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Research Progress on Mechanical Properties of Alkali-Activated Concrete

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Abstract

This paper first introduces the raw materials of alkali-activated cementitious materials, analyzes the mechanical properties of alkali-activated concrete, namely compressive strength, flexural strength, splitting tensile strength, elastic modulus and stress-strain curve, and analyzes the mechanical properties of steel fiber alkali-activated concrete. The results show that the compressive strength and flexural strength of alkali-activated fly ash concrete can be improved by adding appropriate amount of slag. There is a nonlinear relationship between compressive strength and tensile strength of alkali-activated slag concrete. The descending section of the stress-strain curve of alkali-activated slag concrete is relatively steep, which is similar to the descending section of the stress-strain curve of high-strength concrete. Alkali-activated slag concrete has high brittleness. There is a nonlinear relationship between the elastic modulus and compressive strength of alkali-activated slag concrete.

Keywords

Slag; Fly Ash; Alkali-Activated Cementitious Material; Mechanical Properties; Research Progress.

1. Introduction

Concrete is the most widely used building material at present. The most commonly used cementitious material for traditional concrete is ordinary Portland cement [1]. However, every 1 ton of ordinary Portland cement produced emits about 1 ton of CO_2, which poses a great burden on the environment. In addition, cement production consumes a lot of raw materials and energy [2], and produces dust and harmful substances such as CO and SO_2. In order to promote green development, it is urgent to develop a new type of green energy-saving cementitious material. The emergence of alkali-activated cementitious materials has brought hope to this end.

2. Raw Materials of Alkali-Activated Cementitious Materials

2.1. Precursor

The precursors of alkali-activated cementitious materials have a wide range of sources. Not only active aluminosilicate minerals can be used as precursors, but also industrial waste and waste can be used as precursors. Slag, fly ash and metakaolin are common precursors of alkali-activated cementitious materials. Among them, the activity of slag is the highest, the activity of metakaolin is the second, and the activity of fly ash is the weakest. Single slag, fly ash and metakaolin can be used as precursors, and a mixture of slag and fly ash, a mixture of fly ash and metakaolin, and a mixture of slag and metakaolin can also be used as precursors. Adding an appropriate amount of silica fume to alkali-activated slag-fly ash concrete can improve the mechanical properties of alkali-activated slag-fly ash [3].

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2.2. Alkali Activator

Water glass, NaOH and Na_2CO_3 are commonly used alkali activators. Different types of alkali activators will affect the strength of alkali-activated cementitious materials. For alkali-activated slag cementitious materials, studies have shown that [4], the excitation effect of water glass is the best, followed by NaOH, and Na_2CO_3 is the weakest. The strength of water glass activated slag is higher than that of NaOH solution activated slag.

The different content of alkali activator will also affect the strength of alkali-activated cementitious materials. When the precursor is fly ash, Jiao et al. [5] found that under normal temperature curing, with the increase of NaOH content, the compressive strength of alkali-activated fly ash cementitious materials increased first and then decreased. This is because when the alkali concentration is too low, OH^- has limited dissolution of active silicon and aluminum on the surface of fly ash particles, and the formed gel content is too small, resulting in low compressive strength of the material. Then, with the increase of alkali concentration, it is beneficial to the disintegration of vitreous body and the formation of gel in fly ash, which improves the compressive strength of the material. When the OH^- concentration reaches a certain value, continue to increase the amount of alkali, the excessive OH^- in the alkali-activated cementitious material system will dissolve and destroy the structure of the fly ash and the hydration product aluminosilicate gel, thereby reducing the strength of the cementitious material sample.

