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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 behaviors 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 ^{o}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 to 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 ^{o}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.

Keywords: fly ash, geopolymer concrete, post-fire strength, spalling.

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 aluminum (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 behavior to that of traditional OPC concrete members [12-15]. Therefore, heat-cured fly ash based geopolymer concrete is considered as an 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 behaviors, 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 ^{o}C, massive and sudden creep, usually causing failure at 600 ^{o}C, dissociation of $CaCO_3$ at 700 ^{o}C, ceramic binding and complete water loss at 800 ^{o}C and melting at 1200-1350 ^{o}C. Hiekal [17] found that $Ca(OH)_2$ dehydrated between 500 and 600 ^{o}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 to 2 hours 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 hour exposure, the residual strength was 80, 70, 60 and 30% for 200, 400, 600 and 800 ^{o}C respectively. Rates of heating and cooling showed no effect on the residual strength of concrete heated to 600 ^{o}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 et. al. [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 ^{o}C, and maintained higher strengths up to 400 ^{o}C than fly-ash concrete, silica fume concrete and normal OPC concrete. After 400 ^{o}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 ^{o}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 ^{o}C.

Kong and Sanjayan [23] reported a 25% reduction in compressive strength of 25 mm cube metakaolin based geopolymer paste specimens after 10 minutes exposure at 800 ^{o}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 ^{o}C heat and the temperature on the other side was measured as 350 ^{o}C after 35 minutes. As a relatively new material, test results on the behavior 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 ^{o}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 behavior of geopolymer concrete specimens exposed to fires at temperature up to 1000 ^{o}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 ^{o}C in less than 30 minutes, and peak at around 1000 ^{o}C within 2 hours. A petrochemical fire can reach 900 ^{o}C within the first 5 minutes and peak at around 1100 ^{o}C. Tunnel fires have similar heating rate to petrochemical fires but can reach 1350 ^{o}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 ^{o}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 14M 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 sand. Tap water was used in mixing of the concretes. The mixture proportions of the OPC and geopolymer concretes are given in Table 2. The concretes were mixed in a pan type laboratory concrete mixer. Standard slump tests were carried out to determine the workability of fresh concrete. The slump value of OPC concrete was 100 mm and that of geopolymer concrete was 250 mm. Both the concretes had reasonable workability at these values of slump.

2.2 Casting and curing of test specimens

Standard 100 mm × 200 mm cylinders were cast using the OPC and GPC mixtures given in Table 2. Some of the freshly cast cylinder specimens are shown in Figure 1. As shown in Figure 2, a thermocouple was inserted at the centre of some cylinders to measure the temperature at that point during heating of the cylinders inside the furnace. The OPC concrete specimens were cured in water and the geopolymer concrete specimens were heat-cured by using steam. The geopolymer concrete cylinders were divided into two groups and subjected to two different curing regimes. The specimens of the first group were subjected to steam curing at 60 ^{o}C for 24 hours immediately after casting. Steam curing of the second group of specimens started three days after casting and the curing was done at 80 ^{o}C for 24 hours. It was shown by Hardjito et al. [29] that strength of geopolymer concrete increased by increasing of the curing temperature and applying a rest period of up to three days before the start of the steam curing. Therefore, different curing regimes were used to the geopolymer concrete cylinders to achieve a normal strength and a higher strength after the different types of steam curing regimes. The cylinders of the first curing regime are designated by GPN and those of the second curing regime are designated as GPH.

2.3 Test procedure

The specimens were exposed to fire at the age of 28 days after casting. Figure 3 shows a set of cylinders inside the gas fired furnace ready for fire exposure. The door of the furnace was closed and the flame was increased by controlling the flow of gas. This condition of heating the cylinders simulated heating of the concrete from all the sides. This heating is considered to be critical for damage of the concrete by differential temperature between the external surface and inside of the cylinder. The door of the furnace was kept closed during the heating period. The geopolymer and OPC concrete specimens were exposed to fire in the same way. The fire in the furnace was controlled to achieve the initial heating rate of the temperature-time curve recommended in the standards for fire test of building materials. The temperature-time curve recommended in the Australian standard [28] is given by Equation 1.

$$T_t = T_0 + 345\, log_{10}\,(8t + 1) \qquad (1)$$

Where T_t is furnace temperature (^{o}C) at time t (minutes) and T_o is the initial furnace temperature (^{o}C).

The temperature of the air inside the furnace was measured by an in-built thermocouple of the furnace. The temperature at the centre of the cylinder was measured by a K-type thermocouple inserted in the specimens during casting. The thermocouples were connected to electronic data loggers that recorded the measured temperatures. The cylinders were subjected to the peak temperatures of 400, 650, 800 and 1000 ^{o}C. Once the desired peak temperature of the furnace air was achieved, it was maintained in order to raise the temperature inside the cylinder. As expected, the temperature rise at the centre of the cylinder was slower than that of the furnace air. The cylinders were heated for duration of 150 minutes. The temperature at the centre of the cylinders reached the peak furnace air temperature during the heating period. The typical temperature – time variations of the furnace air and at the centre of the cylinders are shown in Figures 4 and 5. The furnace was turned off after heating the specimens for 150 minutes and the specimens were then left to cool down to room temperature by opening the door of the furnace. After cooling down to room temperature, the specimens were tested for concentric compression using a universal testing machine.

