Fire endurance of steel reinforced fly ash geopolymer concrete elements

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ABSTRACT

As a new alternative to OPC, investigation into the fire endurance of geopolymer concrete is of utmost importance in order to ensure safety. Geopolymer and OPC concrete panels of 125 to 175 mm thickness containing a layer of steel mesh were exposed to fire for two hours. Test results show higher heat transfer rate and less cracking and spalling in the geopolymer concrete specimens. The residual load capacity was between 61 and 71% for the geopolymer and between 50 and 53% for the OPC concrete panels. Thus, the reinforced geopolymer concrete elements demonstrated superior fire endurance than the OPC counterparts.

Keywords: Fly ash, fire endurance, reinforced geopolymer concrete, residual strength, spalling.

1. Introduction

The global demand of concrete is increasing with the increasing need for constructions. Ordinary Portland cement (OPC) has long been used as the traditional binder for concrete. However, alternative binders utilising industrial by-products are required in order to reduce the carbon footprint of concrete. It is known that about one tonne of carbon dioxide is emitted into atmosphere in the production of one tonne of cement. Geopolymer is an emerging alternative binder that uses industrial by-products instead of cement. A base material such as fly ash which is rich in silicon and aluminum is reacted by an alkaline solution to produce the geopolymer binder. The base material for geopolymerisation can be a single material or combination of different materials. Materials such as fly ash [1-4], metakaolin [5] and blast furnace slag [6-7] are possible to use as the base material for geopolymer binders. Blending of fly ash with a small quantity of calcium bearing materials have also been used to enhance the early-age properties at room temperature curing conditions [2, 8, 9]. The reaction products were found to be different depending on the type of the base material and the activating alkaline liquids used for geopolymerisation [10]. Among these common base materials, low-calcium fly ash has been found as the most suitable principal binder for geopolymer concrete. Coal-fired power stations worldwide generate large amount of fly ash as a by-product. A substantial part of this fly ash remains unused after different conventional methods of uses. The unused fly ash causes environmental pollutions and the ash ponds occupy vast area of costly land that could be otherwise used for productive purposes. This accumulated volume of the unused fly ash in various countries can be properly utilized as the base material for producing low-emission geopolymer concrete. This can help significantly reduce the carbon footprint of concrete production.

Results of the ongoing studies on various engineering properties [8-11] showed the potential use of fly ash based geopolymer concrete as a construction material. As a new construction material, it is necessary to study the performance of geopolymer concrete in various structural applications. The previous research on fly ash-based geopolymer concrete studied various short-term and long-term properties. Various mix design parameters influencing the strength of geopolymer concrete were investigated. It was shown that heat-cured geopolymer concrete possesses high compressive strength, undergoes low drying shrinkage and moderately low creep, and shows good resistance aggressive agents such as sulfate and acid [1]. Geopolymer concrete showed good bond strength with reinforcing steel which is necessary for its function as a composite material in reinforced concrete [10]. Steel reinforced geopolymer concrete beams and columns showed similar behavior to that of OPC concrete members [12-14]. The existing methods of the design codes were shown to be adequate for the design of geopolymer concrete members. Therefore, fly ash geopolymer is considered as a viable alternative binder for concrete elements such as beams, columns, slabs, walls, footings and other similar structural members.

Possessing adequate fire endurance is of utmost importance for a construction material in order to ensure safety of life and property. Materials with high fire endurance are especially required in areas prone to accidental fire and in structures with high level of importance such as high rise buildings, tunnels, buildings storing hazardous materials, nuclear facilities etc. Assessment of structures after a fire starts with the observation of cracking and spalling since these aspects significantly affect the load bearing capacity of structures. Residual strength of a material after fire exposure indicates the extent of remaining strength, its suitability for further usage and the need for repair. Therefore, comparison of the cracking and spalling damages, and residual strengths of different materials are used to compare their performances in a fire.

Combustibility of geopolymer fibre composites was studied by Lyon et al [15]. It was shown that the maximum temperature capability of carbon fibre reinforced geopolymer composite was more than 800 ^{o}C. This was shown to be much higher than the capabilities of some other similar materials. Compressive strength of geopolymer concrete cylinders was found to increase when tested in the exposure of fire at 800 ^{o}C [16]. Foamed porous fly ash geopolymer paste samples were shown to have increased compressive strength after exposure up to 1000 ^{o}C [17]. Kong and Sanjayan [18] studied the effects of high temperature heat on geopolymers exposed up to 800 ^{o}C. It was shown that metakaolin based geopolymers and their composites remained stable up to 600 ^{o}C, whereas OPC binders experienced a rapid deterioration in compressive strength at around 300 ^{o}C. It was also shown that geopolymer paste samples gained strength by 53%, however identical formulation of composites combined with aggregates experienced a 65% decrease in strength. The decrease in strength was attributed to the incompatibility between the thermal expansion of the aggregate and that of geopolymer paste. While aggregates expanded by 1.2 – 2.5%, the geopolymer paste retracted by 1.6% at 800 ^{o}C. This incompatibility in the thermal expansions of aggregate and paste resulted in internal damage of concrete and thus reduced the strength.

