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Study on the durability of alkali-activated slag based geopolymer containing Portland cement

Yong Cao[1,a], Bo Ding[2,3,b,*], Xueyong Zhu[2,3,c]

[1]Weihai Municipal Government Comprehensive Service Center, Weihai, 264200, China
[2]Shandong Transportation Institute, Jinan, 250102, China
[3]Key Laboratory of Expressway Maintenance Technology Ministry of Transport, Jinan, 250102, China
[a]365612195@qq.com, [b]dingbo1211@163.com, [c]103607652@qq.com
[*]Corresponding author

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Abstract: To expand the application scope of slag-based geopolymer, slag was partially used to *replace* cement, and the durability of slag-based geopolymer repair materials containing Portland cement (AACS) was investigated. The durability of AACS repair materials was comprehensively evaluated by testing compressive strength, frost resistance, and sulfate attack resistance. The results show that within a certain range, compressive strength increases with the increase in cement content and alkali concentration. Compared with ordinary cement mortar and commercial repair materials, AACS exhibits superior sulfate resistance, frost resistance, and overall durability, making it suitable for projects in cold regions and saline-alkali soils.

1. Introduction

In the context of energy conservation and emission reduction, alkali-activated cementitious materials are considered potential alternatives to cement. These materials are produced by mixing industrial aluminosilicate waste (such as fly ash and slag) with an alkaline solution [1]. Relevant studies [2-4] have demonstrated that alkali-activated cementitious materials possess excellent properties such as early strength, high-temperature resistance, corrosion resistance, and frost resistance, making them suitable for applications in fire-resistant and acid-resistant materials, foamed concrete, encapsulation of toxic pollutants, and road repair. Mohammad et al. [5] evaluated the mechanical and durability properties of alkali-activated slag (AAS) mortar, finding that slag-based geopolymer mortar exhibited high bond strength, and NaOH-activated mortar showed better resistance to chloride penetration.

Compared to traditional cement mortar, pure geopolymer materials have relatively lower strength, which presents certain limitations for engineering applications. Some studies have shown [6] that adding Portland cement to geopolymers can improve the strength development deficiencies of pure geopolymer, thereby enhancing the performance of alkali-activated cementitious materials. However, research on the alkali-activated effects of geopolymers containing Portland cement is limited, particularly in terms of durability when used as repair materials, with no relevant studies reported.

Therefore, this study uses Portland cement as an additive and Na_2SiO_3 and NaOH as activators to investigate the effects of different cement addition ratios, different types of alkalis, and varying dosages on the compressive strength and durability of slag-based geopolymers containing Portland cement (AACS). Durability is analyzed through frost resistance and corrosion resistance performance to provide a theoretical basis for partially replacing cement with slag and expanding application scenarios.

2. Experiment

2.1. Raw materials

Cement: Ordinary Portland cement (P O 42.5) produced by Hebei Yanxin Building Materials Co., Ltd.; Slag:S95grade ground granulated blast-furnace slag powder produced by Beijing Shougang Jiayuan Building Materials Co., Ltd. The main chemical compositions of both materials are shown in Table 1; Silica Fume: Premium grade silica fume provided by Beijing Dechang Weiye Construction Engineering Co., Ltd., with technical specifications as shown in Table 2; Na_2SiO_3: Industrial-grade sodium silicate produced by Tianjin Fuchen Chemical Reagent Factory, a white granular solid with a Na_2O ratio of 1.03±0.03; NaOH: White solid granules (96% purity) produced by Beijing Reagent Chemical Reagent Factory; Sand: Ordinary river sand with a fineness modulus of 2.54; Water: Ordinary tap water; A commercially available repair material was selected as a comparison material, a gray-white powder designated as DK. Its XRD diffraction pattern is shown in Figure 1, and its primary mineral compositions are alite (Ca_3SiO_5), gypsum ($CaSO_4$), quartz (SiO_2), and calcite ($CaCO_3$).