3. Test Results and Discussion

3.1 Development of compressive strength

The concrete specimens were tested for compressive strengths at different ages up to 28 days to determine the strength development before exposure to fire. The OPC concrete cylinders were subjected to water curing and the geopolymer concrete cylinders were subjected to two different regimes of steam curing. The geopolymer concrete specimens of group GPN were steam-cured at 60 ^{o}C immediately after casting and those of group GPH were given a rest period of 3 days before beginning of the steam-curing at 80 ^{o}C. The strength developments of the three types of concrete are shown in Figure 6. It can be seen from the figure that the rest period and higher curing temperature contributed to an increase in strength of the geopolymer concrete specimens of group GPH as compared to the specimens of group GPN. There was very little gain in strength in the geopolymer concrete specimens after completion of the steam curing. As usual, strength of the OPC concrete specimens continued to increase gradually to the age of 28 days. The trends of strength development in the geopolymer concrete specimens are similar to those observed by Hardjito et. al. [29].

3.2 Transfer of heat inside concrete

Typical temperature – time curves recorded in the centre of the concrete cylinders exposed to fire are shown in Figures 4 and 5. It can be seen that generally the temperatures at the centre of the geopolymer concrete specimens were higher than those of the OPC concrete cylinders at a given time when the specimens of both types of concrete were subjected to same furnace air temperature. Thus, the peak temperature reached the centre of the geopolymer concrete specimens earlier than in the OPC concrete specimens. This indicates a higher conductivity of the geopolymer concrete as compared to that of the OPC concrete at elevated temperature. This can be considered to be because of the higher content of metal ions such as silicon, aluminium and iron in the fly ash based geopolymer matrix as compared to those in the OPC matrix. The higher contents of these metal oxides in fly ash than in OPC can be seen in Table 1.

3.3 Cracking, spalling and change in appearance of the concrete specimens

The changes in the physical appearance of the geopolymer concrete cylinders of group GPN and GPH are shown in Figures 7 and 8 respectively. There was an obvious colour change in geopolymer concrete after the exposure to the four different temperature ranges. At 400 °C there was not a huge change in colour for the geopolymer concrete samples, with both the GPN and GPH samples displaying a very similar surface colour with the GPH sample having only a slight light brown tinge to it. At 650 °C, the geopolymer concrete specimens displayed a very similar surface colour, but it had changed to a light brown colour. At 800 °C, there was a clear difference from the original colour with both the high and normal strength concretes displaying a dark red colour. Parts of the surface were quite black, but this was able to be rubbed off to reveal the earthy red colour below. At 1000 °C, the red colour became very prominent, with the high strength geopolymer concrete being more distinctive than the normal strength geopolymer concrete. The colour changes of the geopolymer concrete samples were because of the high iron oxide content of the fly ash. A similar colour change to brown in fly ash geopolymers subjected to high temperature heat was also observed by Zhao and Sanjayan [30].

The changes in the physical appearance of the OPC concrete cylinders at different temperature exposures are shown in Figure 9. As shown in the figure, OPC concrete did not display much change in colour when exposed to various temperatures. The only visible difference was that the grey colour became slightly lighter after exposure to the higher temperature fires. This was due to the higher reduction of moisture in the specimens.

Due to the temperature differential between the surface and the centre of the specimens, surface cracking was very prominent in many of the samples after exposure to fire. The most noticeable surface cracking was found in the OPC concrete specimens, due to the rapid moisture loss of the concrete. The surface cracking has occurred also as a result of the differential strain which is caused by a temperature gradient through the cross section of the concrete. At some stages during the fire exposure, the temperature differential between the centre and surface of the specimens was as high as 600 °C which created large amount of differential strain. This huge differential strain caused large amounts of surface cracking, with more cracking evident in the samples exposed to the higher temperature ranges.

The cracks on the surface of specimens were generally evident after exposure to the higher temperature ranges. Heating of the inside of geopolymer concrete was faster and the temperature gradient between the surface and the core was higher in OPC concrete as indicated by the temperature profiles presented in Figures 4 and 5. This difference in the temperature gradients has an effect on the cracking of specimens. Surface cracking of the geopolymer concrete specimens was not as predominant as in the OPC concrete samples. The number and width of cracks occurred after exposure to 1000 ^{o}C fire were much smaller in geopolymer concrete specimens as compared to the OPC concrete specimens. These cracks were very small and difficult to see with the naked eye, as shown in Figures 7 and 8.

