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Guidelines for mix proportioning of fly ash/GGBS based alkali activated concretes

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HIGHLIGHTS

- Effects of paste volume, water content and precursor blend have been quantified.
- Water-to-solid ratio was found to influence compressive strength and setting time.
- Increasing GGBS content in the binder blend resulted in an increase of the strength.
- Step-by-step concrete mix proportioning procedure has been developed and validated.
- Traditional concrete is cheaper but difference is small for high strength concretes.

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ABSTRACT

The effects of paste volume, water content and precursor blend on consistency, setting time and compressive strength of alkali activated concrete (AAC) produced with fly ash (FA) and ground granulated blast furnace slag (GGBS) have been investigated with the aim of developing a suitable mix design procedure. Paste volumes in the range 30–33% were found not to influence the compressive strength but did influence the consistency of the mixes. The water-to-solid ratio was found to influence compressive strength and setting time. Increasing GGBS content in the binder blend resulted in an increase of the compressive strength, but higher GGBS content caused also early setting which may be undesirable. A mix design procedure has been developed and has been used to determine the constituent mix proportions for three classes of concretes, i.e. (a) a ready-mix concrete with nominal strength 35 MPa, (b) a typical structural concrete with nominal strength 50 MPa, and (c) a high strength concrete for precast applications with nominal strength 70 MPa. Cost analysis was carried out to compare the AAC with Portland cement concretes with similar properties. Normal strength Portland cement concrete (PC), as typically used in ready mix industry has been shown to be less expensive than AAC. However, alkali activated concrete can be competitively priced for high strength concretes. An empirical step-by-step procedure is presented for selecting trial mix proportions for concretes with a range of consistency values, setting times and cube compressive strengths.

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1. Introduction

Early investigations on alkali activated binder (AAB) date back to the beginning of the 20th century thanks to pioneering work by Kühl in Germany which was on vitreous slags activated with alkali materials [1]. However, it was only in the last decade that they gained international attention as alternative to Portland cement (PC) based binders, mainly due to the potential reduction of associated CO_2 emissions and for their inherent properties such as high strength, good resistance to chemical degradation, thermal stability and fire resistance, among others [2].

An extensive literature can be found on AAB. Detailed and up-to-date reviews are available [1]. While the majority of the studies have focused on the reaction mechanism and microstructural characterisation of AAB, relatively few investigations have been carried out with the aim of developing guidelines for concrete mix design proportioning [5–13]. Despite this, commercial binders have been marketed in Europe, USA, Australia and India, sometimes labelled as 'geopolymer concrete', and patents have been filed [3,4].

Available studies for mix proportioning on geopolymer or alkali activated concretes (AAC) have mainly focused on neat fly ash (FA)

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as the precursor [5–13]. Factors such as dosage of alkali solutions, water content, elevated curing temperatures (60–100 °C) and curing time are considered to be the important factors influencing the properties of fly ash-based AAC. Studies reported that reinforced concrete structural elements such as full scale beams and columns showed mechanical properties not dissimilar to those of Portland cement-based concrete [12,14]. Recently, a mix design procedure has been proposed for fly ash based geopolymer concretes applicable (1) to when they are cured at 60 or 80 °C, and (2) only to two NaOH solution concentrations [15]. The parameters considered in the design procedure for obtaining required compressive strength and workability were water to geopolymer solid ratio, alkali solution/fly ash and alkali solution/water ratios. Fly ash based geopolymer concrete requires both high chemical dosages and elevated curing temperature to achieve suitable mechanical properties, which may lead to limited applications as a result of higher production costs. Higher chemical activator quantities also increase the embodied energy of AAC making it less favourable as a way for reducing the environmental impact of construction.

Ground granulated blast furnace slag (GGBS) is also used as a precursor on its own or blended with fly ash to produce AAC cured at room temperature with high mechanical performance whilst requiring relatively low activator dosage. However, this option has also some practical challenges to overcome, such as fast setting of high calcium alkali activated systems [16]. Chemical admixtures used as retarders for Portland cement have not proved to be compatible for AAB. Detrimental effects on compressive strength have often been observed with some of them [17]. Till now no new chemical admixtures have been identified that overcome this problem. Mechanical strength for slag-based AAC was found to be higher than that of Portland cement-based concrete produced with similar binder content, water content, and curing temperature [18]. It was also observed that the strength development of slag-based AAC was less affected by the binder content than that of PC concrete. Slag-based AAC also had lower water absorption and lower total porosity than PC concrete. However, these properties decrease with increasing the binder content [18]. Hung and Chang [19] reported that the effect of liquid-to-binder ratio was less pronounced in slag-based AAC than in PC concrete. It was also observed that variables such as sand/aggregate and paste/aggregate ratios affected the fresh and hardened properties of slag-based AAC in a similar way to conventional PC concrete. The 28-day compressive strength was found to reach 80% of the 90-day strength, which is not much dissimilar to PC concrete, thus the 28-day strength can be used for designing slag-based AAC in a similar way to PC concretes.

