Application Research of Alkali Activated Coal Gangue Based Geopolymer in the Field Of Engineering Materials

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Abstract. In response to the requirements of carbon neutrality strategy and the demand for new engineering materials, this study adopts the principle of alkali activation to prepare fully solid waste based geopolymer cementitious materials using NaOH, coal gangue (CG), granulated blast furnace slag (GBFS), and quicklime (QL). The influence of each ratio on the flowability and strength of the cementitious materials is analyzed, and the microstructure evolution mechanism is analyzed by XRD, SEM and other methods. The macroscopic results indicate that the CG content has a significant impact on the flowability of the material; The compressive strength of the specimen shows a peak with the increase of QL content and NaOH. The microscopic results show that with the increase of curing age, the diffraction intensity of SiO_2 decreases, the product of C-(A)-S-H gel increases, the microcrack decreases significantly, the porosity decreases gradually, and the structure becomes more compact. The results of this study provide a scientific basis for the development of low-carbon and environmentally friendly new engineering cementitious materials and sustainable development.

Keywords: Engineering materials; Geopolymer; Strength characteristics; Microstructure.

1 Introduction

In the field of engineering materials, cement, as a key component of concrete, inevitably emits a large amount of carbon dioxide during its production process. At present, using solid waste to replace traditional cement in the preparation of new geopolymer cementitious materials has become an important strategy for achieving green and low-carbon development[1]. This research can not only effectively utilize industrial by-products, reduce their potential pollution to the environment, but also reduce carbon emissions in the material production process, promote sustainable development[2], and provide new directions for the future development of engineering materials. Geopolymers, as a new type of environmentally friendly engineering building material, have excellent mechanical properties, including high compressive strength and good flexural strength, as well as low permeability, which makes them outstanding in resisting chemical erosion and heavy metal solidification[3], and show significant advantages in durability compared to

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traditional cement[4]. Secondly, geological polymers have low thermal conductivity and excellent fire resistance, which can maintain stability at high temperatures. At the same time, their shrinkage and expansion coefficients are low, which helps to reduce the occurrence of cracks. In addition, the strong interfacial bonding between geological polymers and aggregates enhances the stability of the overall structure. These characteristics combined make geopolymers surpass traditional cement in durability and become an attractive alternative material in the fields of construction and engineering[6].

2 Materials and Testing

2.1 Raw Materials

The coal gangue used in this experiment was taken from the Qinghemen area of Fuxin. It was crushed into fine aggregates using a jaw crusher and ground in a ball mill for 40 minutes for later use. Use a laser particle size analyzer to perform particle size analysis on CG, as shown in Fig. 1. The crystal composition of CG was analyzed using X-ray diffraction (XRD), as shown in Fig. 2. The experiment used commercially available GBFS and QL with densities of 3.1g/cm^3 and 3.2g/cm^3, respectively; The specific surface areas are 429m^2/kg and 524m^2/kg, respectively. The main chemical composition of each raw material is shown in Table 1. The experiment used commercially available analytical grade NaOH with a purity greater than 96%.

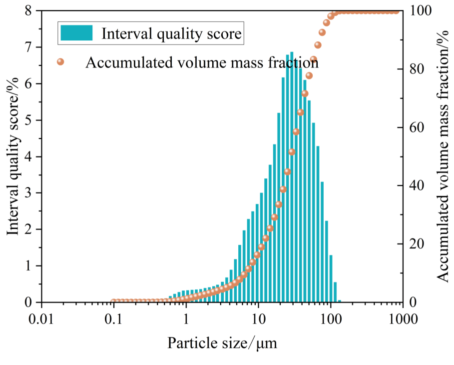


Fig. 1. Particle size distribution curve of coal gangue powder.

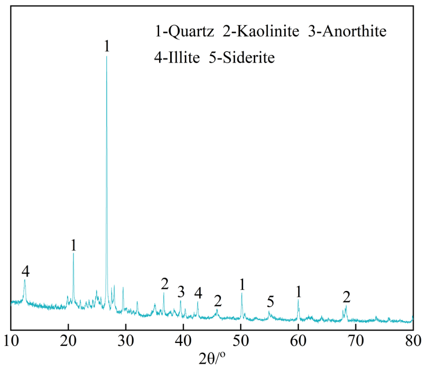


Fig. 2. XRD pattern of coal gangue.

Table 1. Main Chemical Composition of Each Raw Material.