Table 1: Chemical composition of cement and blast furnace slag.

Materials	SiO_2	Al_2O_3	CaO	MgO	SO_3	Fe_2O_3	K_2O	TiO_2	Na_2O	P_2O_5
Cement/%	21.28	4.76	59.6	3.25	3.03	2.70	0.98	0.35	0.22	0.16
Slag/%	33.41	14.23	38.5	9.23	2.09	0.37	0.39	0.79	0.34	0.03

Table 2: Technical indicators of silica fume.

Loss on ignition(%)	Chloride(%)	Silicon dioxide(%)	Specific surface area(m^2/kg)	The ratio of water demand (%)	Activity index(%)
2.56	0.032	94.42	2.09×10^4	110	103

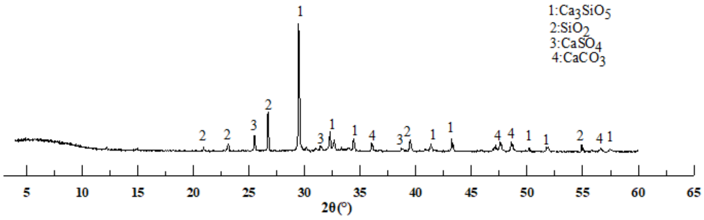


Figure 1: XRD patterns of commercial repair materials

2.2. Mix proportions

Considering the comparison of activators and their activation effects, two activators, NaOH and Na_2SiO_3, were used. The dosage of Na_2SiO_3 (by mass of cementitious material) was set at 2%, 3%, and 4%, while the dosage of NaOH (by mass of cementitious material) was set at 1%, 1.5%, and 2%. Cement was used as an additive with proportions set at 50%, 30%, and 10% (by mass of cementitious material). The water-to-binder ratio was designed to be 0.5. The specific mix proportions are shown in Table 3.

Table 3: Test mix proportion

Number	Cement(g)	Slag(g)	Silica fume (g)	Sand(g)	NaOH(g)	Na_2SiO_3(g)
P0	100	-	-	200	-	-
50P-2S	50	42	8	200	-	2
50P-3S	50	42	8	200	-	3
50P-4S	50	42	8	200	-	4
50P-1H	50	42	8	200	1	-
50P-1.5H	50	42	8	200	1.5	-
50P-2H	50	42	8	200	2	-
30P-2S	30	62	8	200	-	2
30P-3S	30	62	8	200	-	3
30P-4S	30	62	8	200	-	4
30P-1H	30	62	8	200	1	-
30P-1.5H	30	62	8	200	1.5	-
30P-2H	30	62	8	200	2	-
10P-2S	10	82	8	200	-	2
10P-3S	10	82	8	200	-	3
10P-4S	10	82	8	200	-	4
10P-1H	10	82	8	200	1	-
10P-1.5H	10	82	8	200	1.5	-
10P-2H	10	82	8	200	2	-

Note: P0 represents the ordinary Portland cement mortar. 50P-2S and 30P-1H represent the experimental groups with 50% cement content and 2% sodium silicate content, and 30% cement content and 1% sodium hydroxide content, respectively. The others are similar.

2.3. Experimental methods

2.3.1. Preparation of AACS materials and measurement of mechanical properties

Na_2SiO_3 or NaOH was weighed and mixed with water according to the required amounts. The NaOH solution and Na_2SiO_3 solution were prepared 2 hours in advance and cooled to room temperature for later use. Alkali-activated slag-Portland cement mortar was prepared by replacing the mixing water with the pre-prepared alkaline solution, following the mixing method used for cement mortar. The compressive strength was measured according to the method specified in JTG E30-2005 Test Methods of Cement and Concrete for Highway Engineering. The specimen size was 40mm × 40mm × 160mm, and compressive strength tests were conducted after the specimens reached the specified curing age.

