Behavior of MK-based Geopolymer Concrete Circular Columns Exposed to Fire

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Received: Aug. 22, 2020; Accepted: Sep. 08, 2020

The design of the construction buildings should consider the fire resistance of the structural members to reduce the risks of fire exposure. Geopolymer is a promising material that can be used in construction for its desired properties including strength and sustainability. The performance of the MK-based geoploymer concrete columns exposed to fire was investigated and presented in this paper. The columns are short of one meter in length and circular cross section of diameter 150 mm. Twelve columns were tested under axial concentrated loads. The parameters considered as variables of the experimental work are the duration of fire exposure and the cover thickness (15, 25, 35 mm). The experimental results showed that there is an enhancement in the load carrying capacity of the columns subjected to fire for low level of fire about 12 % of the initial strength of the column with the largest thickness. At the highest fire period, the columns experienced loss in strength especially the specimen of the smallest cover thickness by 28 % of its original strength. The reduction in strength is attributed to the cover spalling resulted from the damage caused by fire. However, MK-based GC columns have better performance of cement based RC columns under fire.

Keywords: Circular Column, Cover Thickness, Geopolymer, Fire Resistance, Metakaolin

http://dx.doi.org/10.6180/jase.202102_24(1).0012

1. Introduction

Fire is one of the major disasters threats people lives and properties around the world regardless the causes including, but not limited, wars, terrorist attack, wildfires, and electrical fault. Although the technology provides fire-controlling systems in buildings, the prevention of fire is still hard to achieve, especially in the developing countries. Reinforced concrete is commonly composite material used in the structures. It is well known that concrete has good fire resistance due to its thermal properties. The considerable loss in concrete strength starts at temperatures greater than (350 ^{o}C), the deterioration and spalling of concrete cover occurs at increasing temperature depending on the concrete compressive strength, fire duration, member type, loading condition, cover thickness, cooling method ,..ect. [1–7].

Because of the climate changes resulted from the pollution concerning the production of cement, investigations have been made to use alternative construction materials, which are environmentally friendly. Geopolymer, firstly proposed by Davidovits in 1978 as mineral binder resulted from a chemical reaction of Aluminum and Silicon Oxides under alkaline liquid activator [8], is considered a green material reducing 80 -90 % the emission of CO2 resulted from the cement industry [9]. Therefore, geopolymer can replace the ordinary Portland cement in concrete, the production of geopolymer concrete (GC) depends on the aluminsilicate common sources, including fly ash (FA), metacaoline (MK) and ground granulated blast slag (GGBS). The geopolymer performance exposed to fire has been examined through a number of studies. It was reported that the mass loss and porosity of geopolymer at elevated temperatures rely on its composition, however, chemical stability was observed and the loss in mass was found to be less than 15 % at temperature levels up to 300 ^{o}C, the size and volume of pores increase at 800 ^{o}C and above [10, 11]. Various response of deformation due to thermal exposure was determined for the geopolymer related to water content, alkali cation type and the activator solution, but it is still better than the OPC thermal deformation [12, 13]. The researchers have determined that the geopolymer has much better thermal behavior compared to the OPC [12, 13]. The mechanical properties of the GC also affected by the elevated temperatures, it was found that (MK) experience cracking damage and low residual compressive strength at high temperature, but the proportion of Si/Al in (MK) plays role in improving the residual compressive strength, the proportion of greater than 1.5 lead to minimum loss in compressive strength [14]. The compressive strength of (MK) increases with the increase of the temperature up to 400 °C, from 400-1000 °C, the residual strength decreased, but still greater than the cement based specimen [15], another study revealed that the 10 % water presence in in MK causes to loss the strength about 32 % and 43 % at temperatures (400 and 800 °C), respectively [16, 17]. FA based GC has less compressive strength at ambient temperature than MK-based GC, while the later losses 28 % its strength at 800 oC and AF gains 300 % of its compressive strength [18]. It was determined that the specimen shape affected the residual compressive strength, at 800 °C, the FA cube sample compressive strength increased, panels lost 40 % of its initial strength, the maximum reduction in strength was found to be in cylinders samples approximately equal to 85 % [19–21]. The larger initial compressive strength, the larger ductility reduction is at 800 °C [19]. In addition, the cooling method influences the residual compressive strength at elevated temperatures. The flexural behavior of the reinforced FA/ GGBS GC reinforced beam was investigated by Ren et al. [22], the authors determined that there is a gain in GC compressive strength by 4 % of its initial strength, at exposure of 400 °C, but at 600 °C great degradation in strength was observed equal to 37 % its initial strength. The ultimate load carrying capacity of the GC beam enhanced by 11 % at 400 °C, and reduced by 1 % at 600 °C of its initial load carrying capacity. However, the GC breams showed larger crack width and less ductility at elevated temperatures as compared to OPC beams exposed to same conditions [22]. Based on the previous studies, it can be determined that there is no general conclusion can be drawn for the mechanical properties of GC affected by elevated temperature, because they depend on several variables such as, raw material, aggregate type, presence of water, mix design, additives use, specimens shape and cooling method.

