents the strength parameters;
P is the penetration pressure obtained by the experiment.

2.2.2. Circle Shear Test

The principle of the circle shear test is to use indenter and ring support which is smaller than the size of cylindrical test specimens, to load the test specimen, thus simulating the actual road stress. The size of the test specimens was 95 mm × Φ150 mm, and its indenter diameter was 40 mm, the outer diameter of the ring was 150 mm, and the internal radius was 80 mm. The loading speed of this experiment is 1 mm/min. A specific picture is shown in Figure 5.

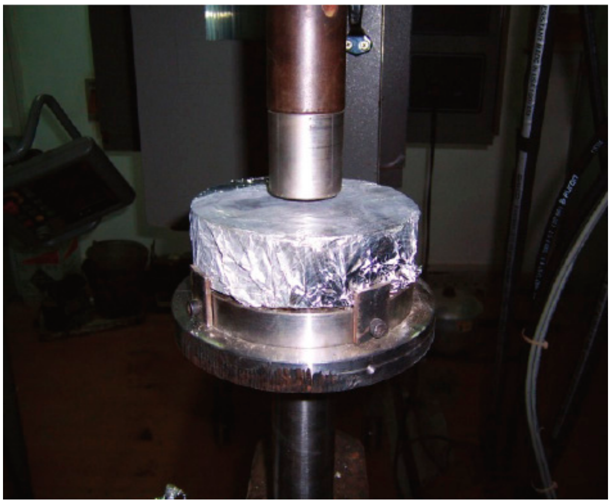


Figure 5. Circle shear test.

The shear strength parameters of the circle shear test are shown in Table 9.

Table 9. Strength parameters of circle shear test.

Parameter Type	C_1	C_3	C_τ
Strength parameter	1.124	0.092	0.516

According to the strength parameters, the two principal stresses and shear stresses can be conveniently calculated by Formula (1) using the penetration pressure obtained from the circle shear test.

2.2.3. Unconfined Compressive Strength Test

In this study, the cohesion c, internal friction angle φ, and shear strength of mixtures were calculated by an unconfined compressive strength test. According to Coulomb-Mohr strength theory, c and φ can be solved by Formula (2).

$$\left\{ \begin{array}{l} \varphi = \arcsin\left(\frac{\sigma_u - \sigma_1 + \sigma_3}{\sigma_u - \sigma_1 - \sigma_3}\right) \\ c = \frac{\sigma_u}{2}\left(\frac{1}{\sin\varphi} - 1\right)\tan\varphi \end{array} \right\} \tag{2}$$

where,
σ_1 is the first principal stress of the circle shear test;
σ_3 is the third principal stress of the circle shear test;
σ_u is unconfined compressive strength and compressive stress.

3. Results and Discussion

This research evaluated the influencing factors of the shear performance of asphalt mixtures from three aspects: asphalt binder, aggregate, and mineral powder.

3.1. Influence of Asphalt Binder on Shear Performance of Asphalt Mixtures

3.1.1. Influence of Asphalt Types on Shear Performance of Asphalt Mixtures

To evaluate the shear performance of the mixtures, three different SBS-modified asphalts and three different 70# asphalt binders were selected in this research. The shear strength was evaluated through two different test methods: a uniaxial penetration test and a circle shear test. The test results are shown in Figure 6.

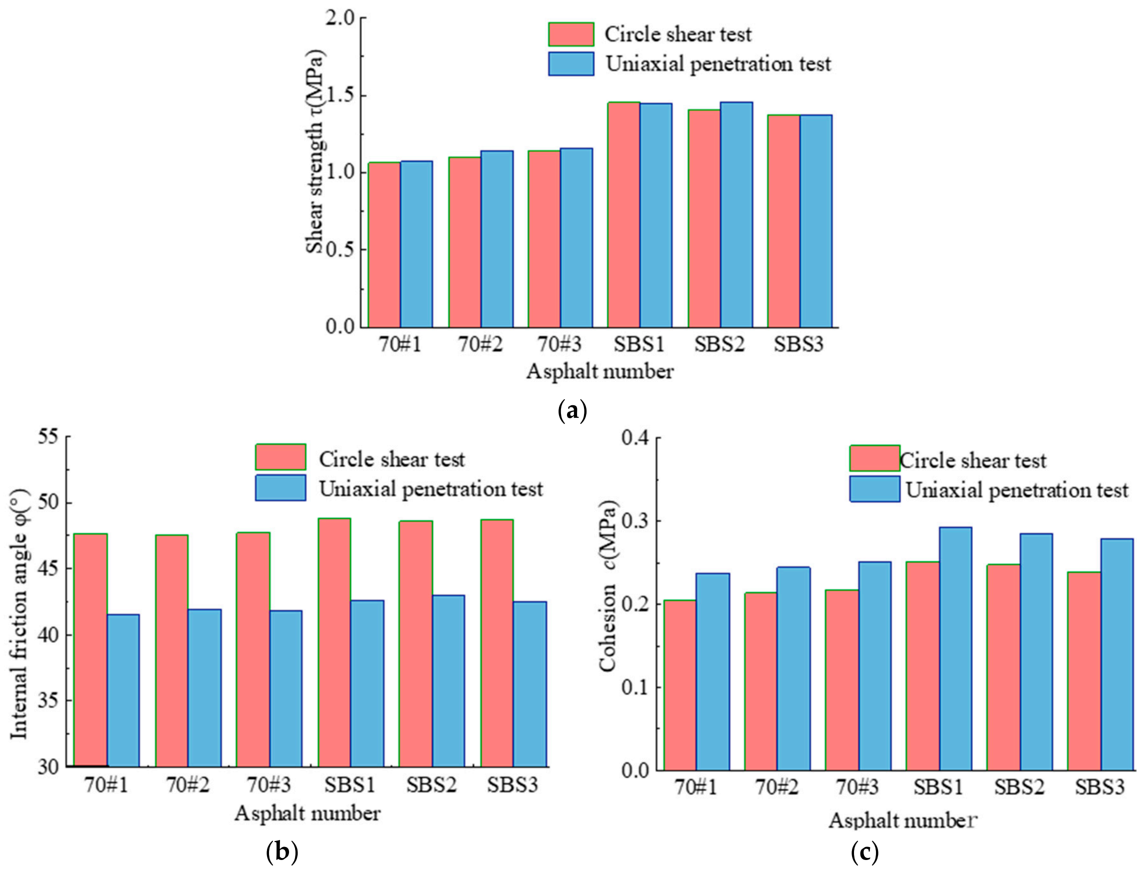


Figure 6. Shear strength, internal friction angle, and cohesion of different asphalts. (**a**) Shear strength; (**b**) Internal friction angle; (**c**) Cohesion.