Some studies have investigated the production of geopolymer concrete with blends of fly ash/GGBS [16,20–22]. The main observations from these studies were:

- Consistency decreased with increasing the GGBS content up to 30% by weight of the total binder when the binder was kept constant at 400 kg/m^3. The decrease of the consistency was attributed to the accelerated reaction of the calcium species and the angular shape of GGBS particles compared to the spherical shape of the fly ash [16,20].
- Consistency decreased with the reduction of the activator to binder ratio but it improved with the addition of extra water, which however led to reductions in strength. The addition of slag was found to accelerate the setting at ambient temperature. Maximum slag content of 10% was recommended for achieving concrete with strength and setting times similar to PC concretes [16].
- Compressive strength increased with increasing slag content in the investigated range of up to 30% [21]. Setting time was also reported to decrease as the amount of slag and the concentration of the NaOH solution increased. The "optimum" slag content in an alkali-activated fly ash/slag mixture was proposed to be 15–20% of total binder by weight considering setting time and workability of concrete.

The control of fresh and hardened properties of fly ash/GGBS concrete through a suitable mix design procedure is still desired. Reaction processes and products are completely different from those of Portland cement, and the empirical procedures usually adopted for the mix design of PC concretes cannot be used for AAC.

The objectives of this study were:

- To assess the effects of different water/solids ratio, paste volume, fly ash/GGBS blends on the setting time and strength development of AAC.
- To quantify the effect of water content on the binder setting behaviour.
- To determine guidelines for mix proportioning of AAC.
- To compare the cost of AAC and PC concretes with similar compressive strengths and consistency.

The effect of aggregate shape, texture and grading, as well as the effect of other activators (potassium-based solutions, carbonates etc.) and admixtures were not part of this study.

2. Materials and experimental procedures

2.1. Materials

Power Minerals Ltd supplied the fly ash from their Drax Power Station in the UK. The Rietveld method was used for assessing the amorphous content (internal standard of Al_2O_3, 20% in weight, was used). Quartz (4.6%) and mullite (8.1%) were the main crystalline phases identified, whilst hematite (0.5%) and magnetite (0.8%) were also detected. The amorphous content was estimated at 86%. The measured volumetric mass density of the particles was 2.42 g/cm^3. Particle size analysis was carried out with laser diffraction and the obtained mean particle size (d_{50}) was 17 μm.

GGBS was supplied by Civil and Marine Ltd – Hanson Company, West Thurrock, Essex, UK. XRD allowed the identification of akermanite and gehlenite in crystalline state, whereas the amorphous content was found to be higher than 95%. The volumetric mass density of the particles was 2.92 g/cm^3 and the d_{50} was 15 μm.

X-ray diffraction (XRD), with the use of a Philips X'Pert MPD diffractometer (which uses Cu-K-α radiation) determined the mineralogical composition.

X-ray fluorescence (XRF) was used to determine the chemical composition of the precursor materials. Main oxides are shown in Table 1.

Chemical activators were: NaOH in powder form of 99% purity and sodium silicate as a solution with SiO_2 to Na_2O molar ratio of 2.055. The commercial sodium silicate solution, produced by Fisher Scientific, had the following composition: 12.8% of Na_2O, 25.5% of SiO_2, 61.7% of water, by weight. NaOH solution with concentration 30% by weight (Molarity ≈ 10 M) was prepared by dissolving NaOH in tap water. Chemical activators were added in the mixes according to the alkali dosage (M+) and the alkali modulus (AM).

M + is the mass ratio of sodium oxide (Na_2O) in the activating solution (i.e. Na_2O from NaOH solution + Na_2O from sodium silicate solution) to the binder dry mass:

$$M+ = \frac{Na_2O}{flyash + GGBS} \quad (1)$$

Alkali modulus (AM) is the mass ratio Na_2O/SiO_2 in the alkali solutions.

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