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Research Article

Investigation on the Properties of Concrete Containing Oil Shale Waste Ash as a Substitute for Cement

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Oil shale waste ash (OSWA) can be divided into semicoke ash (SA), power plant ash (PPA), and grinding ash (GA), which changes the properties of binding materials in varying degrees as partial replacements of cement in cement concrete. Fluidity of cement paste test is formed to reflect the compatibility between binding materials and admixture, using the mixture of cement to test compressive strength, flexural strength, and brittleness coefficient, to determine the mixing ratio of OSWA. The optimal amount of OSWA replacing cement was optimized by orthogonal test method, and the mechanical properties and frost resistance durability tests were carried out to clarify the reasonable amount and properties of OSWA replacing cement with cement concrete. The results show that appropriate admixtures should be taken into account when OSWA is used to replace cement in order to achieve the workability of cement concrete. The brittleness coefficient and crack resistance of cement concrete can be improved by adding proper PPA and GA. The oil shale cement concrete should not be used in the parts that require high frost resistance. It is feasible to replace cement with OSWA, and the fine powder type and mixing amount can be selected according to the actual project demand.

1. Introduction

As an unconventional oil resource, oil shale is rich in resources and is listed as an important alternative energy source in the 21st century [1]. It is a nonrenewable fossil energy and has important economic value like oil, natural gas, and coal. At present, more than 90% of the oil shale resources are extracted by low-temperature dry distillation or burned for heating and power generation. Due to the high degree of mineralization and low oil content of oil shale, a large amount of OSWA will be produced after process [2]. The treatment method of OSWA is to discard it directly and pile it near the factory, which not only causes a large amount of waste of resources, but also increases land occupation and has a great impact on the surrounding ecology and living environment. Therefore, it is of great significance to the comprehensive utilization of OSWA [3, 4].

The composition of OSWA contains SiO2 and Al2O3, which has a certain pozzolanic activity. OSWA can be ground to replace part of cement and used in cement concrete, which can reduce the project cost. Relevant scholars have done some scientific research on OSWA cement concrete. Ji et al.'s experiment proved that the 3-day strength decreased significantly, and the 28-day strength was relatively stable with the increase of OSWA content [5]. The research results of Wang and Luo showed that after mechanical and chemical composite activation, the early flexural strength, compressive strength, and late compressive strength of mortar prepared by replacing 20% cement with OSWA slag increased by 30%, 31%, and 17%, respectively [6]. Wang et al. took three kinds of OSWA as admixtures and determined the compressive strength, flexural strength, and brittleness coefficient of the test block through the ISO test of cement mixture [7]. The experimental results proved that the compressive and flexural strength of the test block are better than those of the pure cement block when the content of PPA is 10%, and the crack resistance of the test block is the best when the content of GA is 30%. Al-Hamaiedh et al. used OSWA to replace mortar cement, and the 28-day compressive strength of mortar with weight ratios of 10%, 20%, and 30% decreased by 7.4%, 11.7%, and 23%, respectively, compared with the strength of pure cement mortar, and the setting time of cement increased by 20 min, 30 min, and 50 min, respectively [8]. Khedaywi et al. conducted a test study on the tensile fatigue characteristics of OSWA asphalt mixture pavement. The results of the study showed that the stiffness modulus of the asphalt mixture will also change when the oil shale slag content is different. When the content of OSWA is 10%~15%, the stiffness modulus of the asphalt mixture can be effectively improved. When the ash content is 10%, the performance of the asphalt mixture reaches the best state [9, 10]. Arinakoroljova et al. used OSWA as a soft soil material stabilized by the binder and cement. The test results show that mixing OSWA in cement can change the strength and stability of the mixture to a certain extent and can reduce the cement. The different dosage and mixing amount of OSWA will lead to different overall strengths of OSWA and cement mixture [11–15].

According to the research results at home and abroad, it is basically feasible to make concrete with OSWA instead of part of cement. To better apply it in highway engineering, it is necessary to further study the mechanical properties and durability of fine powder cement concrete with OSWA. It can meet the demand of road building materials for highway construction and consume OSWA so that oil shale resource mining can truly turn waste into treasure.

2. Raw Material

2.1. Cement. Ordinary 42.5R Portland cement produced by Jilin Yatai Cement Co., Ltd, was used in the test. Cement inspection report is shown in Table 1, which conforms to the requirements of all indicators of Common Portland Cement (GB 175-2007).

2.2. OSWA. Three kinds of waste oil shale fine powder of Wangqing County of Jilin province were selected in the test, which were SA, PPA, and GA. SA is black in color, which is formed by grinding the residual residue of oil shale after dry distillation [16, 17]. PPA is the fly ash produced by oil shale through combustion to generate electricity, and its color is yellow-gray. GA is fine particles produced by oil shale after combustion for power generation. The color of powder ash is also yellow and gray, which is basically the same as the color of PPA [18]. The pictures of SA, PPA, and GA are shown in Figure 1, and the particle composition is shown in Table 2.

2.3. Admixtures. In liquid polycarboxylic acid type water reducing admixture, the indicators are shown in Table 3.

2.4. Water. Take underground well water, with each index to meet the specification requirements.

2.5. Standard Sand. In order to explain the performance of using waste OSWA to replace cement and reduce the impact of sand on the cements for determination of strength, ISO standard sand was used in cement mortar test and the compatibility test of OSWA cement cementitious material and admixture [19]. The mass of standard sand of each group of specimens was 1350 ± 2 g.

2.6. Coarse Aggregate. Test for basalt with coarse aggregate, the coarse aggregate quality requirements to meet Technical Specification for Construction of Highway Bridge and Culvert (JTG/T3650-2020) level II standard [20], and the performance index of the coarse aggregate are shown in Table 4, and the gradation is shown in Figure 2.

2.7. Fine Aggregate. Fine aggregate used river sand in cement concrete test; its fineness modulus is 2.97, which belongs to coarse gradation of medium sand. The technical indexes of river sand are shown in Table 5, which meet the relevant requirements of Technical Specification for Construction of Highway Bridge and Culvert (JTG/T3650-2020).

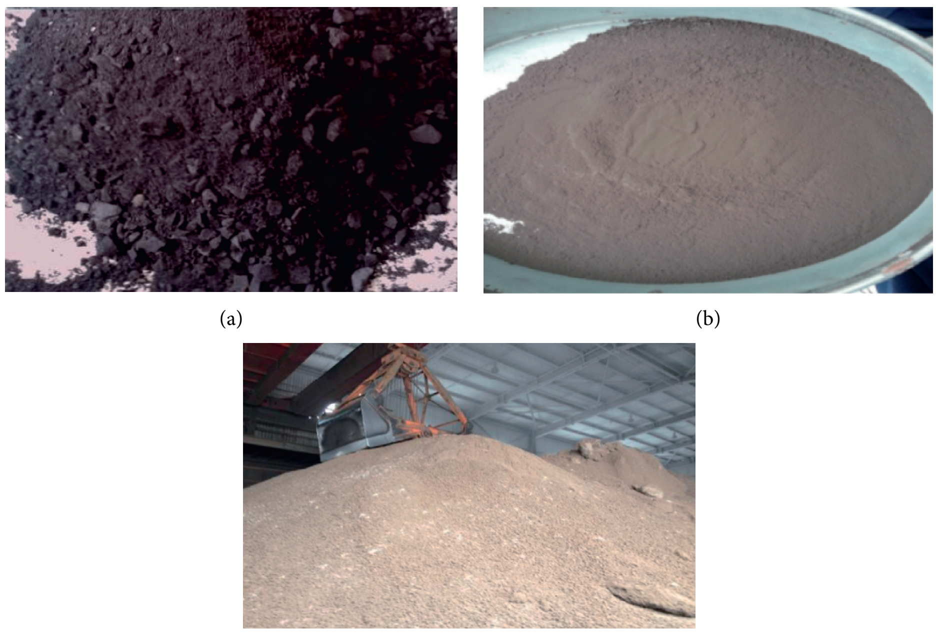
3. Experimental Methods

3.1. Compatibility Test. Fluidity of cement paste was tested to analyze the compatibility between cement slurry and three kinds of OSWA [21]. After a certain amount of cement, admixtures, and water was added to the cement paste mixer, the stirred paste was poured into the truncated cone mold, the truncated cone mold was then lifted, and the maximum free flow diameter of the cement paste on the glass plane could be measured. The dosage of cementitious material was 300 g, water was 87 g, and W/B was 0.29. When stirring, it is as follows: first slow 120 s, stop 15 s, and fast 120 s [22]. The mixed cement slurry was quickly injected into the truncated cone round mold, scraped with a scraper, the truncated cone round mold was lifted in the vertical direction, and the stopwatch was turned on at the same time. The cement slurry flowed on the glass plate for 30 s, the maximum diameter of the two directions perpendicular to each other was measured with a ruler, and the average value was taken as the fluidity of the cement slurry. In order to evaluate the compatibility between the admixture and the cementitious material, the dosage of the cementitious material and water should not be changed when the dosage of the admixture increases.

3.2. Test of Brittleness Coefficient of Cement Mortar. In order to study the influence of the addition of OSWA slag fine powder on the crack resistance of cement mortar, the brittleness coefficient index is used to evaluate its crack resistance, that is, the ratio of compressive strength and flexural strength in the same age period. During the test, in order to express the influence of OSWA on the crack resistance of sand and gravel, fine aggregates with the same grading were used for the test, that is, river sand used in Table 5, whose grading is shown in Figure 3.

Table 1: Inspection report of cement.

Properties	Specific surface area (m^2/kg)	Setting time (min)		Compressive strength (MPa)		Flexural strength (MPa)		Soundness (mm)	MgO (%)	SO_3 (%)	Cl^- (%)	Normal consistency (%)	Loss on ignition (%)
		Initial	Final	3-day	28-day	3-day	28-day						
Standard values	≥300	≥45	≤600	≥17.0	≥42.5	≥3.5	≥6.5	≤5.0	≤5.0	≤3.5	≤0.06	—	≤5.0
Actual values	383	180	365	24.52	46.44	4.38	7.55	1.5	1.23	2.28	0.009	27.2	1.57



(a) (b) (c)

Figure 1: Raw material pictures: (a) SA; (b) PPA; (c) GA.

Table 2: Granular composition of three fine powders of OSWA residue.

	Sample	Mesh size (mm)			
		0.075	0.15	0.3	0.6
Pass rate (%)	PPA	74.6	88.6	98.5	100
	GA	95.7	100		
	SA	98.3	100		

Table 3: Water reducer test report.

Properties	Water reducing rate (%)	Cl^- (%)	OH^- (%)	Na_2SO_4 (%)	Air content (%)	Bleeding rate (%)
Standard values	≥25	≤0.1	≤3	≤0.5	≤6.0	≤60
Actual values	27.8	0.04	1.1	0.04	3.7	48

Table 4: Basalt gravel performance index table.