Previous studies [19, 20] on fly ash geopolymer concrete cylinders after fire exposure showed that residual strength was higher than the original strength for relatively low temperature such as up to 200 ^{o}C. Then residual strength decreased with further increase in fire temperature. However, the strength retained by geopolymer concrete cylinders was higher than that by OPC concrete specimens up to 600 ^{o}C. The strength loss of geopolymer concrete cylinders exposed to high temperature heat such as 800 to 1000 ^{o}C was similar to that of OPC concrete cylinders.

These previous studies were limited to the tests on small cube or cylinder specimens subjected to high temperature heat on all sides of the specimens. No study has been conducted to investigate the damages occurred in larger geopolymer concrete specimens reinforced with steel bars and strength retained by reinforced elements after a fire exposure. It is necessary to investigate the extent of damage and residual strength of steel reinforced geopolymer concrete elements at high temperature since real structures are mostly made of reinforced concrete members. The presence of steel and the number of sides of a specimen exposed to fire can have significant influence on the damage and strength loss. For example, the distribution of temperature inside a wall exposed to fire on one side will be different from that exposed to fire on both sides. This paper presents a study on the damages and residual strength of reinforced fly ash based geopolymer concrete panels exposed to standard ISO 834 [21] fire which is commonly used for testing of building materials. OPC and geopolymer concrete panels were exposed to fire on one side for two hours and then cooled down to normal temperature. Cracking and spalling damages in the two types of concrete specimens were inspected and the post-fire strengths were determined using compression tests. The behaviours of geopolymer concrete panels are compared with those of traditional OPC concrete panels.

2. Materials and methods

Experimental work was carried out in the laboratory to study the behaviour of steel reinforced panels of OPC and geopolymer concretes exposed to high temperature fire. The panels were of different thickness with the same amount of reinforcement. They were exposed to standard fire for two hours and then cooled down to room temperature by turning off the furnace. The transfer of heat through the specimens was recorded by using thermocouples. The damages in terms of cracking and spalling of the specimens were observed during fire exposure and after cooling down. The specimens were loaded to failure in concentric compression in order to study the failure behaviour and determine the strength retained by them after the fire exposure.

2.1 Materials

Concrete was mixed in the laboratory for casting of the test specimens. General purpose Portland cement was used for OPC concrete specimens and commercially available class F (ASTM 618) [22] fly ash was used to manufacture the geopolymer concrete specimens. Percentage of the fly ash passing through a 45 μ sieve was 75% and its loss on ignition was 0.6%. The chemical compositions of cement and fly ash used in making the specimens 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 normal tap water to make 14M solution. The readily available commercial sodium silicate solution had a chemical composition of 14.7% Na_2O, 29.4% SiO_2, and 55.9% water by mass. Both the liquids were mixed together before adding to the fly ash and aggregates. The coarse aggregates were 7, 10 and 20 mm nominal size crushed granite. The fine aggregate was river sand. The aggregates were prepared to SSD condition before mixing of the concrete. Tap water was used in mixing of the concretes. The mixture proportions of OPC and geopolymer concrete are given in Table 2. The mixtures were designed to obtain similar compressive strengths. The steel reinforcement of the test panels was a single layer of 500 MPa normal ductility deformed bars in both directions.

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	21.1	4.7	2.7	63.6	0.5	-	-	2.6	-	2.5
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	Cement	Fly ash	Water	Sodium hydroxide	Sodium silicate	Sand	Coarse aggregate		
							7mm	10mm	20 mm
OPC	385	-	205	-	-	616	412	240	492
GPC	-	408	55	41	103	554	462	277	554

Figure 1(a). Slump of OPC concrete

Figure 1(b). Slump of geopolymer concrete

2.2 Casting of test specimens

Concrete was mixed in the laboratory in a pan type mixer. Workability of fresh concrete was determined by using standard slump test immediately after mixing the concrete. Slump tests of OPC and geopolymer concrete are shown in Figures 1(a) and 1(b) respectively. The slump of OPC concrete varied between 90 and 120 mm and that of geopolymer concrete varied between 200 and 250 mm. Both concretes had reasonable workability and the specimens were cast with sufficient ease. Though geopolymer concrete had a much higher slump than the OPC concrete, they both needed the same level of vibration to compact the concrete. This is because of the relatively higher viscosity of the activator solution used in geopolymer concrete. The geopolymer concrete specimens were cured by using steam and the OPC concrete specimens were cured by spraying water.