However the cracks were still evident, but were generally observed to only temperatures above 800 °C for the geopolymer concrete specimens.

During fire exposures of the OPC concrete cylinders, there were a number of cases of spalling in the 800 °C and 1000 °C temperatures. The pieces of concrete spalled without any explosive sound. The reason for the spalling is the very rapid rise of the furnace air temperature, creating a large thermal gradient between the surface and the internal core of the concrete specimen. The fire temperature caused a rapid rise of the pore pressure in the concrete. This high pore pressure cannot escape the concrete rapidly, which creates a tensile stress in the concrete. Spalling occurs when the tensile stress in concrete caused by this pore pressure exceeds the tensile strength of concrete. The spalling of the OPC concrete cylinders at 800 ^{o}C and 1000 ^{o}C temperatures are shown in Figures 10 and 11 respectively. This type of spalling was not observed in the geopolymer concrete cylinders. A longitudinal section of a geopolymer concrete cylinder after exposure to 1000 ^{o}C fire is shown in Figure 12. As shown in this figure, geopolymer concrete is found to remain mostly solid as compared to the considerable disintegration of OPC concrete shown in Figure 11. The reason for higher resistance against disintegration and spalling of the geopolymer concrete specimens is considered to be its inherent higher tensile strength than that of OPC concrete. It was shown by comparison of the test data on the splitting tensile strengths of OPC and geopolymer concrete that heat-cured fly ash based geopolymer concrete tends to have higher tensile strength than OPC concrete of the same compressive strength [9]. The extensive cracking and spalling of the OPC concrete indicates that this may reduce the effective cross-sectional area of an OPC concrete member when exposed to high temperature fire. Such reduction in the effective cross-sectional area may eventually reduce the load capacity of the OPC concrete member. The relatively less cracking and spalling of geopolymer concrete indicates its better endurance in fire as compared to OPC concrete.

3.4 Residual strength of concrete after exposure to fire

The mean compressive strengths obtained from the cylinder samples of GPN, GPH and OPC concrete before and after exposure to fires at different temperatures are given in Table 3. The percentage residual strengths for each temperature exposure are also given in the table. It can be seen from the table that the normal strength geopolymer concrete gained some strength, with a residual strength of 107% after the 400 °C exposure temperature. After exposure to 400 °C temperature, the high strength geopolymer concrete and the OPC concrete had residual strengths of 93% and 90% respectively. Thus, the normal strength geopolymer concrete displayed considerably better residual strength than the high strength geopolymer and OPC concretes at this temperature. This is considered to be because of further geopolymerisation of the normal strength geopolymer concrete in the fire exposure.

It can be seen from Table 3 that all three types of concrete lost strength rapidly after 400 ^{o}C exposure. The normal strength geopolymer concrete displayed higher residual strength than the other two types of concrete up to 650 °C exposure. At this temperature range, the normal strength geopolymer concrete samples yielded a mean residual compressive strength of 83%. The high strength geopolymer concrete and OPC concrete showed average residual strengths of 59% and 51% respectively. Thus, the normal strength geopolymer concrete retained higher percentage of strength than the high strength geopolymer concrete and OPC concrete after 650 ^{o}C exposure. This is because of additional reaction of the binder in the normal strength geopolymer concrete specimens by the heat of fire since they were initially cured at a lower temperature than the high strength geopolymer concrete specimens.

At 800 °C, there is generally complete loss of water in OPC concrete, which has a significant impact on the compressive strength of the sample. Because of this phase change, the residual strength of OPC concrete dropped from 51% to a very low of 21%. Both the geopolymer concretes showed similar (27 – 29%) residual strengths at this temperature range.

At 1000 °C, the residual strengths were very low for all the tested mixtures. The GPH, GPN and OPC concrete samples retained average residual compressive strengths of 18%, 16% and 11% respectively. The severe strength loss of the specimens at this temperature occurred mainly because of the extensive cracking of the specimens. Furthermore, there was spalling of substrates in the OPC concrete specimens. The OPC concrete specimens suffered disintegration because of the greater loss of bonding between the binder and aggregates as a result of complete dehydration. The high thermal strain in the samples due to rapid heating rate of fire is the main contributing factor of the strength loss in concrete at this temperature. Generally, the less cracking and spalling, and higher residual compressive strength of fly ash based geopolymer concrete as compared to OPC concrete indicate its better performance after high temperature fire exposure. This observation is consistent with the higher fracture energy of geopolymer concrete as compared to OPC concrete of similar compressive strength, as shown in a previous study [31].

3.5 Mass loss and microstructure of geopolymer concrete after exposure to fire

The mass losses of the concrete samples due to fire exposure were determined from the masses of the cylinders before and after the fire exposure. The average values of mass loss in the three types of concrete after exposure to fires at different temperature are plotted in Figure 13. The exact values of the mass loss in the OPC concrete specimens could not be determined for exposures to fires at 800 and 1000 ^{o}C because of spalling of the specimens. However an increasing trend of the mass loss in the OPC concrete up to 650 ^{o}C can be seen in Figure 13.

