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SLAG VALORISATION IN CONSTRUCTION MATERIALS: MECHANICAL PROPERTIES AND RHEOLOGY OF ALKALI ACTIVATED CONCRETE CONTAINING GGBS

Raffaele VINAI, Ali RAFEET, Marios SOUTSOS, Wei SHA

School of Planning, Architecture and Civil Engineering, Queen's University Belfast, BT9 5AG United Kingdom

r.vinai@qub.ac.uk, arafeet01@qub.ac.uk, m.soutsos@qub.ac.uk, w.sha@qub.ac.uk

Introduction

Worldwide, building sector calls for the production of 4 billion tonnes of cement annually[1], consuming more than 40 % of global energy[2]. Representing in EU28 about 8.8 % of GDP, 29 % of industrial employment and with a turnover of 92.5 billion euro in 2013[3], building sector has the potential for absorbing the high volume of slag produced by iron and steel-making industry. One opportunity is the utilisation of blast furnace slag as binder for concrete. Although already used with Portland cement (PC) in traditional concrete, increasing concerns on CO_2 emissions from PC drove the attention towards the development of cementless concrete by alkali activation of aluminosilicate precursors[4]. These materials differ from the PC in terms of mechanical and rheological properties. In this study, a blend of 60 % pulverised fuel ash (pfa) and 40 % ground granulated blast furnace slag (ggbs) has been used for concrete production. Although a vast literature is available on geopolymer and alkali activated (AA) pastes and mortars, relatively little work is focused on engineering properties of AA concrete[5-9]. AA concrete has been shown to develop higher compressive strength than the comparable reference concrete[5], but setting time and workability are more difficult to control as being dependent on several parameters (activators, slag proportion)[7-9]. Moreover, little experience exists on the effects of paste content on strength[6] and workability. The objective of this study was to analyse the effects of binder content, paste content and water to solid ratio on mechanical and rheological properties of the concrete.

Materials and methods

Ggbs utilised in this research was supplied by Hanson Ltd, UK (CaO 43.7 wt.%, SiO_2 29.4 wt.%, Al_2O_3 11.2 wt.%, MgO 6.9 wt.%, SO_3 1.8 wt.%). Pfa was supplied by Power Minerals Ltd, UK (SiO_2 46.8 wt.%, AL_2O_3 22.5 wt.%, Fe_2O_3 9.2 wt.%, CaO 2.2 wt.%). Commercial chemicals were used as activators, namely solid NaOH at commercial grade (99 % purity), prepared in solution at 30 % w/w, and sodium silicate solution with SiO_2:Na_2O ratio = 2:1. Alkali dosage (M+) was defined as the mass ratio of total Na_2O in the activating solution to the binder. Alkali modulus (AM) was defined as the mass ratio Na_2O/SiO_2 in the activating solution. The water/solids ratio was defined as the ratio between the total water mass and the mass of solid components (binder + alkalis). Paste volume was calculated as the volume of binder + activating solutions + added water. Natural aggregates were used in the following proportions (of aggregates volume): 40 % sand, 60 % coarse aggregates. Aggregates were oven dried before use and pre-wetted before mixing to bring them to saturated-surface-dry conditions. Curing was carried out in plastic boxes (> 90 % relative humidity) kept at 20 °C. 10 mixes (labelled C1 to C10, Table 1) were cast. Pfa/ggbs ratio was set at 60 %/40 % (in weight), while the alkali dosages were M+ = 7.5 and AM = 1.25. 9 cubes (100 mm) were cast for testing at 1, 7, and 28 days for all mixes apart from C1, where 15 cubes (100 mm) for testing at 1, 7, 28, 56 and 90 days, plus 3 cylinders (diam. 100 mm, h. 200 mm) for determining the elastic modulus at 28 days were cast. 3 cubes of C1 were used for ultrasonic wave propagation velocity measurement (UPV), with daily readings until 28 days and on a weekly base thereafter.

Results and discussion

Table 1 summarises the mix parameters and obtained results. Some mixes were unsuccessful: C2 set in the mixer; C5 was too dry and only 6 cubes were cast; C9 was too dry and no cubes were cast.

Table 1: Mixes data, uniaxial compressive strength (UCS), standard deviations in bracket

Label	Binder cont. (kg/m^3)	w/s ratio	Paste volume	UCS 1day (MPa)	UCS 7days (MPa)	UCS 28days (MPa)	Slump (mm)
C1*	514	0.37	43.9%	12.2 (1.1)	41.8 (1.6)	61.8 (1.7)	280
C2	500	0.30	38.1%	-	-	-	-
C3	450	0.37	37.8%	14.6 (0.4)	49.0 (2.3)	70.4 (0.1)	280
C4	400	0.37	33.3%	8.2 (0.1)	44.9 (0.7)	69.1 (1.4)	220
C5	350	0.37	29.4%	2.8 (0.3)	35.1 (1.5)	-	10
C6	350	0.40	30.4%	4.0 (0.1)	38.5 (1.0)	60.4 (0.4)	35
C7	400	0.40	34.9%	14.7 (0.5)	42.3 (1.8)	66.7 (1.1)	260
C8	450	0.34	36.4%	15.3 (1.7)	47.0 (0.8)	72.3 (1.4)	190
C9	400	0.34	32.4%	-	-	-	-
C10	350	0.45	32.4%	3.4 (0.5)	33.2 (1.0)	56.1 (1.7)	155

* UCS 56 days: 63.8 (1.4) MPa; UCS 90 days: 65.8 (4.7) MPa.