The test panel specimens were 500 mm × 500 mm in size. Three OPC concrete panels and three geopolymer concrete panels were cast. Thicknesses of the panels were 125, 150 and 175 mm. The reinforcement consisted of three bars of 12 mm diameter in each direction, distributed in the mid-depth of the section. The panels were compacted by using an electrically operated concrete vibrator. Casting of typical geopolymer concrete test panels are shown in Figure 2. A thermocouple was inserted in the centre of the panel to a depth of 25 mm from the top surface to measure the transfer of heat through the specimen when the opposite face would be exposed to fire. The geopolymer concrete panels were steam cured immediately after casting at 60 ^{o}C for 24 hours and then left in ambient condition until testing. The OPC concrete panels were cured by covering with hessians and spraying water for 14 days after casting. Accompanying standard 100 mm × 200 mm cylinders were cast together with the test panels in order to determine compressive strength of concrete. The cylinders were cured in the same condition as the test panels.

2.3 Method of testing

The specimens were exposed to fire at 28 days after casting. Figure 3 shows a test panel set in the furnace for fire exposure. The furnace was turned on and the flame was increased by controlling the flow of gas. The face of the panel inside the furnace was exposed to fire and the opposite face was exposed to room temperature. This condition of heating is considered as the most critical for damage of the concrete by differential temperature between the heated face and the unheated face. The gaps between the test panel and the furnace were closed so that heat of the fire could not reach the unheated face of the panel. The geopolymer and OPC concrete specimens were exposed to fire in the same way. The fire in the furnace was controlled to achieve the heating rate recommended in the standards for fire test of building materials [21, 23]. The heating rate recommended in the ISO 834 [21] standard is given by Equation 1.

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

Where T_t is furnace temperature (^oC) at time t (minutes) and T_0 is the initial furnace temperature (^OC).

The temperature of the air inside the furnace was measured by an in-built thermocouple in the furnace and that at 25 mm depth from the unheated face of the test panel was measured by the thermocouple inserted in the specimen during casting. The furnace was turned off after heating the specimens for two hours and the specimens were then left to cool down normally to room temperature leaving the door of the furnace open. After cooling down to room temperature, the specimens were tested under concentric compression using a universal testing machine. The compression test of a panel is shown in Figure 4. The panels were loaded to failure and the test failure loads were recorded.

