Construction and Building Materials 154 (2017) 229–235

Contents lists available at ScienceDirect

Construction and Building Materials

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

Performance of geopolymer concrete composed of fly ash after exposure to elevated temperatures

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HIGHLIGHTS

- The temperature performance of Fly Ash alkali-activated concretes was evaluated.
- The residual strength of FA/GBFS concrete at 700 °C was 23,71 MPa.
- The residual strength of FA/OPC and FA/GBFS at 1100 °C was 5.5 MPa and 15 MPa respectively.
- New crystalline phases at 1100 °C were identified.
- These concretes perform better at high temperatures compared to Portland concrete.

ARTICLE INFO

Article history:
Received 10 May 2017
Received in revised form 11 July 2017
Accepted 29 July 2017
Available online 4 August 2017

Keywords:
Fly ash
Granulated blast furnace slag
Concrete
Alkali-activated concrete
Thermal behaviour

ABSTRACT

Alkaline activated concretes based on a mixture of fly ash (FA) and blast furnace slag (GBFS), as well as FA and Portland cement (OPC), both at a ratio of 80:20, were exposed to temperatures between 25 °C and 1100 °C. Then, the physicochemical and mechanical changes were evaluated. The results indicate that the activated concretes have better performance than the reference ones (100% OPC). At temperatures of 1100 °C, the residual strengths of the FA/GBFS and FA/OPC concretes are 15 and 5.5 MPa, respectively, unlike the OPC concrete that lost 100% of its strength. At temperatures above 900 °C, the activated matrix densified, and the crystalline phases, such as sodalite, nepheline, albite and akermanite, are identified.

1. Introduction

Portland cement concrete is one of the most utilized materials in the construction world, and it traditionally incorporates Portland cement (OPC) in a range between 10 and 15% of its total mass; the rest of the concrete is composed of coarse and fine aggregates, water and potentially other components or additives. However, the production of OPC has led to great environmental concerns because of the high generation of CO_2 when produced, which is estimated to be between 0.7 and 1 ton per ton of OPC [1], as well as the excessive consumption of natural resources, such as limestone and energy, needed in its production. Furthermore, it must be kept in mind that concretes made of Portland cement have some durability problems [2,3] (sulphate attack, corrosion of reinforcement, alkali-aggregate reaction, low fire resistance, etc.), which are difficult to solve; 40–50% of the construction industry's budget is used for repairs of concrete. All this makes the search for alternative cementing materials that reduce CO_2 emissions to the atmosphere and improve some of the deficiencies of Portland cement one of the main objectives of the scientific community, along with the development of new materials and technologies that allow an advancement towards a more sustainable construction industry. Alkaline cements meet these criteria [1,4].

Alkaline cements are obtained through a reaction between a preferably aluminosilicate type material and a solution of alkaline activators. Depending on the chemical composition of the raw material, the reaction product could be a three-dimensional aluminosilicate gel (for low Ca systems) or a hydrated calcium silicate gel with a high grade of substituent aluminium (for high Ca systems) [5–7]. The raw material for the production of alkaline activated cements usually comes from industrial by-products, e.g., fly ash and blast furnace slag, which can replace cement clinker by up to 100% in activated systems. For this reason, alkaline activated cements are generally considered to be environmentally

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http://dx.doi.org/10.1016/j.conbuildmat.2017.07.208

friendly construction materials that have a great potential for sustainable development. In addition, concretes made with alkaline cements can exhibit properties such as high strength at early ages, high resistance to chemical attack, and good resistance to fire [8–14]. However, most studies conducted to evaluate the thermal stability of alkaline activated concretes are limited to temperatures up to 800 °C [13–18].

Generally, when conventional Portland concrete is exposed to fire, it reaches temperatures of approximately 800 °C within the first 30 min. After this temperature is reached, the rate of the temperature rise becomes very slow and is approximately constant between 1000 and 1100 °C, which is achieved in approximately 2.0–2.5 h [11]. Once a concrete structure is continuously exposed to this intense fire, severe shedding of the concrete and structural damage occur. The damage affects the stability of the structural steel, and as a result, it can cause the structure to collapse with obvious consequences of risk to human life and high economic costs. Portland cement pastes play a predominant role in this behaviour. This is attributable, among other factors, to the decomposition of the Portland cement hydration products responsible for the mechanical properties of the concrete. In contrast, in alkaline activated concretes, it is claimed that the high temperatures can contribute to the partial sintering of their components, which could significantly increase the compressive strength [16,17,19–22]. Davidovits (2008) determined that materials with both sodium and potassium exhibited excellent fire resistance up to 1200 °C [23]. Barbosa and MacKenzie (2003) found similar results for mixtures of activated metakaolin with sodium hydroxide and sodium silicate [19]. They determined that there was a contraction due to water loss between 100 and 200 °C; between 250 and 800 °C, they found that the samples did not show dimensional changes; and above 800 °C, there was a change in density or a change in volume due to the crystallization of new phases. These authors, however, do not believe that this contraction is caused by a melting point or a viscous flowing process. In any case, they consider that this process stops abruptly between 880 and 900 °C. The sample then retains its dimensional stability until it finally melts at temperatures of 1000–1300 °C, depending on slight variations in the composition. Bakharev (2006) found that Na-activated fly ash exposed to a temperature of 800 °C exhibits cracking due to shrinkage and a slight decrease in strength, which is related to a drastic increase in the mean pore size and deterioration of the aluminosilicate gel [16]. Martin et al., (2015) studied the behaviour of alkaline activated cements based on activated fly ash with a solution of sodium silicate and sodium hydroxide and compared them with conventional cement based samples (OPC) [22]. The authors reported that the alkaline activated samples showed an increase in strength above 600 °C, unlike the OPC samples, which, at this same temperature, exhibited a total loss of mechanical strength.

