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Workability and mechanical properties of alkali-activated fly ash-slag concrete cured at ambient temperature

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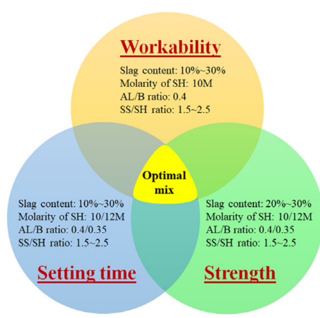
HIGHLIGHTS

- Workability of alkali-activated fly ash-slag (AAFS) concrete measured.
- Mechanical properties of AAFS concrete measured.
- Effects of slag content, molarity of SH, AL/B ratio and SS/SH ratio estimated.
- Prediction equations for splitting tensile strength and flexural strength proposed.
- Optimal mixtures of AAFS concrete for engineering application obtained.

GRAPHICAL ABSTRACT



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ABSTRACT

Alkali-activated fly ash-slag (AAFS) concrete is a new blended alkali-activated concrete that has been increasingly studied over the past decades because of its environmental benefits and superior engineering properties. However, there is still a lack of comprehensive studies on the effect of different factors on the fresh and hardened properties of AAFS concrete. This paper aims to provide a thorough understanding of workability and mechanical properties of AAFS concrete cured at ambient temperature and to obtain the optimal mixtures for engineering application. A series of experiments were carried out to measure workability, setting time, compressive strength, splitting tensile strength, flexural strength and dynamic elastic modulus of AAFS concrete. The results showed that workability and setting time decreased with the increase of slag content and molarity of sodium hydroxide solution (SH). Compressive strength increased with the increase of slag content and molarity of SH as well as the decrease of alkaline activator to binder (AL/B) ratio, but it did not have significant relationship with sodium silicate to sodium hydroxide (SS/SH) ratio. In addition, equations provided by ACI code, Eurocode and previous researchers for ordinary Portland cement concrete overestimated the values of splitting tensile strength, flexural strength and dynamic elastic modulus of AAFS concrete. The optimal mixtures of AAFS concrete were set as slag content of 20–30%, AL/B ratio of 0.4, 10 M of SH, and SS/SH ratio of 1.5–2.5 considering the performance criteria of workability, setting time and compressive strength.

1. Introduction

Alkali-activated materials (AAM) is an inorganic binder derived by the reaction of an alkali metal source (solid or dissolved) with a solid silicate powder such as fly ash (FA) and slag [1]. To date, AAM has been recognized as a promising alternative binder to ordinary Portland cement (OPC) because of its environmental benefits and superior engineering properties [2–5]. The manufacture of OPC is known as a significant contributor to greenhouse gas emissions accounting for around 5% of global CO_2 emissions [6,7]. In comparison, there are about 55–75% less greenhouse gas emissions in the

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production of FA and slag [8]. Thus, the application of AAM as a binder can significantly reduce the CO_2 emissions of concrete production.

FA has been increasingly considered as a suitable raw material for alkali-activated concrete (AAC) due to its wide availability and adequate composition of silica and alumina. Previous studies [9–19] reported that alkali-activated fly ash (AAF) concrete has excellent mechanical and durability properties when it is cured at elevated temperature. Normally, the curing temperature of 60–85 °C is required to activate FA as the reactivity of FA at ambient temperature is too low to be activated by alkali activators [20–22]. Such curing condition may be suitable for manufacturing precast concrete members, but it is not suitable for cast-in-situ concrete in practice. Therefore, it is vital to develop a new type of AAC without curing at elevated temperature, which will widen the practical application of AAC. In addition, the cost and energy consumption associated with the heat curing process will also be reduced.

In order to achieve ambient curing, some researchers attempted to improve the reactivity of FA in alkaline environment [23]. In particular, one of the acceptable attempts is to add some calcium containing materials such as slag in AAC [24]. The addition of slag would accelerate FA dissolution and enhance reaction products formation in room curing condition [25]. Both the early and later age properties of AAF concrete are also significantly affected by the additional slag. Until now, an increasing number of studies have been undertaken to investigate the effect of slag on the engineering properties of AAF [2,3,26–30]. Nath and Sarker [2,3,31] studied the influencing factors on the fresh and hardened properties of alkali-activated fly ash-slag (AAFS) concrete. It was found that the dominant influencing factors are the slag replacement level for FA along with the type and content of alkaline activator. One main limitation of this research is that the different activating conditions were not fully considered. For example, the effect of slag content on the properties of AAFS concrete may be affected by the activator with different molarity. Lee [29,32] also explored the mechanical properties of AAFS concrete and suggested a proper slag content of 15–20% of total binder considering the setting time and compressive strength of AAFS concrete. However, it should be noted that the workability of AAFS concrete was not considered in the selection of slag content. In addition, an optimal mixture of AAFS concrete should not only include the slag replacement level but also the alkaline activator to binder (AL/B) ratio, molarity of sodium hydroxide (SH) solution and sodium silicate to sodium hydroxide (SS/SH) ratio, etc. Thus, it is of importance to conduct a comprehensive research focusing on the effects of different factors on the fresh and hardened properties of AAFS concrete and to evaluate the optimal mixtures by taking into account the basic performance criteria of workability, setting time and compressive strength.