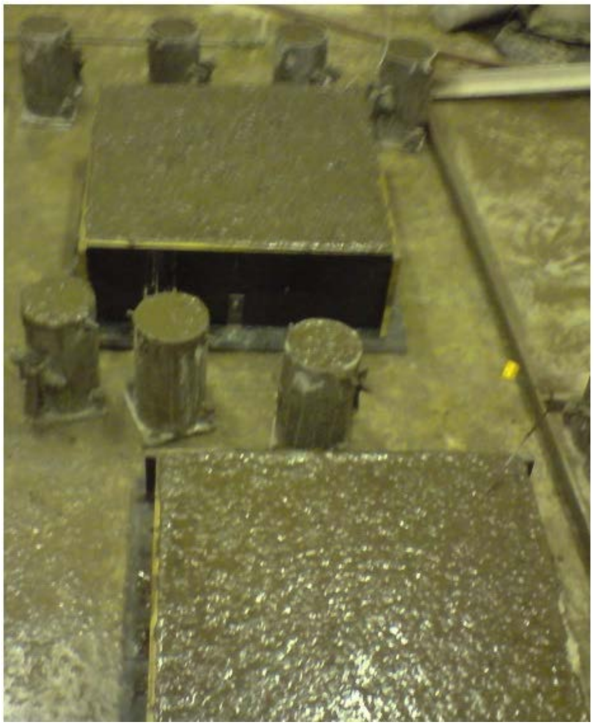

Figure 2. Casting of the geopolymer concrete test panels

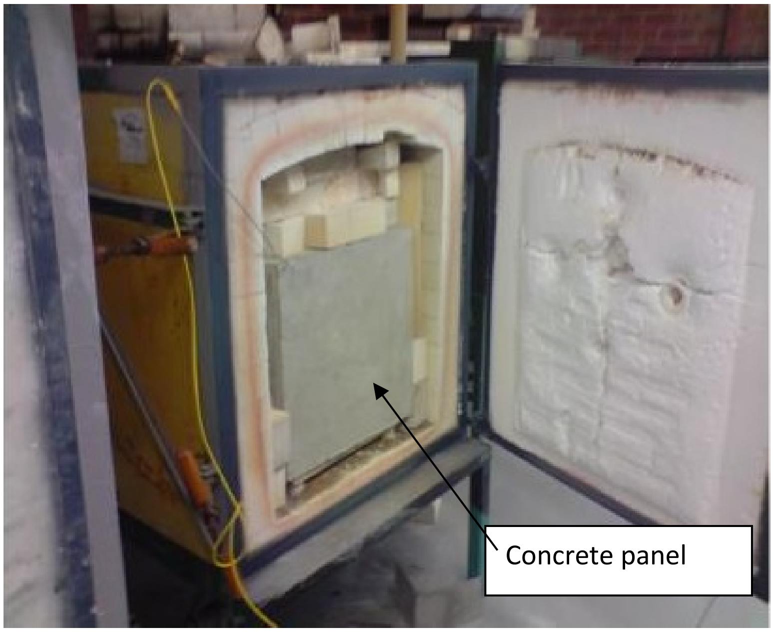

Figure 3. A concrete test panel set for fire exposure

Figure 4. Post-fire compression test of a concrete panel

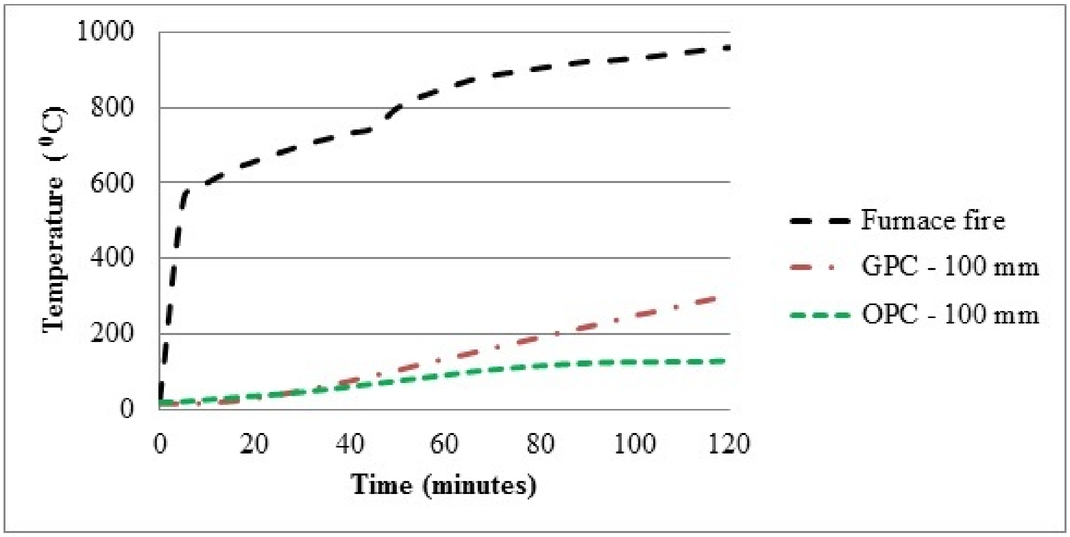

Figure 5. Temperature at 100 mm depth in the 125 mm thick panels

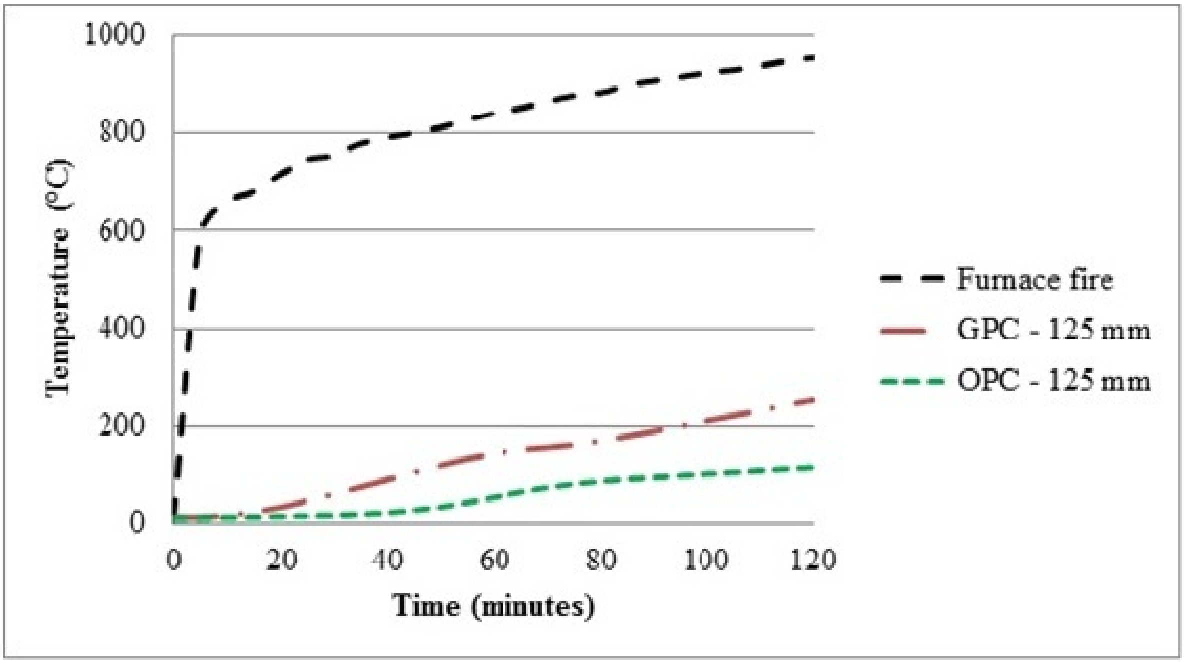

Figure 6. Temperature at 125 mm depth in the 150 mm thick panels

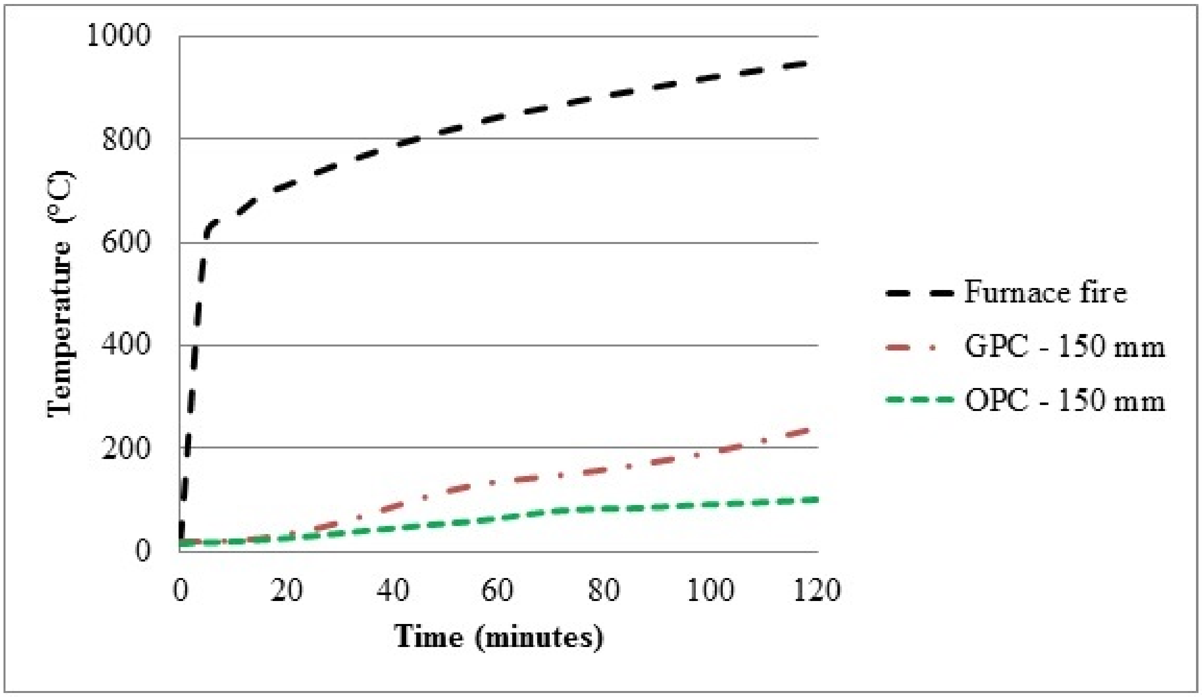

Figure 7. Temperature at 150 mm depth in the 175 mm thick panels

3. Test results and discussion

3.1 Transfer of heat inside concrete panels under fire exposure

The temperature-time curves of the fire inside the furnace during the 2 hours of fire exposure of the 125, 150 and 175 mm panels are shown in Figures 5, 6 and 7 respectively. The increase of temperature with time at 25 mm depth from the unheated face of the panels is also plotted in these figures. As shown in Figure 5, the temperatures measured at the end of the heating period in the 125 mm geopolymer and OPC concrete panels were 302 and 129 ^{o}C, respectively, when the furnace temperature was 960 ^{o}C. The highest temperatures in the 150 mm panels were 253 and 115 ^{o}C in the geopolymer and OPC concrete specimens, respectively, as shown in Fig 6. Similarly, the maximum temperatures in the 175 mm panels were 228 and 101 ^{o}C for the geopolymer and OPC concrete panels, respectively (Figure 7). As expected, temperature near the unheated face decreased with the increase of the panel thickness in both types of concrete.

Comparing the temperature-time curves of the OPC and geopolymer concrete panels in each figure, it can be seen that the temperature at a given time was higher in the geopolymer concrete panel than in the OPC concrete panel of the same thickness. Therefore, the geopolymer concrete panels showed a higher thermal conductivity than the OPC concrete panels at high temperature. Similar behaviour was also observed previously in the tests of cylinder specimens exposed to fire from all directions [20]. Subaer and van Riessen [24] measured a higher thermal conductivity value of hardened geopolymer paste than OPC paste samples. This higher thermal conductivity resulted in a a fastre travel of heat and smaller thermal gradient in the geopolymer concrete panels than in the OPC concrete panels. Thus, it can be said that the heat transfer rate of fly ash geopolymer concrete is generally higher than OPC concrete when exposed to the high temperature heat of fire.