As shown in Figure 6a, the average shear strengths of SBS-modified asphalt were 2.730 MPa and 4.200 MPa for the circle shear test and uniaxial penetration test, respectively. Moreover, the average of 70# was 2.134 MPa and 3.312 Mpa for circle shear and uniaxial penetration tests, respectively. Results found that the shear strength of SBS was 35.0% higher than that of 70# on average for the circle shear test and was 35.6% higher than that of 70# for the uniaxial penetration test, which indicated that compared with 70#, the SBS could significantly improve the shear performance of mixtures. The reason was that the SBS created a network structure in the asphalt binder, which greatly improved the binder strength. The result also found that the circle shear and uniaxial penetration tests showed similar trends.

Figure 6c showed that the average cohesions of SBS-modified asphalt were 0.246 MPa for the circle shear test and 0.285 MPa for the uniaxial penetration test, and the values of 70# asphalt were 0.212 MPa and 0.244 MPa for circle shear tests and uniaxial penetration test, respectively. The result from experiments found that the cohesion of mixtures with SBS-modified asphalt binder was about 17% higher than mixtures with 70# asphalt binder, while Figure 6b showed that the average internal friction angles of SBS-modified asphalt were 48.7° for circle shear tests and 42.7° for uniaxial penetration tests. Values for 70# asphalt were 47.6° and 41.8° for the circle shear and uniaxial penetration tests, respectively, which was almost unchanged. The results indicated that cohesion plays an important role in asphalt viscosity, leading to different shear strengths.

The internal friction angle of mixtures largely depends on gradation, aggregate morphology, and the friction force of the contact surface; therefore, whether SBS-modified or 70# asphalt was used, the internal friction angle of the mixture remains relatively constant. The binding effect of asphalt adheres the mineral aggregate into a stable skeleton in asphalt mixtures. The binding performance of asphalt positively affects the cohesion of the mixture. Furthermore, due to the better bonding performance of asphalt mortar and the more stable skeleton effect between minerals, the internal friction angle of the SBS-modified asphalt mixture is larger than that of 70#.

3.1.2. Influence of Asphalt Properties on Shear Performance of Asphalt Mixtures

For evaluating influences of penetration, softening point, and ductility on the shear performance of asphalt mixture, the shear strength tests of three different SBS-modified asphalts and three types of 70# asphalts were evaluated. The rest results are shown in Figure 7.

As illustrated in Figure 7a,b, the shear strength of mixtures was negatively connected with penetration and ductility of asphalt binder and had a larger connection with penetration, with R^2 reaching 0.91 for circle shear and 0.91 for uniaxial penetration test, which indicated a good linear relationship. Figure 7c demonstrated that the shear strength and softening point of asphalt has a good linear relationship, with R^2 of 0.97 for circle shear and 0.97 for uniaxial penetration test, indicating that mixtures' shear performance has a strong association with the penetration, ductility, and softening point.

3.1.3. Influence of Asphalt Contents on Shear Performance of Asphalt Mixtures

As introduced in Section 2.1.1, the asphalt-aggregate ratios of specimens were 4.0%, 4.5%, 5.0%, 5.5%, and 6.0%. Uniaxial penetration and circle shear tests were carried out between the specimens with different asphalt contents. The test results are shown in Figure 8.

