Resilient Structures and Sustainable Construction
Edited by Pellicer, E., Adam, J. M., Yepes, V., Singh, A., and Yazdani, S.

ISBN: 978-0-9960437-4-8

THERMAL RESISTANCE OF ALKALI ACTIVATED SLAG CONCRETE

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This study investigated the thermal resistance of Alkali Activated Slag (AAS) concrete. Alkali Activated Slag cement is an environmentally friendly alternative to Portland cement, which can be produced by using an alkaline solution to activate the binding effect of the blast furnace slag. Heat from fire changes the physical and mechanical properties of concrete. Given the decisive role of thermal resistance in the operation and performance of structures, it is necessary to evaluate the effect of heat on the performance of AAS concrete. In this study, a series of tests were arranged to examine the effect of slag percentage on thermal resistance of AAS concrete. AAS concrete samples from mixes, with different slag percentage, were subjected to 20, 200, 400, 600, and 800˚C temperature and change in their compressive strength were measured and compared with that of samples made by ordinary Portland cement concrete. The results show that the thermal resistance of AAS concrete is higher than ordinary concrete.

Keywords: Alkaline solution, Blast furnace slag, High temperature, Compressive strength, Mass reduction, Ordinary concrete.

1 INTRODUCTION

The increasing need for cement in concrete construction has had an environmental impact including about 7 percent share of CO_2 emissions to the atmosphere (Gartner 2004, Mohebi *et al*. 2015). One solution for environmentally friendly concrete production is to use alkali activated slag (AAS) concrete which is produced through the activation of slag with an alkaline solution and without use of Portland cement. Fire is one of the most dangerous phenomena that a structure may be encountered during its lifetime. The performance of normal concrete at elevated temperatures has extensively been studied and its characteristics have been well-established (Li *et al*. 2004, Ingham 2009, Xiao and König 2004). The reduction of strength of normal concrete due to physical and chemical changes in the microstructure of concrete is caused by changes in hydration products. By increasing the temperature, a decrease in the compressive strength of concrete will happen. Up to 300˚C, fine cracks are observed on the concrete surface. At temperatures above 400˚C, calcium hydroxide ($CaOH_2$) is decomposed to other products. Calcium silicate gel (C-S-H) as the major component of cement paste and the main factor influencing the strength of concrete is decomposed at 600˚C. With decomposition of hydration products at 800 ˚C concrete completely loosed its compressive strength. The aim of this study was to investigate compressive strength variations of AAS concrete containing varying amounts of blast furnace slag after heating at 20, 200, 400, 600, and 800°C. For this purpose, all specimens with the age of 7, 28, and 90 days were subjected to elevated temperature. After cooling the specimens at ambient temperature, the changes in compressive strength were measured.

2 MATERIALS AND MIX DESIGN

In this study, Esfahan Steel Company (ESC) blast furnace slag was used. Table 1 shows XRF chemical analysis of the slag. According to the specifications of the slag used in this study, CaO/SiO_2 equals 1.079 and Al_2O_3/SiO_2 is equal to 0.447.

Table 1. Chemical composition (wt%) of the ESC blast furnace slag.

Element	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O
Mass (%)	34.8	37.5	6.4	0.51	8.6	2.49	0.9	0.38

In the experimental program, a mixture of two types of alkaline solutions including sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was used. Solid sodium hydroxide was dissolved in water with a purity of 98% to obtain a concentration of 6 M. Liquid sodium silicate with a SiO_2/Na_2O ratio of 2.6 (Na_2O = 15%, SiO_2 = 39% and H_2O = 46%) was used. The materials used in this study included gravel and crushed sand in accordance with the standard ASTM C33 (2003). The sand with a fineness modulus (FM) of 2.81, sand value of 76%, aggregate density of 2.54 gr/cm^3, water absorption of 2.86% and maximum aggregate size of 4.75 mm was used. The gravel with a grain size of 4.75 to 12 mm and 12 to 19 mm, water absorption of 0.88% and aggregate density of 2.65 gr/cm^3 was used. A naphthalene-based superplasticizer in the F category of the standard ASTM C494 (2003) was used.

Table 2 shows the mix designs of the alkali activated slag concretes. The mix designs are presented for a cubic meter of the alkali activated slag concrete. The ratio of water to solids is the ratio of water to the sum of slag, solid sodium hydroxide and solid sodium silicate.

Table 2. The mix designs of the alkali activated slag concretes.

