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Alkali activation of mortars containing different replacement levels of ground granulated blast furnace slag

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ABSTRACT

The aim of the present study is to investigate some properties of alkali-activated mortars containing slag at different replacement levels. Ground granulated blast furnace slag was used at 0%, 20%, 40%, 60%, 80% and 100% replacement by weight of cement, and liquid sodium silicate having three different Na dosages was chosen as the alkaline activator. In this research, carbonation resistance measurements and compressive and flexural strength tests were performed on the mortar specimens with size of 40 × 40 × 160 mm. The findings obtained from the tests showed that carbonation depth values of the mortars decreased with the increase of activator dosage. Additionally, compressive and flexural strength values increased with the increase in activator concentration and slag replacement level. Portland cement/slag mortars activated by liquid sodium silicate exhibited lower strength than the slag alone activated by the same activator.

1. Introduction

Most cement plants consume large amounts of energy and produce a number of undesirable products which negatively affect the environment. For this reason, the extensive investigations on alternative inorganic materials which could replace conventional cement have been recently conducted to reduce greenhouse gas emissions from cement kilns. In this regard, blast furnace slag (BFS) plays a very important role. BFS refers in particular to the slag produced from the manufacture of pig iron. If the molten slag is quenched sufficiently rapidly it forms a glassy material, when finely ground, that is called "ground-granulated blast-furnace slag" or GGBS [1]. GGBS is often used in concrete as a supplementary cementitious material with partial replacement to ordinary Portland cement (OPC). However, the low early strength of the GGBS concretes constitutes an obstacle for many applications. This problem can be overcome by using alkali-activated slag (AAS) as the type of binder which can potentially yield early high-strength concrete [2].

AAS is a blend of a vitreous blast furnace slag and activators, which are chemical species capable of enhancing slag reactivity during hydration [3]. When compared with traditional cements and concretes, AAS binders present some advantages such as earlier and higher mechanical strengths, lower heat of hydration and stronger resistance to chemical attack [4]. Many valuable research results have been reported on AAS binders which have recently received much attention from the academic field. Bakharev et al. [5] studied alkali activation of Australian slag cements. They reported that liquid sodium silicate provided the best activation compared to sodium hydroxide and sodium carbonate activators in terms of compressive strength. Liquid sodium silicate with a SiO_2/Na_2O ratio (modulus, Ms) of 0.75% and a 4% sodium concentration was recommended for use in AAS concrete. Bakharev et al. [6], studying the effect of elevated curing temperature on properties of AAS concrete, concluded that heat treatment considerably accelerates strength development, but at later ages the compressive strength was reduced compared to concrete cured at room temperature. They also concluded that heat curing considerably reduces shrinkage of AAS concrete, making it comparable to OPC concrete. Collins and Sanjayan [7,8] studied early age strength, workability and mechanical properties of AAS concrete. They concluded that one day compressive strength comparable to OPC concrete was achievable with AAS as the sole binder. Jimenez et al. [9], who studied the flexural and compressive mechanical strength of alkali-activated slag mortar, reported that liquid sodium silicate gave the highest mechanical strengths. Another important factor was the concentration of the activator, followed by curing temperature, and the fineness of the slag. Atiş et al. [10], who studied influence of activator on the strength and drying shrinkage of AAS mortar, concluded that there was an optimum SiO_2/Na_2O ratio for liquid sodium silicate to obtain the highest compressive and

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flexural tensile strength. They also reported that slag mortar made with liquid sodium silicate had a high drying shrinkage, and AAS mortar was more brittle than OPC mortar. Bakharev et al. [11] and Puertas et al. [12] also found that alkali silicate- or hydroxide-activated slag mortars and concretes are more rapidly carbonated than comparable OPC mixes, and that this degradation can lead to an important decrease in compressive strength. Byfors et al. [13] noted that AAS concrete exhibited a higher carbonation rate than Portland cement concrete for the equivalent compressive strength grade. On the other hand, Bernal et al. [14] reported that alkali-activated binders were, on the whole, highly resistant to carbonation contrary to some claims in the literature.

This investigation is focused on the effect of the GGBS replacement on carbonation and mechanical strength (flexural and compressive) properties of mortars activated by liquid sodium silicate with 4%, 6% and 8% Na.

2. Properties of materials used

2.1. Cement

The cement used was ASTM Type I normal Portland cement (42.5 MPa) with a specific gravity of 3.16 g/cm^3 and a Blaine specific surface area of 325 m^2/kg. The chemical composition is given in Table 1.

2.2. Ground slag

Ground slag was obtained from the Iskenderun Iron–Steel Factory in Turkey. Its chemical oxide composition is given in Table 1. The specific gravity of the slag was 2.81 g/cm^3 and its Blaine specific surface area was about 425 m^2/kg. It is classified as a category 80 slag according to ASTM C 989 [15] hydraulic activity index.