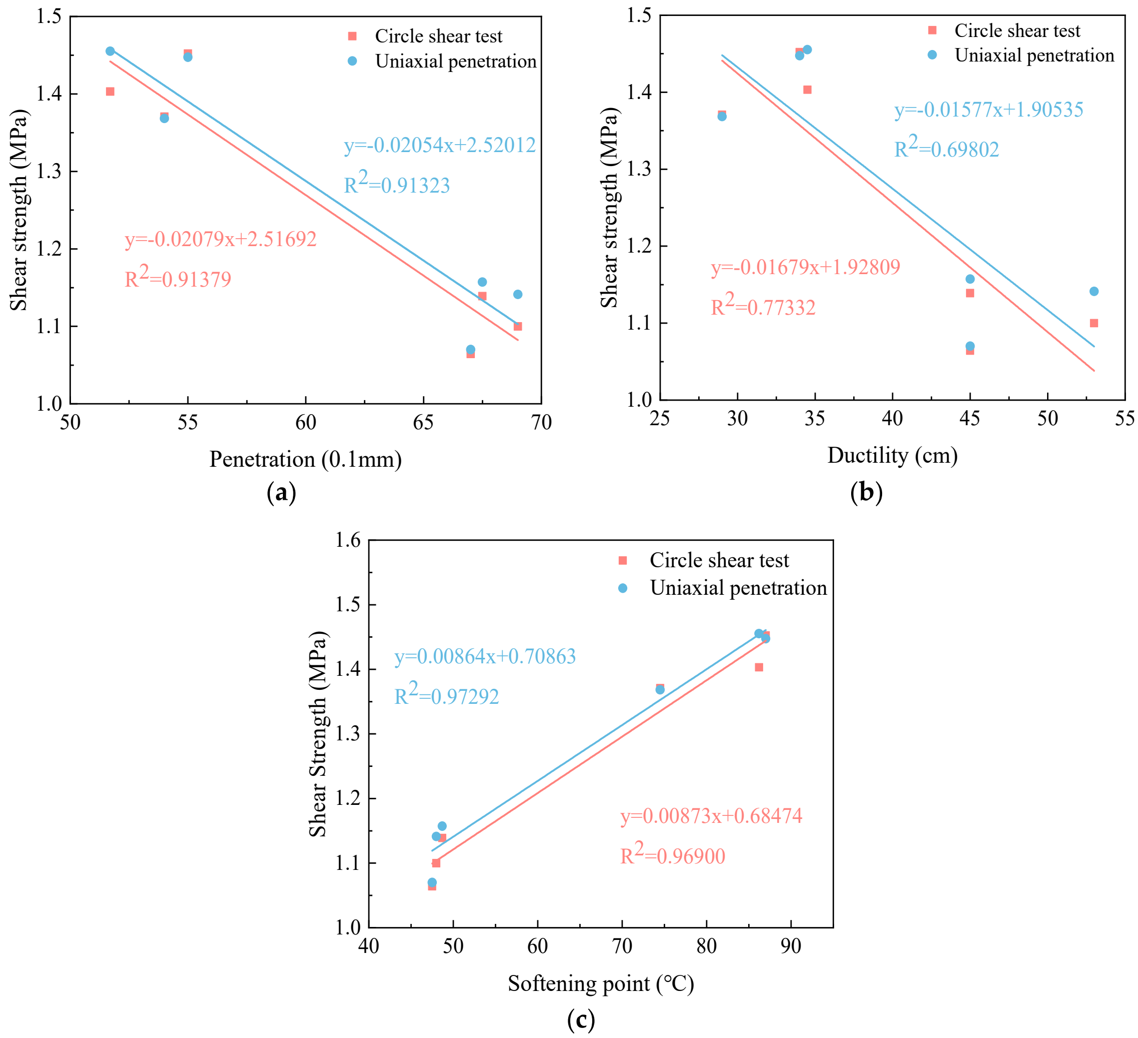


Figure 7. Relationships between shear strength of tests and three indexes. (**a**) Penetration; (**b**) Ductility; (**c**) Softening point.

Figure 8a showed that when the asphalt–aggregate ratio was less than 4.5%, the shear strength of mixtures increased from 1.292 MPa to 1.464 MPa for circle shear tests and 1.317 MPa to 1.487 MPa for uniaxial penetration tests. The shear strength varied little when the asphalt–aggregate ratio was between 4.5% and 5.0%. It can be inferred from the curves that the optimal asphalt-aggregate ratio of mixtures was around 4.7%, which was lower than that of the Marshall test; thus, it is suggested that designing the asphalt content following the shear strength test would be better in the design of high-traffic highways. Both shear strengths of circle shear and uniaxial penetration test showed a similar trend; the shear strength of mixtures decreased rapidly when the asphalt–aggregate ratio was larger than 5.0%, with strength values of 1.367 MPa and 1.393 MPa, respectively.

The internal friction angle evaluated by the two test methods showed the same trend in Figure 8b. With the increased content of asphalt binder, the internal friction angle of mixtures increased slightly, reaching the maximum value of 49.4° for the circle shear test and 43.8° for the uniaxial penetration test. Figure 8c showed that the cohesion of mixtures appeared to have the same trend as the shear strength, which indicated that the cohesion mainly impacted the shear performance of asphalt mixtures under different asphalt–aggregate ratios.

When the asphalt content is small, the asphalt is not sufficient to form the structural asphalt film to bond mineral aggregates. Furthermore, the structural asphalt film gradually forms with the increase of asphalt, which is generally wrapped around the surface of mineral aggregate to increase the adhesion between asphalt mortar and aggregates. Asphalt mortar will have the highest bonding force when the amount of asphalt is enough to form a film and fully bond the surface of mineral powder particles. However, as the amount of asphalt continues to increase, the mineral aggregate particles are gradually pushed away by the excess asphalt (also called "free asphalt"). The free asphalt does not interact with mineral powder, so as the free asphalt in the asphalt binder increases, the adhesive force of the asphalt binder decreases. Upon increasing the asphalt content to a certain amount, the cohesion of asphalt mixtures will be largely determined by the free asphalt; thus, its shear strength remains essentially unchanged.