Properties	Apparent relative density (kg/m^3)	Bibulous rate (%)	Firmness (%)	Clay content (%)	Flat and elongated particles (%)	Crush value (%)	Mud content (%)
Standard values	≥2600	≤2	≤8	≤1	≤10	≤20	≤0.2
Actual values	2859	1.90	3.45	0.75	9.71	15.0	0.13

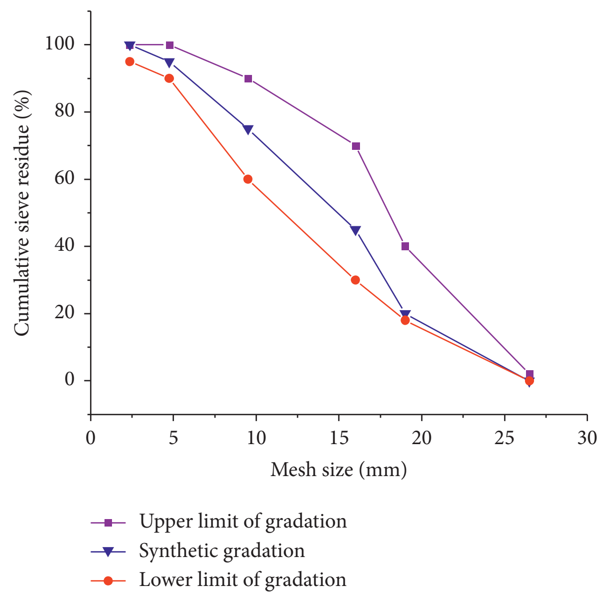


Figure 2: Grading curve of coarse aggregate.

Table 5: Technical specification of river sand.

Properties	Fineness modulus	Clay content (%)	Apparent density (kg/m^3)	Loose bulk density (kg/m^3)	Firmness (%)
Standard values	2.5–3.2	<3	≥2500	≥1400	<8
Actual values	2.97	0.92	2613	1397	4.3

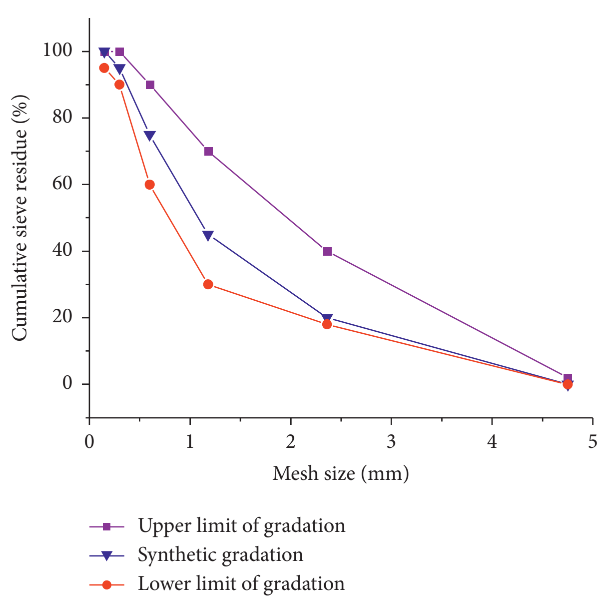


Figure 3: Grading curve of fine aggregate.

4. Compatibility of OSWA Cement Cementitious Materials and Admixtures

4.1. Selection of Fineness of OSWA. In order to study the compatibility between OSWA and admixture, firstly, the relationship of mortar strength should be determined when different fineness of OSWA replaces the same amount of cement [23]. PPA produced by power generation was selected as the research object and processed by different grinding methods and different grinding times to obtain five kinds of PPA with different fineness [24]. The particle size distribution and corresponding specific surface area are shown in Table 6.

The average particle size of the samples decreased gradually with the increase of grinding time, and the particle size distribution of the samples became more and more uniform, as shown in Figure 4. As the average particle size of the sample decreases, its specific surface area gradually increases, indicating that the binding area between particles increases, and the strength of the mortar increases, as shown in Figures 5–7.

PPA with different fineness was substituted for 20% cement to carry out cement mortar test, flexural strength, and compressive strength test. The test results are shown in Table 7.

It can be seen from Tables 7 and 8 that, with the increase of particle size, the 3-day compressive strength, the 3-day bending strength, and the 28-day compressive strength all decreased gradually, but the 28-day compressive strength had little change. The 3-day flexural strength of the specimens with average particle size of 1.629 μm, 3.992 μm, and 8.776 μm is higher than that of the pure cement standard specimens [25]. The 3-day and 28-day compressive strength of the specimens with average particle size of 1.629 μm is higher than that of the pure cement standard specimens, indicating that the finer the particle size is, the better the mechanical properties are. D90 of Fineness B is 77.185 μm, which in highway engineering equivalent to the idea that more than 90% of the particles can pass 0.075 mm sieve. In order to investigate the impact of three kinds of OSWA on

Table 6: Particle size distribution and specific surface area of PPA with different fineness.

Fineness	D10 (μm)	D50 (μm)	D90 (μm)	Dav (μm)	Specific surface area (m^2/g)
A	1.417	12.863	104.245	38.330	8.206
B	1.277	8.849	77.185	23.635	6.443
C	0.934	3.953	24.112	8.776	8.468
D	0.957	2.944	8.523	3.992	12.111
E	0.690	1.396	2.870	1.629	19.534

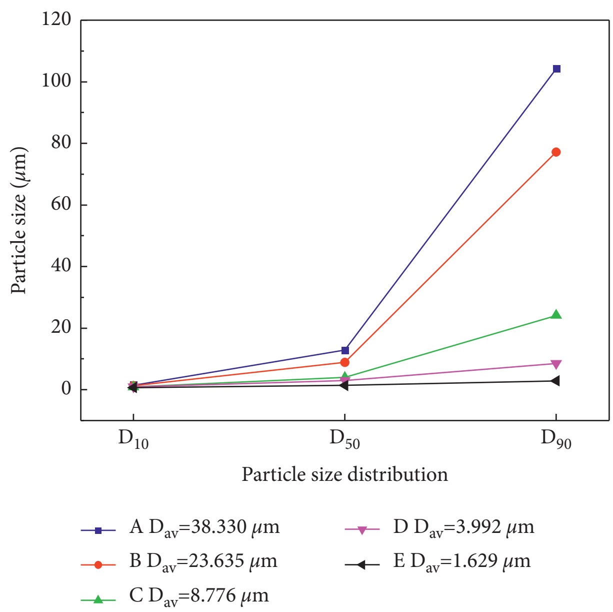


Figure 4: Particle size distribution of PPA with different fineness.

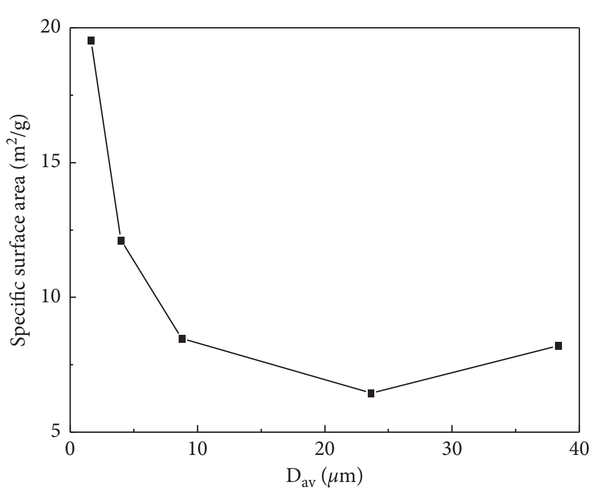


Figure 5: Relationship between average particle size and specific surface area.

the performance of cement concrete, in the following test, all kinds of fine powders were passed through 0.075 mm sieve to reduce the influence of particle size on compatibility, mortar strength, and cement concrete performance [26].

4.2. Compatibility Test Design. Generally, the admixtures with low content, large fluidity, and small fluidity loss have good compatibility with saturation point admixtures. In order to compare and analyze the compatibility of three kinds of fine powder and admixtures, four kinds of cementing materials, namely, pure cement (PC), SA + cement (SAC), PPA + cement (PPAC), and GA + cement (GAC), were selected to test the fluidity of cement paste after the initial time, 30 s, and 60 s, respectively [27–29]. The compatibility of cement and OSWA residue to water reducing agent was studied by choosing the OSWA residue as 20%. The dosage of cementitious material was 300 g, water was 87 g, and W/B was 0.29. The dosage of water reducer selected in the test is 0.4%, 0.6%, 0.8%, 1.0%, 1.2%, 1.4%, and 1.6%, respectively.

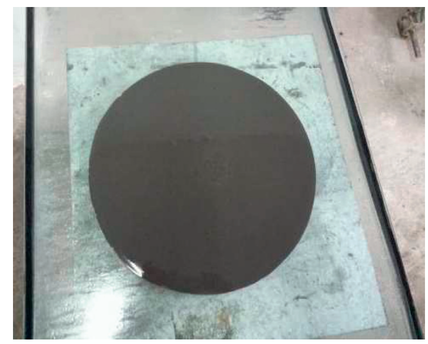


Figure 6: The fluidity of cement paste after 30 s.

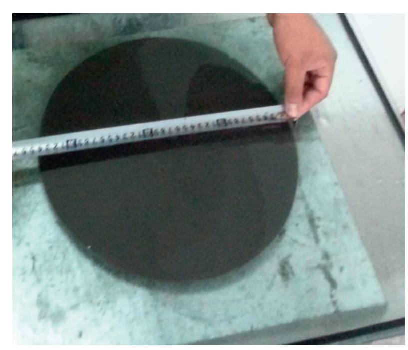


Figure 7: Measurement of net slurry fluidity.

4.3. Test Results and Analysis

4.3.1. Paste Fluidity of Different Cementitious Materials. The changes of different admixtures and initial fluidity, 30-second fluidity, and 60-second fluidity of the four cementing materials are shown in Figure 8.

Table 7: Influence of PPA with different fineness on flexural and compressive strength of cement mortar.

Average particle size (μm)	3-day flexural strength (MPa)	28-day flexural strength (MPa)	3-day compressive strength (MPa)	28-day compressive strength (MPa)
A	3.76	8.54	20.72	38.48
B	5.69	8.22	22.62	41.98
C	5.89	8.34	24.69	51.65
D	6.16	10.49	28.69	46.11
E	7.55	8.67	32.69	56.87
PC	5.84	10.18	31.26	46.12

Table 8: The saturation point of four kinds of cementitious materials.