Materials	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3
QL	0.90	86.72	0.37	0.19	1.87	--	--	0.16
GBFS	34.50	34.00	17.70	1.03	6.01	0.89	0.68	1.64
CG	59.50	3.18	21.64	8.01	1.54	3.12	0.90	0.40

2.2 Sample Preparation

This experiment used NaOH as the alkaline activator and aimed to study the uniaxial compressive strength and flowability of cementitious materials at different ages. A total of 15 single factor experiments were conducted with three factors and five levels. The specific mix design is shown in Table 2.

Table 2. Experimental Factor Level Table.

level	Factor		
	CG/%	QL/%	NaOH/%
1	45	5	3
2	50	10	4
3	55	15	5
4	60	20	6
5	65	25	7

2.3 Testing Methods and Processes

The flowability of freshly mixed mud shall be tested for cementitious materials in accordance with GB/T8077-2012 "Test Method for Uniformity of Concrete Admixtures". The compressive strength test is conducted in accordance with the "Method for Testing the Strength of Cement Mortar (GB/T17671-2021)", using the WDW-100E miniature universal testing machine produced by Jinan Times Assay Co., Ltd. for strength testing.

3 Results and Discussion

3.1 Analysis of Flow Performance Test Results

The test results of the flowability of the specimens are shown in Table 3, and the addition of CG and QL has a significant impact on the flowability performance of the specimens. With the increase of CG content, the flowability of the specimen showed a rapid downward trend. Compared with the benchmark specimen with a content of 45%, when it increased by 65%, it decreased by 24.74%. The increase in QL dosage also shows a decreasing trend, with a decrease of 9.09% when it reaches 25%.

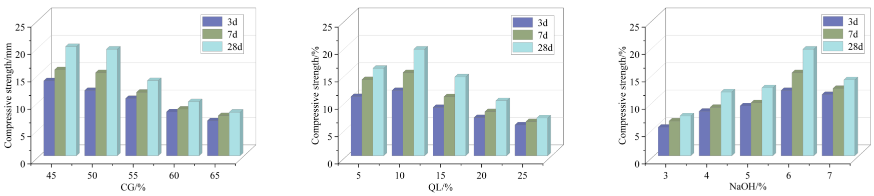
Table 3. Fluidity of cementitious materials under different mix proportions.

Number	QL/%	CG/%	NaOH/%	Fluidity/mm
A1	5	50	6	187
A2	10	50	6	181
A3	15	50	6	177
A4	20	50	6	173
A5	25	50	6	170
B1	10	45	6	194
B2	10	50	6	181

B3	10	55	6	165
B4	10	60	6	154
B5	10	65	6	146
C1	10	50	3	189
C2	10	50	4	186
C3	10	50	5	184
C4	10	50	6	181
C5	10	50	7	178

3.2 Test Results and Analysis of Compressive Strength

Fig. 3 shows the variation trend of compressive strength of cementitious material specimens under different ratios. As shown in Fig. 3(a), with the increase of CG content and the decrease of GBFS content, the compressive strength of the specimens at each age gradually decreases. This is due to the reduction of Ca/Si ratio, which limits the formation of calcium-based gel products, resulting in a significant decline in the compressive strength of the specimens. From Fig. 3(b), it can be seen that when the QL content is 10%, the compressive strength of the specimen reaches its peak at various ages (3 days, 7 days, and 28 days), which are 11.93 MPa, 15.18 MPa, and 19.48 MPa, respectively. As shown in Fig. 3(c), with the increase of NaOH content, the compressive strength of the specimen shows a trend of first increasing and then decreasing.



(a) CG dosage (b) QL dosage (c) NaOH dosage

Fig. 3. The influence of various factors on the compressive strength of cementitious material specimens: (a), (b), (c).

3.3 Analysis of XRD Test Results

Fig. 4 shows the X-ray diffraction patterns of specimen A2 at different curing ages. According to Fig. 4, the main crystal phases include quartz, calcite, and zeolite. According to the analysis of XRD spectrum by Jade, the existence of the diffraction peak of calcium zeolite ($Ca[Al_2Si_3O_{10}]\cdot 3H_2O$) was detected near 2θ° to 30°, indicating the formation of C-A-S-H gel phase[7]. As the maintenance age increases, the diffraction peak of SiO_2 decreases, and SiO_2 crystals are activated by OH - ions, increasing the number of active Si-O-Si bonds[8], promoting condensation reactions, and increasing the formation of silicate aluminate zeolite products[8].