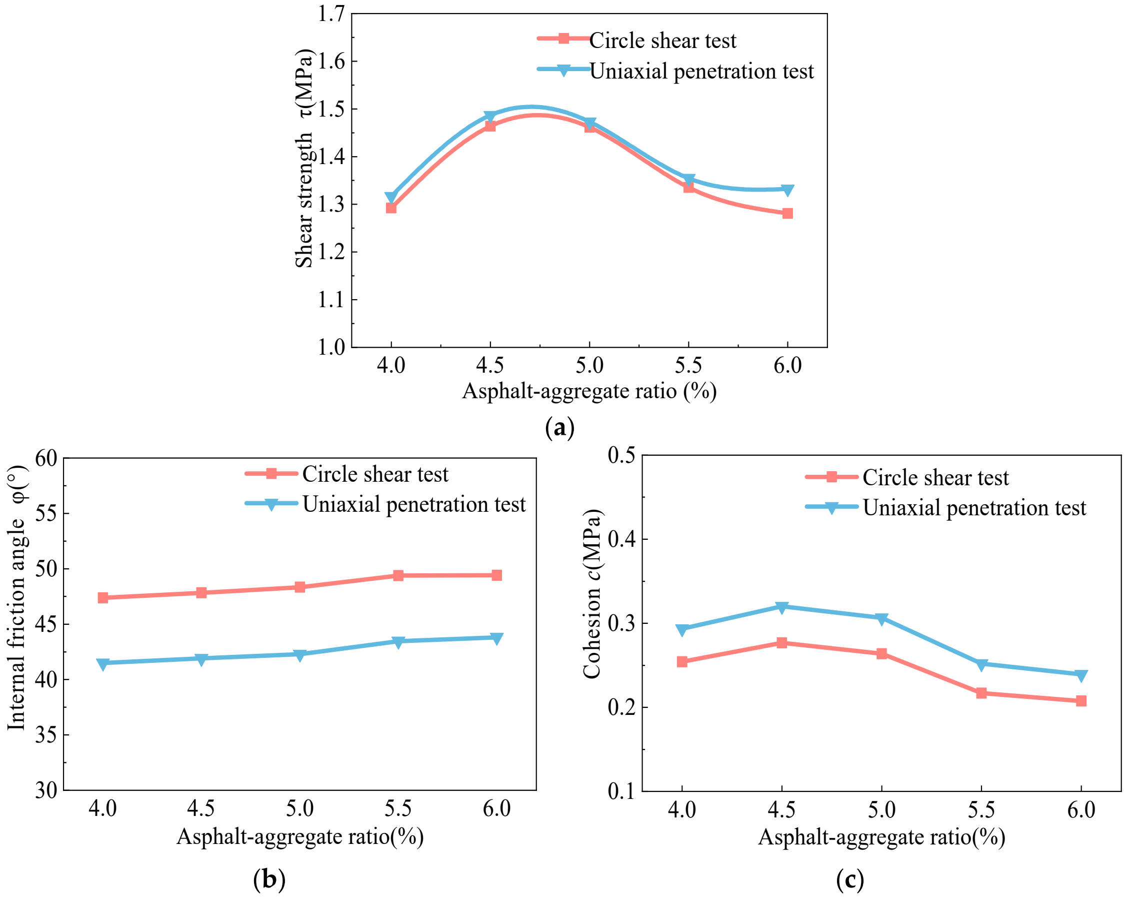


Figure 8. Shear strength, internal friction angles, and cohesion of different asphalt contents. (**a**) Shear strength; (**b**) Internal friction angle; (**c**) Cohesion.

3.2. Influence of Aggregate on Shear Performance of Asphalt Mixtures

3.2.1. Influence of Different Gradations on Shear Performance of Asphalt Mixtures

For exploring the impacts of aggregate gradation on the shear strength of asphalt mixtures, mixtures with five typically used gradations (AC-13F, AC-13M, AC-13C, SMA-13, and AC-16) under circle shear and uniaxial penetration test were evaluated. The experimental results are shown in Figure 9.

Figure 9a showed that the shear strength for AC-13 was 1.498 MPa for the circle shear test and 1.478 MPa for the uniaxial penetration test, and it was 1.549 MPa for the circle shear test and 1.572 MPa for the uniaxial penetration test; according to the results, the shear strength of mixtures increased as nominal maximum aggregate size increased. The shear strength for SMA-13 was 1.511 MPa for the circle shear test and 1.538 MPa for the uniaxial penetration test. Compared with that of AC-13, the results indicated that the SMA had a better shear strength than AC gradation when mixtures had the same nominal maximum aggregate size. According to the shear strength of three gradations, which were AC-13C, AC-13F, and AC-13M, the result indicated that the increase of coarse aggregate content does not necessarily improve the shear strength, and reasonable gradation played a significant role. The shear strength test of the circle shear test and uniaxial penetration test showed similar tread with the average value of 1.484 MPa for circle shear and 1.478 MPa for the uniaxial penetration test.