Time	Content of admixture at saturation point (%)			
	PC	SAC	PPAC	GAC
Initial	0.6	0.8	0.8	0.8
30 s	0.6	0.8	0.8	0.8
60 s	0.6	1.0	0.8	0.8

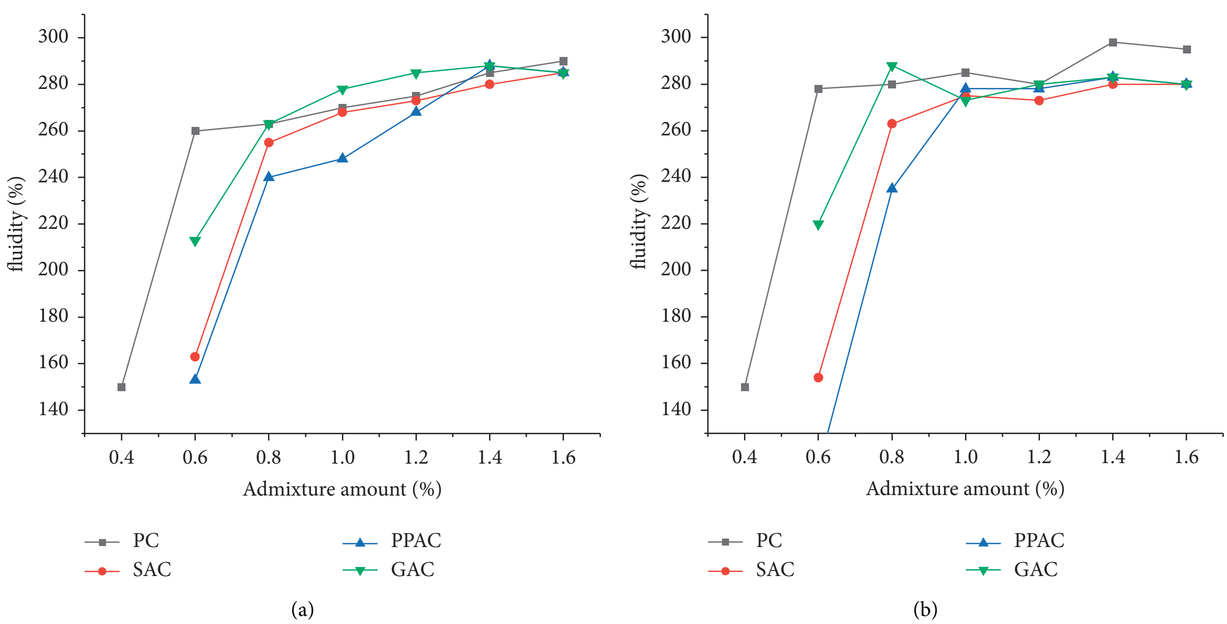


Figure 8: Continued.

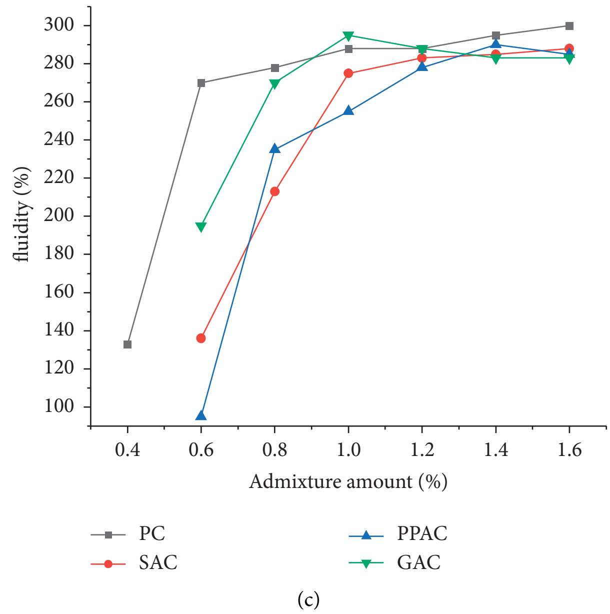


Figure 8: The fluidity change curve of four kinds of cementitious materials with the increase of admixtures. (a) Initial fluidity curve; (b) curve of 30-second fluidity; (c) curve of 60-second fluidity.

The paste fluidity of pure cement slurry in the water reducer content of 0.4% was 150 mm, which basically had no change at the age of 30 s and decreased to 131 mm at the age of 60 s. When the water reducer content of the three kinds of OSWA is 0.4%, due to its large water absorption rate, more water is needed to maintain the flow than that of cement, resulting in insufficient water demand, and the test piece cannot be measured without forming.

Four different gelling materials' fluidity of net cement slurry is increased with the increase of dosage of water reducing agent; this is because the water reducing agent added to the new mix of cement paste can destroy the flocculation structure of gelled material particles, particles dispersed gel material effect, so as to release the flocculation structure of free water and increase water slurry liquid mixture [30]. When the amount of superplasticizer is small, the effect of superplasticizer is more and more obvious with the increase of the amount of superplasticizer. This is because the amount of superplasticizer is enough to evenly distribute in the cement slurry at this time, so it has a greater impact on the liquidity. However, after the dosage of water reducing agent reaches a certain degree (>0.8%), the dispersion effect of the water reducer on the gel material has reached the maximum. If the content of water reducing agent continues to increase, the ability of excess water reducing agent to disperse the gel material particles is sharply reduced, effect on cement paste fluidity increase is small, and the dosage of water reducing agent reached saturation point.

According to the results of saturation point test of each group, the saturation point of PC is 0.6% at the initial stage, which is the lowest. But the saturation point of GAC is 0.8% and not obvious. The saturation point of SAC and PPAC is 0.8%, but the fluidity of SAC is a little larger [31, 32]. Through the above analysis, it can be known that the compatibility of four kinds of cementing materials and admixtures from high to low in the initial stage is PC > GAC > SAC > PPAC. After the initial time 30s, the saturation point of PC is 0.6%, which is still the lowest. After adding oil shale waste slag powder, the three kinds of cementing materials have the same saturation point, all of which are 0.8%, but the fluidity is different. The compatibility between the high fluidity and the admixture is high, so the compatibility of the four kinds of cementing materials after the initial time 30 s from high to low is PC > GAC > SAC > PPAC. After the initial time 60 s, the saturation point of PC is 0.6%, which is still the lowest. The saturation point content of GAC and PPAC is the same, which is 0.8%, and the fluidity of GAC is greater than that of PPAC. The saturation of SAC is the largest, which is 1.0%, so the compatibility of the four cementing materials from high to low after the initial time 60 s is PC > GAC > PPAC > SAG.

According to the above analysis, the addition of waste OSWA decreases the compatibility between cementing materials and admixtures. That is to say, when waste OSWA is added to replace part of cement, more admixtures need to be added to reach its saturation point. According to the results of saturation point test, GA is the best choice to replace cement, and SA is the worst.

4.3.2. Analysis of Loss Rate of Cement Slurry Fluidity. The gradual loss of cement slurry fluidity reflects the influence of admixtures on the fluidity loss of cementitious materials to a certain extent. Under the same other conditions, the good fluidity of slurry will lead to the better flow performance of the whole system. Generally, the loss rate of cement slurry fluidity saturation point after the initial time 60s is recorded as an important assessment index. The smaller the loss rate of fluidity is, the better the compatibility between the admixture and the cementitious material is [33]. Figure 9 shows the cement slurry fluidity loss rates of the four cementing materials when they reach the saturation point after the initial time 60 s.

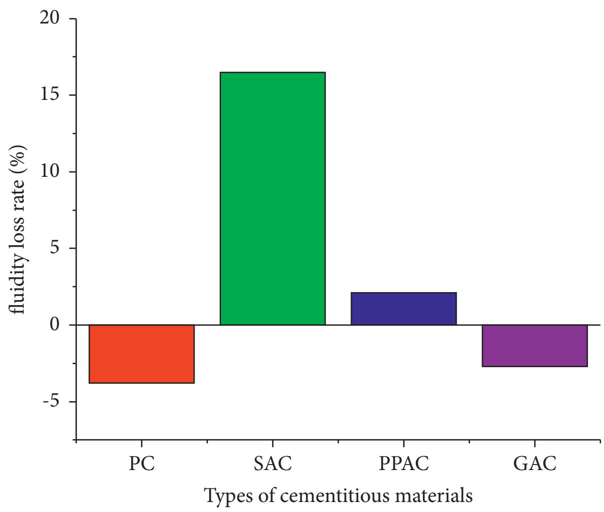


FIGURE 9: Loss rate of net slurry fluidity at saturation point after the initial time 60 s.

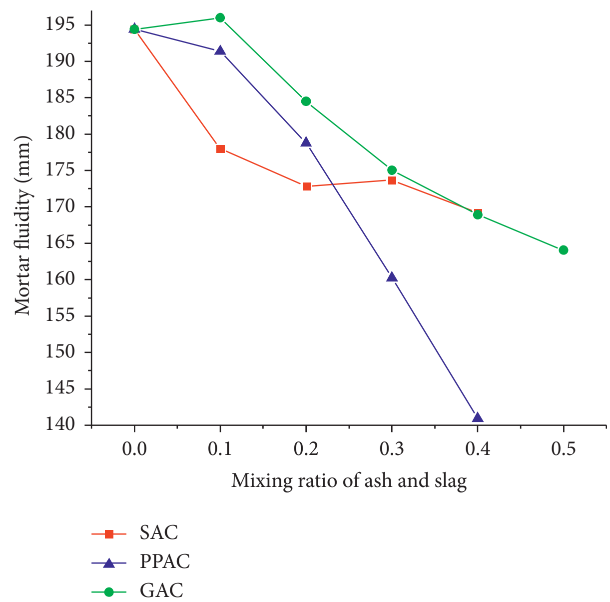


FIGURE 10: Effect of different dosage of waste residue on fluidity of colloidal sand.

From the above saturation point, the four kinds of gelled material fluidity loss rate can be concluded from high to low in turn for SAC, PPAC, GAC, and PC. The fluidity loss of SAC and PPAC rate is positive, indicating that the fluidity becomes worse after the two kinds of waste slag powder are mixed. The fluidity loss of GAC is negative; it shows that the fluidity of GAC is better, which can guarantee the workability of cement concrete and improve the engineering quality of cement concrete structure [34].

5. Characteristics of Cement Mortar Containing OSWA

In order to study the concrete performance of OSWA in place of cement, it is necessary to study the performance of its mortar first. Through the analysis of the fluidity, strength, and brittleness coefficient of cement mortar, various OSWA in place of cement and reasonable mixing amount are proposed.

5.1. Determination of Reasonable Mixing Amount of OSWA instead of Cement. In order to clarify the reasonable mixing amount of OSWA instead of cement, cement mortar tests were carried out on three kinds of OSWA with 10wt%, 20wt%, 30wt%, and 40wt% of cement, and the fluidity, compressive strength, and flexure strength of mortar were measured. Standard sand was used in the test to reduce the influence of sand on the test results [35, 36]. The fluidity of three kinds of OSWA and mortar is shown in Figure 10, and Figure 11 shows the 3-day strength of mortar with different OSWA contents and the 28-day strength of mortar is shown in Figure 12.

As can be seen from Figure 10, the fluidity of mortar sand mixed with waste OSWA showed a decreasing trend with the increase of the added amount. The decrease rate of GAC was slightly slower and showed a linear decrease relationship with the increase of additive amount. There is an inflection point when PPA is about 10%~20%, which indicates that the ash content should not exceed 20%. When the amount of SA is 10%, the fluidity sharply fell; however, with the increase of the dosage, the fluidity tends to be flat, and when the dosage is greater than 30%, the fluidity tends to be GAC. According to the changing trend of fluidity, GA should be selected as the admixture, and its influence on fluidity is relatively small. In general, the dosage should not be greater than 20%.

As can be seen from Figure 11, with the increase of the amount of waste OSWA, the 3-day flexural strength and compressive strength showed an obvious trend of decline. The 3-day compressive strength of cement mortar is 28.37 MPa, and the 3-day flexural strength is 6.3 MPa. From the results, the 3-day flexural strength of the three kinds of waste OSWA is less than that of cement mortar. In terms of 3-day compressive strength, the overall trend of the three admixtures is basically the same, all decreasing with the increase of the content. The 3-day compressive strength of the three kinds of waste OSWA is lower than that of cement mortar, and when the content exceeds 10%, none of them meet the requirements of the specification.

