REINFORCED GEOPOLYMER CONCRETE AFTER EXPOSURE TO FIRE

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ABSTRACT

Geopolymer is an alternative binder for concrete. Heat-cured fly ash based geopolymer concrete can be an ideal material for precast concrete members. This paper presents the residual strength of reinforced geopolymer concrete after exposure to fire. Ordinary Portland cement (OPC) and geopolymer concrete wall panels of 500 mm× 500 mm (19.7 in ×19.7 in) size and thickness of 125, 150 and 175 mm (4.9 in, 5.9 in and 6.9 in) were exposed to fire on one side up to 960 ^{0}C for two hours. The specimens were reinforced with a single layer of steel mesh. Compressive strengths of the geopolymer and OPC concrete varied in the range of 42 to 50 MPa (6 to7.3 ksi). The specimens were cooled down to normal temperature after exposure to fire and tested under concentric compressive load. The test failure loads were compared with the calculated failure loads of the original unheated specimens. The failure load of the geopolymer concrete members was in the range of 61 to 71% of the calculated original values. The range of the failure loads of OPC concrete members was 50 to 53% of the original strengths. Therefore, the geopolymer concrete specimens retained higher post-fire strengths as compared to the OPC concrete specimens.

Keywords: Compression member, Fly ash, Geopolymer, Reinforced concrete, Post-fire strength.

INTRODUCTION

The demand of cement is continuously increasing with the increase of population and the subsequent increase in the use of concrete as a construction material. Ordinary Portland Cement (OPC) has been traditionally used as the binding agent in concrete. About one ton of carbon dioxide is emitted into the atmosphere in the production of one ton of cement. Therefore, alternative binders utilising industrial by-products will be helpful to reduce the increasing trend of green house gas emission. Geopolymer is an emerging alternative binder for concrete that uses a by-product material instead of cement. A base material such as fly ash 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. Source materials such as low calcium fly ash[1-3], high calcium fly ash[4], metakaolin[5] and blast furnace slag[6, 7] can be used to make geopolymer. Although different source materials are used to manufacture geopolymers, basically the reaction of the source materials with an alkaline solution results in a compact well-cemented composite. The coal-fired power stations generate substantial amount of fly ash as a by-product. Use of fly ash in geopolymer concrete (GPC) can help reduce the carbon footprint of concrete.

The results of recent studies[8-11] have shown the potential use of fly ash based geopolymer concrete as a construction material. It is important to study the performance of geopolymer concrete in various structural applications for its use in the construction industry. The previous research on fly ash-based geopolymer concrete studied the short-term and long-term properties. Various parameters influencing the strength of geopolymer concrete were investigated[2, 11]. It was shown that heat-cured geopolymer concrete possesses high compressive strength, undergoes very little drying shrinkage and moderately low creep, and shows good resistance to sulfate and acid attacks. Geopolymer concrete showed higher bond strength with reinforcing steel as compared to OPC concrete[9]. Geopolymer concrete beams and columns showed similar behavior to that of OPC concrete members[12, 13]. Therefore, heat-cured geopolymer concrete can be an ideal material for precast concrete members.

Investigation into the structural performance of a material under fire is important for the safety of life and property. Residual strength of a material after exposure to high temperature heat indicates the endurance of the material in case of a fire. Previous studies[14, 15] on plain concrete cylinders showed that geopolymer concrete gained strength at exposure to relatively low temperature such as 200 ^{0}C. The strength loss of geopolymer concrete cylinders exposed to heat of high temperature such as 800 ^{0}C to all faces was similar to that of OPC concrete cylinders. The strength loss of reinforced concrete members at high temperature is considered to be different because of the presence of the reinforcement and the difference in the exposure of the faces to heat. This paper compares heat transfers and the post-fire strengths of reinforced geopolymer and OPC concrete panels exposed to fire of up to 960 ^{0}C. The OPC and geopolymer panels were exposed to fire on one side and then cooled down to normal temperature. The cracking and spalling behaviors were observed and the post-fire strengths were determined from compression tests.