3. Mechanical Properties of Alkali-Activated Cementitious Materials

3.1. Compressive Strength

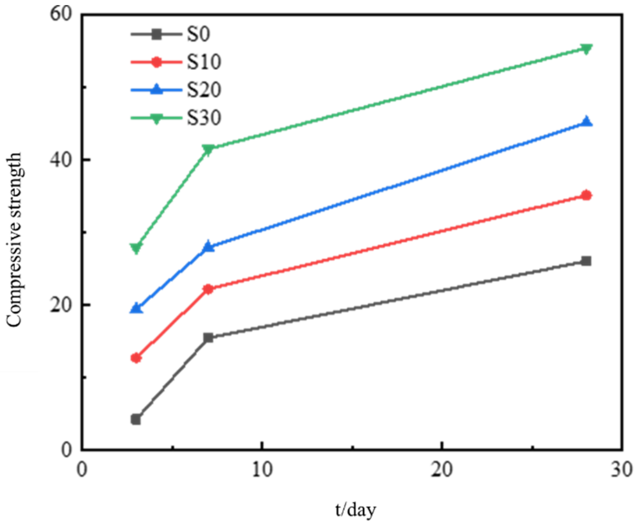

Fig 1. Effect of different amounts of slag on the development of compressive strength of alkali-activated slag-fly ash concrete

Alkali-activated concrete is a new type of green material. The mechanical properties of alkali-activated concrete should be studied from the compressive strength. When slag is used as a precursor, the activity of slag is higher, and alkali-activated slag concrete has higher early strength. However, when fly ash is used as a precursor, the early strength of alkali-activated fly ash concrete under normal temperature curing is low. In order to improve the early strength of alkali-activated fly ash concrete, slag and fly ash can be combined as precursors.

At present, scholars have studied the compressive strength of alkali-activated slag-fly ash concrete. Some scholars believe that with the increase of slag content, the compressive strength of alkali-activated slag-fly ash concrete gradually increases [6-8]. The test results of Nath and

Sarker [6] are shown in Figure 1. Compared with alkali-activated fly ash concrete without slag, the 20-day compressive strength of alkali-activated fly ash concrete with 10 %, 20 % and 30 % slag increased by 33 %, 74 % and 110 %, respectively. The test results of Vikas and Rao [7] are shown in Table 1. As the slag content gradually increases from 0 % to 100 %, the compressive strength of alkali-activated slag-fly ash concrete gradually increases. However, some scholars believe that with the increase of slag content, the compressive strength of alkali-activated slag-fly ash concrete increases first and then decreases. Xia et al. [9] studied the effect of different fly ash replacement rates on the compressive strength of alkali-activated slag concrete. The test results are shown in Fig. 2. The results show that when the fly ash replacement rate increases from 0 % to 10 %, 20 %, 30 %, 40 %, 50 % and 60 %, the compressive strength of alkali-activated slag-fly ash increases first and then decreases.

Table 1. 28-day compressive strength of alkali-activated slag-fly ash concrete

Serial number	Silicon modulus of water glass	
	Ms1.99	Ms2.92
F100S0	11.5	16.2
F90S10	16.8	24.6
F80S20	24.2	31.4
F70S30	31.9	38.8
F60S40	38.5	48.5
F50S50	44.2	52.2
F40S60	52.1	58.1
F30S70	60.5	66.5
F20S80	68.2	74.7
F10S90	75.8	82.9
F0S100	88.4	93.2

