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Study on Mechanical Properties of Slag Alkali Activated Cementitious Materials

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Abstract: The fluidity and mechanical properties of mortar with Portland cement, blast furnace slag and copper slag as cementitious materials and sodium hydroxide and sodium silicate as activator were studied. The results show that compared with Portland cement mortar of the same strength, the sodium silicate alkali activated slag mortar with modulus of 1.2 has similar fluidity and shorter setting time, the fluidity of the system was increased and the setting time was prolonged by using steel slag instead of 50% slag. Compared with Portland cement mortar, the steel slag delayed the early strength development of the alkali-activated mortar, while the increase of strength is more obvious in the later.

Keywords: slag alkali-activated mortar; fluidity; mechanical properties

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1. Introduction

Traditional cement concrete has been widely used in civil engineering due to its favorable mechanical properties, cost-effectiveness, and ease of construction. However, considering that it is the third largest contributor to CO_2 emissions, there is a need for alternative cementitious materials to replace traditional cement in order to meet infrastructure demands. Additionally, river sand resources, an essential component ofconcrete production, are facing severe scarcity. Moreover, each year a significant amount of construction waste (approximately 1.8 billion tons) is generated from buildings reaching their service life or undergoingdemolition; however, the utilization rate of these resources remains below 5%, significantly lower than that observed in some developed countries and regions[1].

With the rapid development of China's power industry and the increase in electricity consumption, the emission of fly ash in the flue gas of coal-fired power plants has been increasing year by year. Fly ash is mainly composed of oxides such as SiO_2, Al_2O_3, and Fe_2O_3, and its appearance is similar to cement. This type of industrial waste not only occupies a large amount of land when stacked, but also pollutes water bodies and damages the acid-base balance of the soil over time. If discarded fly ash is utilized as a resource, it can effectively solve environmental pollution and other hazards, allowing coal resources to exert greater utilization value. Scholars at home and abroad have prepared fly ash based polymer cementitious materials and studied their mechanical properties. Dombrowski et al.[2] studied the effect of calcium and its content on the formation, hardening, and properties of fly ash based polymers. Calcium and silicon in fly ash form C-S-H phase, which improves the strength of the test samples. Peng Hui et al[3]. found that the most critical factor affecting the mechanical properties of geopolymers is the concentration of the activator, followed by the modulus of the alkaline activator. Meng

Xianxian[4] et al. studied the effect of different Si and Al contents on the strength of fly ash geopolymer. The results showed that when the Al content was high, the early strength growth rate of the sample was faster, and when the Si content was high, the later strength growth rate of the sample was faster. C-S-H colloid had a promoting effect on the improvement of the sample strength. Hu [5] and Komnitsas[6]. found that the concentration of sodium hydroxide solution has a significant impact on the strength of alkali activated fly ash based polymers. In addition, maintenance temperature and age are also important factors affecting the mechanical properties of geopolymers, but the impact of these variables is only significant when the concentration of alkaline activators is sufficient to drive the polymerization reaction of alumino silicates.

2. Experiment

2.1. Raw materials

The 52.5 grade Portland cement, Granulated blast furnace slag (GGBS) and steel slag have been selected as binder for test[7]. The flexural and compressive strength of Portland cement with PII 52.5 is 8.8MPa and 60.0MPa. The chemical composition and phase composition of cement are shown in **Table 1** and **Table 2** respectively.

Table 1. The chemical compositions and LO1 of PC (wt.%)

CaO	SiO2	Al2O3	MgO	SO3	K2O	Na2O	Fe2O3	LO1
64.47	20.8/7	4.87	2.13	2.52	0.65	0.11	3.59	2.40

Table 2. Main composition of PC by XRD/Rietveld method(wt.%)

CaO	SiO2	Al2O3	MgO	SO3	K2O	Na2O	TiO2	Fe2O3	LO1
41.21	32.64	12.38	6.52	3.98	0.22	0.23	0.53	0.35	1.45

Alkalinity coefficient of GGBS can be expressed as parameter Kb= CaO + MgO/SiO_2 + Al_2O_3 =1.06, Mass coefficient Kq = CaO + MgO + Al_2O_3 /SiO_2 + TiO_2 =1.81. Activity Index of 28d is 96%. The composition of mortar is shown in **Table 3**.

Table 3. The chemical compositions and LO1 of GGBS (wt.%)

C3S	C2S	C3A	C4AF	CaCO3	CaSO4.2H2O	CaSO4.0.5H2O
64.47	20.87	4.87	2.13	2.52	0.65	0.11

Analysis the pure sodium hydroxide is first mixed with water, cooled to room temperature, stirred with sodium silicate, cooled for 24 h, the prepared alkali activator modulus is 1.2 (molar ratio of SiO_2 to Na_2O) , the content of Na_2O in slag is 3.31%. The mortar samples were formed in a plastic mould and covered with plastic wrap. After 1 day, the mould was removed and placed in the curing room for 28 days. It should be noted that the alkali-activated mortar has a lower density than Portland cement mortar. In order to ensure that each group of mortar ratio is the same, in the amount of single-side sand, the alkali-activated mortar is smaller than the corresponding Portland cement group.

Table 4. Mix proportions for AAS mortars and PC mortar (kg/m³)

Group	Cement	GGBS	Steelslag	Water	NaOH	Waterglass	Sand
C	764.1			305.9			1529.0
G		686.2		167.8	19.4	154.4	1372.0

SG	343.1	343.1	167.8	19.4	154.4	1372.0

2.2. Experiments

The cement paste has been prepared for setting time test. The cement mortar prisms with dimension of 40*40*160mm^3 have been prepared for strength testing after 1d, 3d, 7d and 28d curing age respectively.