Mixture	Slag kg/m^3	Sodium hydroxide kg/m^3	Sodium silicate kg/m^3	Aggregate kg/m^3			water kg/m^3	Water/Solids	Superplasticizer kg/m^3
				Sand	4.75-12 mm	12-19 mm			
S300	300	16	40.5	959	575	384	125	0.35	3
S350	350	18.6	47.2	902	541	361	146	0.35	3.5
S400	400	21.3	54	846	507	338	166	0.35	4
S450	450	24	60.8	789	473	316	187	0.35	4.5
S500	500	26.6	67.5	733	440	293	208	0.35	5

To compare the thermal performance of alkali activated slag concrete with normal concrete, specimens of normal concrete were constructed. The mix design for this type of concrete was the same as the AASC. Table 3 shows the mix designs for normal concrete with three different grades of 300, 400, and 500 kg of cement per cubic meter of concrete.

3 MIXING AND TEST METHOD

At first, aggregates and cement were mixed together. An alkaline solution of sodium hydroxide and sodium silicate was then gradually added to the mixture. Then, water and superplasticizer were added. 150 mm cubic molds were filled and placed for 24 hours at room temperature and then the specimens were removed from the molds. The specimens were then placed in a water pond to be cured until the age of 7, 28, and 90 days. The industrial heat treatment furnace was used for heating the specimens. The furnace was used for heating the cubic specimens at 200, 400, 600, and 800°C. The specimens were maintained at each temperature for 1 h and then were taken out of the furnace. The specimens were exposed to temperature rise without an external force to reach the final temperature. The temperature remained constant for 1 h to reach thermal equilibrium. Then, the specimens were cooled down. The rate of temperature rise was adjusted according to the amount of fuel provided to the blower. Finally, to evaluate the thermal resistance of AAS specimens, compressive strength of specimens was measured at ambient temperature. Figure 1 shows cubic specimens of alkali activated slag concrete and normal concrete with Portland cement ruptured under compressive strength test. The compressive strength was obtained in accordance with standard BS 1881 (1970).

Table 3. The mix designs of Portland cement concrete.

Mix	Cement kg/m^3	Aggregate kg/m^3			Water kg/m^3	Water/Cement	Superplasticizer kg/m^3
		Sand	4.75-12 mm	12-19 mm			
C300	300	1033	620	413	105	0.35	3
C400	400	945	567	378	140	0.35	4
C500	500	856	514	343	175	0.35	5

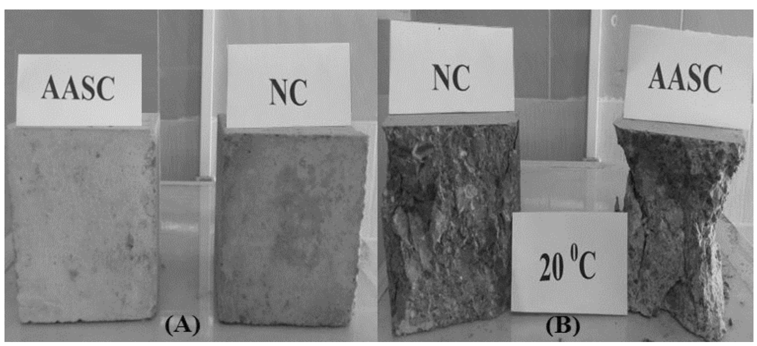

Figure 1. Alkali activated slag concrete (AASC) and normal concrete with Portland cement (NC), (A) before and (B) after compressive strength test.

4 RESULTS AND DISCUSSION

Alkali-activated slag concrete and normal concrete with Portland cement at the age of 7, 28 and 90 days after curing were heated in a fossil-fuel-fired (gas-fired) furnace at 200, 400, 600 and 800°C. The compressive strength of specimens was measured after cooling at ambient temperature.

4.1 Compressive Strength Test Results

The compressive strength of cubic specimens with dimensions of 150 × 150 × 150 mm was measured after curing in a water pond and placement in the air in accordance with the standard BS 1881 (1970). Tables 4 and 5 show the compressive strength of alkali activated slag concrete and normal concrete with Portland cement, respectively.

Table 4. Compressive strength of AAS concrete at ages of 1, 7, 28, and 90 days (MPa).

Age (days)	Mixture				
	S300	S350	S400	S450	S500
1	8.4	9.3	10.7	11.6	13.3
7	38.9	45.4	48.9	53.9	63.1
28	46.0	54.3	57.6	60.9	70.4
90	65.8	70.7	76.7	81.2	92.6

Table 5. Compressive strength of normal concrete at ages of 1, 7, and 28 days (MPa).