2.3.2. Measurement of AACS material durability

The freeze-thaw resistance test was conducted according to the slow-freezing method described in DL/T 5151-2001 Test Code for Hydraulic Concrete, with the starting test age being 28 days. Four days prior to the test age, the specimens were immersed in water for 4 days before beginning the freeze-thaw cycles. The sulfate attack resistance test was conducted according to GB/T 50082-2009 Standard for Test Methods of Long-Term and Durability Performance of Ordinary Concrete. At the age of 28 days, the specimens were taken out and dried in an oven for 48 hours at a controlled temperature of 80±5°C. The specimens were then immersed in a 5% sodium sulfate solution for 16 hours, followed by drying in a constant temperature oven for 8 hours, which constituted one cycle.

3. Results and discussion

3.1. Compressive strength of AACS materials

The compressive strength test results of AACS cementitious materials are shown in Figure 2. The compressive strength of the system decreases as the cement content decreases. Within a certain range, the compressive strength increases with the increase in alkali content, indicating that both cement and alkali contribute to the strength development of AACS cementitious materials. For the 28-day compressive strength, the 30P-2S, 30P-3S, 10P-2S, and 10P-3S groups were 38.22 MPa, 39.79 MPa, 26.94 MPa, and 28.24 MPa, respectively. From the perspective of alkali concentration, the strength of AACS cementitious materials increases with the increase in concentration within a certain range, but when the alkali concentration is too high, the strength of the cementitious materials decreases. This phenomenon occurs because a low-concentration alkaline solution promotes the dissolution and reconfiguration of silicon and aluminum monomers in slag, leading to the rapid accumulation of hydration products. However, under high OH^- concentration, the concentrations of Si^{4+} and Al^{3+} increase rapidly, and due to the common ion effect, the elevated ion concentrations hinder the precipitation of Ca^{2+}[7], thereby delaying the strength development of the system. This result is consistent with the findings of A. Palomo[6], but whether the system's hydration continues in the later stages requires further investigation.

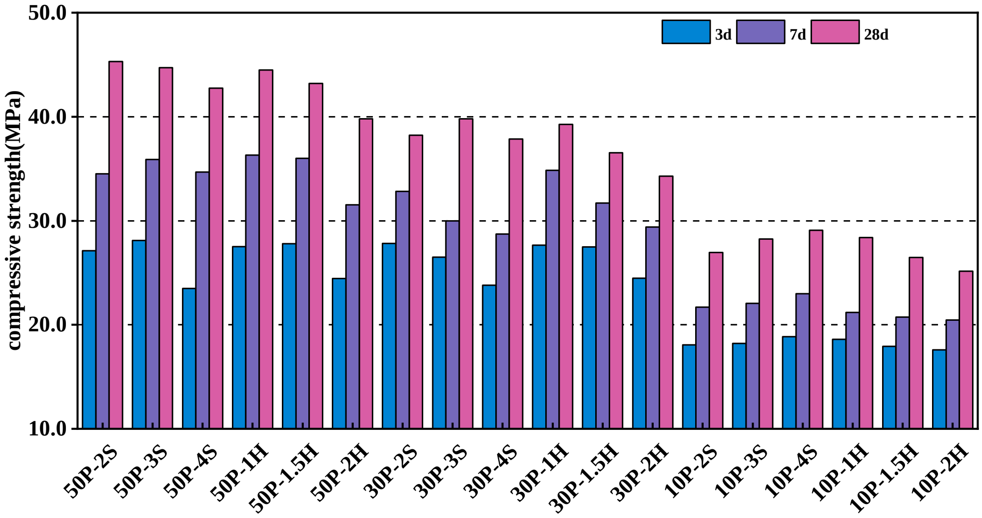
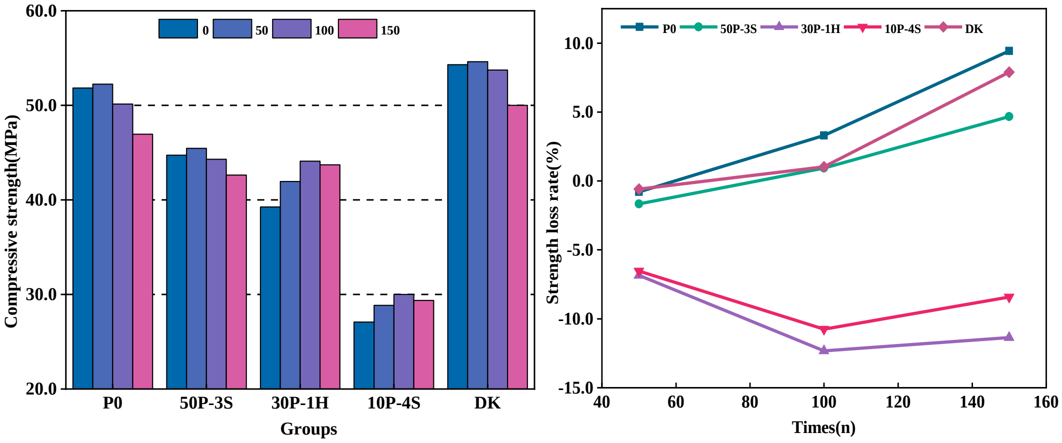