3. Results and Discussion

3.1. Fluidity

The setting time of cementitious materials is one of its important properties in practical production and application, which can directly affect the mixing, transportation and pouring time of cement concrete. The setting time of alkali-activated mortar is very short[8]. It is generally considered that the setting time of alkali-activated slag is less than 30 minutes. The main factors affecting the setting time of slag are the characteristics of slag, composition and amount of activator, curing condition and curing time, etc., most of the retarders suitable for Portland cement are not suitable for alkali-activated cementitious systems, and the most widely used retarders for alkali-activated cementitious materials are mainly high-dose phosphates or borates. However, it is disadvantageous to the strength development of alkali-activated cementitious materials and has a high cost. Changing the composition of precursor materials can effectively adjust the setting time, and the cost is lower and the effect is better[9].

The test results of setting time and fluidity of three groups of mortars are shown in table. The results showed that the initial and final coagulation time of Group G were 45 min and 60 min respectively, which were significantly lower than those of the other two groups. This is because alkali-activated materials and Portland cement hydration process are different, alkali solution can be quickly activated material dissolved and re-polymerization of hydration products produced strength. Steel slag can prolong the setting time of slurry by replacing slag. Because the vitreous content of steel slag is lower than that of slag, the hydration activity is lower and the reaction is slower. From the physical chemistry point of view, the bond energy intensity of the chemical bonds in different oxide compositions is different[10-11]. The Si-O bond energy reaches 444 kJ, while the Al-O bond energy is 221~280 kJ. In comparison, the Ca-O bond energy is the smallest, it is only 134kJ, so the Ca^{2+} in the amorphous phase will be dissolved before the other two ions, and gradually combine with the SiO_4^{2-} and AlO_2 in the solution to form the hydrate gel C-A-S-H. Ca-O in the amorphous phase can be understood as a weak link in the system, which is the cause of rapid condensation of alkali-activated cementitious materials. According to the analysis of chemical composition of raw materials, the content of calcium in slag is significantly higher than that in steel slag. The fluidity of the system was increased by replacing slag with steel slag because the specific surface area of steel slag was smaller than that of slag, and the water requirement was less under the same quality condition. At the same time, because of the rapid reaction of slag, the surface will form a layer of hydration products film, which is not conducive to slurry fluidity[12].

Table 5. Setting time and fluidity of different groups

Group	Initial setting(min)	Final setting(min)	Fluidity(mm)
C	150	240	250
G	45	60	230
SG	50	90	270

3.2. Mechanical strength

The flexural strength and compressive strength of three groups of mortars with different curing ages obtained by mechanical properties experiments are shown in **Figure 1**. In both Portland cement and alkali-activated group, the compressive strength and flexural strength increased with the increase of curing age, which was mainly due to the increase of the internal reaction of paste with the increase of curing age, the reaction products are continuously produced and filled in the pores, making the matrix more compact and thus producing higher strength. In the alkali-activated group, the compressive strength and flexural strength of the slag group (SG) were the highest from 1d to 28d age, while the early strength of the slag group developed faster than that of the Portland cement group. The 3d compressive strength was 60.1MPa, which is 83.1% of the 28d compressive strength. The 3d compressive strength of Portland cement group is 48.9MPa, which is 77.34% of its 28d strength.

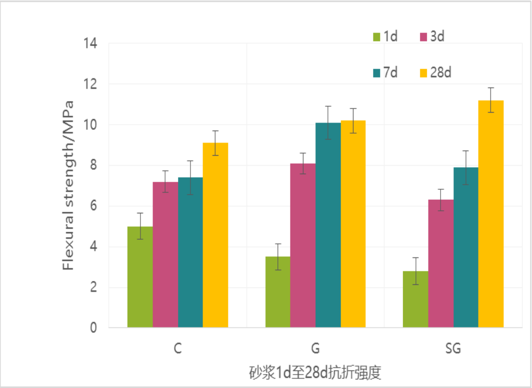

Figure 1. The flexural strength of cement paste with **different** curing stage

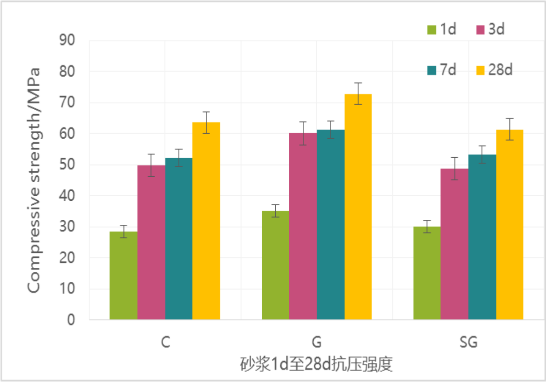

Figure 2. The compressive strength of cement paste with different curing stage

Because of its low activity, when steel slag was used as cementitious material instead of slag, its 28d compressive strength was slightly decreased by 9.6% and 15.3%, respectively. For steel slag group, the compressive strength of steel slag at 28d was increased by 22.6% compared with that of steel slag at 7d. In the early stage of hydration, these crystalline phases are difficult to dissolve, but with the progress of hydration, the activity of crystalline phases is gradually excited, and react with alkali activator to form hydration products, fill the pores, and improve the mechanical properties of the system.

4. Conclusions

- Compared with Portland cement mortar of the same strength grade, the alkali-activated slag mortars made from sodium hydroxide and sodium silicate with modulus of 1.2 have similar fluidity and shorter setting time. The use of steel slag instead of 50% slag increases the fluidity of the system and prolongs the setting time.
- Compared with Portland cement mortar, the strength of alkali-activated mortar developed rapidly. Adding steel slag and nickel slag could delay the early strength development of the system, but with the hydration, the activity of both was gradually excited. Compared with the nickel slag group, the strength of the steel slag group increased more obviously.

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Disclosure Statement

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