As can be seen from Figure 12, with the increase of SA content, both the 28-day flexural strength and compressive strength showed an obvious trend of decline. The 28-day compressive strength of cement mortar is 55.6 MPa, and the 28-day flexural strength is 9.32 MPa. The 28-day flexural strength of PPAC and GAC is similar, and SAC has the lowest strength. The 28-day flexural strength of the three kinds of OSWA is less than that of PC. From the results of 28-day compressive strength, the three kinds of OSWA all showed a downward trend, and the compressive strength of GAC was the highest among the three kinds of waste OSWA.

5.2. The Characteristics of OSWA in Place of Cement. In order to clarify the feasibility of the three kinds of waste slag

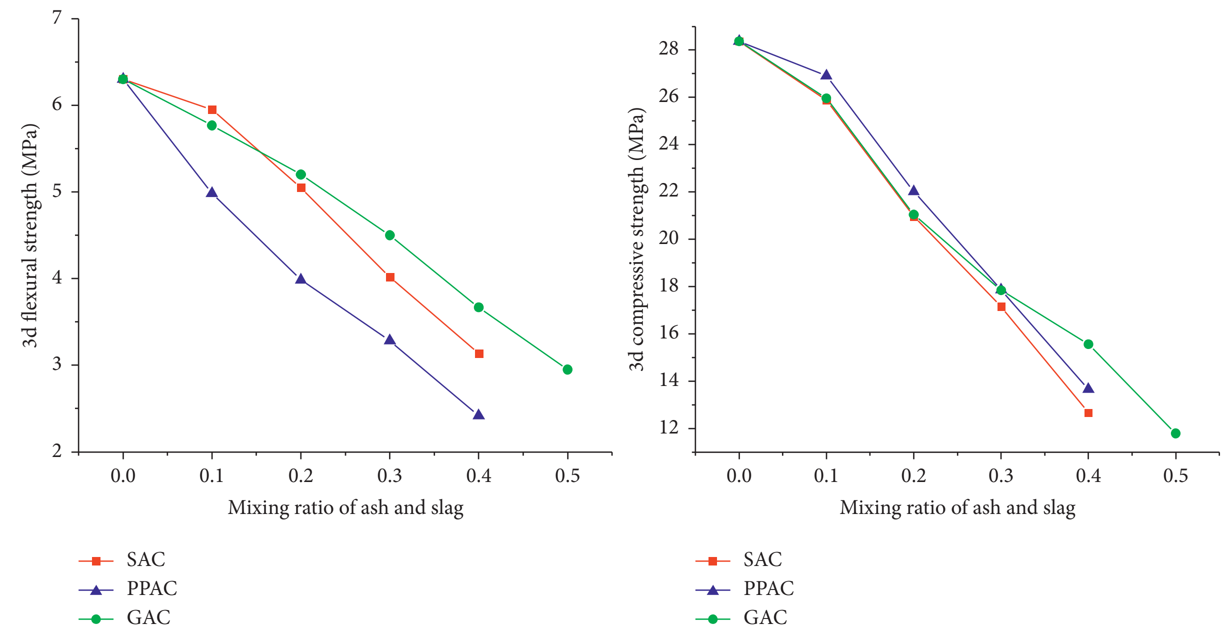


Figure 11: 3-day strength comparison diagram of mortar with different dosage of oil shale waste residue powder.

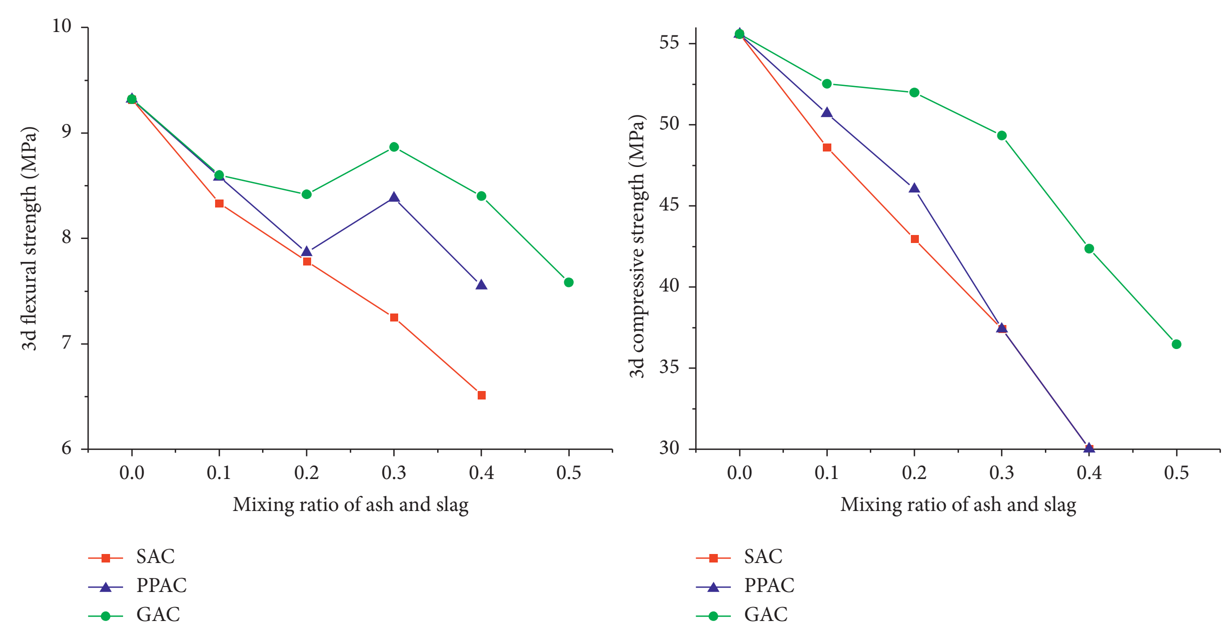


Figure 12: The 28-day strength comparison diagram of mortar with different dosage of OSWA.

powder replacing cement, ordinary river sand was selected to do mortar test. The amount of the three kinds of waste slag powder replacing cement was 10%, 20%, and 30%, respectively. The flexural and compressive strength and brittleness coefficient of the three kinds of OSWA were investigated with the indexes at the age of 7 days, 28 days, 60 days, and 90 days to verify the long-term strength and toughness of the three kinds of OSWA (Figure 13).

The ordinary river sand was screened and tested with the same grade mixture. The mass of standard sand in each group was 1350 ± 2 g. The specific gradation is shown in Table 2. The gradation meets the requirements of sand in the required specification. In the test, 10wt% (45 g), 20wt% (90 g), and 30wt% (135 g) of the three kinds of OSWA were, respectively, used to replace part of cement, and each group of specimens was numbered. The number of gelled material specimens was shown in Table 9, and the number of pure cement was PC. The mass ratio of cementitious material, water, and sand is 450 : 225 : 1350.

5.2.1. Flexural Strength. The flexural strength of OSWA at different ages is shown in Figure 14(a).

Figure 13: Test of mortar with different dosage of three kinds of OSWA.

Table 9: The number of gelled material specimens.

Species	Dosage (%)	Number
SAC	10	SAC1
	20	SAC2
	30	SAC3
PPAC	10	PPAC1
	20	PPAC2
	30	PPAC3
GAC	10	GAC1
	20	GAC2
	30	GAC3

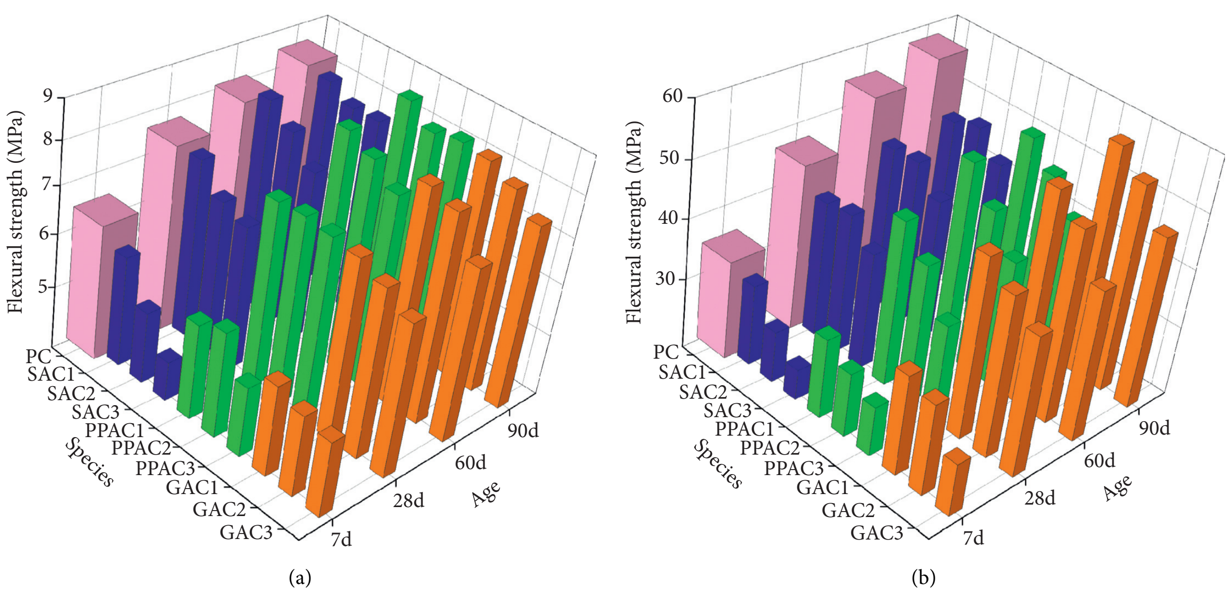
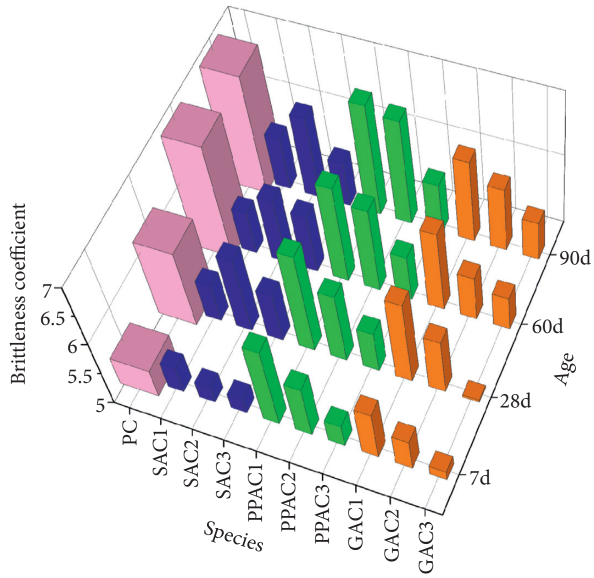


Figure 14: Continued.



(c)

Figure 14: The characteristics of OSWA in place of cement. (a) Flexural strength; (b) compressive strength; (c) brittleness coefficient.

