Construction and Building Materials 143 (2017) 272–279

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Comparison of long term performance between alkali activated slag and fly ash geopolymer concretes

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HIGHLIGHTS

- Engineering properties of FAGP concrete improve from 28 to 540 days from casting.
- Continuing gel production of FAGP concrete densify microstrucre over time.
- Mechanical properties of AAS concrete decrease between 90 and 540 days from casting.
- Disjoining pressure & self-desiccation effect propagate cracks in AAS in long term.
- FAGP concrete is behaving in a similar manor to PC concrete.

ARTICLE INFO

Article history:
Received 29 December 2016
Received in revised form 1 March 2017
Accepted 14 March 2017

Keywords:
Fly ash geopolymer
Alkali activated slag
Mechanical properties
Durability
Long term performance

ABSTRACT

This paper reports the comparison of engineering properties of alkali activated slag (AAS) and low calcium fly ash geopolymer (FAGP) concretes up to 540 days. The results showed that the AAS concrete had higher compressive and tensile strength, elastic modulus and lower permeation characteristics than FAGP concrete in the initial 90 days. However, a reduction in AAS concrete performance was observed between 90 and 540 days, while an increase was noted in FAGP concrete over the same time period. The microscopy revealed that both reactions progressed beyond 90 days with the slag–alkali producing excess C–S–H gel which was observed to increase the crack propagation and crack width at latter ages, attributed to the combined effect of disjoining pressure and self-desiccation. The fly ash geopolymerization also continued following an initial 24 h heat curing resulting in a crack-free dense microstructure at 540 days. Overall the discrepancy in microstructural development beyond 90 days in the two concretes would explain the contradictory performance over the longer time frame.

1. Introduction

Concrete is the most widely used construction material in society today. Concrete is conventionally produced by using Portland cement (PC) as the primary binder with the ratio of PC in traditional concrete being approximately 10–15% by the mass of concrete. However, the production of PC has led to environmental concerns over the production of CO_2. Cement production has been estimated as contributing between 5 and 7% of the current anthropogenic CO_2 emissions worldwide [1,2], with the production of 1 ton of cement producing from 0.6 up to 1 ton of CO_2, depending on the power plant [3–5]. This had led to the adoption of waste materials, such as fly ash (FA) and ground granulated blast-furnace slag (GGBS), as a replacement for PC due to their ability to enhance the physical, chemical and mechanical properties of cements and concretes. More recently research has shown that it is possible to develop geopolymer concretes based solely on waste materials activated directly, without the presence of PC, utilizing an alkaline activator [6–12]. A major benefit of geopolymer concrete is that the reduction of CO_2 emission by 26–45% with the replacement of PC with no adverse economic effects [13–15].

In the geopolymerization process, alumina and silica species in FA rapidly react with highly alkaline activator solution and produce a three-dimensional polymeric chain and ring structure consisting of Si–O–Al–O bonds. The schematic formation of the final geopolymer product is sodium-aluminosilicate (N–A–S–H) gel, which governs the properties of low calcium fly ash geopolymer (FAGP) concrete [16]. Conversely, in AAS concrete, the calcium silicate hydrates (C–S–H) gel is the main resultant product of

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http://dx.doi.org/10.1016/j.conbuildmat.2017.03.153
0950-0618/

geopolymerisation, which is similar to the primary binding phase of PC and blended cement concretes [17].

Hardjito & Rangan [18] and Fernandez-Jimenez et al. [19] studied the mechanical properties of FAGP concrete up to 90 days and observed that it has a comparable compressive strength, higher flexural and splitting tensile strength, but a lower elastic modulus to that of PC concrete. Ryu et al. [20] showed that the splitting tensile strength to compressive strength ratio at 28 days ranged between 7.8 and 8.2%, similar to that of PC concrete. Neupane et al. [21] and Loya et al. [22] also found that the relationship between elastic modulus and compressive strength of FAGP concrete is similar to that of PC concrete. Research has also demonstrated similar mechanical properties for AAS concrete to PC concrete for periods up to 90 day [17,23,24], though a reduction of compressive strength with time has been reported by Collins and Sanjayan [25], while Bernal et al. [23] found that AAS concrete has a comparable compressive strength, but higher flexural strength than PC concrete.

Considering the permeation characteristics, Bernal et al. [26] showed that the binder content of the concretes has a particularly strong effect on the water absorption properties of AAS concrete. Collins and Sanjayan [27] reported that AAS concrete has a lower water absorption due to the presence of very refined, tortuous and closed porosity in the concrete. Moreover, Olivia et al. [28] stated that fly ash geopolymer concrete exhibits low water absorption and sorptivity compared to the PC concrete. The water/binder ratio and well-graded aggregate influence were noted to influence the permeation characteristics. However, these studies were only conducted up to 90 days, and there is no comparison between AAS and fly ash geopolymer concretes over the long term.

In order to function as a construction material, it is imperative that both AAS and FAGP concretes maintain their performance over the design life of a structure. This paper reports the details of an experimental research program that has been undertaken to investigate a range of mechanical and durability properties of AAS and FAGP concrete up to 540 days. The properties assessed were compressive strength, flexural and splitting tensile strength, elastic modulus, water absorption and water permeability.

2. Significance of research

Published research to date on AAS and FAGP concrete has been reported their performance only up to 90 days (short term), in each study using a mixing process unique to that study, with no comparison of long term performance between them. This research reports the performance of AAS and FAGP concretes up to one and half year while applying the same mixing process, providing a systematic long term comparison study of the engineering properties between them. Research data presented here thus will be extremely useful to comprehend the long term behavior of AAS and FAGP concretes.