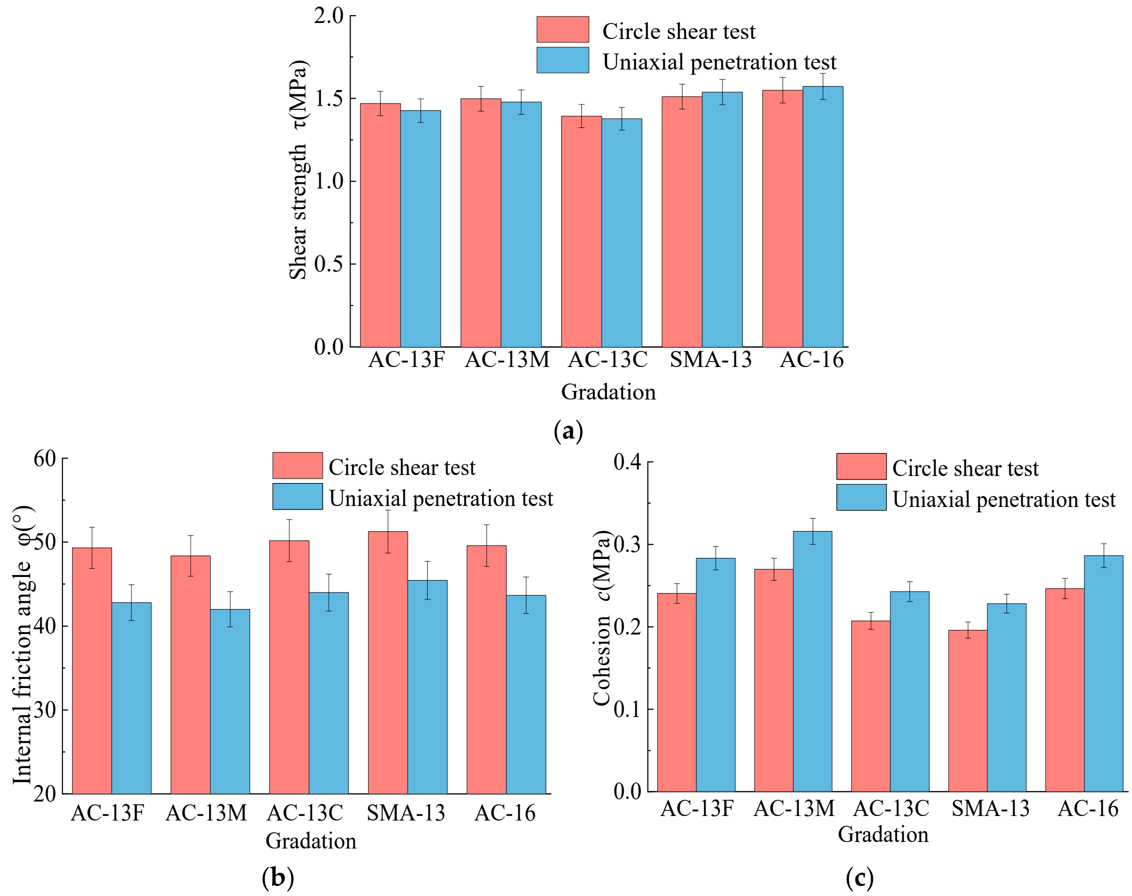


Figure 9. Shear strength, internal friction angle, and cohesion of mixtures with different gradations. (**a**) Shear strength; (**b**) Internal friction angle; (**c**) Cohesion.

Figure 9b shows that the trend of internal friction angle was SMA-13 > AC-13C > AC-16 > AC-13F > AC-13M, and cohesion was AC-13M > AC-16 > AC-13F > AC-13C > SMA-13. The results found that the SMA-13 had the maximum internal friction angle, which was 51.3° for the circle shear test and 45.4° for the uniaxial penetration test, and had the minimum cohesion, which was 0.196 MPa for the circle shear test and 0.228 MPa for uniaxial penetration test, which indicated that the shear strength was mainly provided by interlocking of aggregates.

3.2.2. Influence of Aggregate Silt Content on Shear Performance of Mixtures

A necessary condition for good bonding between asphalt and aggregates is whether asphalt completely covers aggregates, but aggregate cannot be completely clean in practical engineering. Therefore, the impacts of aggregate silt content on the shear strength of mixtures were evaluated.

Influence of Silt Content of Coarse Aggregate on Shear Strength

Uniaxial penetration and circle shear tests were carried out on specimens of a coarse aggregate containing different silt content; the shear strength tests were conducted before and after the high-temperature immersion Marshall test.

As shown in Figure 10, SC_1, IC_1, and CC_1 represent the circle shear test's shear strength, internal friction angle, and cohesion before the high-temperature immersion Marshall test. SC_2, IC_2, and CC_2 represent the shear strength, internal friction angle, and cohesion of the circle shear test after the high-temperature immersion Marshall test. SU_1, IU_1, and CU_1 represent the shear strength, internal friction angle, and cohesion of the uniaxial penetration test before the high-temperature immersion Marshall test. SU_2, IU_2, and CU_2 represent the shear strength, internal friction angle, and cohesion of the uniaxial penetration test after the high-temperature immersion Marshall test.

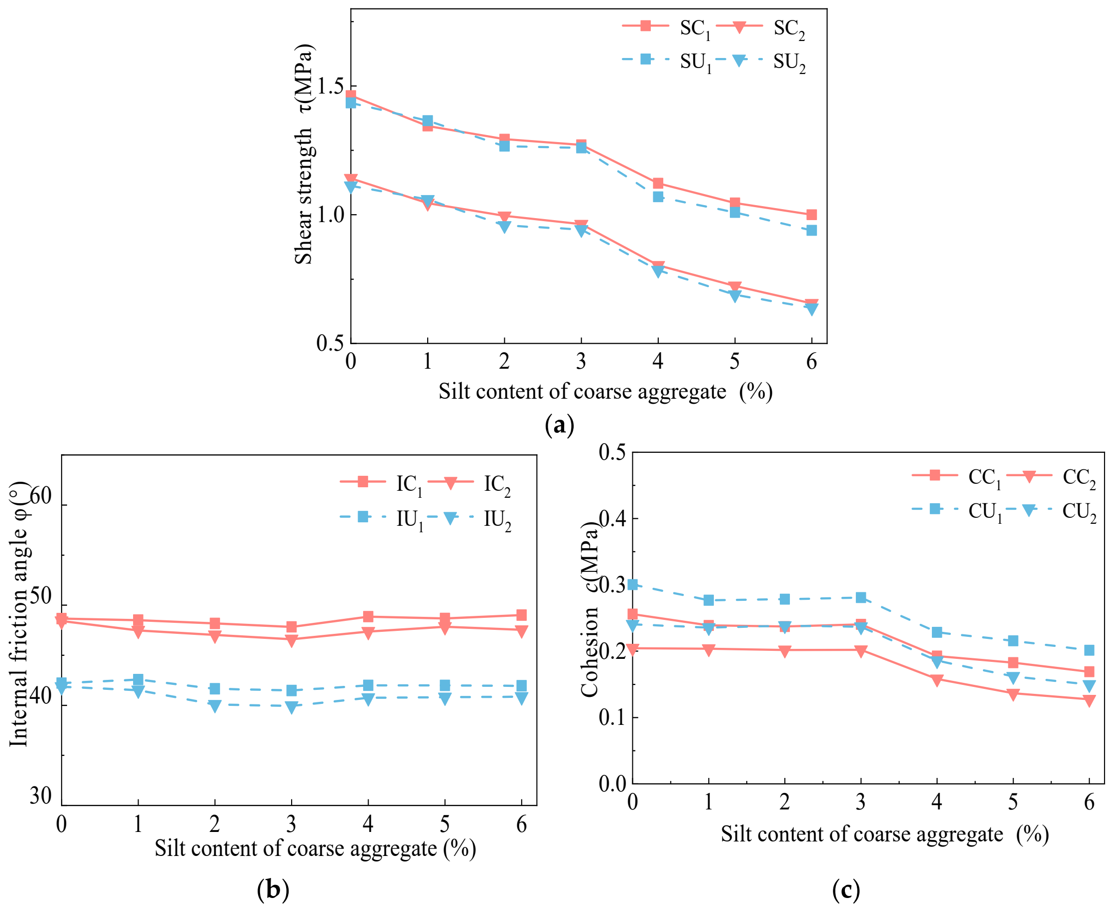


Figure 10. Shear strength, internal friction angle, and cohesion of coarse aggregate containing silt specimen before and after high-temperature immersion Marshall test. (**a**) Shear strength; (**b**) Internal friction angle; (**c**) Cohesion.