The main purpose of this study is to provide a thorough understanding of workability, setting time and mechanical properties of AAFS concrete cured at ambient temperature. Low calcium FA and ground granulated blast-furnace slag (GGBS) were used as binder materials. Alkaline activator was prepared by mixing SH and SS solution. Special attention was paid to the main influencing factors, including FA/GGBS ratio, AL/B ratio, molarity of SH and SS/SH ratio on the workability, setting time, compressive strength, splitting tensile strength, flexural strength and dynamic elastic modulus development of AAFS concrete. Splitting tensile strength, flexural strength and dynamic elastic modulus were further analysed using existing standards and codes in order to propose prediction equations suitable for AAFS concrete. Finally, the optimal mixtures of AAFS concrete were obtained based on the performance criteria of workability, setting time and compressive strength.

2. Experimental program

2.1. Materials

In this study, low calcium FA and GGBS were used as binder. The chemical compositions of FA and GGBS are listed in Table 1. The mean particle size of FA and GGBS is 26.81 and 14.77 μm, respectively. Alkaline activator (AL) was mixed by sodium hydroxide (SH) with distilled water and sodium silicate solution (SS). The SiO_2 to Na_2O ratio of SS was 2.0 with chemical composition of 30.71 wt% SiO_2, 15.36 wt% Na_2O and 53.93 wt% H_2O. Since the modified polycarboxylate-based superplasticizers (SPs) have a significant effect on the workability of AAFS [29], it was used to improve the workability of AAFS in this work. The properties of this SPs are given in Table 2. Natural sand with a nominal maximum size of 2 mm was used as the fine aggregate. Coarse aggregates (CA) were prepared by mixing crushed granite with nominal maximum sizes of 10 and 20 mm. Fine aggregates and coarse aggregates were used in saturated surface dry (SSD) condition according to ASTM C128-15 [33] and ASTM C127-15 [34], respectively.

2.2. Mixture proportions

AAFS specimens with different FA/GGBS ratio, AL/B ratio, molarity of SH and SS/SH ratio were prepared and tested in this work. The optimal scope of mixture proportions was selected according to the relevant studies [2,3,6,28,29,32]. The mix proportions of AAFS concrete are listed in Table 3 and labelled with specific codes. The labels 'A', 'B', 'C', and 'D' represent different specimen series, while the numbers, '10′, '15′, '20′, '25′ and '30′, stand for the percentages of GGBS replacement for FA by weight, respectively. In Series A, mixture 1 (A10) to mixture 5 (A30) refer to those with GGBS content of 10%, 15%, 20%, 25% and 30% of total binder, respectively. The AL/B ratio in these mixtures was kept constant at 0.4 with molarity of SH and SS/SH ratio of 10 M and 2.0, respectively. In Series B, i.e., mixture 6 (B15) to mixture 8 (B25), the molarity of SH was changed from 10 M to 12 M while the AL/B ratio and SS/SH ratio were kept constant at 0.4 and 2.0, respectively. In Series C, i.e., mixture 9 (C15) to mixture 11 (C25), the AL/B ratio was changed from 0.4 to 0.35 while the molarity of SH and SS/SH ratio were kept as 10 M and 2.0, respectively. In Series D, the SS/SH ratios for mixture 12 (D15) and mixture 13 (D25) were 1.5 and 2.5, respectively. The SPs content was kept constant at 1% of the total binder for all mixtures. As such, the effect of slag content on the engineering properties of AAFS can be studied through Series A containing various slag content ranging from 10% to 30% of binder by weight. The effect of SH molarity can be investigated using Series A and Series B containing SH molarity of 10 and 12, respectively. Series A and Series C with AL/B ratios of 0.4 and 0.35 respectively were also designed to estimate the effect of AL/B ratio. Furthermore, Series A and Series D were conducted to evaluate the effect of SS/SH ratio on the engineering properties of AAFS with various SS/SH ratios ranging from 1.5 to 2.5.

The concrete mixtures were proportioned based on the unit volume of 1 m^3 while the total binder content was kept constant as 400 kg/m^3. The ingredient contents of binder were calculated based on their weight ratio. The total volume of aggregates was the residual volume except binder volume. The aggregates were mixed by the volume of 10 mm, 20 mm and fine aggregates with 22%, 43% and 35%, respectively. In addition, the mix proportions of AAFS pastes were similar to those of concrete mixtures excluding aggregates (see Table 3).

Table 2
Properties of superplasticizers.

Specific gravity (25 °C)	pH (25 °C)	Content of chloride ion (%)	Content of alkaline (%)
1.08	4–5	≤0.1	≤0.4

Table 1
Chemical compositions (wt%) of FA and GGBS.

Oxide	SiO_2	Al_2O_3	CaO	MgO	K_2O	Fe_2O_3	TiO_2	Na_2O	SO_3
FA	53.24	26.42	3.65	9.55	2.57	1.65	0.86	0.76	0.56
GGBS	36.77	13.56	37.60	7.45	0.55	0.41	0.79	0.25	1.82