3. Experimental procedure

3.1. Materials used

The GGBS was a construction grade slag conforming to Australian Standard, AS 3582.2 [29], with the basicity coefficient of 0.81 and the hydration modulus of 1.5. The low calcium, class F FA conforming to Australian standard, AS 3582.1 [30] was obtained from Tarong power station in Australia. The chemical composition, particle size distribution and mineralogical composition of fly ash and GGBS, determined by X-ray fluorescence (XRF), Malvern particle size analyzer instruments and X-ray diffraction (XRD), respectively are shown in Table 1 and 2. Brunauer Emmett Teller (BET) method by N_2 absorption was used to determine the fly ash surface area.

The alkaline activator used in AAS and FAGP concretes consisted of a mixture of Commercially available sodium silicate solution with a specific gravity of 1.53 and an alkaline modulus ratio (Ms) equal to 2 (where Ms = SiO_2/Na_2O, Na_2O = 14.7%, SiO_2 = 29.4% and 55.9% H_2O by mass), and sodium hydroxide solution. A 15 M NaOH solution was used for the manufacture of the FAGP and a 10 M NaOH solution used for the AAS. The selection of two different molarity in sodium hydroxide solution is dependent on the mix optimization based on 28-day compressive strength Both coarse and fine aggregate were prepared in accordance with AS 1141.5 [31]. The aggregate was in a saturated surface dry condition. The fine aggregate was river sand in uncrushed form with a specific gravity of 2.5 and a fineness modulus of 3.0. The coarse aggregate was crushed granite aggregate of two-grain sizes: 7 mm, 2.58 specific gravity and 1.60% water absorption, and 10 mm, 2.62 specific gravity and 0.74% water absorption. Demineralized water was used throughout the experiment.

3.2. Mix proportions and specimen preparations

Mix proportions used in AAS and FAGP concretes were based on a previous study, which is summarized in Table 3 [32]. The activator modulus (SiO_2/Na_2O in alkaline activator) is fixed at 1.0 for both concretes while Na_2O dosage (Na_2O in alkaline activator/FA) is fixed at 5% and 15% in the AAS and FAGP concretes, respectively. The ratio of components, such as binder (GGBS or FA), alkaline activator, aggregate and water, was calculated based on the absolute volume method [33]. The total aggregate in the concrete was kept to 64% of the entire mixture by volume for all mixes. A water solid ratio (w/s) of 0.44 and 0.37 was used to prepare the AAS and FAGP concrete, which gave a consistent workability in the mixing process. The total liquid and solid content is shown in Table 3. The mass of water in the mix was taken as the sum of mass of water contained in the sodium silicate, sodium hydroxide and added water. The mass of solid is taken as the sum of binder (GGBS or FA), the solids in the sodium silicate and the sodium hydroxide solution.

The mixing of concretes was carried out using a 120 liter concrete mixer. The dry materials (GGBS or FA, fine aggregates and coarse aggregates) were mixed first for 4 min. Then activator and water were added to the dry mix and mixed continuously for another 8 min until the mixture was glossy and well combined. The mixture was then poured into moulds and vibrated using a vibration table for 1 min to remove air bubbles. After vibration both AAS and FAGP concrete specimens were kept at room temperature (23 °C) for 1 day. The AAS specimens were demoulded, water-cured (23 °C) for 6 days and kept at room temperature until being tested. The FAGP specimens were heat-cured (80 °C) using dry oven for 24 h, the moulds were removed from the oven and left to cool to room temperature before demoulding, and the samples were kept at room temperature until being tested.

3.3. Testing

The compressive strength test was performed by MTS machine with a loading rate of 20 MPa/min according to AS 1012.9 [34]. The flexural and splitting tensile strength tests were conducted to determine the tensile strength of concretes in accordance with AS 1012.11 [35] and AS 1012.10 [36] respectively. The flexural tensile strength test was carried out on a MTS machine with additional testing apparatus under a four point bending test with a loading rate of 1 MPa/min. The splitting tensile strength test was performed on MTS machine equipped with splitting tensile strength test equipment under a loading rate of 1.5 MPa/min. The elastic modulus was determined using Tecnotest concrete testing machine coupled with the compressometer/extensometer with a loading rate of 0.25 MPa/s in accordance with AS 1012.17 [37], and dry density was measured accordance with AS 1012.12.2 [38].

The ultrasonic pulse velocity test was conducted in accordance with ASTM C597 standard [39] using a portable ultrasonic non-destructive digital indicating tester with a 54 kHz transducer. The water permeability tests were performed using the Autoclam Permeability System. Water is admitted into the test area through a priming pump and the pressure inside is increased to 0.5 bar at the end of the priming. The quantity of water flowing into the concrete is recorded every minute for duration of 15 min. The water absorption test was carried out in accordance with AS 1012.21 [40] standard to determine the immersed absorption. Immersed absorption (*Ai*) is the ratio (%) of the mass of water contained in a concrete specimen, and was used to determine the water absorption of concrete specimens. The apparent volume of permeable void (AVPV) percentage is also measured in accordance with AS 1012.21 standard [40]. The specimens of 100 mm diameter × 200 mm long cylinders were cut into four equal slices for both experiments and the result reported is the average of the results for the four slices. All tests were conducted at 28, 56, 90, 180, 360 and 540 days of casting. The reported test results in each specific test for each concrete are an average of three samples.

The microstructure development was observed using scanning electron microscopy (SEM) imaging employing backscatter electron detector with 15 eV of energy. Energy dispersive X-ray spectroscopy (EDS) analysis was performed using Oxford instruments nano-analysis software (AZtec 2.1) to determine the chemical composition of the reacted geopolymer. Specimens were cut using a diamond saw to a size of 2–4 mm in height and 5–10 mm in diameter. The samples were subsequently carbon coated and then mounted on the SEM sample stage with conductive, double-sided carbon tape. A total of three samples were investigated for each geopolymer concrete.