Figure 2: The setting time and strength of different combinations of AACS materials

3.2. Freeze-thaw cycles of AACS repair materials

The compressive strength and strength loss rate of five repair materials were tested after 50, 100, and 150 freeze-thaw cycles, and the results are shown in Figure 3. As seen in the figure, AACS repair materials exhibit good freeze-thaw resistance, with a trend of reduced compressive strength loss as the slag content increases. During the cycling process, a slight increase in compressive strength was observed for all five repair materials after 50 cycles, likely due to the continued hydration of cementitious materials that had not fully reacted at earlier stages, leading to an increase in strength. As the number of cycles increased, significant differences in strength changes among the different repair materials became apparent: after 100 freeze-thaw cycles, the strength losses for the P0, 50P-3S, and DK groups were 3.3%, 0.94%, and 1.03%, respectively, while the 30P-1H and 10P-4S groups not only did not experience a decrease in strength but continued to increase, with growth rates of 12.33% and 10.74% over the initial strength, respectively. This phenomenon suggests that the hydration reaction of slag continues over long-term curing, indicating that the alkali activation effect of slag is a prolonged process, during which the hydration products in the system gradually increase, leading to continuous strength growth. Zhu Jing[8] found through experimental research that the compressive strength of alkali-slag cementitious materials increased by 18.8% at 60 days compared to 28 days, and this value reached 41.2% at 180 days.

After 150 freeze-thaw cycles, the strength loss further increased for the P0, DK, and 50P-3S groups, with the strength loss in the P0 and DK groups being greater than that in the 50P-3S group. The compressive strength of the 30P-1H and 10P-4S groups showed a slight decrease compared to the 100-cycle mark, indicating that at this stage, the adverse effects of freeze-thaw damage began to dominate. However, the specimen strength remained higher than the initial strength. From the perspective of strength loss evaluation, the freeze-thaw resistance of the repair materials ranked as follows: AACS repair materials > commercial repair materials > ordinary cement mortar repair materials.



