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Effect of fire exposure on cracking, spalling and residual strength of fly ash geopolymer concrete

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ABSTRACT

Fly ash based geopolymer is an emerging alternative binder to cement for making concrete. The cracking, spalling and residual strength behaviours of geopolymer concrete were studied in order to understand its fire endurance, which is essential for its use as a building material. Fly ash based geopolymer and ordinary portland cement (OPC) concrete cylinder specimens were exposed to fires at different temperatures up to 1000 °C, with a heating rate of that given in the International Standards Organization (ISO) 834 standard. Compressive strength of the concretes varied in the range of 39–58 MPa. After the fire exposures, the geopolymer concrete specimens were found to suffer less damage in terms of cracking than the OPC concrete specimens. The OPC concrete cylinders suffered severe spalling for 800 and 1000 °C exposures, while there was no spalling in the geopolymer concrete specimens. The geopolymer concrete specimens generally retained higher strength than the OPC concrete specimens. The Scanning Electron Microscope (SEM) images of geopolymer concrete showed continued densification of the microstructure with the increase of fire temperature. The strength loss in the geopolymer concrete specimens was mainly because of the difference between the thermal expansions of geopolymer matrix and the aggregates.

1. Introduction

The global demand of concrete continues to increase in order to meet the increasing demand of infrastructures. Ordinary portland cement (OPC) has been traditionally used as the binder for concrete. However, cement production is associated with the emission of considerable amount of greenhouse gases. Therefore, development of alternative binders utilising industrial by-products is considered vital to help reduce the carbon footprint of concrete production. Geopolymer is an emerging alternative binding agent that uses an industrial by-product material instead of cement. A base material that is rich in silicon (Si) and aluminium (Al) is reacted by an alkaline solution to produce the geopolymer binder. The base material for geopolymerisation can be a single material or combination of various materials. Materials such as low calcium fly ash [1,2], high calcium fly ash [3], metakaolin [4], blast furnace slag [5,6] and a combination of fly ash and blast furnace slag [7] have been used to produce geopolymer binders. Although different source materials can be used to manufacture geopolymer binders, low-calcium fly ash has been extensively used and found to be the most practical source material suitable for concrete applications. The coal-fired power stations generate substantial amount of fly ash as by-products. Therefore, the use of fly ash based geopolymer concrete (GPC) in constructions have the potential to reduce the carbon footprint of concrete manufacture.

The results of recent studies [8–11] have shown the effectiveness of low-calcium fly ash based geopolymer concrete as a construction material. As a relatively new construction material, it is essential to study the performance of geopolymer concrete in various structural applications. The previous research on fly ash based geopolymer concrete studied numerous short-term and long-term properties. Various parameters influencing the strength of geopolymer concrete were investigated [1,2]. It was shown that heat-cured geopolymer concrete possesses high compressive strength, undergoes low drying shrinkage and moderately low creep, and shows good resistance to aggressive agents such as sulphate. Geopolymer concrete shows good bond strength with reinforcing steel, which is essential for its function as a composite material in reinforced concrete structures [9]. Reinforced geopolymer concrete beams and columns showed similar behaviour to that of traditional OPC concrete members [12–15]. Therefore, heat-cured fly ash based geopolymer concrete is considered as an

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ideal construction material for precast concrete elements such as beams, columns, slabs, walls and similar other structural members for building constructions.

In addition to other structural behaviours, it is vital to understand the fire endurance of a construction material in order to ensure safety for life and property. The extent of cracking, spalling and residual strength of a material after exposure to high temperature fire gives indication of the fire endurance of the material. This paper presents a study on the fire endurance of fly ash based geopolymer concrete.

Molecular structures are stable at certain temperatures. This stability is affected when the temperature conditions change. The temperature level is the fundamental parameter that affects molecular structure and hence is responsible for material deterioration. Exposure time and heating rates are also important parameters. In a composite material such as concrete, the difference between the thermal expansions of the aggregates and the binder matrix causes stresses at the interface which may result in cracking. Despite being classified as an indirect effect of temperature, micro cracking due to incompatible expansion can be the main cause of failure of a composite material in a fire. The molecular changes and microstructural stresses cause deterioration of compressive strength and other mechanical properties of the material.

Portland cement based concrete is a composite material that mainly consists of aggregates, cement and water. It is a reasonably dense and porous material, and it undergoes the damage mechanisms in fire. Khoury [16] proposed dissociation of $Ca(OH)_2$ at 300–400 °C, massive and sudden creep, usually causing failure at 600 °C, dissociation of $CaCO_3$ at 700 °C, ceramic binding and complete water loss at 800 °C and melting at 1200–1350 °C. Heikal [17] found that $Ca(OH)_2$ dehydrated between 500 and 600 °C. Mohamedbhai [18] studied the effects of exposure time and rates of cooling on residual strength of heated concrete, using 100 mm cubic samples. The exposure time of 1–2 h was found to be enough for the temperature to penetrate the 100 mm cubic samples and cause most of the compressive strength loss. The effect of higher temperature reduced the time required to cause strength loss, which is related to the increase of thermal conductivity at higher temperatures. After 1 h exposure, the residual strength was 80%, 70%, 60% and 30% for 200, 400, 600 and 800 °C respectively. Rates of heating and cooling showed no effect on the residual strength of concrete heated to 600 °C and beyond, but had some effect at lower temperatures, possibly due to the buildup of pore pressure. The effects of cooling on concrete were examined by Khoury [19]. Cooling strains (shrinkage) was found to be a function of the aggregate cement interaction causing cracking and not related to concrete age, initial moisture content or heating rate.