Figure 10a shows that the changing trend of shear strength before and after the high-temperature immersion Marshall test both dropped as the silt content increased, and the shear strength had the highest value when the silt content was 0%. In addition, when the silt content increased, the ratio of shear strength before and after the high-temperature immersion test decreased, indicating that the asphalt mixture had more water damage.

It was found in Figure 10c that coarse aggregate silt content significantly impacts cohesion; when the silt content was less than 3%, the cohesion of asphalt mixtures gradually declined from 0.256 MPa to 0.241 MPa with a slight drop of 5.8% as the silt content increases and then considerably reduced with a drop of 29.9% from 0.241 MPa to 0.169 MPa when the silt content was greater than 3%. However, Figure 10b shows it had a limited effect on the internal friction angle.

This is because the shear strength of mixtures depends on the adhesion between structural asphalt film and the aggregates. The adhesion between structural asphalt surface and aggregates reduces when the aggregate surface is covered with silt. When the silt content of the mixture is less than 3%, a small amount of free asphalt outside the structural asphalt film is absorbed, but the structural asphalt film is not significantly affected, which has limited effects on the asphalt mixture's shear strength. When the silt content continues to increase, then the free asphalt is completely absorbed, and the excess silt absorbs the structural asphalt, making the structural asphalt film thinner and unable to completely cover aggregates, which affects the adhesion between structural asphalt film and the aggregate, and provides a channel for water penetration, and further results in a significant decrease in shear strength.

Influence of Silt Content of Fine Aggregate on Shear Performance

The uniaxial penetration test and circle shear test were carried out on the specimens of a fine aggregate containing different content of silt, and the tests were conducted before and after the high-temperature immersion Marshall test; results are shown in Figure 11.

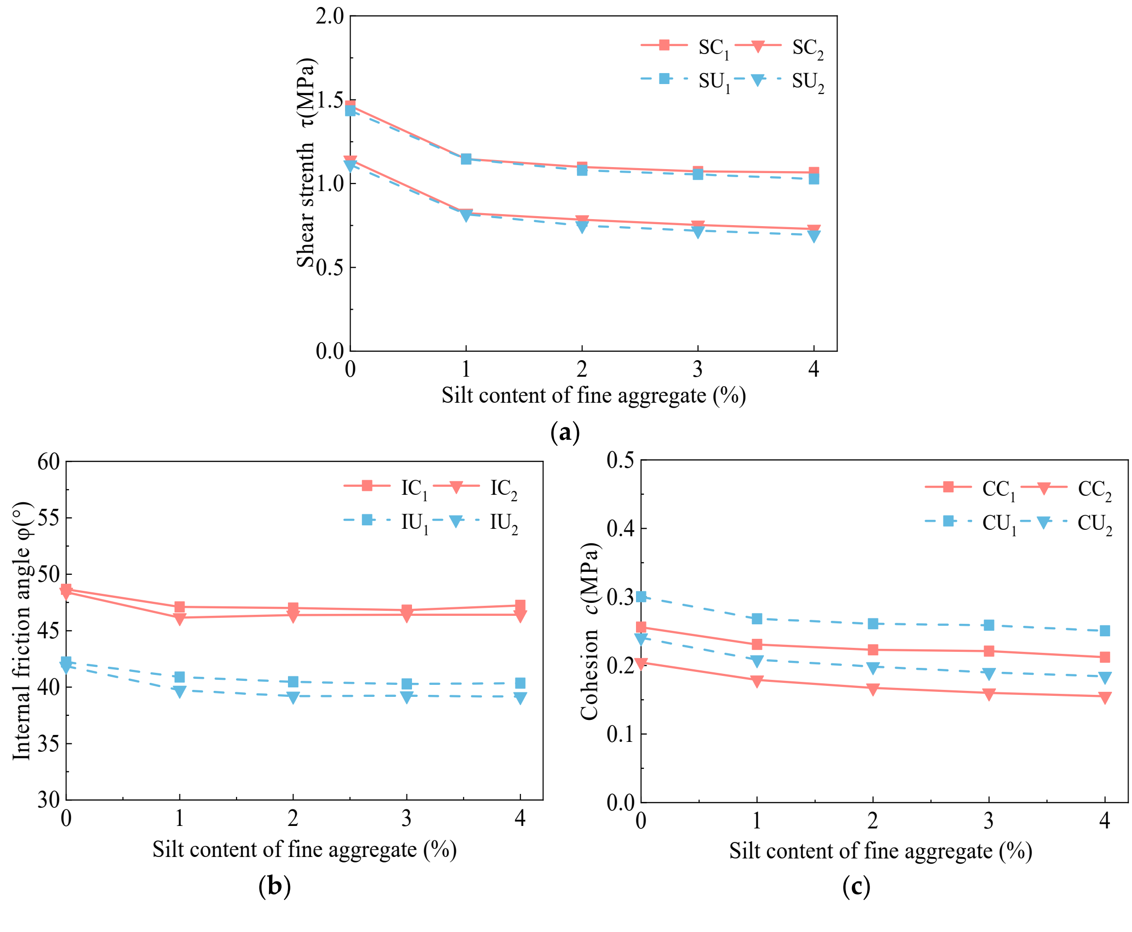


Figure 11. Shear strength, internal friction angle, and cohesion of fine aggregate containing silt specimen before and after high-temperature immersion Marshall test. (**a**) Shear strength; (**b**) Internal friction angle; (**c**) Cohesion.