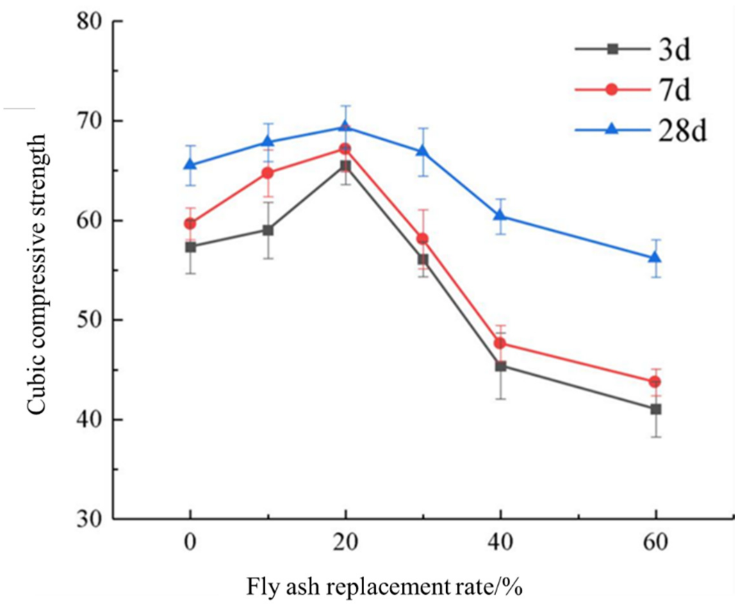

Fig 2. Compressive strength of alkali-activated slag-fly ash concrete with different fly ash replacement rates

In summary, for the compressive strength of alkali-activated slag-fly ash concrete, some scholars believe that with the increase of slag content, the compressive strength of alkali-activated slag-fly ash concrete gradually increases, and some scholars believe that with the increase of slag content, the compressive strength of alkali-activated fly ash-slag increases first and then decreases. Although the research conclusions of scholars are different, it can be concluded that when the slag content is within a certain range, the compressive strength of alkali-activated slag-fly ash concrete gradually increases with the increase of slag content.

3.2. Flexural Strength

Flexural strength is an important control index for the application of alkali-activated concrete to pavement.

Xia et al [9] studied the effect of different dosage of fly ash on the flexural strength of alkali-activated slag concrete. The results show that when the replacement rate of fly ash increases from 0 % to 10 %, 20 %, 30 %, 40 %, 50 % and 60 %, the flexural strength of alkali-activated slag-fly ash increases first and then decreases. The relationship between compressive strength and flexural strength of alkali-activated concrete is proposed, as shown in Equation (1):

$$f_f = 0.19 f_{cu}^{1.37} \tag{1}$$

Fang et al. [10] studied the effect of different content of slag on the flexural strength of alkali-activated fly ash concrete. The results show that with the increase of slag content, the flexural strength of alkali-activated fly ash concrete increases gradually.

Nath and Sarker [11] studied the effect of replacing fly ash with 0 %, 10 % and 15 % slag on the flexural strength of alkali-activated fly ash concrete. The results show that with the increase of slag content, the flexural strength of alkali-activated fly ash increases first and then decreases.

Wan et al. [12] proposed the relationship between compressive strength and flexural strength of alkali-activated slag concrete, as shown in Equation (2):

$$f_f = 1.78\sqrt{f_{cu}} \tag{2}$$

Huang et al. [13] proposed the relationship between compressive strength and flexural strength of alkali-activated slag-fly ash concrete, as shown in formula (3):

$$f_f = 0.09 f_{cu}^{0.96} \tag{3}$$

In summary, the incorporation of an appropriate amount of slag can improve the flexural strength of alkali-activated fly ash concrete. For the relationship between compressive strength and flexural strength of alkali-activated concrete, scholars have different research conclusions. It can be seen that there is a nonlinear relationship between compressive strength and flexural strength of alkali-activated concrete.

3.3. Split Tensile Strength

Splitting tensile strength is one of the important indexes to evaluate the cracking resistance of concrete in structural design. Some scholars have put forward the relationship between the compressive strength and tensile strength of alkali-activated concrete. Xia et al [9] put forward the relationship between the compressive strength and tensile strength of alkali-activated slag concrete, as shown in formula (4):

$$f_{ct} = 0.06 f_{cu}^{1.04} \tag{4}$$

Wan et al. [12] used sodium hydroxide and sodium silicate to activate slag, and obtained the relationship model between splitting tensile strength and compressive strength of alkali-activated slag concrete, as shown in Equation (5):

$$f_{ct} = 0.53\sqrt{f_{cu}} \tag{5}$$

Aliabdo et al. [14] proposed the relationship between compressive strength and tensile strength of alkali-activated slag concrete, as shown in formula (6):