EXPERIMENTAL WORK

Experimental work was carried out in the laboratory to observe the behaviours of reinforced OPC and geopolymer concrete panels exposed to fire. The panels were of different thickness with the same amount of reinforcement. They were exposed to fire for two hours, cooled down to normal temperature and then subjected to concentric compression to determine the failure loads.

MATERIALS

The concretes used to cast the test specimens were mixed in the laboratory. General purpose Portland cement was used for OPC concrete. Fine grade and Class F (ASTM 618)[16] fly ash commercially available in Western Australia was used to make geopolymer concrete. The percentage of the fly ash passing through a 45 μ 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. Sodium hydroxide pellets were dissolved in water to make 14M solution. The 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 stone. The sand used was river sand. Tap water was used in mixing the concretes. The mixture proportions of OPC and geopolymer concrete are given in Table 2. These mixture proportions were obtained based on previous studies[1] and by carrying out trial mixes before the actual mixes. The reinforcement was Australian 500 MPa normal ductility steel deformed bars.

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		
							7mm	10mm	20 mm
OPC	385	-	205	-	-	616	412	240	492
GPC	-	408	55	41	103	554	462	277	554

*1 lb / yd^3 = 0.593278 kg / m^3

TEST SPECIMENS

Concrete was mixed using a pan type laboratory concrete mixer. Slump tests were carried out to determine the workability of fresh concrete. The slump of OPC concrete varied between 90 and 120 mm (3.5 in and 4.7 in) and that of geopolymer concrete varied between 200 and 220 mm (7.9 in and 8.7 in). The test panels were 500 mm × 500 mm (19.7 in × 19.7 in) in size. The size of the test panels was limited by the size of the available furnace for fire exposure. The reinforcement consisted of three 12 mm (0.47 in) diameter bars in each direction, distributed in the middle of the section. Three different panels with the thicknesses of 125, 150 and 175 mm (4.9 in, 5.9 in and 6.9 in) were cast by using OPC and geopolymer concretes. The panels were compacted by using an electrically operated concrete vibrator. Casting of a typical geopolymer concrete test panel is shown in Fig. 1. A thermocouple was inserted in the middle of the panel to a depth of 25 mm (1 in) from one face to measure the transfer of heat through the specimen when the other face would be exposed to fire. Standard 100 mm × 200 mm (3.9 in ×7.9 in) cylinders were cast for compressive strength tests. The geopolymer concrete specimens were steam cured at 60 ^{0}C for 24 hours and then left in ambient condition until testing. The OPC concrete specimens were cured in ambient temperature by spraying water.

Fig. 1 Casting of a Geopolymer Concrete Test Specimen

TEST PROCEDUE

The specimens were exposed to fire at 28 days after casting. Fig. 2 shows a panel set in the gas-fired furnace. The furnace was turned on and the panel was heated on the face which was inside the furnace. This condition of heating is considered to be 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 door of the furnace was kept partially closed during the heating period for safety reason. The geopolymer and OPC panels were exposed to fire in the same way. The fire in the furnace was controlled to achieve the temperature - time curve as close as possible to that recommended in the Standards for fire test of building materials[17, 18]. The temperature-time curve recommended in the Australian Standard[18] is given by Equation 1.

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

Where T_t is furnace temperature (^{0}C) at time t (minutes) and T_0 is the initial furnace temperature (^{0}C).

The temperature at 25 mm depth from the unheated face was measured by the thermocouple inserted in the specimens. The furnace was turned off after heating the panels for two hours and the panels were then left to cool down to normal temperature. After cooling down to normal temperature, the panels were tested for concentric compression using the Universal Testing Machine. The compression test of a panel is shown in Fig. 3. All the panels except the 175 mm geopolymer concrete panel were loaded to failure and the test failure loads were recorded.