As can be seen from Figure 14(a), compared with PC, SAC only has a higher 60-day flexural strength of SAC1 than that of PC, while other conditions are all lower than those of PC, indicating that SA has no obvious effect on improving the flexural strength of cement mixture. In the three 7-day tests of PPAC, the flexural strength of PPAC is relatively poor compared with that of PC, but with the growth of age, the flexural strength of PPAC increases greatly, while the 28-day flexural strength is not different from that of PC [37]. The 60-day flexural strength of PPAC1 and PPAC2 is slightly higher than that of PC, which indicates that PPA has a certain effect on changing the flexural strength of cement mixture and is stronger than that of pure cement in later stage. The 7-day flexural strength of GAC1 and GAC2 is much lower than that of PC, but with the increase of age, the flexural strength of GAC1 and GAC2 is not much different from that of PC [38]. The 60-day flexural strength of GAC1 and GAC2 is higher than that of pure cement, while the flexural strength of GAC3 is always lower than that of PC, indicating that GA has a good effect on changing the flexural strength of cement mixture. However, when the dosage is too large, the flexural strength of the mixture decreases with the increase of the dosage.

5.2.2. Compressive Strength. The compressive strength of OSWA at different ages is shown in Figure 14(b). It can be seen from Figure 14(b) that, compared with PC, the compressive strength of SAC at different ages with all contents is far less than that of PC, which indicates that it cannot improve the compressive strength of the specimen as cement mixture. Compared with PC, the compressive strength of all the content of PPAC is less than that of PC at different ages; only PPAC1 is less different than PC. With the increase of the content of PPA, the compressive strength of PPAC decreases, indicating that it cannot improve the compressive strength of specimens. Compared with GAC and PC, the compressive strength of GAC1 is higher than that of PC, and the compressive strength of GAC2 is lower than that of PC, but the difference is not significant. The compressive strength of GAC3 is far lower than that of PC, indicating that the compressive strength can be improved by adding GA appropriately when it is used as the additive of mixture [29, 39].

5.2.3. Brittleness Coefficient. Brittleness coefficient can reflect the crack resistance of mortar and concrete [40, 41]. The ratio of compressive strength to flexural strength at the same age is used to express the brittleness coefficient. The test results are shown in Figure 14(c).

As can be seen from Figure 14(c), the 7-day brittleness coefficient of SAC shows a decreasing trend, and the remaining ages first increase and then decrease with the increase of the content. It initially indicates that the reasonable content of SA should be no more than 20%. The brittleness coefficient of PPAC and GAC decreased significantly with the increase of the mixing amount and was far lower than that of PC, indicating that PPAC and GAC could effectively improve the crack resistance of the test block. If the strength met the requirements, the replacement amount could be appropriately increased.

Through the analysis of flexural strength, it can be seen that PPA and GA have a good effect on changing the flexural strength of cement mixture, but the mixing amount should not exceed 20%. Through the analysis of compressive strength, it is found that the proper addition of GA as the admixture can improve the compressive strength, but the content of GA should not exceed 30%, and the compressive strength of GA is far lower than that of PC when the content of GA is 30%. Through the comparison of brittleness coefficient, it is found that PPA and GA can effectively improve the crack resistance of cement. To sum up, PPA and GA have good effects as admixtures, which can improve strength and crack resistance. Then, these two OSWA are used to conduct performance tests of cement concrete.

5.2.4. Micromechanism Analysis. The products formed after the hydration of cement are closely bound to each other, but the existence of tiny pores can also be seen, mainly the pores left after the free water participates in the hydration reaction. SEM was used to observe the microscopic morphology of PC, GAC, and SAC, and the results are shown in Figures 15–17.

The microscopic morphology of GAC1 and PC is basically the same. It can be seen from Figure 16(a) that only a small amount of GA with large particle size exists in the slurry, and these particles are evenly dispersed in the material to form large polycrystals with high stress and good mechanical properties. Due to the small amount of GA, no large amount of oil shale GA particles was observed, and no obvious defects existed. GA combined well with cementing materials. However, as shown in Figure 16(b), with the increase of GA, the interface of GA particles increases. Because the binding force between GA particles and cementitious materials is relatively weak, the damage first occurs from the interface between GA particles and cementitious materials, which means that the cement is more likely to be destroyed under the external action. This explains why the mechanical properties of oil shale powder decrease gradually with the increase of GA.

Figure 17 shows the microscopic morphology of SAC1. At low multiples, there is little difference between SAC1 and PC, but at high multiples, it can be seen that SA particles are surrounded by hydration products. There is about 1% oil content in SA, and its LOI is larger than that of PPA and GA. It is obvious from the figure that SA particles exist in crystallization good slab $Ca(OH)_2$ crystal. There are interfaces between SA and cement hydration products, and these interfaces are weak areas. When subjected to external forces, these interfaces will be destroyed first. Therefore, the mechanical properties of cement mortar will be greatly reduced if the amount of SA is too large.

6. Performances of Cement Concrete Containing OSWA

6.1. Test Design. There are many factors affecting the strength and workability of concrete. The design and analysis are carried out through orthogonal test design, and the orthogonal test L9 (34) flexural with four factors and three levels is selected. The factors and level values of the orthogonal test are shown in Table 10.

6.2. Test Analysis of GAC

6.2.1. Range Analysis. See Figure 18 for the difference between the dosage of water reducer and the compressive strength of GAC.

It can be seen from Figure 18(a) that the dosage of water reducer increases significantly with the increase of the mixing amount of GA, while W/B and the total amount of glue material increase, leading to the decrease of the dosage of water reducer. With the increase of sand ratio, the dosage of water reducer first increases and then decreases. According to the calculation results of range, it can be seen that the dosage of GA has the greatest effect on the dosage of water reducer. In order to meet the requirements of construction workability, it is necessary to adopt a lower dosage of GA, a higher water-binder ratio, a lower sand rate, and a higher total amount of rubber material, which can effectively reduce the dosage of water reducer and meet the requirements of construction workability.

It can be seen from Figure 18(b) that the 7-day strength decreased significantly with the increase of W/B and decreased slightly with the increase of sand ratio. The 7-day strength increased slightly with the increase of the total amount of rubber material, and the 7-day strength increased first and then decreased significantly with the increase of the dosage of GA. According to the range calculation, W/B has the greatest influence on the 7-day strength, followed by the mixing amount of GA. A lower W/B, a lower amount of GA, a lower sand rate, and a moderate total amount of rubber material should be used to improve the 7-day strength.

As can be seen from Figure 18(c), the 28-day compressive strength of the test block increases with the increase of the amount of cementitious material. With the increase of the content of GA, the compressive strength of the test block increases first and then decreases, indicating that GA can effectively improve the strength of the test block. However, when the content of GA is too large, the compressive strength of the test block begins to decrease. With the increase of W/B, the compressive strength of the test block decreases, indicating that the low W/B is conducive to the condensation of the test block. With the increase of sand percentage, the compressive strength of the test block increases all the time, indicating that increasing the sand percentage can improve the compressive strength of the test block in the later period.

Range analysis shows that a series of measures can be taken to improve the early and late strength of cement concrete:

(a) The early strength of concrete can be improved by decreasing W/B and moderately reducing the mixing amount of GA
(b) The late strength of concrete can be improved by decreasing W/B and appropriately increasing the dosage of cementitious materials
(c) Adding GA can improve the compressive strength of cement concrete, and the effect is most obvious when the content is 10%

6.2.2. Analysis of Variance. The results of variance analysis of GA are shown in Table 11.

It can be seen from the variance calculation results that when the addition of superplasticizer is used as the

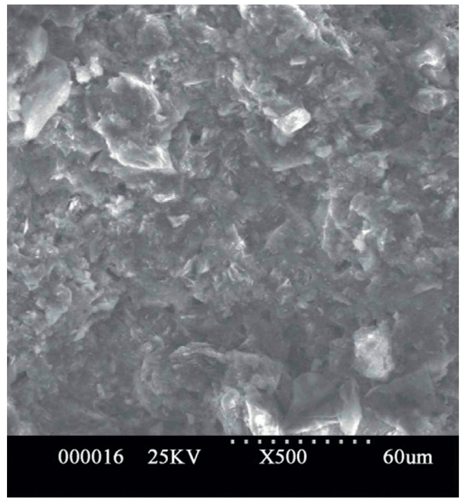


Figure 15: Micromorphology of PC.

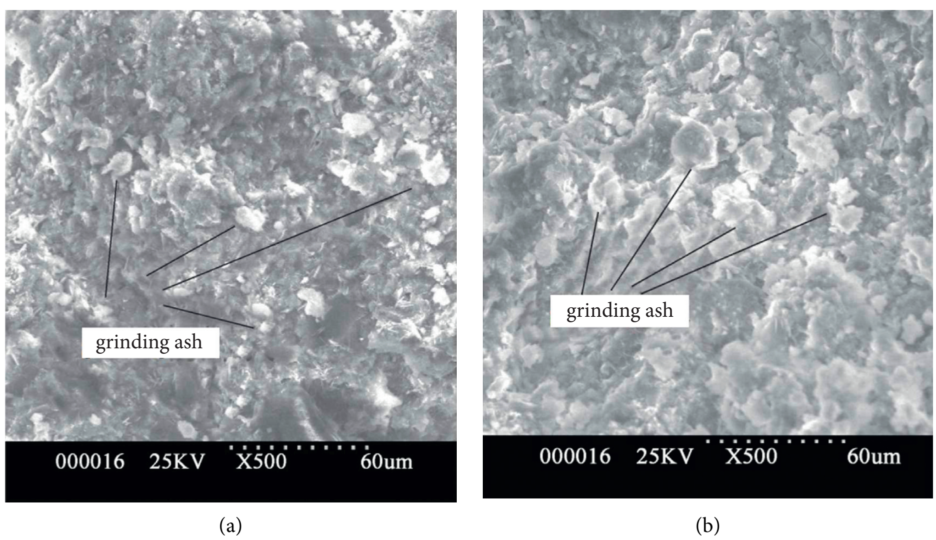


Figure 16: Micromorphology of GAC. (a) GAC1; (b) GAC3.