$$f_{ct} = 0.5554\sqrt{f_{cu}} \tag{6}$$

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Lee and Lee [15] proposed a prediction equation for the splitting tensile strength of alkali-activated fly ash-slag concrete, as shown in Equation (7):

$$f_{ct}=0.45\sqrt{f_{cu}} \tag{7}$$

Sofi et al. [16] studied the compressive strength and splitting tensile strength of alkali-activated mortar and alkali-activated concrete made of slag and fly ash. According to the test results, the relationship between compressive strength and splitting tensile strength was obtained, as shown in Equation (8):

$$f_{ct}=0.48\sqrt{f_{cu}} \tag{8}$$

Thomas and Peethamparan [17] studied the compressive strength and splitting tensile strength of alkali-activated fly ash concrete and alkali-activated slag concrete, and proposed the relationship between the compressive strength and splitting tensile strength of alkali-activated concrete, as shown in formulas (9) and (10):

$$f_{ct}=0.4f_{cu}^{\frac{7}{9}} \tag{9}$$

$$f_{ct}=1.08\sqrt{f_{cu}} \tag{10}$$

In summary, for the relationship between the compressive strength and splitting tensile strength of alkali-activated concrete, the results obtained by scholars are not uniform. It can be seen that there is a nonlinear relationship between the compressive strength and tensile strength of alkali-activated concrete.

3.4. Compressive Stress-strain Curve

The compressive stress-strain curve of concrete is the most basic constitutive relation.

Thomas and Peethamparan [17] found that compared with the stress-strain curve of alkali-activated fly ash concrete, the descending section of alkali-activated slag concrete is very steep, showing high brittleness.

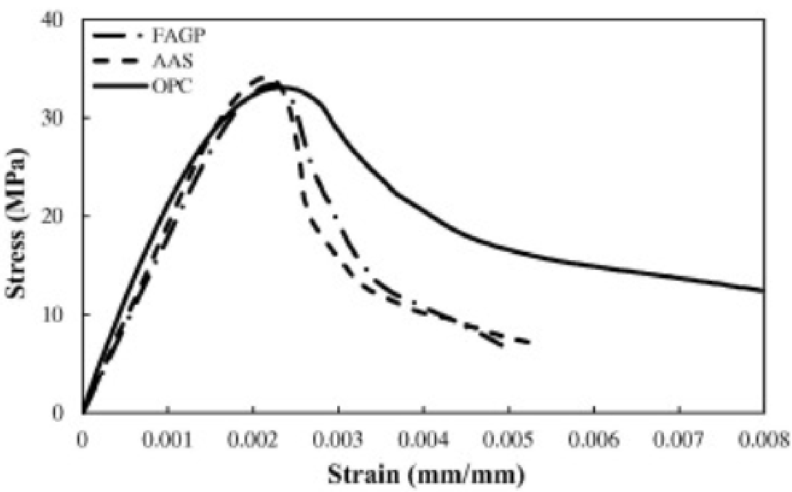

Fig 3. Stress-strain curves of ordinary concrete, alkali-activated fly ash concrete and alkali-activated slag concrete

Tang et al. [18] studied the stress-strain curve of alkali-activated slag-fly ash concrete. The results show that compared with the stress-strain curve of alkali-activated fly ash concrete without slag, the stress-strain curve of alkali-activated fly ash concrete with slag has a higher peak point, and the slope of the rising section increases and the descending section is steeper.

Farhan et al. [19] studied the stress-strain curves of alkali-activated fly ash concrete, alkali-activated slag concrete and ordinary concrete. The stress-strain curves of 28-day alkali-activated fly ash concrete, alkali-activated slag concrete and ordinary concrete are shown in Fig. 3.Compared with the stress-strain curve of ordinary concrete, the descending section of the stress-strain curve of alkali-activated fly ash concrete and alkali-activated slag fly ash shows a faster decline.