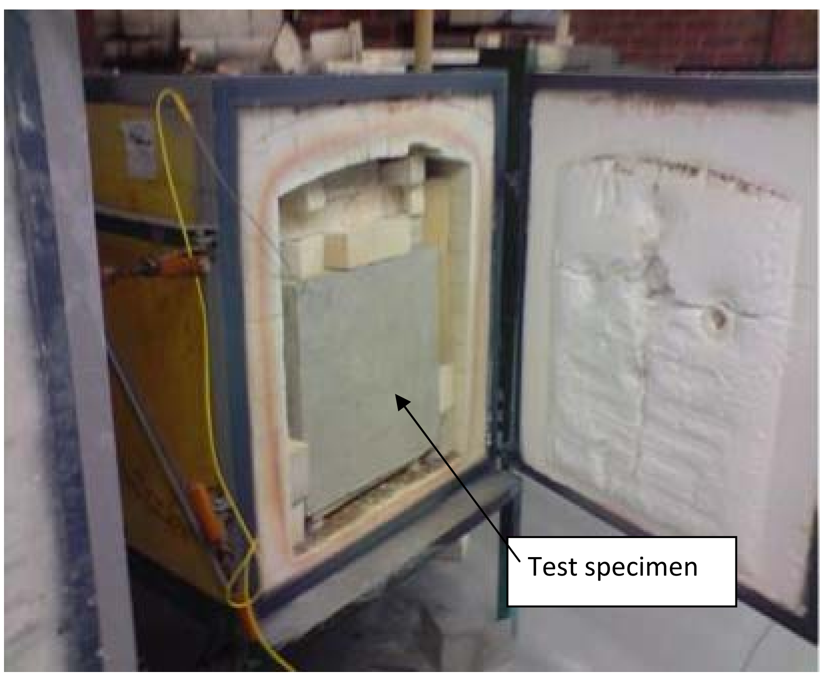

Fig. 2 Test Panel Set for Exposure to Fire

Fig. 3 Post-Fire Concrete Panel Test under Compression

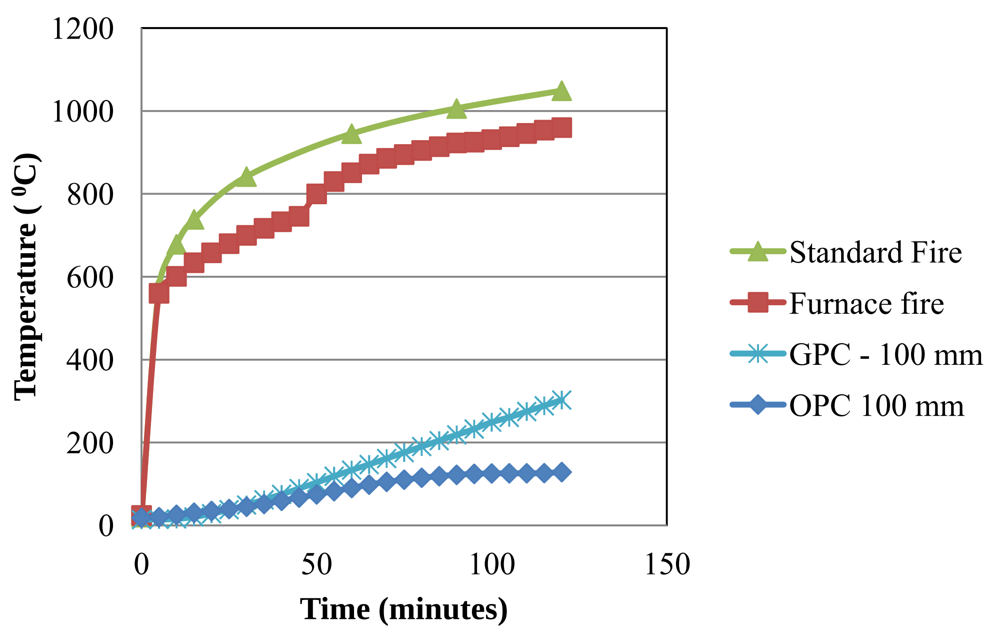

Fig. 4 Temperature – Time Curves for 125 mm (4.9 in) Panels

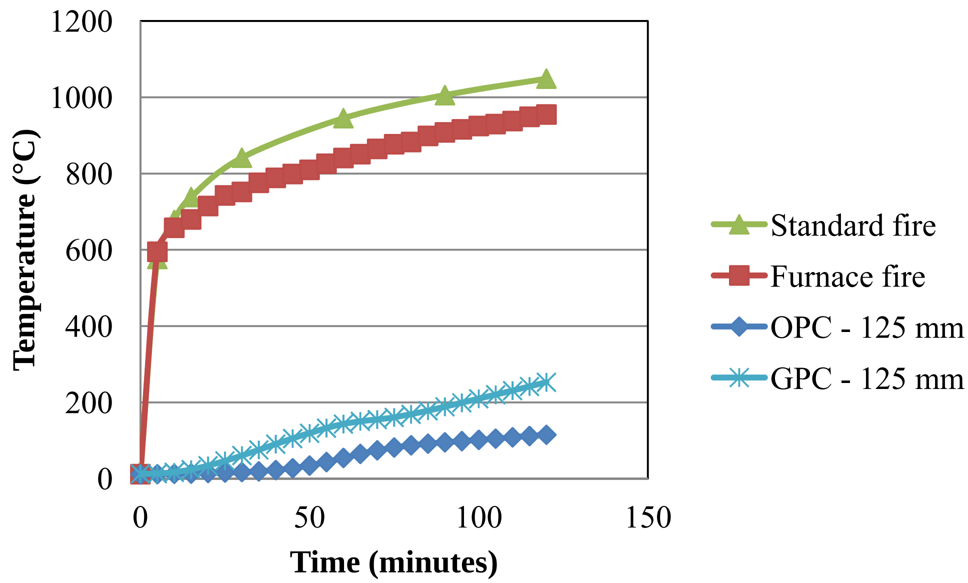

Fig. 5 Temperature – Time Curves for 150 (5.9 in) mm Panels

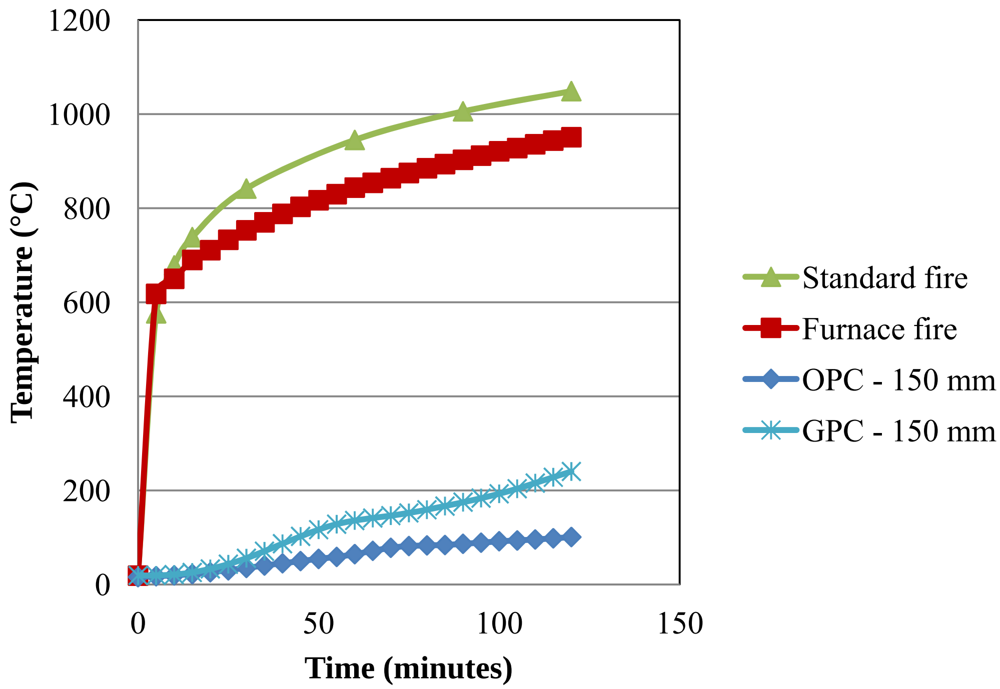

Fig. 6 Temperature – Time Curves for 175 (6.9 in) mm Panels

TEST RESULTS AND DISCUSSION

HEAT TRANSFER THROUGH CONCRETE PANELS EXPOSED TO FIRE

The temperature-time curves of the fire inside the furnace during the 2-hour heating period of the 125, 150 and 175 mm panels are shown in Figs. 4, 5 and 6 respectively. The standard fire curve given by Equation 1[18] is also shown in these Figures. It can be seen that the actual temperature-time curves at the fire-exposed face of the panels were close to that of the standard fire. The temperature at 25 mm (1 in) depth from the unheated face of these panels is also shown in these Figures. As expected, temperature near the unheated face is less for the thicker panels than that of the thinner panel of the same type of concrete. Comparing the temperature-time curves, it can be seen that the temperature is higher in the geopolymer concrete panel than in the OPC concrete panel of the same thickness. The differential temperature between the heated and unheated faces was generally smaller in the geopolymer concrete panels than in the OPC concrete panels. Thus, it can be said that the heat conductivity of geopolymer concrete is generally higher than OPC concrete when exposed to the high temperature heat of fire.

(a) 150 mm OPC concrete panel (b) 150 mm GPC panel

Fig. 7 Failure of the OPC and GPC Panels

Table 3 Load Capacity of the Test Panels