(a) Compressive strength (b) Strength loss rate

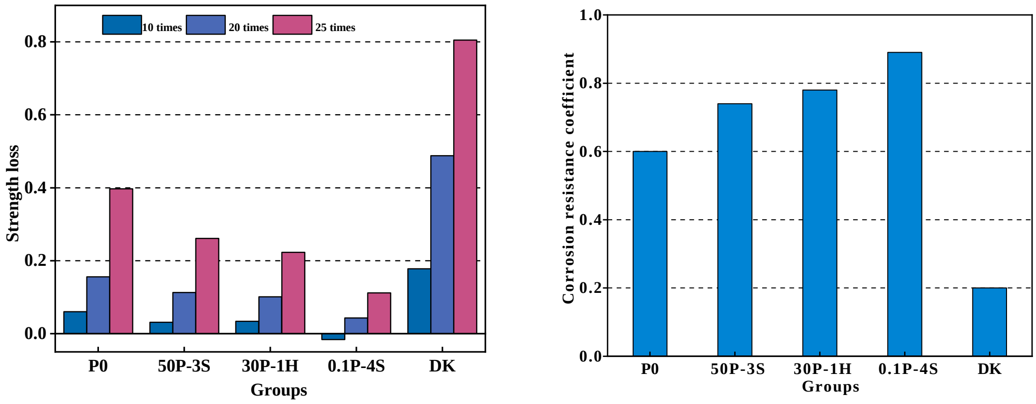
Figure 3: Compressive strength and strength loss rate of different repair materials under freeze-thaw cycles

3.3. Sulfate attack on AACS repair materials

The corrosion resistance coefficient is defined as the ratio of the compressive strength of the cementitious material after undergoing a certain number of acid-base corrosion cycles to its initial strength, reflecting the material's ability to resist corrosion. Figure 4 shows the changes in compressive strength of different repair materials after 10, 20, and 25 sulfate attack cycles, as well as the changes in corrosion resistance coefficient after 25 cycles. As shown in the figure, the compressive strength of all the repair materials decreases as the number of cycles increases. In terms of material composition, alkali-activated slag-based cementitious materials containing Portland cement exhibit better resistance to sulfate attack compared to ordinary cement mortar. This is because the gel network formed by the hydration products of alkali-activated slag is denser. Additionally, due to the incomplete hydration of slag in the early stages, the system's density and strength may increase further with time as slow hydration continues. For example, when the cement content is 10%, the specimen's strength does not decrease but shows a slight increase after 10 corrosion cycles.

Under the same number of cycles, the loss of compressive strength of cementitious materials tends to decrease as the slag content increases. After 25 cycles, the compressive strength losses for the 50P-3S, 30P-1H, and 10P-4S groups were 26.1%, 22.3%, and 11.2%, respectively, further indicating that the addition of slag enhances the system's resistance to sulfate attack. Among the sulfate attack test results, AACS repair materials performed the best, followed by ordinary cement mortar repair materials, while commercial repair materials performed the worst: after 25 cycles, the compressive strength loss reached 80.5%, and the corrosion resistance coefficient dropped to 0.2.

Throughout the cycling process, the rate of strength loss in the test groups gradually increased. This is because once micro-damage, such as cracks, occurs on the specimen surface due to corrosion, each subsequent cycle accelerates the degradation process. With the loss of the protective effect of the mortar surface layer, metal salt ions can easily penetrate the internal structure of the repair mortar, exacerbating internal structural damage and ultimately leading to a significant reduction in specimen strength.



(a) Compressive strength loss (b) Corrosion resistance coefficient after 25 cycles

Figure 4: Strength change and corrosion resistance coefficient of specimen

4. Conclusion

The physical and mechanical properties of alkali-activated slag-based cementitious materials containing Portland cement (AACS) were investigated, along with the application of AACS as a concrete repair material. The following conclusions were drawn:

(1) The strength of AACS materials is primarily derived from the hydration reactions of cement and slag. Within a certain range, the compressive strength of AACS increases with the increase in cement content and alkali concentration.

(2) AACS repair materials exhibit excellent durability. This is reflected in their minimal strength loss after sulfate attack, with significantly better sulfate resistance compared to ordinary cement mortar and commercial repair mortars. Regarding freeze-thaw resistance, the continuous hydration of slag during long-term curing allows AACS repair materials to maintain their strength more effectively during freeze-thaw cycles, demonstrating good freeze-thaw resistance. These properties make AACS materials potentially suitable for repair applications in cold regions and saline-alkali environments, where resistance to freezing and corrosion is critical.

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