It can be seen that the stress-strain curve of alkali-activated slag mortar and alkali-activated slag concrete is steeper, which indicates that the alkali-activated slag concrete has higher brittleness, and the stress-strain curve of alkali-activated slag concrete is similar to that of high-strength concrete. The brittleness of alkali-activated fly ash concrete increases after adding slag.

3.5. Elastic Modulus and Poisson 's Ratio

The relationship between the elastic modulus and compressive strength of sodium hydroxide activated slag concrete and the relationship between the elastic modulus and compressive strength of sodium hydroxide activated slag concrete were proposed by Wan et al. [12], as shown in formulas (11) and (12):

$$E=4727\sqrt{f_{cu}} \tag{11}$$

$$E=4167\sqrt{f_{cu}} \tag{12}$$

The relationship between the elastic modulus and compressive strength of ordinary concrete in ACI 318-11 is shown in Equation (13):

$$E=4700\sqrt{f_{cu}} \tag{13}$$

Eq. (11) is basically close to Eq. (13), while Eq. (12) is lower than Eq. (13). Wan et al. [12] believed that because the crystallinity of sodium hydroxide-activated slag is significantly higher than that of water glass-activated slag, the crystalline product plays the role of micro-aggregate to a certain extent, which limits the longitudinal deformation during the loading process and increases the elastic modulus to a certain extent.

Lee and Lee [15] proposed the relationship between elastic modulus and compressive strength of alkali-activated fly ash / slag concrete, as shown in Equation (14):

$$E=5300f_{cu}^{1/3} \tag{14}$$

Thomas and Peethamparan [17] obtained the range of Poisson 's ratio of alkali-activated fly ash concrete and alkali-activated slag concrete is 0.127 ± 0.003, and proposed the relationship between elastic modulus and compressive strength of alkali-activated fly ash concrete and alkali-activated slag concrete, as shown in formulas (15) and (16):

$$E=4400\sqrt{f_{cu}} \tag{15}$$

$$E=2900f_{cu}^{3/5} \tag{16}$$

Yuan Zhensheng et al [20] obtained the Poisson 's ratio of alkali-activated fly ash-metakaolin concrete, and the Poisson 's ratio is between 0.17 and 0.31.

In summary, there is no unified conclusion on the relationship between elastic modulus and compressive strength of alkali-activated concrete. It can be seen that there is a nonlinear relationship between elastic modulus and compressive strength of alkali-activated concrete. There are few studies on Poisson 's ratio of alkali-activated cementitious materials, and the research results of scholars are not the same.

4. Conclusion

In this paper, the raw materials, compressive strength, splitting tensile strength, flexural strength and stress-strain curve of alkali-activated cementitious materials are reviewed. The following conclusions can be drawn:

(1) Slag, fly ash and metakaolin are common precursors of alkali-activated cementitious materials. Water glass, NaOH and Na_2CO_3 are commonly used alkali activators. Different types and dosages of alkali activators will affect the strength of alkali-activated cementitious materials.

(2) Adding appropriate amount of slag can improve the compressive strength and flexural strength of alkali-activated fly ash. There is a nonlinear relationship between compressive strength and tensile strength of alkali-activated slag concrete. There is a nonlinear relationship between the elastic modulus and compressive strength of alkali-activated slag concrete.

(3) The descending section of the stress-strain curve of alkali-activated slag concrete is steep, which is similar to the descending section of the stress-strain curve of high strength concrete. Alkali-activated slag concrete has high brittleness.

References

[1] Zhao J, Wang K, Wang S B, et al. Effect of elevated temperature on mechanical properties of high-volume fly ash-based geopolymer concrete, mortar and paste cured at room temperature [J]. Polymers, 2021, 13(9): 1473.

[2] Liu Y Q, Zhu W P, Yang E H. Alkali-activated ground granulated blast-furnace slag incorporating incinerator fly ash as a potential binder[J]. Construction and Building Materials, 2016, 112: 1005-1012.