3.2 Damage of test specimens by cracking and spalling

The typical cracks developed on the fire exposed face of the OPC concrete panels after 2 hours of fire exposure are shown in Figures 8 (a) and 8 (b). The typical cracks developed in a geopolymer concrete specimen are shown in Figure 9. It can be seen from these figures that there were cracks in the specimens of both types of concrete. However, relatively wider cracks were observed in the OPC concrete panels as shown in Figure 8 (b). The widths of the cracks in geopolymer concrete panels were relatively small as shown in Figure 9. As shown in Figure 8 (a), the 125-mm OPC concrete panel also suffered by spalling of concrete from a corner. No such spalling was observed in any of the geopolymer concrete panels. Similar spalling was also observed in some OPC concrete cylinders with no spalling of the geopolymer concrete cylinders of the previous tests [20]. The relatively less damage in the geopolymer concrete panels than in the OPC concrete panels is attributed to the smaller temperature differential in geopolymer concrete panels, as shown in Figures 5 to 7. The colour of the geopolymer concrete changed to red after the exposure to fire. This is attributed to the presence of high iron content of the fly ash used to make the geopolymer concrete. As the distance increased from the fire exposed face inside the specimen, the redness gradually decreased with the decrease of temperature.

Figure 8(a). Corner spalling of the 125 mm thick OPC concrete panel

Figure 8(b). Typical cracks in the OPC concrete panels

Figure 9. Typical cracks and colour change in the geopolymer concrete panels after fire exposure

Figure 10(a). Failure of the 125 mm OPC concrete panel

Figure 10(b). Failure of the 125 mm GPC panel

Figure 11(a). Failure of the150 mm OPC concrete panel Figure 11(b). Failure of the 150 mm GPC panel

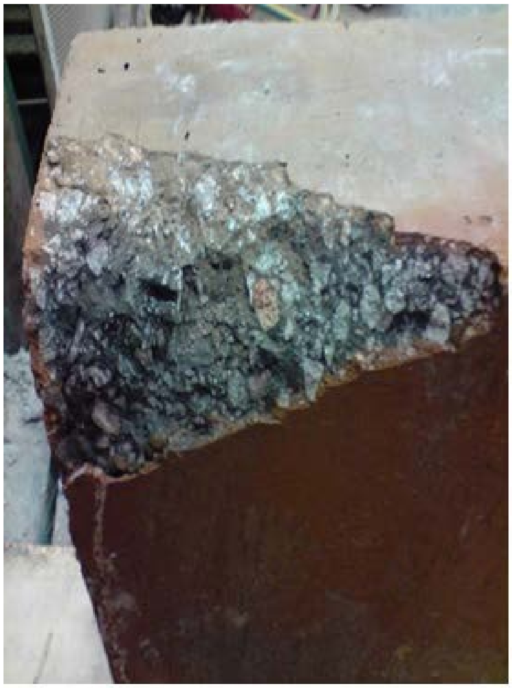

Figure 12(a). Failure of the 175 mm OPC concrete panel Figure 12(b). Failure of the 175 mm GPC panel

3.3 Failure and residual strength of the panels in compression

Numerous cracks were observed on the fire-exposed faces of both types of concrete panels after cooling. This was expected because of the differential temperature in the panels across the depth and because of thermal shocks in the heating and cooling stages. Typical failures of the OPC and geopolymer concrete panels are shown in Figures 10 to 12. As shown in Figures 10 (a) and (b), both 125 mm thick OPC and geopolymer concrete panels failed by complete crushing of the concrete in the fire exposed side and bucking of the reinforcing steel bars in the direction of fire exposure. Failure of the 150 mm thick geopolymer concrete panel occurred mainly by splitting of concrete along a plane parallel to the direction of loading, as shown in Figure 11(a). The OPC concrete panel of the same thickness occurred by a combination of splitting and crushing of concrete in the fire-exposed side (Figure 11(b)). As shown in Figures 12 (a) and (b), the 175 mm thick geopolymer concrete panel only damaged locally at the corner whereas the OPC concrete panel of the same thickness failed by complete splitting of the concrete. The post-fire load capacities of the panels obtained from the tests are given in Table 3.

The original load capacity of each panel before exposure to fire is calculated by using Equation 2, considering the panel as a stocky reinforced concrete member under concentric compression.

$$P = f_{cm}\left(A_g - A_s\right) + A_s f_y \quad (2)$$

where P is the load capacity, f_{cm} is the mean concrete compressive strength obtained from cylinders; A_g is the gross cross-sectional area of the panel, A_s is the area of reinforcing steel and f_y is the yield strength of steel.