The normal and high strength geopolymer concretes showed a similar mass loss curves, with relatively higher mass loss in the high strength geopolymer concrete. It can be seen from Figure 13 that most of the mass loss occurred at 400 °C. The mass loss of the concretes at 400 ^{o}C was 2.5% and 4% for GPN and GPH respectively. The rate of mass loss reduced in the geopolymer concretes after this temperature while that of the OPC concrete continued at a similar rate until 650 ^{o}C. The mass loss of the normal strength and high strength geopolymer concrete specimens at 1000 ^{o}C were 4.3% and 4.8% respectively.

The microstructures of the geopolymer concrete specimens subjected to high temperature fire were investigated by scanning electron microscopy (SEM). The SEM images of the GPN specimens after exposures to 650, 800 and 1000 ^{o}C are shown in Figures 14 (a) to 14 (c). It can be seen from these figures that the geopolymer microstructures became denser with the increase of fire temperature up to 1000 ^{o}C. This change has occurred in the microstructure because of sintering and further geopolymerisation of fly ash with the increase of temperature. Thus, the geopolymer microstructure remained stable after exposure to high temperature fires. This is consistent with the observation of Kong et al [32] that reported a 6% increase in strength of fly ash based geopolymer paste after exposure to heat of 800 ^{o}C. The strength of geopolymer paste increased with the increasing compactness of the microstructure at this temperature. However, the strength loss of the concrete specimens after high temperature exposure is mainly because of the thermal shock and the incompatibility between thermal expansions of the geopolymer matrix and the aggregates. It was shown by Kong and Sanjayan [25] that the thermal expansions of geopolymer paste and aggregates were different at high temperature exposure. This difference in thermal expansions initiates the damages in concrete which eventually results in the reduction of compressive strength.

4. Conclusions

Low calcium fly ash based geopolymer concrete specimens were exposed to fires at 400, 650, 800 and 1000 ^{o}C with the temperature rising at a rate given in the standards for fire tests of construction materials. Companion OPC concrete cylinders were also exposed to fires of same temperature profile. The cracking, spalling, mass loss and residual strength of OPC and geopolymer concrete specimens were compared after exposure to fires at different temperatures. The microstructure of geopolymer concrete after exposure to high temperature fire was observed by SEM images. The following conclusions are drawn from the test results:

- Generally, heat travelled at a faster rate in geopolymer concrete than in OPC concrete when exposed to fire. This resulted in less temperature gradient inside geopolymer concrete than in the OPC concrete specimens. Significant changes in colour occurred in geopolymer concrete after exposure to temperatures above 650 ^{o}C, ranging from brown to red.
- Significant spalling occurred in the OPC concrete specimens for fires at 800 and 1000 ^{o}C. Such spalling did not occur in the geopolymer concrete specimens exposed to the same fire temperatures. Extensive surface cracking appeared in the OPC concrete

cylinders after fire exposure to 400, 650, 800 and 1000 ^{o}C. However, only minor surface cracklings were observed in the geopolymer concrete specimens subjected to fire temperatures of at 800 and 1000 ^{o}C. This shows a better resistance to spalling and cracking of geopolymer concrete in comparison to OPC concrete specimens in fire.

- After 400 ^{o}C fire, the average residual strength of geopolymer concretes were in the range of 93% and 107%, and that of OPC concrete was 90%. After 650 ^{o}C, the residual strength of geopolymer concretes was between 59% and 82%, and that of OPC concrete was 52%. Thus, the geopolymer concrete retained higher percentage of strength than the OPC concrete specimens up to 650 ^{o}C. The residual strengths of the concretes ranged from 21 to 29% and 11 to 16% after exposures to 800 and 1000 ^{o}C respectively.
- The average mass loss of geopolymer concrete was up to 4.8% after exposure to 1000 ^{o}C, which was mainly because of the loss of moisture at the high temperature. The geopolymer microstructure remained stable and compact after exposure to high temperature fire. However, the strength loss of the concrete was mainly because of the strain developed by the differential expansions between geopolymer matrix and the aggregates.