Poon et al. [20] studied normal and high strength concretes with pozzolanic materials. Metakaolin concrete increased strength up to 200 °C, and maintained higher strengths up to 400 °C than fly-ash concrete, silica fume concrete and normal OPC concrete. After 400 °C all the high strength concretes rapidly deteriorated. The metakaolin concrete had the lowest final residual compressive strength despite showing better early strength gain, indicating that it is particularly susceptible to a certain high temperature range. Variations in the performance of pozzolanic concretes in high temperature exposure are common. High early strength gains and good stability between 200 and 400 °C followed by rapid deterioration and final compressive strength lower than normal concrete is commonly reported [20,21]. Li et al. [22] studied the effect of high temperature heat and strain rate on the residual strength of ternary blended concrete containing fly ash and silica fume. Remarkable strength loss was reported after 400 °C.

Kong and Sanjayan [23] reported a 25% reduction in compressive strength of 25 mm cube metakaolin based geopolymer paste specimens after 10 min exposure at 800 °C. Cheng and Chiu [24] conducted tests on 10 mm thick small geopolymer panels made of metakaolin and granulated slag filler. One side of the panel was exposed to 1100 °C heat and the temperature on the other side was measured as 350 °C after 35 min. As a relatively new material, test results on the behaviour of fly ash based geopolymer concrete subjected to fires at different temperature are scarce in literature. Some initial studies [25,26] showed that fly ash geopolymers gained strength at exposure to relatively low temperature heat such as 200 °C and lost strength at exposure to heats of higher temperature. Therefore, a comprehensive study was conducted to understand the changes that occur in low-calcium fly ash based geopolymer concrete when subjected to fires at higher temperatures. This paper presents a study on the behaviour of geopolymer concrete specimens exposed to fires at temperature up to 1000 °C. The specimens were exposed to fires of different peak temperatures following the heating rate of ISO 834 [27] fire curve in a gas fired furnace. The peak temperature was maintained for certain duration and then the specimens were cooled down to room temperature. The extent of heating inside the specimens and the resulting cracking and spalling were observed before conducting the compression tests to determine the post-fire residual strengths. Companion OPC concrete specimens were subjected to fires of same temperature profile and tested similarly. Comparisons are then made between the results obtained for the two types of concrete experiencing the same fire exposure.

2. Experimental details

Fire has a significant impact on materials. A building fire can reach 850 °C in less than 30 min, and peak at around 1000 °C within 2 h. A petrochemical fire can reach 900 °C within the first 5 min and peak at around 1100 °C. Tunnel fires have similar heating rate to petrochemical fires but can reach 1350 °C in the first hour [16]. Design codes such as ISO 834 [27] and AS 1530 [28] provide standard fire curves for testing of materials though a real fire can be different in different situations because the parameters like combustibility of the material, location, humidity and air flow are not likely to be the same in any two fires.

In this study, standard 100 mm × 200 mm geopolymer and OPC concrete cylinder specimens were subjected to fires up to 1000 °C with the heating rate similar to that of ISO 834 standard. Both types of concrete cylinders were exposed to identical temperature profile and the transfer of heat inside the specimens was recorded by using thermocouples. The damages in terms of cracking and spalling of the specimens during fire exposure and after cooling down to room temperature were determined. The specimens were then weighed to determine the mass loss and subjected to compression tests to determine the residual strengths. Scanning electron microscopic images were obtained to observe the microstructure of the geopolymer matrix after exposure to high temperature fires.

2.1. Materials

Concrete was mixed in the laboratory to cast the test specimens. General purpose Portland cement was used for OPC concrete. Commercially available Class F (ASTM: C618) fly ash was used to manufacture geopolymer concrete. The percentage of the fly ash passing through a 45 μm sieve was 75%. The chemical compositions of the cement and fly ash are given in Table 1. The alkaline liquids for geopolymer concrete were sodium hydroxide and sodium silicate solutions. Commercial sodium hydroxide pellets were dissolved in water to make 14 M solution. The sodium silicate solution had a mass composition of 14.7% Na_2O, 29.4% SiO_2, and 55.9% water. Both the liquids were mixed together before adding to fly ash and aggregates. The coarse aggregates were 10 and 20 mm nominal size crushed granites. The sand used was river