Table 3 Load capacity of the test panels

Concrete	Panel thickness (mm)	Cylinder Compressive strength, f_{cm} (MPa)	Original panel strength (Eq. 2), kN	Post-fire panel strength P_{test} (kN)	% strength retained, P_{test} / $P_{original}$	Mean % strength retained
OPC	125	50	3278	1645	50	51.6
	150	45	3529	1873	53	
	175	46	4179	2185	52	
GPC	125	46	3029	2146	71	65.6
	150	50	3903	2368	61	
	175	42	3830	2500	65	

The mean cylinder compressive strength corresponding to each panel is given in the Table 3. For each test panel, area of the reinforcing steel was 339 mm^2 and yield strength of steel was 500 MPa. The load capacities of the unheated panels calculated by Equation 2 are given in Table 3. The percentage of strength retained after exposure to fire is calculated for the panels by dividing the post-fire load capacity by the calculated original load capacity. The residual strengths of the two types of concrete panels of the same thickness are also compared in the plot of Figure 13. It can be seen from Table 3 and Figure 13 that the percentage of original strength retained by the geopolymer concrete panel is higher than that by the OPC concrete panel of the same thickness. The failure loads of the geopolymer concrete panels varied from 61% to 71% of the calculated original values and those of the OPC concrete panels were between 50% and 53% of the original strengths. The reason for higher percentage of strength retained by the geopolymer concrete panels is attributed to the smaller temperature differential between the heated and unheated faces than that of the OPC concrete panels. The smaller temperature differential has caused relatively less internal damage in the geopolymer concrete panels. It was shown in the previous study [20] that the residual strengths of cylinder specimens exposed to ISO 834 fire for 2 hours was 17% and 12% for geopolymer concrete and OPC concrete respectively. The results obtained for the reinforced concrete panels show similar trend to those for the cylinder specimens. However, the percentage residual strengths of the reinforced concrete panels are much higher than those of the cylinder specimens. This is because of the presence of steel reinforcement in the panels, their larger size as compared to the cylinders and the difference in the exposure to fire.

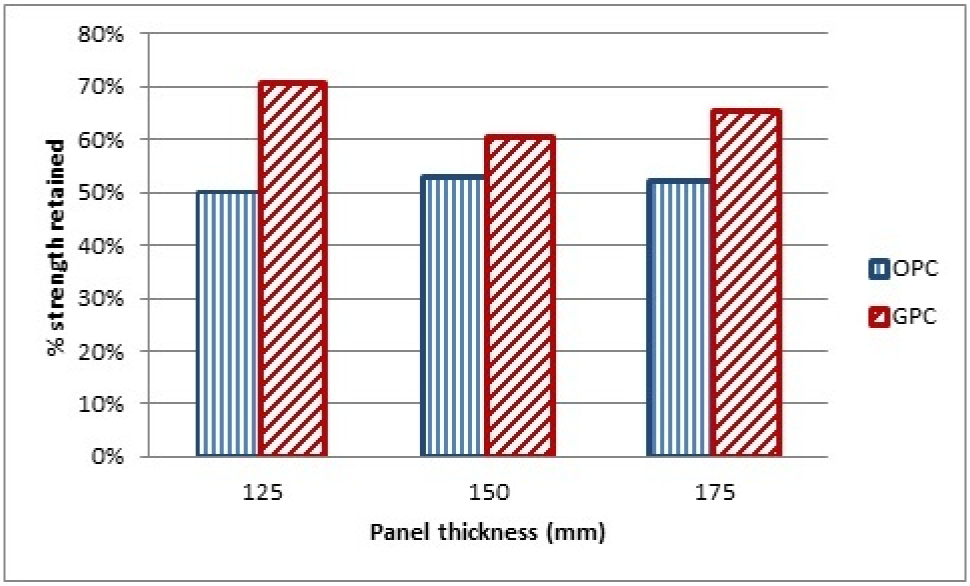

Figure 13. Residual strengths of the OPC concrete and GPC test panels

4. Conclusions

Six 500-mm square reinforced OPC and geopolymer concrete panels of 125, 150 and 175 mm thickness were exposed to fire of up to 960 ^{0}C temperature for two hours. The panels were then cooled down and tested under compressive load. The heat transfer at high temperature was generally faster in geopolymer concrete panel than in the OPC concrete panel of same thickness. This resulted in smaller temperature differential in the geopolymer concrete panels. The damages by cracking and spalling were less in the geopolymer concrete panels than in the OPC concrete panels. Compression tests of the panels after cooling down to room temperature showed that the geopolymer concrete panels retained higher percentage of strength than the OPC concrete panels. The mean value of the percentage strength retained by the geopolymer and OPC concrete panels was 66% and 52% respectively. The higher residual strength of the reinforced geopolymer concrete specimens is attributed to the less internal damage because of the less temperature differential than in the OPC concrete specimens. This shows the superior fire endurance of steel reinforced fly ash geopolymer concrete elements than that of OPC concrete elements.