Age (days)	Mixture		
	C300	C400	C500
1	6.2	8.7	12.4
7	30.4	41.8	49.2
28	39.5	53.1	60.0

As is clear from the results in Table 4, the compressive strength of AAS concrete increases at all ages with increasing the slag content. Similarly, according to results presented in Table 5, by increasing the cement content, the compressive strength of concrete at the ages of 1, 7 and 28 days increases. Comparing the compressive strengths of 1, 7 and 28-day alkali activated slag concrete and normal concrete with Portland cement, it is evident that the compressive strength of alkali activated slag concrete is higher than that of normal concrete with Portland cement of the same grade. On average, the 1-day and 28-day strength of alkali activated slag concrete is 1.22 and 1.14 times the normal concrete, respectively. This can be attributed to several reasons including the finer structure of the slag compared with the normal Portland cement (slag and cement blain equal to 4,500 and 3,270 cm^2/g, respectively) leading to a denser and less porous structure of ASSC as compared with normal concrete. On the other hand, the presence of an alkaline solution of sodium silicate in AASC as a source of silica (SiO_2) increases C-S-H gel production leading to an increased compressive strength.

Table 6 presents the compressive strength of 28-day AASC specimens at different temperatures. It shows that the compressive strength decreased with increasing temperature.

Table 6. Compressive strength of 28-day AASC specimens at different temperatures.

Temperature (°C)	20	200	400	600	800
Compressive strength (MPa)	46.0	44.2	39.2	34.5	13.8

Notably, the compressive strength of AASC specimens decreased about 25% up to 600°C. This shows the high thermal resistance of alkali activated slag concrete so that it retains 75 percent of its compressive strength up to 600°C. The compressive strength of AASC specimens significantly decreased from 600 to 800°C so that 70 percent of its compressive strength was reduced. The compressive strength decreased with a gentle slope from 20 to 600°C, but a sharp decline was observed in the compressive strength from 600 to 800°C.

According to the variations of the compressive strength of normal concrete with temperature, Figure 2, the compressive strength of specimens increased at all temperatures with increasing cement content. However, the compressive strength decreases with a gentle slope up to 400˚C and then decreases sharply from 400 to 800˚C. About 50% of the compressive strength of the normal concrete is retained at 600˚C. However, about 10% of compressive strength remains at 800˚C.

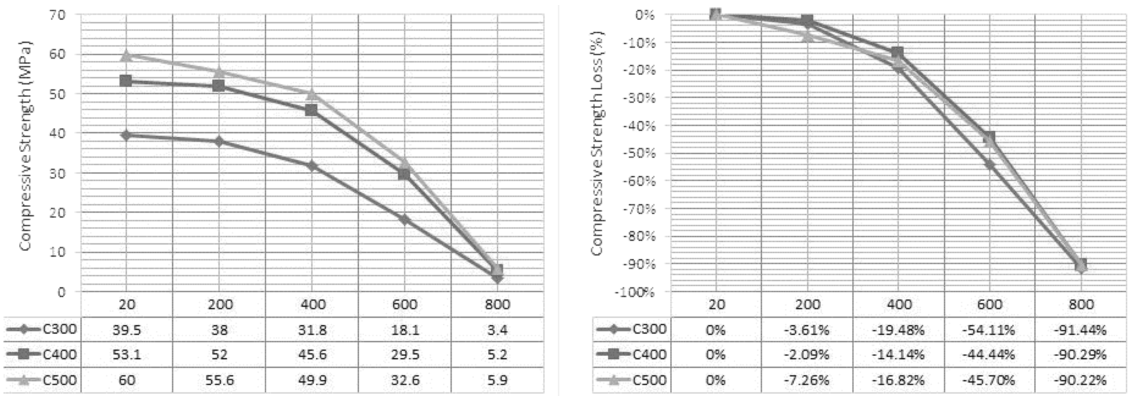

Figure 2. Compressive strength of 28-day normal concrete at different temperatures.

Comparing the results of AASC with those of normal concrete, it can be concluded that the AASC showed a higher thermal resistance than normal concrete of the same grade. Alkali activated slag concrete retained 75% and 30% of its compressive strength respectively up to 600 and 800˚C. Generally, compressive strength decreased with increasing temperature due to reduction in chemically bonded water because of dehydration and partial decomposition of C-S-H. The coarse pore structure and complete dehydration at elevated temperatures and removal of water from hydrated pores to the extent that happened in the first stage of dehydration can be noted as other reasons. On the other hand, the main reason for the significant reduction in compressive strength at temperatures above 600˚C is the rupture of C-S-H gel as the main factor influencing the concrete strength.

5 CONCLUSION

Based on the results obtained in this study the following conclusions can be drawn:

1. The compressive strength of AASC increased with increasing slag content of the alkali activated slag concrete.
2. The compressive strength of alkali activated slag concrete was higher than that of normal concrete with Portland cement. The compressive strength of 28-day and 90-day alkali activated slag concrete was respectively 1.15 and 1.5 times that of normal concrete.
3. The compressive strength of concrete decreased with increasing temperature. At 800˚C, the compressive strength of alkali activated slag concrete and normal concrete decreased 70 and 90%, respectively.
4. The thermal resistance of alkali activated slag concrete was higher than that of normal concrete. In general, the alkali activated slag concrete showed a very good thermal performance.

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