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REFERENCES

1. Hardjito D, Wallah SE, Sumajouw DMJ, Rangan BV. On the development of fly ash-based geopolymer concrete. ACI Mater J, 2004; 101(6): 467-72.
2. Fernandez- Jimenez A, Palomo A. Engineering properties of alkali-activated fly ash concrete. ACI Mater J 2006; 103(2):106-12.
3. Chindaprasirt P, Chareerat T, Sirivivatnanon V. Workability and strength of coarse high calcium fly ash geopolymer. Cem. Concr. Comp. 2007; 29:224-29.
4. Davidovits J. High-alkali cements for 21st century concretes. ACI Special Publication. SP 144; 1994: P. 383-98.
5. Bakharev T, Sanjayan J, Cheng Y. Alkali activation of Australian slag cements. Cem. Concr. Res. 1999; 29:113-20.
6. Fernandez-Jimenez A, Palomo JG, Puertas F. Alkali activated slag mortars: mechanical strength behaviour. Cem. Concr. Res. 29 (1999) 1313-1321.
7. Deb PS, Nath P, Sarker PK. Strength and permeation properties of slag blended fly ash based geopolymer concrete. Advanced Mater. Res. 2013; 651: 168 – 173.
8. Rangan BV. Studies on low-calcium fly ash-based geopolymer concrete. Indian Concr. J. 2006; 80: 9-17.
9. Sarker PK. Bond strength of reinforcing steel embedded in geopolymer concrete. Mater. Struct. 2011; 44:1021-30.
10. Sarker PK. Analysis of geopolymer concrete columns, Mater. Struct. 2009; 42:715-24.
11. Fernandez- Jimenez A, Palomo A. Composition and microstructure of alkali activated fly ash binder: effect of the activator Cem. Concr. Res. 2005; 35:1984-92.
12. Sumajouw DMJ, Hardjito D, Wallah SE, Rangan BV. Fly ash-based geopolymer concrete: study of slender columns. J. Mater. Sci. 2007; 42:3124-30.
13. Sumajouw DMJ, Hardjito D, Wallah SE, Rangan BV. Flexural behavior of fly ash-based geopolymer concrete beams, Proceedings of the Concrete Institute of Australia 22nd Biennial Conference, 16 – 19 October, 2005, Melbourne, Australia,.

14. Chang EH, Sarker PK, Lloyd N, Rangan BV. Shear behavior of reinforced fly ash-based geopolymer concrete beams, Proceedings of the Concrete Institute of Australia 23rd Biennial Conference, 18 – 20 October, 2007, 679 – 687, Adelaide, Australia.
15. Rahman M, Sarker PK. Geopolymer concrete columns under combined axial load and biaxial bending, CONCRETE 2011 Conference, 12-14 October, 2011, Perth, Western Australia.
16. Khoury GA. Effect of fire on concrete and concrete structures. Fire Concr. 2000; 2:429–47.
17. Heikal M. Effect of temperature on the physico-mechanical and mineralogical properties of homra pozzolanic cement pastes. Cem. Concr. Res. 2000; 30:1835–39.
18. Mohamedbhai GTG. Effect of exposure time and rates of heating and cooling on residual strength of heated concrete. Mag. Concr. Res. 1986; 38:151–58.
19. Khoury GA, Grainger BN, Sullivan PJE. Strain of concrete during fast cooling form 600 ^{o}C under load. Mag. Concr. Res. 1986; 38:3–12.
20. Poon CS, Azhar S, Anson M, Wong YL. Performance of metakaolin concrete at elevated temperatures. Cem. Concr. Comp. 2003; 25: 83–89.
21. Papayianna I, Valliasis T, Heat deformations of fly ash concrete. Cem. Concr. Comp. 2005; 27: 249– 254.
22. Li, Z, Xu J, Bai E. Static and dynamic mechanical properties of concrete after high temperature exposure. Mater. Sci. Eng. A. 2012; 544:27 – 32.
23. Kong DLY, Sanjayan JG. Damage due to elevated temperatures in metakaolinite-based geopolymer pastes, International Workshop on Geopolymer and Geopolymer Concrete, September 28–29, 2005, Perth, Australia.
24. Cheng TW, Chiu JP. Fire-resistant Geopolymer Produced by Granulated Blast Furnace Slag. Miner. Eng. 2003; 16:205–10.
25. Kong DLY, Sanjayan JG. Damage behavior of geopolymer composites exposed to elevated temperatures. Cem. Concr. Comp. 2008; 30:986-91.
26. Sarker PK, de Meillon T. Geopolymer concrete after exposure to high temperature heat, Recent Developments in Structural Engineering, in A. Zingoni (ed.), Mechanics and Computation, Millpress, Rotterdam, The Netherlands, 2007, pp.1566 – 1571.

27. ISO 834. International Standards Organization, Fire Resistance Tests, Elements of Building Construction, Switzerland, 1980.
28. AS 1530.4. Australian Standard, Methods for Fire Tests on Building Materials, Components and Structures, Australia, 1997.
29. Hardjito D, Rangan BV. Development and properties of low-calcium fly ash-based geopolymer concrete. Research Report GC1, Faculty of Engineering, Curtin University of Technology, Perth, Australia, 2005.
30. Zhao R, Sanjayan, JG. Geopolymer and portland cement concrete in simulated fire. Mag. Concr. Res. 2011; 63(3): 163-73.
31. Sarker PK, Haque R, Ramgolam KV. Fracture behaviour of heat cured fly ash geopolymer concrete. Mater. Des. 2013; 44: 580-6.
32. Kong DLY, Sanjayan JG, Sagoe-Crentsil K. Comparative performance of geopolymers made with metakaolin and fly ash after exposure to elevated temperatures. Cem. Concr. Res. 2007; 37: 1583–9.