Concrete type	Thickness, mm	Mean cylinder compressive strength, f_{cm}, MPa*	Original strength, $P_{original}$, (Eq. 1), kN**	Post-fire strength, P_{test} , kN	% strength retained, P_{test} / $P_{original}$	Average % strength retained
OPC	125	50	3278	1645	50%	52%
	150	45	3529	1873	53%	
	175	46	4179	2185	52%	
GPC	125	46	3029	2146	71%	66%
	150	50	3903	2368	61%	
	175	42	3830	2500#	> 65%	

*1 ksi = 6.89475 MPa **1 kip = 4.44822 kN # Not failed

POST-FIRE STRENGTH OF THE PANELS

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. However, no spalling of pieces of concrete occurred because of thermal shocks during heating or cooling stages. Colour of the geopolymer concrete turned to red after exposure to fire. This is mainly because of the higher percentage of iron oxide in the fly ash than in cement. Failure of the panels was characterised by crushing of the concrete mainly on the fire exposed face and buckling of the longitudinal reinforcement. Typical failures of the OPC and GPC panels are shown in Fig. 7. The post-fire load capacity of the test panels are given in Table 3. The 175 mm thick geopolymer concrete panel was loaded to the safe maximum capacity of the machine without failure. The failure load of this panel would be higher than 2500 kN (562 kip).

The original unheated strength of each panel is calculated by using Equation 2, considering the panel as a stocky reinforced concrete member under compression.

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

Where P is the load capacity, f_{cm} is the concrete compressive strength, A_g is the gross cross-sectional area, A_s is the area of reinforcing steel and f_y is the yield strength of steel.