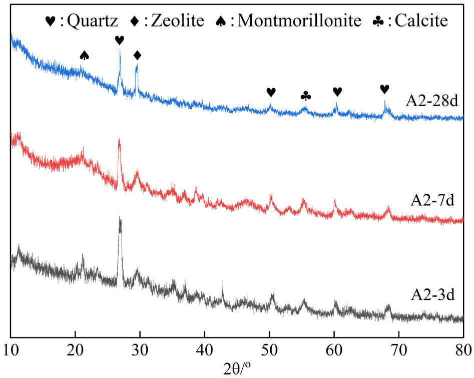
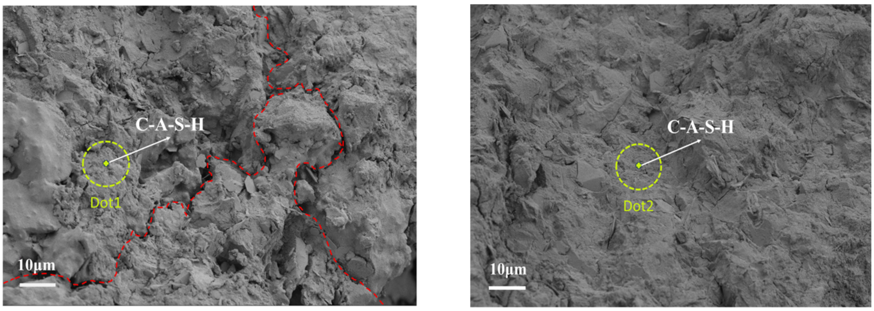


Fig. 4. XRD patterns of A2 at different curing ages.

3.4 Analysis of SEM Test Results

Fig. 5 reveals the scanning electron microscope (SEM) microstructure of A2 specimen at different curing ages. Fig. 6 shows the EDS energy spectrum analysis of typical products. From Fig. 5(a), it can be observed that in the early stage of the polymerization reaction, the overall structural properties of the microstructure are poor, with a large number of microcracks and a few coarse cracks. EDS analysis is shown in Fig. 6(a). The main elements are Ca, O, Si, Al and Na. It is speculated that C-(A)-S-H may be mixed with a small amount of N-A-S-H gel[10]. It can be observed from Fig. 5(b) that a large number of gel products are produced in the late reaction period, which extrude or fill the cracks. The unreacted coal gangue and $Ca(OH)_2$ crystalline material are tightly wrapped by the polymerized gel, and a new dense structure is formed through physical adsorption. As shown in Fig. 6(b), compared with 3d, the Al content in the gel product increases, the Si content decreases, and the Al/Si increases, indicating that the degree of polymerization is deepened. The formation of C-(A)-S-H and other gel with higher degree of polymerization provides a denser structure for the system[1111].



(a) 3d-1k (b) 28d-1k

Fig. 5. Microscopic morphology of A2 specimen at different curing ages.

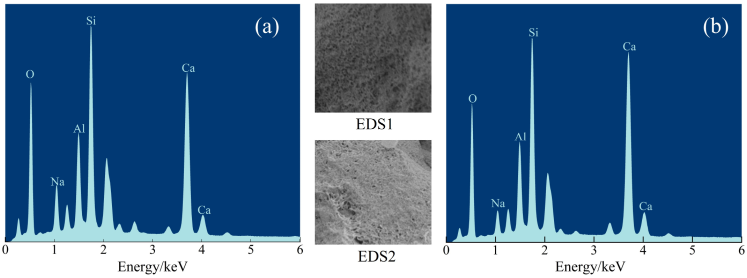


Fig. 6. EDS analysis of typical products of A2 specimen.

4 Conclusion

(1) The content of CG has a significant impact on the flowability of cementitious mat erials; With the increase of QL and NaOH dosage, the compressive strength show s a trend of first increasing and then decreasing.

(2) The microscopic results indicate that the diffraction peak of SiO_2 decreases with t he increase of curing age, the microstructure becomes denser, and the porosity gra dually decreases; EDS energy spectrum analysis shows that the production of alu minosilicate products such as C-(A)-S-H increases.

(3) The development of this new type of cementitious material responds to the green and low-carbon transformation needs of the construction industry, providing scien tific basis for new directions and sustainable development of new engineering ma terials.

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