Table 1. Chemical compositions of cement and fly ash (mass %)

Compounds	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	TiO_2	MgO	P_2O_5	SO_3
Cement	20.4	4.8	2.9	64.2	0.29	-	-	2.0	-	2.4
Fly ash	50.8	26.9	13.5	2.05	0.33	0.57	1.57	1.33	1.46	0.31

Table 2. Mixture proportions of concrete (kg / m^3)

Mix-ture	Cement	Fly ash	Water	Sodium hydroxide	Sodium silicate	Sand	Coarse aggregate	
							10mm	20mm
OPC	334	-	177	-	-	643	404	860
GPC	-	408	20	41	103	647	554	647

Table 3. Compressive strength before fire and percentage residual strength after fire

	GPN		GPH		OPC	
Temp. °C	Compr. strength f_{cm} (MPa) (Std. dev)	Residual strength (%)	Compr. strength f_{cm} (MPa) (Std. dev)	Residual strength (%)	Compr. strength f_{cm} (MPa) (Std. dev)	Residual strength (%)
23	39 (2.2)	100	58 (3.5)	100	42 (2.6)	100
400	42 (2.4)	107	54 (2.1)	93	38 (2.9)	90
650	32 (2.9)	83	34 (1.8)	59	22 (2.2)	51
800	11 (0.8)	27	17 (0.7)	29	9 (0.6)	21
1000	6 (0.5)	16	11 (0.6)	18	5 (0.5)	12

Figure 1. Concrete cylinder specimens after casting

Figure 2. A typical concrete cylinder with thermocouple

Figure 3. Cylinder specimens set up in furnace for fire exposure

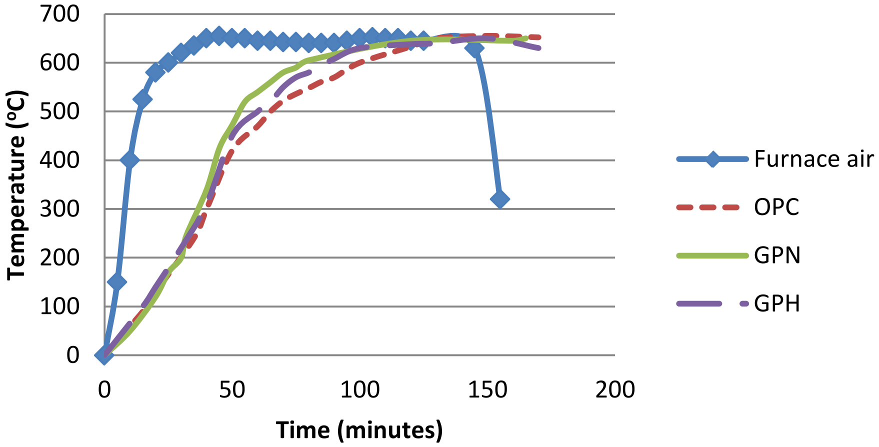


Figure 4. Temperature-time graph in concrete samples exposed to fire at 650 °C

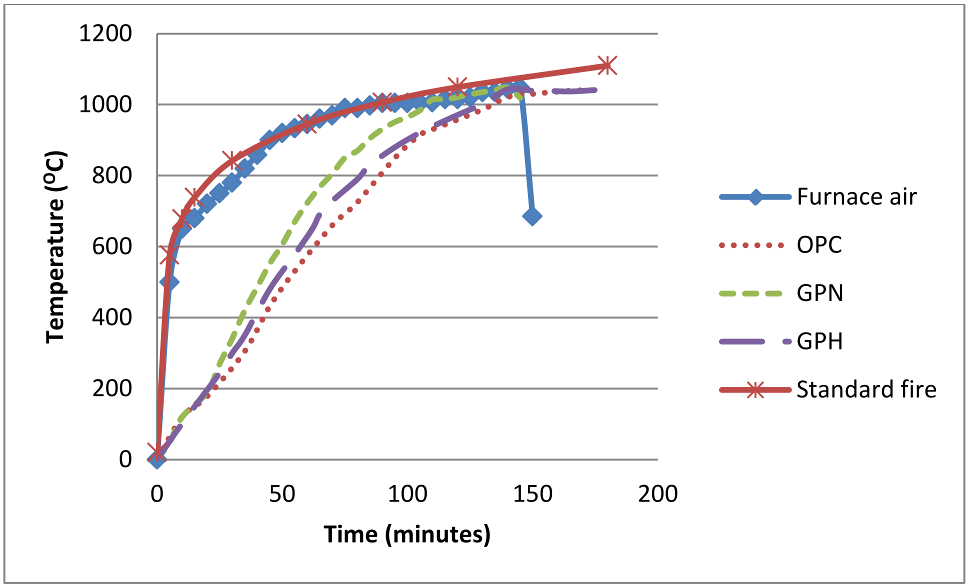


Figure 5. Temperature-time graph in concrete samples exposed to fire at 1000 ^{o}C