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References

1. Hardjito, D., Wallah, S. E., Sumajouw, D. M. J. and Rangan, B. V., “On the Development of Fly Ash-Based Geopolymer Concrete”, *ACI Materials Journal*, V. 101, No. 6, 2004, pp. 467-472.
2. Nath, P., Sarker, P. K., “Effect of GGBFS on Setting, Workability and Early Strength Properties of Fly Ash Geopolymer Concrete Cured in Ambient Condition”, *Construction and Building Materials*, V. 66, 2014, pp. 163-171.
3. Fernandez- Jimenez, A., Palomo, A., “Engineering properties of alkali-activated fly ash concrete”, *ACI Materials Journal*, 103, No. 2, 2006, pp.106-112.
4. Chindaprasirt, P., Chareerat, T. and Sirivivatnanon, V., “Workability and strength of coarse high calcium fly ash geopolymer”, *Cement and Concrete Composites*, V. 29, 2007, pp. 224-229.
5. Davidovits, J., “High-Alkali Cements for 21st Century Concretes”, Concrete Technology Past, Present and Future, *ACI Special Publication*, SP 144, 1994, pp. 383-398.
6. Bakharev, T., Sanjayan, J. and Cheng, Y., “Alkali activation of Australian slag cements” *Cement and Concrete Research*, V. 29, 1999, pp. 113-120.
7. Fernandez-Jimenez, A. Palomo, J. G. and Puertas, F., “Alkali activated slag mortars: mechanical strength behavior”, *Cement and concrete Research*, V. 29, 1999, pp. 1313-1321.
8. Deb, P., Nath, P., Sarker, P. K., “The Effects of Ground Granulated Blast Furnace Slag Blending with Fly Ash and Activator Content on the Strength and Workability of

Geopolymer Concrete Cured at Ambient Temperature”, *Materials and Design*, V. 62, 2014, pp. 32-39.

9. Nath, P., Sarker, P. K., “Use of OPC to improve setting and early strength properties of low calcium fly ash geopolymer concrete cured at room temperature”, *Cement and Concrete Composites*, V. 55., 2015, pp. 205 – 214.
10. Fernandez- Jimenez, A. and Palomo, A., “Composition and microstructure of alkali activated fly ash binder: effect of the activator”, *Cement & Concrete Research*, 35, 2005, pp. 1984-1992.
11. Sarker, P. K., “Bond strength of Reinforcing Steel Embedded in Geopolymer Concrete”, *Materials and Structures*, V. 44, 2011, pp. 1021 – 1030.
12. Rahman, M., and Sarker, P. K., “Geopolymer Concrete Columns under Combined Axial Load and Biaxial Bending”, *CONCRETE 2011 Conference*, Oct 12-14, 2011: Perth, Western Australia: The Concrete Institute of Australia.
13. Sumajouw, D. M. J., Hardjito, D., Wallah, S. E., and Rangan, B. V., “Fly Ash-Based Geopolymer Concrete: Study of Slender Columns”, *Journal of Materials Science*, V. 42 No. 9, 2007, pp. 3124-3130.
14. Chang, E. H., Sarker, P. K., Lloyd, N. and Rangan, B. V., “Shear Behaviour of Reinforced Fly Ash-Based Geopolymer Concrete Beams”, *Proceedings of the Concrete Institute of Australia 23rd Biennial Conference*, Adelaide, Australia, October 18 – 20, 2007, pp. 679 – 687.
15. Lyon, R. E., Balaguru, P. N., Foden, A., Sorathia, U., Davidovits, J., Davidovics M., “Fire resistant aluminosilicate composites”, Fire and Materials, V. 21, 1997, pp. 61-73.
16. Shaikh, F. U. A. and Vimonsatit, V., “Compressive strength of fly ash based geopolymer concrete at elevated temperature”, Fire and Materials, 2014, DOI: 10.1002/fam.2240.
17. Abdullah, M. M. A. B., Jamluddin, L, Hussin, K., Bnhussain, N., Ghazali, C. M. R., Ahmad, M. I., “Fly ash porous material using geopolymerization process for high temperature exposure”, International journal of molecular sciences, V. 13, 2012, pp. 4388-4395.

18. Kong, D. L. Y., and J. G. Sanjayan, “Damage behavior of geopolymer composites exposed to elevated temperatures”, *Cement and Concrete Composites*, V. 30, No. 10, 2008, pp. 986-991.
19. Sarker, P. K. and de Meillon, T., “Geopolymer concrete after exposure to high temperature heat” *Recent Developments in Structural Engineering, Mechanics and Computation*, Zingoni A. (ed.), Millpress, Rotterdam, The Netherlands, 2007, pp. 1566 – 1571.
20. Sarker, P. K., Kelly, S. and Yao, Z. T., “Effect of fire exposure on cracking, spalling and residual strength of fly ash geopolymer concrete”, Materials and Design, V. 63, 2014, pp.584-592.
21. International Standards Organisation, Fire Resistance Tests, Elements of Building Construction (ISO 834), Switzerland, 1980.
22. ASTM Standards, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (ASTM C 618 – 08), USA, 2008.
23. Australian Standard, Methods for Fire Tests on Building Materials, Components and Structures (AS 1530.4), Australia, 1997.
24. Subaer, van Riessen, A., “Thermo-mechanical and microstructural characterisation of sodium poly (sialate-siloxo) (Na-Pss) geopolymers”, Journal of Materials Science, V. 42, 2007, pp. 3117-3123.