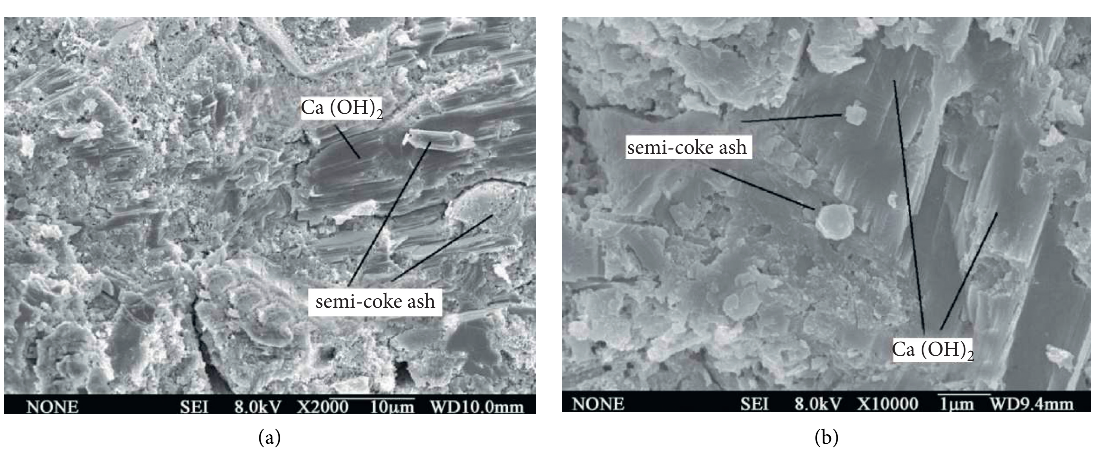
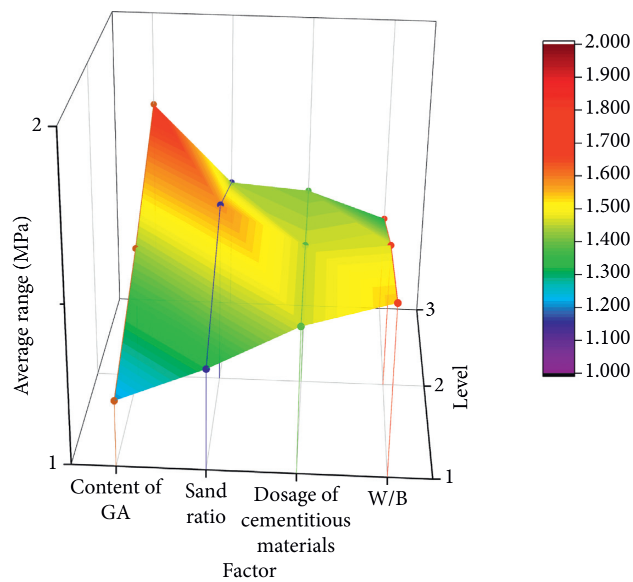


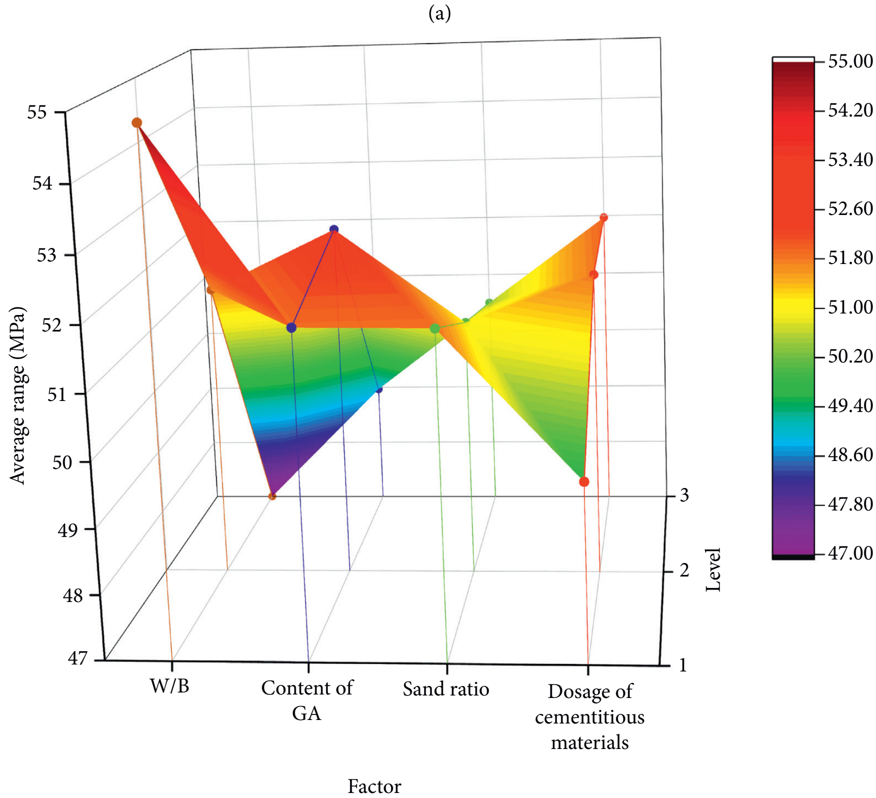
Figure 17: Microstructure of SAC1. (a) X2000; (b) X10000.

Table 10: Factor-level table.

Level	Factor			
	Dosage of cementitious materials (kg/m^3)	Content of waste slag powder	W/B	Sand ratio
1	410	0	0.32	36
2	440	10%	0.34	38
3	470	20%	0.36	40

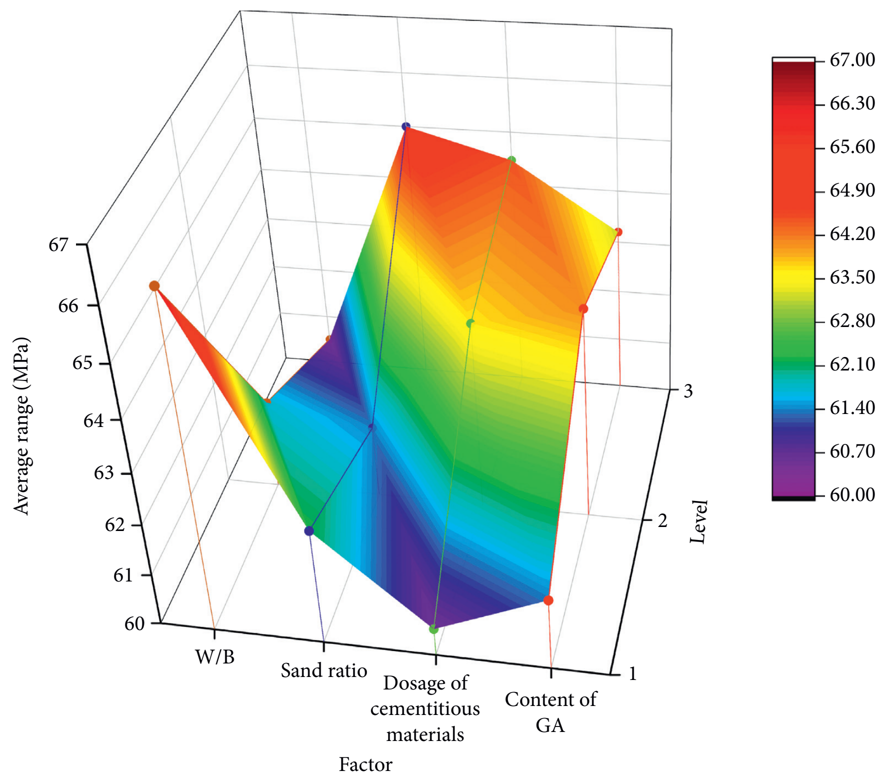


(a)



(b)

Figure 18: Continued.



(c)

Figure 18: Diagram of mixing amount of water reducer and compressive strength of GAC. (a) The dosage of water reducing agent range; (b) compressive strength at 7 days; (c) compressive strength at 28 d.

Table 11: Results of variance analysis of GA.

Factors		Dosage of cementitious materials	Content of GA	W/B	Sand ratio	Error
Water reducing dose	Sum of squares of deviation	0.003	0.361	0.069	0.102	0.00
	F test	1.000	120.333	23.000	34.000	
	Statistical significance		**	*	*	
7-day compressive strength	Sum of squares of deviation	9.576	22.162	93.069	2.976	2.98
	F test	3.218	7.447	31.273	1.000	
	Statistical significance			*		
28-day compressive strength	Sum of squares of deviation	25.776	11.402	58.109	21.309	11.40
	F test	2.261	1.000	5.096	1.869	
	Statistical significance					

comparison index, the degree of influence of factors is as follows: content of GA > sand ratio > W/B > dosage of cementitious materials, and the amount of GA has the greatest influence on the addition of superplasticizer [42]. That is to say, if using GA instead of cement, with the increase of mixing amount, the need to increase the dosage of water reduction increases rapidly. The variance analysis of the 7-day and 28-day compressive strength of GAC shows that the influence of W/B on concrete strength is significant; in the case that the amount of GA is not much, the 28-day strength of cement concrete and long age strength impact is not significant; with considering dosage of water reducing agent, its reasonable substitute cement content should be 10–15%.

6.3. Test Analysis of PPAC

6.3.1. Range Analysis. See Figure 19 for the range of water reducer and compressive strength of PPAC.

Range analysis of the PPA water reducing agent adding quantity can draw the following conclusion:

In the calculation results of water reducer dosage range, the range value is content of PPA > sand ratio > W/B > dosage of cementitious materials [43]. The smaller range of each factor should be taken, so as to reduce the addition amount of water reducer. If PPA is used to replace cement with concrete, and the construction workability requirements are met to ensure the construction quality, the replacement amount of PPA and sand ratio should be reduced,

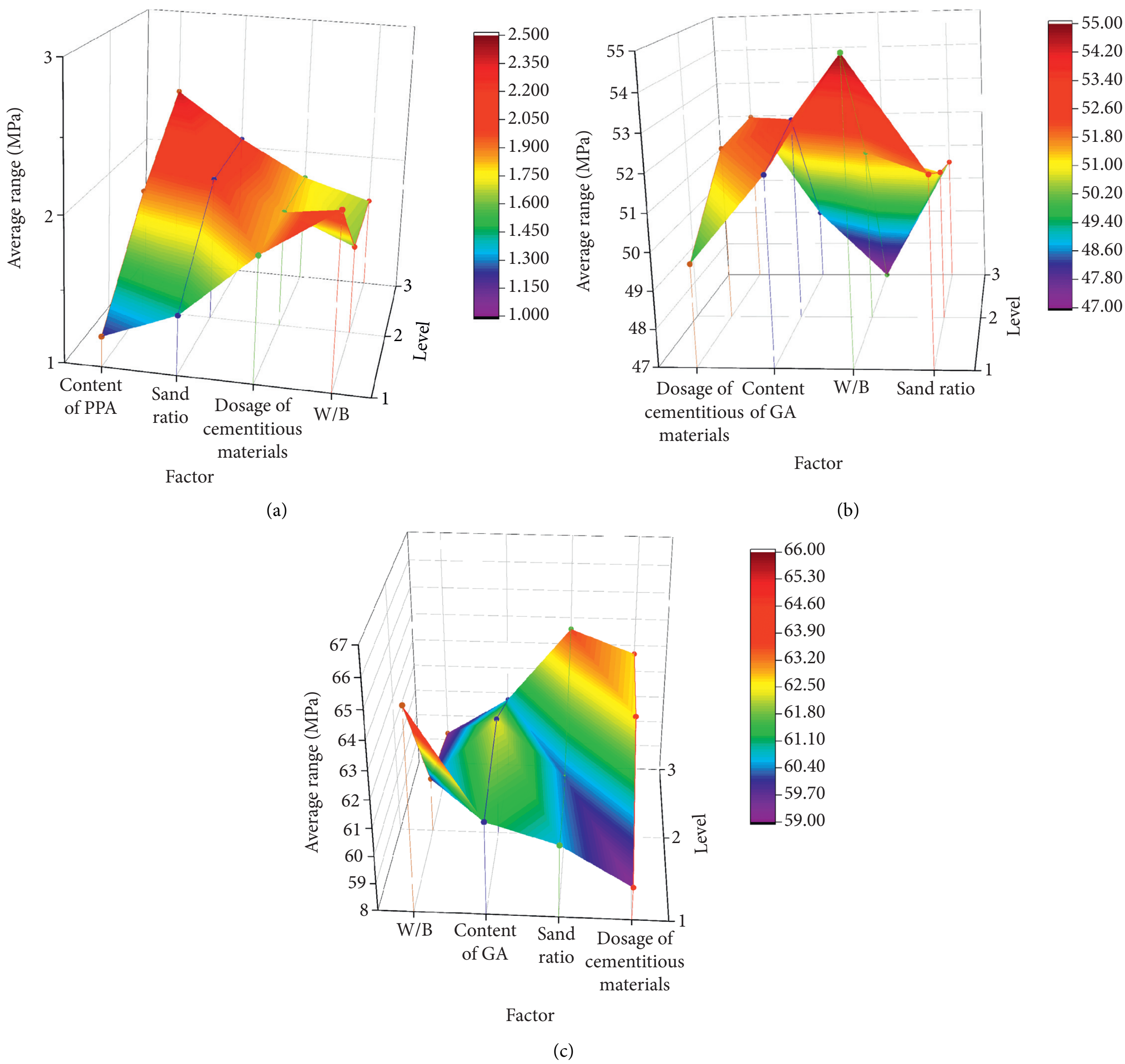


FIGURE 19: Diagram of mixing amount of water reducer and compressive strength of PPAC. (a) The dosage of water reducing agent range; (b) the 7-day compressive strength; (c) the 28-day compressive strength.

and W/B and the total amount of cementitious materials should be increased. For example, the combination of 3 levels of plastic material total, 2 levels of PPA content, 2 levels of W/C, and 1 level of sand rate can add less water reducing agent and meet the construction workability.