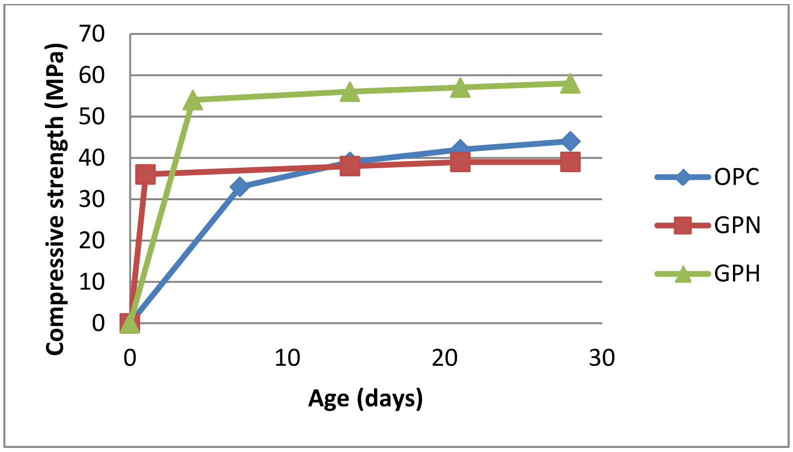


Figure 6. Compressive strength development of the concretes.

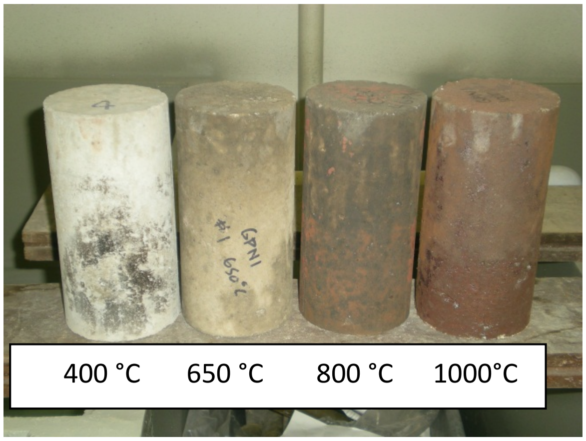


Figure 7. Geopolymer concrete specimens of group GPN after 400, 650, 800 and 1000°C exposure

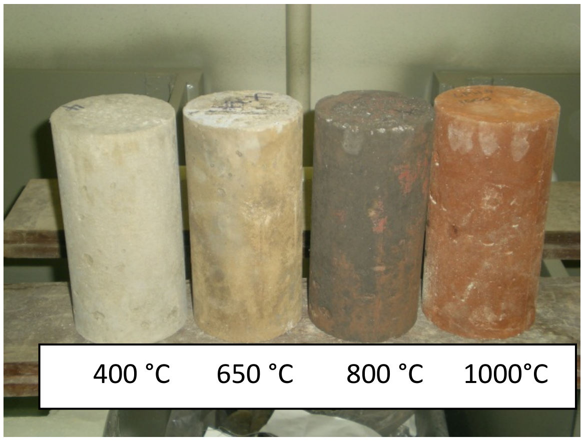


Figure 8. Geopolymer concrete specimens of group GPH after 400, 650, 800 and 1000°C exposure.