The results led to the following conclusions:

- The higher the binder content, the higher the compressive strength. The only exception was C1, which showed a reduction in strength compared with binder content of 400 and 450 kg/m^3. The high paste volume presumably brought segregation effects of aggregates, and the final strength was affected by the uneven aggregate distribution in the matrix.
- Binder content of 450 kg/m^3 gave the highest strength (C8, 72 MPa after 28 days).
- With binder contents higher than 350 kg/m^3, slump was usually higher than 190 mm. When low binder content was utilised (350 kg/m^3) slump values lower than 50 mm were recorded for w/s ratios up to 0.40 (C6).
- Mixes with low w/s ratios showed very fast setting. When w/s = 0.30 was used (C2), the mix set in the mixer bowl. The reduction of w/s ratio is not therefore a viable way for controlling the workability of the mixes, as it has lower threshold related to the setting time. Some mixes were too dry to be cast properly (only 6 cubes cast for C5, no cube cast for C9 due to low paste content and low w/s ratio).
- Increase of binder from 350 to 450 kg/m^3 resulted in a strength reduction of about 13 MPa. However, 60 MPa were achieved with the low binder content.
- W/s ratio effect on strength was moderate (reduction of about 3 MPa) for values until 0.40. Afterwards the strength reduction was more pronounced.

Ultrasonic wave propagation velocity (UPV) and elastic properties

UPV and elastic modulus were measured on C1 samples. Results from UPV and the obtained relationship between UPV and UCS are shown in Figure 1. The obtained relationship is linear, whereas the models proposed in literature for UPV vs UCS follow an exponential trend. UPV is influenced by the elastic modulus and the density of the material[10]. For concretes, these properties are related to the type and proportion of aggregates, physical properties of the paste (which relate to the w/s ratio), binder composition and maturity of the concrete. Instead, the strength of a geopolymer AA concrete is related to w/s ratio, binder composition, and activators dosage. Thus, correlations between the pulse velocity and strength of concrete have to be established for each specific concrete mix.

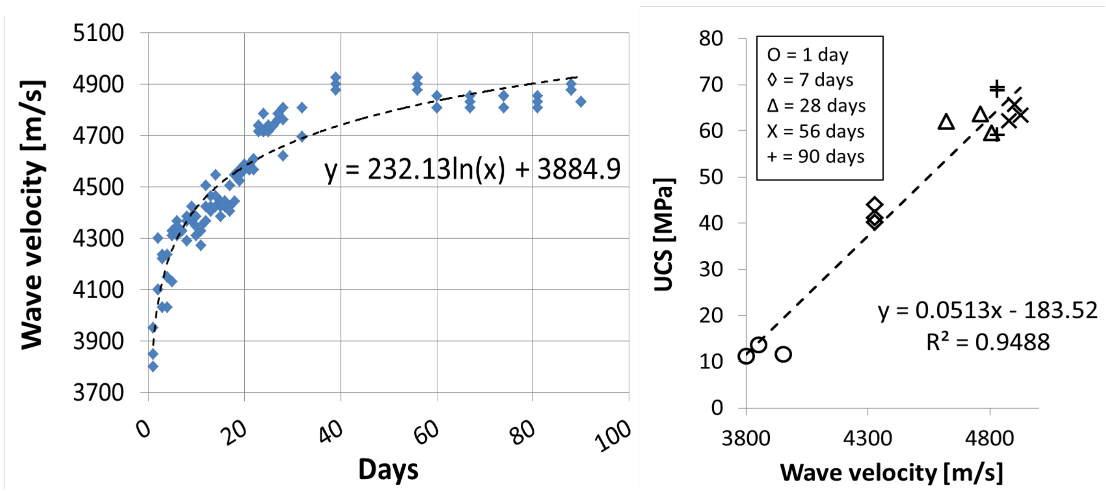

Figure 1: (left) UPV measurements on C1 samples over 90 days. (Right) relationship between UPV and UCS for C1 at different ages (from 1 to 90 days).

From the theory of elastic wave propagation, the dynamic elastic modulus can be calculated as a function of UPV, density and Poisson's ratio. Considering the values of these factors in this case, E_{dyn} at 28 days can be estimated at 48–50 GPa.
The static elastic modulus has been measured on 3 cylinders by means of two LVDT transducers mounted on the opposite sides of samples, with a measurement base of 100 mm, following the BS standard[11]. Calculated E_{st} at 28 days was 25.6 ± 0.75 GPa.
It is observed that E_{st} is about one half of the E_{dyn}. This difference is due to the dissimilar levels of applied strain involved in the two tests. Literature results on rocks samples show that E_{dyn} was consistently greater than E_{st}, even up to 4–8 times[12].

Conclusions

The following conclusions can be drawn:

- high binder content led to higher strength but did not allow the control of workability of the mix. Reduction of paste volume has an effect on the strength development (about 13 MPa) but high strengths can still be obtained (> 60 MPa);
- w/s ratio plays a role in the setting time and therefore a minimum w/s ratio exists for each binder blend that allows a reasonable setting time (i.e. greater than 60 min) that should not be exceeded. W/s ratio does not affect dramatically the strength development except in the case of very high values (≥ 0.40);
- UPV measurements showed a relationship with strength, and is a useful tool for estimating the evolution of mechanical parameters of geopolymer concrete;

- static elastic modulus measured at 28 days for one sample with very high paste content was around 25 GPa, similar to PC concretes. Mixes with lower paste content would exhibit higher stiffness.

Further research is ongoing particularly on low paste proportions (≤ 33 %), to determine the effect of w/s ratio on slump and strength.

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