[3] Ma W, He Z Y. Mechanical Property Modification of Alkali-activated Slag Fly Ash-based Geopolymer and its Concrete Property [J]. Multipurpose Utilization of Mineral Resources: 1-13.

[4] Zhang X. Study on Preparation and Mechanical Properties Modification of Alkali-activated Slag Cementitious Material [D]. Xinyang Normal University, 2021.

[5] Jiao X D, Li H, Zheng W K, et al. Effect of Direct Current Pre-curing on Early Age Strength of Fly Ash Activated by NaOH[J]. Bulletin of the Chinese Ceramic Society, 2019, 38(11): 3484-3489.

[6] Nath P, Sarker P K. Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition[J]. Construction and Building Materials, 2014, 66: 163-171.

[7] Vikas G, Rao T D G. Setting time, workability and strength properties of alkali activated fly ash and slag based geopolymer concrete activated with high silica modulus water glass[J]. Iranian Journal of Science and Technology-Transactions of Civil Engineering, 2021, 45(3): 1483-1492.

[8] Guo Z J, Li W K. Study on Properties of Alkali Activated Slag/Fly Ash Composite Concrete [J]. Journal of China & Foreign Highway, 2022, 42(5): 216-220.

[9] Xia D T, Wu C, Cui K, et al. Effect of Fly Ash and Silica Fume Contents on Mechanical Properties of Alkali-Activated Slag-Based Concrete[J]. Journal of Southwest Jiaotong University,2024, 59(05): 1113-1122.

[10] Fang G H, Ho W K, Tu W L, et al. Workability and mechanical properties of alkali-activated fly ash-slag concrete cured at ambient temperature[J]. Construction and Building Materials, 2018, 172: 476-487.

[11] Nath P, Sarker P K. Fracture properties of GGBFS-blended fly ash geopolymer concrete cured in ambient temperature[J]. Materials and Structures, 2017, 50(1): 32.

[12] Wan X M, Zhao Y, Zhao T J, et al. Mechanical Properties of Alkali-activated Slag Concrete [J]. Materials Reports, 2018, 32(12): 2091-2095.

[13] Huang H, Guo M X, Zhang W, et al. Mechanical property and microstructure of geopolymer concrete based on fly ash and slag [J]. Journal of Harbin Institute of Technology, 2022, 54(3): 74-84.

[14] Aliabdo A A, Abd Elmoaty A E M, Emam M A. Factors affecting the mechanical properties of alkali activated ground granulated blast furnace slag concrete[J]. Construction and Building Materials, 2019, 197: 339-355.

[15] Lee N K, Lee H K. Setting and mechanical properties of alkali-activated fly ash/slag concrete manufactured at room temperature[J]. Construction and Building Materials, 2013, 47: 1201-1209.

[16] Sofi M, Van Deventer J S J, Mendis P A, et al. Engineering properties of inorganic polymer concretes (IPCs)[J]. Cement and Concrete Research, 2007, 37(2): 251-257.

[17] Thomas R J, Peethamparan S. Alkali-activated concrete: Engineering properties and stress–strain behavior[J]. Construction and Building Materials, 2015, 93: 49-56.

[18] Tang Z, Hu Y, Tam V W Y, et al. Uniaxial compressive behaviors of fly ash/slag-based geopolymeric concrete with recycled aggregates[J]. Cement and Concrete Composites, 2019, 104: 103375.

[19] Farhan N A, Sheikh M N, Hadi M N S. Investigation of engineering properties of normal and high strength fly ash based geopolymer and alkali-activated slag concrete compared to ordinary Portland cement concrete[J]. Construction and Building Materials, 2019, 196: 26-42.

[20] Yuan Z S. Experimental Study on Basic Mechanical Properties and High-temperature Spalling Mechanism of Geopolymer Concrete [D]. South China University of Technology, 2018.