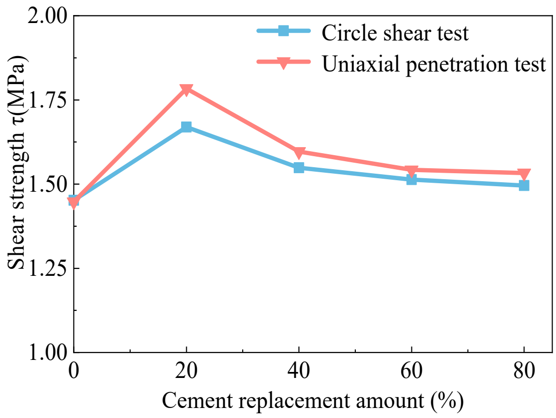
Figure 11 showed that the silt content of fine aggregate greatly influenced the shear strength and cohesion of mixtures, but its internal friction angle was not affected much. Figure 11a shows that the changing trend of shear strength before and after the high-temperature immersion Marshall test both dropped as the silt content increased. The shear strength had the highest value when the silt content was 0%, which was 1.463 MPa for the circle shear test and 1.435 MPa for the uniaxial penetration test. Moreover, the result showed that when the silt content in fine aggregate increased to 1%, it had a drop of over 20% in internal friction angle, cohesion, and shear strength, which indicated that a small amount of silt content in fine aggregate significant reduced the shear performance when compared to those without silt. This is because the cohesion of mixtures is primarily provided by asphalt mortar, and the silt content of fine aggregate seriously affects the adhesion of asphalt mortar, causing a decrease in asphalt mixture shear strength.

3.3. Influence of Mineral Powder on Shear Performance

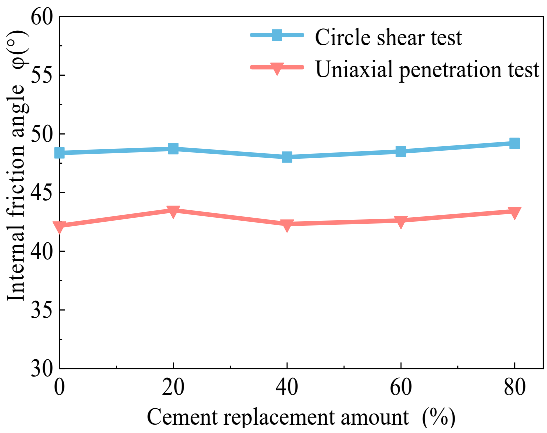
The impacts of cement and phosphorus slag powder (PSP) separately on the shear performance of mixtures were evaluated by replacing parts of mineral powder with cement and PSP.

3.3.1. Cement Replaces Mineral Powder

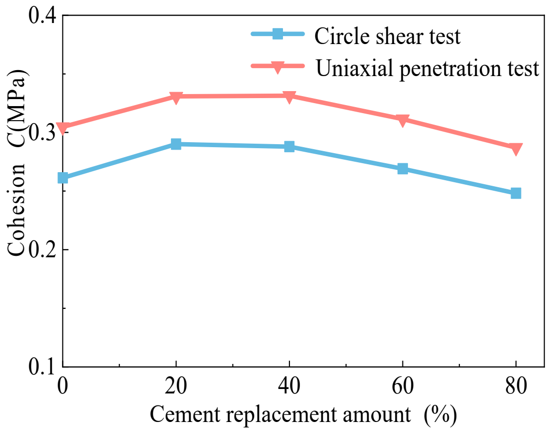
In this research, the impact of different cement replacement levels on shear strength, internal friction angle, and cohesion was evaluated. A total of five different replacement levels of 0%, 20%, 40%, 60%, and 80% were compacted, and the experimental results were as shown in Figure 12.



(**a**)



(**b**)



(**c**)

Figure 12. Influence of cement replacement amount on Shear strength, internal friction angle, and cohesion. (**a**) Shear strength; (**b**) Internal friction angle; (**c**) Cohesion.

Figure 12a showed that when the cement replacement increased from 0% to 20%, the shear strength of the asphalt mixture increased rapidly from 1.452 MPa to 1.669 MPa for the circle shear test and increased from 1.447 MPa to 1.784 MPa for uniaxial penetration test, and when the cement replacement content continued to increase, the shear strength started to decrease and then generally became stable. As illustrated in Figure 12b, the cement content's impact on the internal friction angle was small, which can be inferred that the cement did not affect the internal friction angle much.

As shown in Figure 12c, When the cement content was less than 20%, the cohesion of the mixture increased gradually from 0.161 MPa to 0.290 MPa for circle shear and increased from 0.305 MPa to 0.331 MPa for the uniaxial penetration test. When cement content was increased from 20% to 40%, the cohesion of the mixture remained stable, and then with the addition of cement, the cohesion of the mixtures gradually decreased, which indicated that cement had a great influence on cohesion when the content was over 40%.

The reason was that cement is an alkaline material with a higher PH than mineral powder, and asphalt contained a small quantity of acidic resin, which served as a bonding agent. During the mixing process, the carboxylic acid and sulfoxide of acid resin reacted with the CaO of cement to form compounds with greater absorbability, which improved the asphalt aggregate adhesion. Because cement has a larger specific surface area than mineral powder, thus consumed more asphalt to form a structural film with the same thickness when the cement was less than 20%. Since carboxylic acid and sulfoxide continuously reacted with CaO, the adhesion of the asphalt binder was continuously enhanced, and the shear strength of the mixture was continuously increased. When the cement replacement quantity reached 20%, the asphalt content of the mixture generally became insufficient to form a structural film and decreased the shear strength of the asphalt mixture.

3.3.2. PSP Replaces Mineral Powder

For evaluating the impacts of PSP on the replacement of mineral powder on the shear performance of asphalt mixture, five different replacement levels of 0%, 5%, 10%, 15%, and 20% were evaluated in this research. The impact of different replacement levels on the shear strength, internal friction angle, and cohesion is shown in Figure 13.