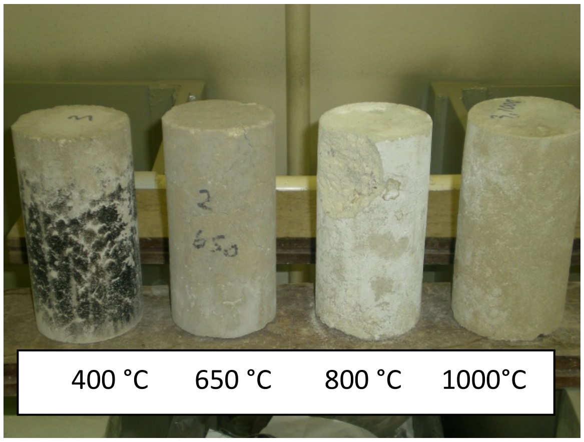


Figure 9. OPC concrete specimens after 400, 650, 800 and 1000 °C exposure

Figure 10. Cracking and spalling of OPC concrete after 800 °C exposure

Figure 11. Cracking and spalling of OPC concrete after 1000 °C exposure

Figure 12. Longitudinal section of geopolymer concrete after 1000 °C exposure

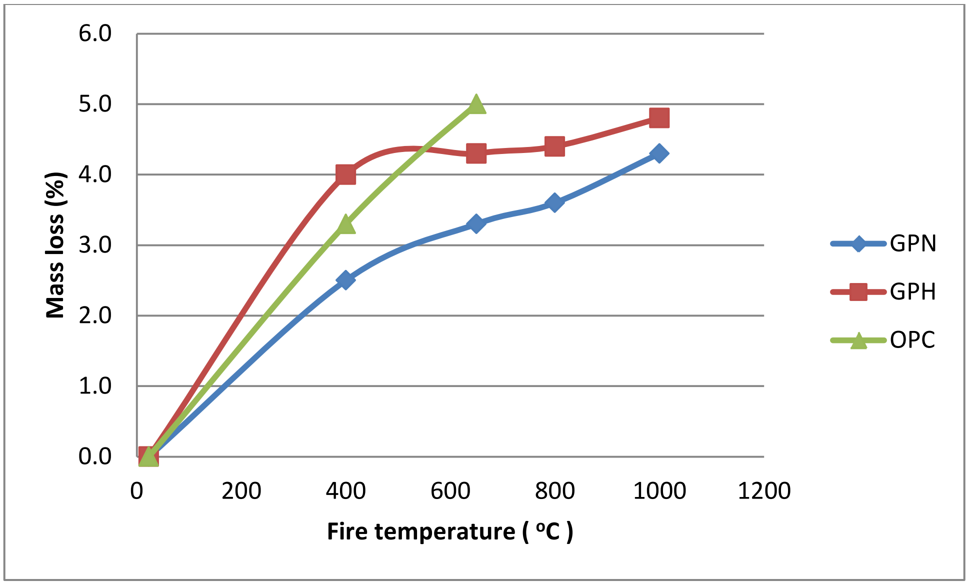
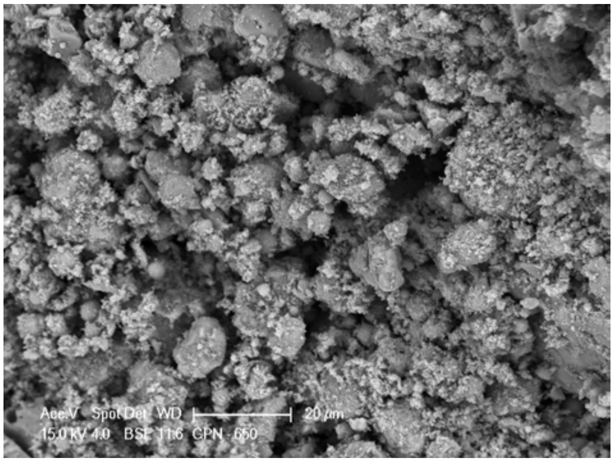
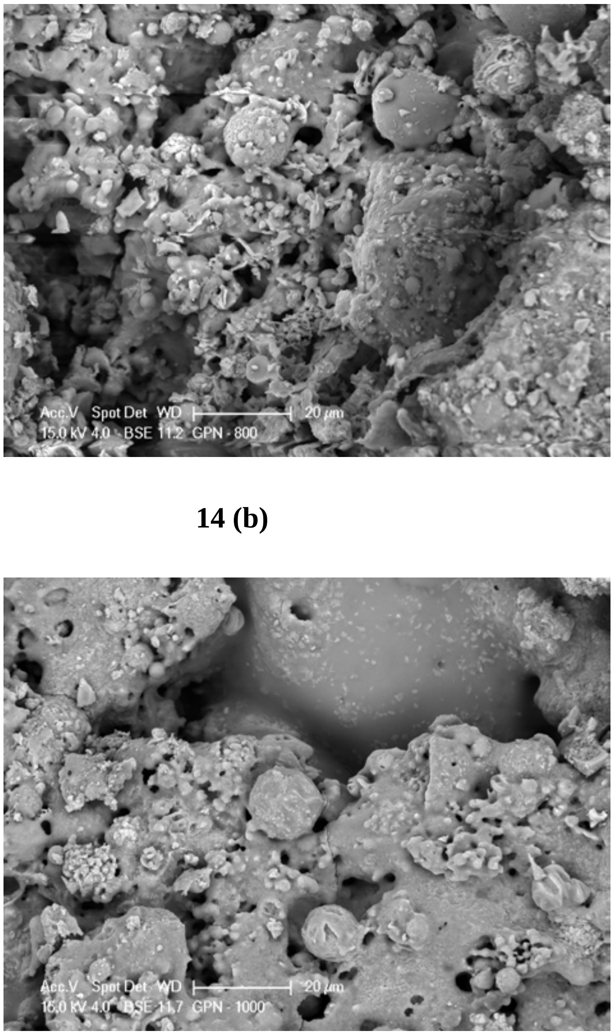


Figure 13. Mass loss of concrete after exposure to fires of different temperature



14 (a)



14 (b)

14 (c)

Figure 14. SEM images of GPN specimens after exposure to fire of (a) 650 °C, (b) 800 °C and (c) 1000 °C