At the age of 7 days, with the increase of cementitious material content, the compressive strength of the test block first increases and then decreases. With the increase of PPA, the compressive strength of the test block first increases and then decreases, indicating that PPA can effectively improve the strength of the test block, but the content should not be too large, and the strength drops sharply when the content exceeds 10%. With the increase of W/B, the compressive strength of the test block decreases, indicating that the low W/B is beneficial to improve the compressive strength of cement concrete. With the increase of sand percentage, the strength of the test block decreases first and then increases, but when the sand percentage exceeds 38, the strength increase is not obvious.

At the age of 28 days, the compressive strength of the test block increases with the increase of the dosage of cementitious materials. With the increase of the content of PPA, the compressive strength of the test block increases first and then decreases, indicating that the PPA can effectively improve the strength of the test block. However, when the mixing amount is too large, the condensation effect decreases, and the compressive strength of the test block begins to decrease. With the increase of W/B, the compressive strength of the test block decreases, indicating that the low W/B is conducive to the condensation of the test block. With the increase of sand percentage, the compressive strength of the test block decreases first and then increases, and the high

Table 12: Results of variance analysis of PPA.

Factors		Dosage of cementitious materials	Content of PPA	W/B	Sand ratio	Error
Water reducing dose	Sum of squares of deviation	0.005	2.105	0.617	0.796	0.01
	F test	1.000	421.000	123.400	159.200	
	Statistical significance		**	**	**	
7-day compressive strength	Sum of squares of deviation	7.709	15.369	57.509	3.236	3.24
	F test	2.382	4.749	17.772	1.000	
	Statistical significance			(*)		
28-day compressive strength	Sum of squares of deviation	23.582	4.069	61.749	19.629	4.07
	F test	5.796	1.000	15.175	4.824	
	Statistical significance			(*)		

sand percentage has a great effect on the compressive strength of the test block in the later period.

6.3.2. Analysis of Variance. See Table 12 for the calculation results of variance analysis of PPAC.

It can be seen from the variance calculation results that the influence degree of these factors on the incorporation amount of water reducing agent is PPA > sand ratio > W/B > dosage of cementitious materials successively. The amount of GA mixing has the greatest influence on the amount of water reducing agent. That is to say, if GA is used instead of cement, with the increase of GA, the water reducer needs to increase rapidly.

Variance analysis of the 7-day and 28-day compressive strength of PPAC shows that W/B has certain influence on the strength of cement concrete. In the case of small amount of PPA, there is little influence on the 28-day strength of cement concrete and even the strength at long age. This needs to be considered comprehensively with the amount of water reducing agent; the reasonable amount of replacement cement should be 10%.

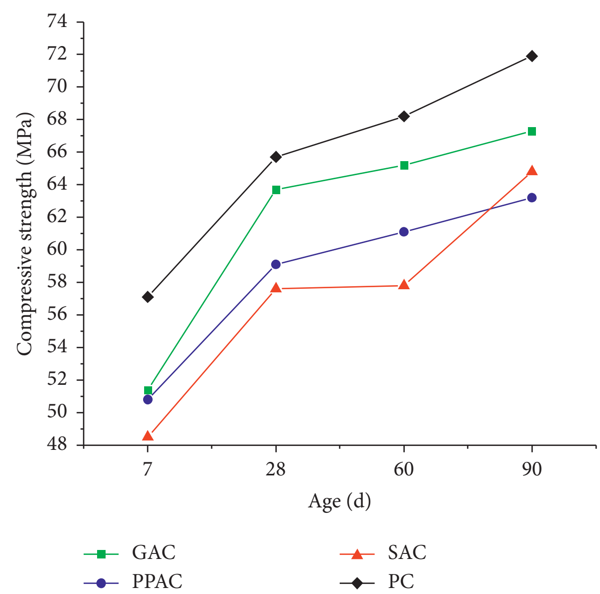


Figure 20: The long age compressive strength of oil shale cement slag concrete.

6.4. Long Age Compressive Strength. According to the results of the comparative test, the optimal mix ratio is 470 g of cementing material, 10% of cement replaced by OSWA, 0.34 of W/B, and 36 of sand ratio. The compressive strength of the specimens formed with three kinds of OSWA replacing 10% cement was measured at the age of 7 days, 28 days, 60 days, and 90 days. The long-term compressive strength of cement concrete mixed with OSWA was analyzed. The specific test results are shown in Figure 20.

6.5. Antifreeze Performance. The frost resistance test of concrete was carried out according to Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing in Test Methods of Cement and Concrete for Highway Engineering (JTG E30-2005). Specimen specifications are prisms of 100 mm × 100 mm × 400 mm, with 3 pieces in each group.

The mixture ratio in the previous section was selected, that is, the total amount of cementitious material was 470 g, OSWA substituted for cement was 10%, W/B was 0.34, and the sand ratio was 36. Three kinds of OSWA were molded separately in place of 10% cement to measure the 28-day compressive strength of the specimens and analyze the frost resistance of cement concrete mixed with OSWA. See Figure 21 for 250 antifreeze tests in which the three kinds of OSWA replaced cement and PC, with rapid freeze-thaw test results of 4 groups of cement concrete specimens, including the relative dynamic elasticity modulus of concrete, mass loss, and relative index of durability as shown in Figure 22 and Table 13.

It can be seen from the table that the frost resistance of pure cement concrete is higher than that of cement concrete mixed with OSWA, which can reach F300. The frost resistance of cement concrete mixed with GA and PPA can reach F250, while the frost resistance of cement concrete mixed with SA can barely reach F250 [44]. It indicates that the cement concrete with OSWA should be made as far as possible in the position with low frost resistance grade such as concrete pile.

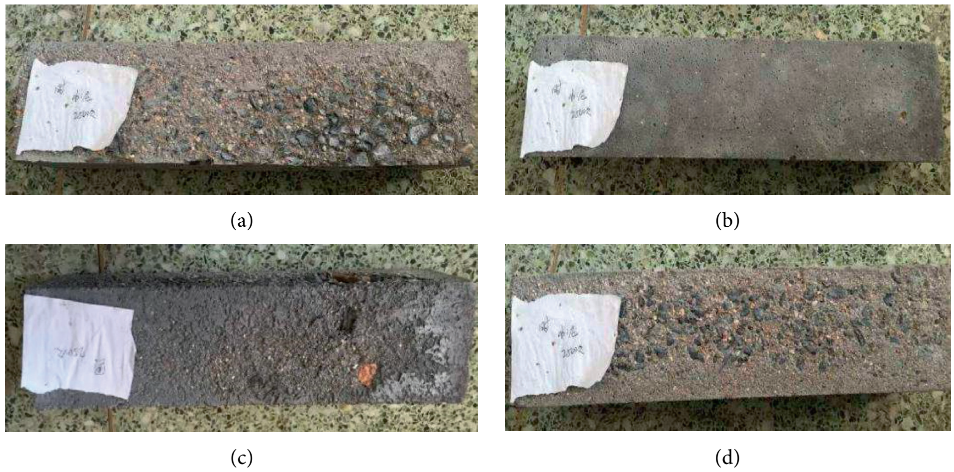


Figure 21: Tests on freezing resistance of three kinds of OSWA instead of cement and PC. (a) PPAC. (b) PC. (c) SAC. (d) GAC.

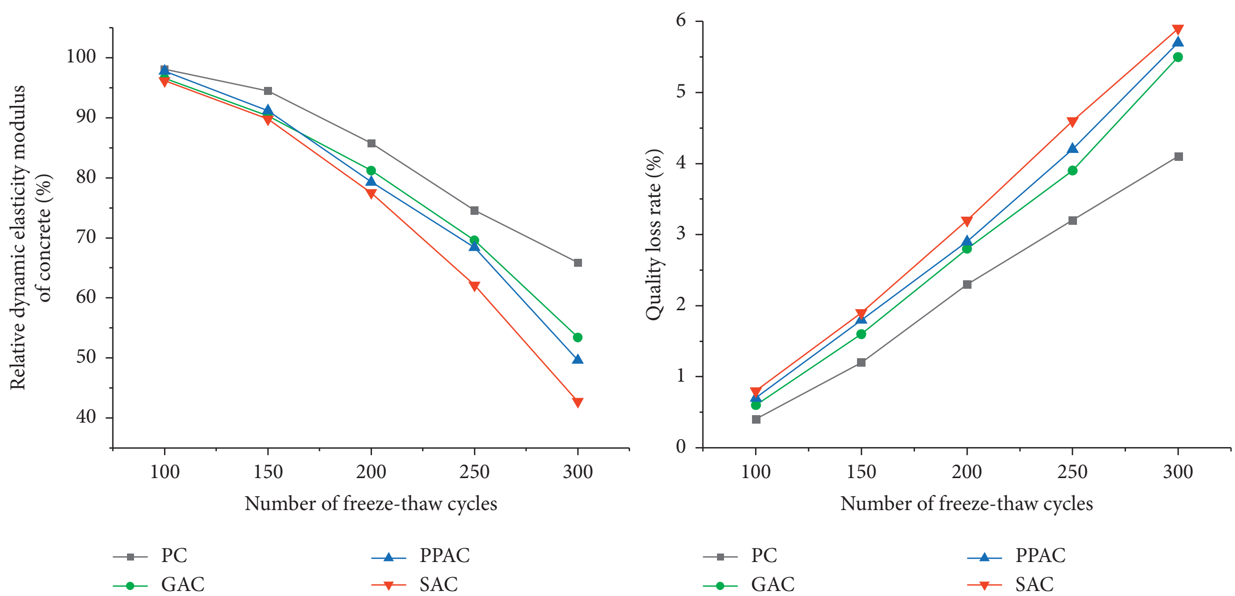


Figure 22: Relative dynamic modulus and mass loss rate of three kinds of OSWA in place of cement.

Table 13: Relative durability index.