Based on the above results, the objective of the present study was to evaluate the performance of alkaline activated concretes composed of a binary mixture of a Colombian fly ash (FA) from an industrial boiler with blast furnace slag (GBFS) or with type I Portland cement (OPC), both in proportions of 80/20, which were exposed to temperatures of 25, 300, 500, 700, 900 and 1100 °C. The behaviours of these mixtures were compared with that of a conventional concrete.

1. Materials and experimental procedure

2.1. Materials

In the present study, fly ash (FA), a by-product of coal combustion in a boiler located in a paper mill, was used as the precursor of the alkaline activated concrete. The chemical composition of the FA, determined using X-ray fluorescence, is presented in Table 1. It is composed of approximately 56.5% silica, alumina and iron oxides and has a low content of calcium oxide (6.68%). The high unburned content (LOI = 20.67%) is noteworthy because it is a value that grossly exceeds the limit in ASTM C618 (6% maximum), as is the relatively high content of sodium oxides (7.94%). These latter characteristics limit the use of this material as a pozzolanic addition to Portland cement and justify the search for other recovery alternatives.

Binary mixtures of fly ash with blast furnace slag (GBFS) and Portland cement (OPC) in proportion 80/20 were prepared. The slag comes from the *Acerías Paz del Río Company*, which, according to the chemical composition included in Table 1, has a quality coefficient ($((CaO + MgO + Al_2O_3)/(SiO_2+TiO_2))$) and a coefficient of basicity ($K_b = CaO + MgO/SiO_2 + Al_2O_3$) of 1.92 and 1.03, respectively, which means that it is classified as a neutral slag. The OPC used in the mixture (Table 1) corresponds to a highly blended cement, in this case with the addition of limestone (estimated percentage 20%). The mean particle size D(4;3), determined using the laser granulometry technique in a Mastersizer 2000 device, was 22.1 μm, 17.8 μm and 21.5 μm for the FA, GBFS and OPC, respectively. A mixture of commercial sodium silicate (Na2SiO3·nH2O), with the composition by mass of SiO2: 32.24%, Na2O: 11.18% and H2O: 55.85%, and 96.7% pure industrial sodium hydroxide (NaOH) was used as alkali activator. NaOH pellets were dissolved in water and after 30 min was added the silicate solution; the proportion of each one was selected to obtain the molar ratios specified in the mix.

Table 1
Bulk Chemical composition of materials (% of oxides by mass).

Oxides, %	FA	GBFS	Cement (OPC)
SiO_2	28.53	31.99	20.20
Al_2O_3	19.18	14.54	7.00
Fe_2O_3	8.80	1.12	4.80
Na_2O	7.94	0.23	–
CaO	6.68	46.86	58.40
SO_3	2.71	0.82	–
MgO	2.24	1.05	–
TiO_2	1.62	0.54	–
Others	1.65	1.03	–
LOI	20.67	1.82	9.60

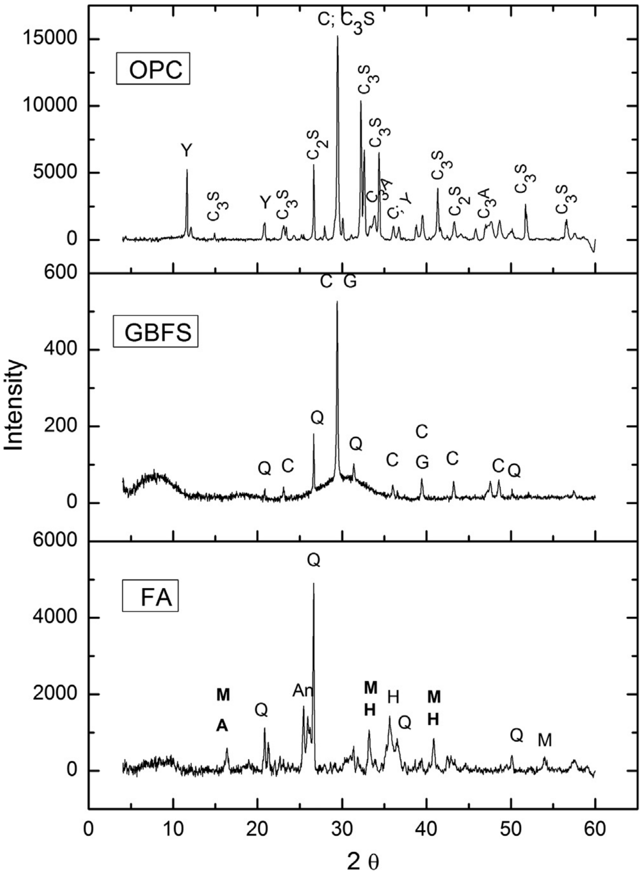

Fig. 1. Mineralogical composition of the raw materials (XRD).