The mean unheated cylinder compressive strength corresponding to each panel is given in the Table 3. For each test panel, area of the reinforcing steel is 339 mm^2. Yield strength of steel used in the calculation is 500 MPa. These calculated load capacities of the unheated panels are given in Table 3. The percentage of strength retained after exposure to fire is calculated for each panel by dividing the post-fire load capacity by the calculated original load capacity. It can be seen from Table 3 that the percentage of original strength retained by the GPC panel is higher than that by the OPC concrete panel of the same thickness. The failure load of the geopolymer concrete members was in the range of 61 to 71% of the calculated original values. The range of the failure loads of OPC concrete members was 50 to 53% of the original strengths. The possible reason for the higher percentage of strength retained by the GPC panels is their smaller temperature differential between the heated and unheated faces than in the OPC panels. The smaller temperature differential is thought to cause less internal damage in the GPC panels than in the OPC panels.

CONCLUSIONS

Six 500 mm square reinforced OPC and geopolymer concrete panels of 125, 150 and 175 mm thickness were made and exposed to fire of up to 960 ^{0}C temperature for two hours. The fire temperature-time curves were close to the standard fire curve. The panels were then cooled down and tested under compressive load. The heat transfers during the heating stage were generally higher through GPC panels than through the OPC panels. Thus, the temperature differential between the fire-exposed face and the opposite face was smaller in the GPC panels than in the OPC concrete panels. The GPC panels retained higher strength after exposure to fire than the OPC concrete panels. This is thought to be because of less internal damage in the GPC specimens by fire than in the OPC specimens.

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