Specimen number	Number of freeze-thaw cycles	Relative index of durability (%)
PC	F300	65.9
GAC	F250	58.0
PPAC	F250	57.0
GAC	F250	51.8

7. Conclusions

In this paper, through the fluidity test of net slurry, mortar strength test, and cement concrete strength and durability test analysis, the following conclusions are drawn:

(1) The fineness of oil shale waste slag has a significant effect on the strength of cement mortar. When the average particle size is less than 10 μm, the strength of cement mortar can be increased by 10%~20%, and the fineness of fine powder can be guaranteed when the application is appropriate.

(2) With the addition of oil shale ash, the saturation point of cementing material increases from 0.6% to 0.8%, and the fluidity loss is nearly 30%. Therefore, appropriate admixtures should be considered to increase workability of cement concrete.

(3) Through the analysis of orthogonal test of oil shale fine powder cement concrete, the water-binder ratio and the amount of water reducing agent have significant influence on the strength of cement concrete.

(4) The strength and frost resistance of cement concrete decrease with the increase of oil shale waste slag content, but the brittleness coefficient can be increased by about 20%; that is, the crack resistance of cement concrete can be improved, and the fine powder content of oil shale waste slag should be controlled within 10%~20%.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] W. Salah Alaloul, M. Al Salaheen, A. B. Malkawi, K. Alzubi, A. M. Al-Sabaeei, and M. A. Musarat, "Utilizing of oil shale ash as a construction material: a systematic review," *Construction and Building Materials*, vol. 299, Article ID 123844, 2021.

[2] C. Zou, Z. Yang, J. Cui et al., "Formation mechanism, geological characteristics and development strategy of nonmarine shale oil in China," *Petroleum Exploration and Development*, vol. 40, no. 1, pp. 15–27, 2013.

[3] W. Wu, X. He, C. Wu, J. He, and W. Yang, "Fracture performance of GFRP-RC beams with working cracks in alkaline environment for eight years," *Construction and Building Materials*, vol. 299, Article ID 123757, 2021.

[4] H. H. Abdullah, M. A. Shahin, and M. L. Walske, "Geomechanical behavior of clay soils stabilized at ambient temperature with fly-ash geopolymer-incorporated granulated slag," *Soils and Foundations*, vol. 59, no. 6, pp. 1906–1920, 2019.

[5] G. J. Ji, C. M. Yang, and S. C. Gan, "Production of portland cement with oil shale ash," *Journal of Jilin University (Earth Science Edition)*, vol. 42, no. 04, pp. 1173–1178, 2012.

[6] S. J. Wang and F. Luo, "Study on compound activation of oil shale ash as cement admixture," *Fly Ash Comprehensive Utilization*, vol. 3, no. 3, pp. 0003–0006, 2018.

[7] Z. X. Wang, X. L. Wang, and C. L. Shi, "Mortar test on cement mixing material with oil shale ash," *Journal of Beihua University (Natural Science)*, vol. 17, no. 04, pp. 545–548, 2016.

[8] H. Al-Hamaiedh, O. Maaitah, and S. Mahadin, "Using oil shale ash in concrete binder," *Electronic Journal of Geotechnical Engineering*, vol. 15, 2010.

[9] S. H. Aljbour, "Production of ceramics from waste glass and Jordanian oil shale ash," *Oil Shale*, vol. 33, no. 3, pp. 260–271, 2016.

[10] M. Uibu, P. Somelar, L.-M. Raado et al., "Oil shale ash based backfilling concrete - strength development, mineral transformations and leachability," *Construction and Building Materials*, vol. 102, pp. 620–630, 2016.

[11] R. Chen, G. Cai, X. Dong, D. Mi, A. J. Puppala, and W. Duan, "Mechanical properties and micro-mechanism of loess roadbed filling using by-product red mud as a partial alternative," *Construction and Building Materials*, vol. 216, pp. 188–201, 2019.

[12] A. Arulrajah, E. Yaghoubi, M. Imteaz, and S. Horpibulsuk, "Recycled waste foundry sand as a sustainable subgrade fill and pipe-bedding construction material: engineering and environmental evaluation," *Sustainable Cities and Society*, vol. 28, pp. 343–349, 2017.

[13] L. Vallner, O. Gavrilova, and R. Vilu, "Environmental risks and problems of the optimal management of an oil shale semi-coke and ash landfill in Kohtla-Järve, Estonia," *The Science of the Total Environment*, vol. 524-525, pp. 400–415, 2015.

[14] L. Vallner, O. Gavrilova, and R. Vilu, "Environmental risks and problems of the optimal management of an oil shale semi-coke and ash landfill in Kohtla-Järve, Estonia," *The Science of the Total Environment*, vol. 524-525, pp. 400–415, 2015.

[15] H. Wei, Y. Zhang, J. Cui, L. Han, and Z. Li, "Engineering and environmental evaluation of silty clay modified by waste fly ash and oil shale ash as a road subgrade material," *Construction and Building Materials*, vol. 196, pp. 204–213, 2019.

[16] X. Han, I. Kulaots, X. Jiang, and E. M. Suuberg, "Review of oil shale semicoke and its combustion utilization," *Fuel*, vol. 126, no. 12, pp. 143–161, 2014.

[17] H.-p. Liu, W.-x. Liang, H. Qin, and Q. Wang, "Synergy in co-combustion of oil shale semi-coke with torrefied cornstalk," *Applied Thermal Engineering*, vol. 109, pp. 653–662, 2016.

[18] L.-M. Raado, T. Hain, E. Liisma, and R. Kuusik, "Composition and properties of oil shale ash concrete," *Oil Shale*, vol. 31, no. 2, pp. 147–160, 2014.

[19] J. TG. H20, *Highway Performance Assessment Standard*, Ministry of Transport of the People's Republic of China, Beijing, China, 2007.

[20] J. TG. T3650, *Technical Specification for Construction of Highway Bridge and Culvert*, Ministry of Transport of the People's Republic of China, Beijing, China, 2020.

[21] L.-M. Raado, T. Hain, E. Liisma, and R. Kuusik, "Composition and properties of oil shale ash concrete," *Oil Shale*, vol. 31, no. 2, p. 147, 2014.

[22] J. TG. E60, *Field Test Methods of Subgrade and Pavement for Highway Engineering*, Ministry of Transport of the People's Republic of China, Beijing, China, 2008.

[23] S. Dimter, T. Rukavina, and K. Minažek, "Estimation of elastic properties of fly ash-stabilized mixes using nondestructive evaluation methods," *Construction and Building Materials*, vol. 102, pp. 505–514, 2016.

[24] Y. Zhao, J. Gao, Z. Xu, S. Li, X. Luo, and G. Chen, "Combined effect of slag and clay brick powder on the hydration of blended cement," *Construction and Building Materials*, vol. 299, Article ID 123996, 2021.

[25] S. Wang, X. Jiang, X. Han, and J. Tong, "Investigation of Chinese oil shale resources comprehensive utilization performance," *Energy*, vol. 42, no. 1, pp. 224–232, 2012.

[26] D. Lv, Z. Li, H. Liu et al., "The characteristics of coal and oil shale in the coastal sea areas of huangxian coalfield, eastern China," *Oil Shale*, vol. 32, no. 3, pp. 204–217, 2015.

[27] L.-M. Raado, T. Hain, E. Liisma, and R. Kuusik, "Composition and properties of oil shale ash concrete," *Oil Shale*, vol. 31, no. 2, pp. 147–160, 2014.

[28] S. Nov, H. Cohen, and Y. Knop, "Treated oil shale ashes as a substitute for natural aggregates," *Sand and Cement in Concrete Israel Journal of Chemistry*, vol. 60, no. 5-6, pp. 638–643, 2020.

[29] M. M. Radwan, L. M. Farag, S. A. Abo-El-Enein, and H. K. Abd El-Hamid, "Alkali activation of blended cements containing oil shale ash," *Construction and Building Materials*, vol. 40, pp. 367–377, 2013.

[30] J. T. G. E42, *Test Methods of Aggregate for Highway Engineering*, Ministry of Transport of the People's Republic of China, Beijing, 2005.

[31] X. Liu, X. Zhang, H. Wang, and B. Jiang, "Laboratory testing and analysis of dynamic and static resilient modulus of subgrade soil under various influencing factors," *Construction and Building Materials*, vol. 195, pp. 178–186, 2019.

[32] Y. Yang, X. Lu, and Q. Wang, "Investigation on the co-combustion of low calorific oil shale and its semi-coke by using thermogravimetric analysis," *Energy Conversion and Management*, vol. 136, pp. 99–107, 2017.

[33] Q. Wang, J. R. Bai, J. X. Ge, Y. Z. Wei, and S. Y. Li, "Geochemistry of rare earth and other trace elements in Chinese oil shale," *Oil Shale*, vol. 31, no. 3, pp. 266–277, 2014.

[34] S. Deng, Z. Wang, Q. Gu, F. Meng, J. Li, and H. Wang, "Extracting hydrocarbons from huadian oil shale by subcritical water," *Fuel Processing Technology*, vol. 92, no. 5, pp. 1062–1067, 2011.

[35] J. Bai, Z. Bai, Q. Wang, and S. Li, "Process simulation of oil shale comprehensive utilization system based on Huadiantype retorting technique," *Oil Shale*, vol. 32, no. 1, pp. 66–81, 2015.

[36] L. Zhang, X. Zhang, S. Li, and Q. Wang, "Comprehensive utilization of oil shale and prospect analysis," *Energy Procedia*, vol. 17, pp. 39–43, 2012.

[37] G.-M. Gao, D.-R. Liu, H.-F. Zou, L.-C. Zou, and S.-C. Gan, "Preparation of silica aerogel from oil shale ash by fluidized bed drying," *Powder Technology*, vol. 197, no. 3, pp. 283–287, 2010.

[38] K. H. Mo, P. Visintin, U. J. Alengaram, and M. Z. Jumaat, "Prediction of the structural behaviour of oil palm shell lightweight concrete beams," *Construction and Building Materials*, vol. 102, pp. 722–732, 2016.

[39] G. Li, W. Wang, T. Long et al., "A general and facile method to prepare uniform gamma-alumina hollow microspheres from waste oil shale ash," *Materials Letters*, vol. 133, pp. 143–146, 2014.

[40] J. Feiteira, E. Gruyaert, and N. De Belie, "Self-healing of moving cracks in concrete by means of encapsulated polymer precursors," *Construction and Building Materials*, vol. 102, pp. 671–678, 2016.

[41] N. Taranu, M. Abdelhadi, A. Rotaru, and M. Gavrilescu, "Compressive strength analysis on problematic soils stabilized with fly ash in Jordan," *Environmental Engineering and Management Journal*, vol. 17, no. 8, pp. 1855–1861, 2018.

[42] H. Qin, Y. Yue, H. Liu, and Q. Wang, "Current status and prospect of oil shale retorting technologies in China," *Chemical Industry and Engineering Progress*, vol. 34, no. 5, pp. 1191–1198, 2015.

[43] A. A. A. Molenaar, S. Akbarnejad, and L. J. M. Houben, "Performance of pavements with blast furnace base courses," in *Proceedings of the Geoshanghai International Conference*, vol. 2010, pp. 476–483377, Shanghai, China, June 2010.

[44] W. Chen, Y. Li, S. Chen, and C. Zheng, "Properties and economics evaluation of utilization of oil shale waste as an alternative environmentally-friendly building materials in pavement engineering," *Construction and Building Materials*, vol. 259, Article ID 119698, 2020.