2.3. Alkali-activator

Liquid sodium silicate (obtained from Sisecam Soda Industrials Corp., Mersin Soda Factory) was used as the alkali activator. Liquid sodium silicate had a SiO_2/Na_2O ratio (modulus, Ms) = 2, and 38–40 Bé.

2.4. Sand

The sand was uncrushed, quartzitic, natural sand with maximum size of 4 mm. The grading complied with the requirements of ASTM C33 [16]. The absorption value of the sand was 1.2% and the relative density at saturated surface dry condition was 2.67.

2.5. Experimental program

The mortar mixture proportions were 1:2.75:0.5 by weight of cement, sand and water, respectively. GGBS was used at 0%, 20%, 40%, 60%, 80% and 100% replacement by weight of cement. For liquid sodium silicate activator, a SiO_2/Na_2O ratio (moduli, Ms) of 0.75 was chosen, and this ratio was obtained by adding NaOH to liquid sodium silicate. Sodium concentration in the mixture proportions were also chosen as 4%, 6%, and 8%. The amount of water was adjusted to obtain a 0.5 water/binder ratio for all the mortar mixes. The amount of water in the activator was taken into account. Prismatic specimens with $40 \times 40 \times 160$ mm dimensions were prepared from both OPC and OPC/slag mortar mixtures for all the testing measurements. After 24 h, the prisms were demoulded and placed in a humidity cabinet at 65% ± 5 relative humidity and 23 ± 2 °C temperature. A summary of the experimental program is presented in Table 2.

The flexural strength measurements were performed on three prismatic specimens using a third point loading test. The compressive strength measurements were carried out using six broken pieces of the prism specimens obtained from flexure test. The strength tests of the specimens were conducted at 7, 28, 90 and 180 days of age according to TS EN 1015-11 [17].

A phenolphthalein method was used to monitor the pH of mortar specimens in the carbonation experiments and the tests were conducted at 7, 28, 90 and 180 days of age. In this method, phenolphthalein is used as an indicator of the pH change in the mortar pore solution. The usual method of studying carbonation is to measure the depth of neutralisation as indicated by a phenolphthalein solution, which has been sprayed onto the fractured concrete surface. This indicator shows a magenta coloured region on the concrete where the pH value exceeds about 9 and a colourless region at the originally exposed surface where carbonation has reduced the pH to below 9. At the time of measurement, a 1% phenolphthalein solution in alcohol was sprayed on a broken surface of the mortar prism after flexural strength test, and the depth of neutralisation was measured. The values were expressed by taking the average of three prismatic specimens.

3. Results and discussion

3.1. Flexural strength

The flexural strength of the mortars was determined at 7, 28, 90 and 180 days, and the test results were presented in Table 3.

As seen in Table 3, the control mortar achieved a flexural strength of 5.1 MPa at the age of 7 days, 4.8 MPa at the age of 28 days, 5.5 MPa at the age of 90 days and 6.0 MPa at the age of 180 days. The flexural strength of liquid sodium silicate-activated mortars containing different replacement levels of GGBS varied between 1.6 MPa and 6.4 MPa at the age of 7 days, 2.2 MPa and 6.7 MPa at the age of 28 days, 2.8 MPa and 6.8 MPa at the age of 90 days, and 2.9 MPa and 7.0 MPa at the age of 180 days. The flexural strength grew with an increase in the Na content in the mix for a constant replacement level of GGBS. On the other hand, a rise in the replacement level of GGBS increased flexural strength for a particular Na dosage, and the maximum flexural strength was obtained from liquid sodium silicate-activated mortars containing 100% slag. However, it was seen that flexural strength of GGBS100 mortar activated by liquid sodium silicate with 8% Na was lower than that of GGBS80 mortar activated by liquid sodium silicate at the same Na concentration. This phenomenon could be attributed to the crackings dependent on the high shrinkage deformations resulting from high Na concentration as discussed in the literature before [18]. Also, it is thought that dry curing conditions in which mortar specimens are kept, could play an important role in the development of these cracks.

Table 1
Physical, chemical and mechanical properties of cement and GGBS.

Chemical composition (%)	Cement	GGBS	Physical properties of Portland cement	
SiO_2	19.71	36.70	Specific gravity	3.16
Al_2O_3	5.20	14.21	Initial setting time (min)	150
Fe_2O_3	3.73	0.98	Final setting time (min)	210
CaO	62.91	32.61	Volume expansion (mm)	1.0
MgO	2.54	10.12	Specific surface (Blaine) (cm^2/g)	3250
Na_2O	0.25	0.42	*Compressive strength (MPa) of cement*	
K_2O	0.90	0.76	2 Days	29.9
SO_3	2.72	0.99	7 Days	41.4
LOI	0.96	NA	28 Days	52.2
			Physical properties of GGBS	
			Specific gravity	2.81
			Specific surface (Blaine) (cm^2/g)	4250
			Pozzolanic activity index (%) of GGBS	
			7 Days	57
			28 Days	85