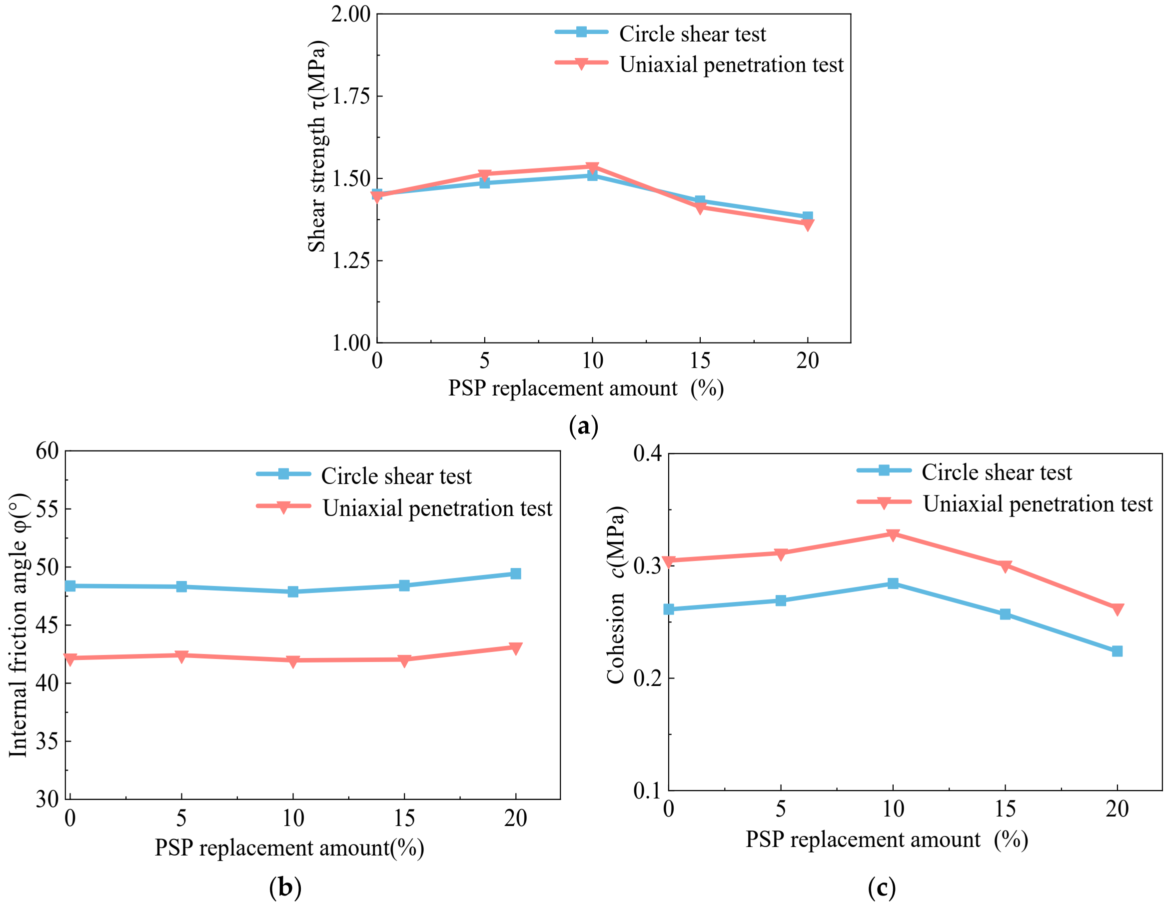


Figure 13. Effects of PSP replacement amount on Shear strength, internal friction angle, and cohesion. (**a**) Shear strength; (**b**) Internal friction angle; (**c**) Cohesion.

Figure 13a showed that when the PSP replacement was less than 10%, the shear strength of mixtures gradually increased and reached the maximum at the content level of

10%, which was 1.509 MPa for circle shear and 1.536 MPa for uniaxial penetration. When PSP replacement content was more than 10%, the shear strength of the asphalt mixture began to decrease.

Figure 13b found that the internal friction angle was 48.4° for circle shear and 42.2° for the uniaxial penetration test when PSP replacement was 0% and increased to 49.4° for circle shear and 43.1° for the uniaxial penetration test when PSP content was 20%, which was nearly unchanged.

Figure 13c illustrates that the cohesion of mixtures increased when PSP replacement increased from 0% to 10%, and the cohesion of the mixture decreased rapidly with the continued increase of PSP content. The result also indicated that the average cohesive force for uniaxial penetration was higher than that of the circle shear test.

Similar to the impact of cement replacement of mineral powder, the particle size of PSP used in this research was much smaller than the size of mineral powder. Thus, PSP had a specific surface area much larger than mineral powder, and the amount of asphalt required for generating a structural asphalt film of the same thickness was much greater. Therefore, when the PSP replacement quantity exceeds 10%, the addition of PSP has a negative impact on the shear performance of mixtures.

4. Conclusions

This paper explored the influence and mechanism of various factors on the shear performance of mixtures. The shear performance tests were carried out using circle shear and uniaxial penetration test methods. As the impact of material composition on the performance of asphalt mixture was complex, based on limited tests, the following conclusions could be obtained:

(1) SBS-modified asphalt binder mainly improves the shear strength of the mixtures by increasing cohesion. It is suggested that the asphalt–aggregate ratio should be reduced appropriately in the design of heavy traffic in high-temperature conditions;
(2) Increasing the maximum nominal aggregate size of gradation can improve the shear strength of the mixture. Increasing coarse aggregate content does not necessarily improve the shear strength of the mixture, and reasonable gradation is the most important;
(3) The shear strength and cohesion of the mixture decrease with the increase of silt content in the coarse or fine aggregate, but the internal friction angle does not change much. It is suggested that the silt content of coarse aggregate should be controlled within 3%, and that of fine aggregate should be controlled within 1%.
(4) It is suggested that 20% cement or 10% PSP replacement of mineral powder can improve the shear strength of the mixture.

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