Despite the extensive studies related to the thermal and mechanical properties of GC exposed to elevated temperatues, limited studies was found regarding the reinforced concrete members. There is no research considers the fire resistance of the reinforced metakaoline- based GC columns, to the authors' knowledge.

In this research, the performance of circular RC columns made of MK-based GC exposed to fire was investigated considering the effect of the fire exposure duration and the cover thickness as parameters of the study.

Metakaolin was selected as a raw material for this study because it is economic, locally available and considered a green material.

2. Experimental Program

The tests were carried out on twelve MK-based geopolymer concrete tied reinforcement columns. The cross section is circular of dimensions 15 cm diameter and 100 cm length, the columns reinforced with 6ϕ 8 mm longitudinal steel bars (steel reinforcement ratio is 0.00284). The lateral reinforcement is ϕ6 placed at 50 mm on a distance of 15 cm at both ends of the columns; 10 cm c/c is the spacing between the ties for the remaining length. Details of the specimens are shown in Fig. 1. The variables considered in this work are the cover thickness and the duration of fire exposure. The specimens were divided into four sets as shown in Table 1.

2.1. Materials

Metakaolin was prepared based on the procedure recommended by Ibraham and Wahab [23]. The Kaoline clay, low cost-locally available material, was grinded and then burnt in a furnace at 700 °C for one hour to produce Metakaolin. It was cooled for 24 hours at room temperature. Sodium hydroxide and sodium silicate were used as the alkaline activating solution with 0.45 % of MK content. A High water reducer superplasticizer was used in the mixture to increase the workability. The fine aggregate was river sand with maximum size of 4.75 mm and 2.6 fineness modulus. The coarse aggregate was crushed gravel stones obtained from a local quarry of 14 mm maximum size. The mix proportion of GC are given in Table 2.

2.2. Preparation of specimens and Casting

The steel reinforcing cages were made for all columns specimens with three different diameters to provide the required covers; they were welded to circular steel plate of dimension 150 mm diameterx10 mm thickness. The cages were placed in the molds which are plastic pipes of circular section. A day prior to casting, the alkaline activating solution was prepared for reactivity improving. The Metakaolin, fine and coarse aggregates were dry-mixed in a mixer for three minutes, Alkaline activator, superplasticizer, and water of 10 % of MK weight were added to the dry materials and mixed for additional four minutes to form the GC [24].

The GC was poured into molds and compacted by an electrical vibrator. Besides, twelve cylinders were cast with GC to determine the compressive strength of the mixture at different levels of fire exposure duration. The columns were demolded one day after casting and were left at the laboratory for 28 days for ambient curing.

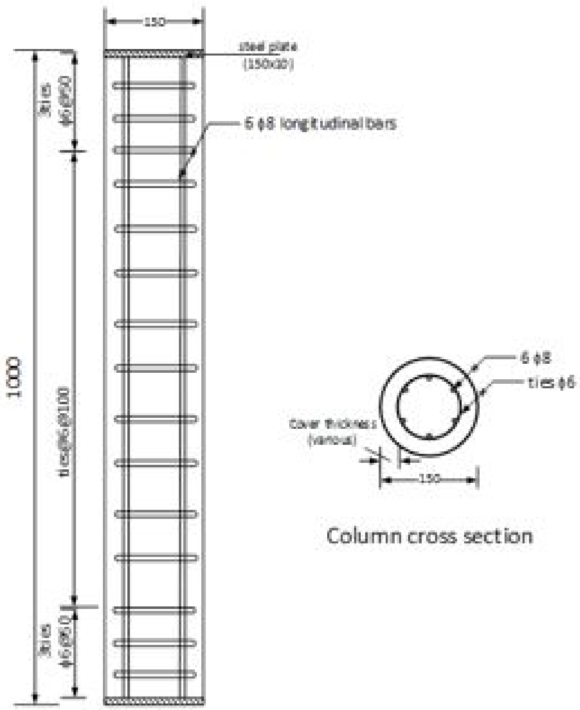

Fig. 1. Column specimens' size and reinforcement details (all dimension in mm).

2.3. Columns Exposed to Fire and Test Setup

The column specimens were exposed to actual fire in open area, the fire temperature was constant equal to 600 °C, there is a change in mechanical properties of MK at 400-600 °C [22], to ensure the fire was constant, an infrared thermometer "Testo 835" was used to measure the fire temperature. Each three columns out of twelve columns in addition to cylinders were exposed to same fire duration of 10, 15 and 20 minutes as mentioned before, using the time scale for column models time scale for column models taking the advantage of the correlation behavior between the model and prototype [25, 26]. Then the columns were cooled in air for 24 hours. The columns were tested under the application of concentrated load by a hydraulic universal testing machine of 3000 kN capacity, the loading was applied gradually up to the failure of column specimens. The corresponding cylinders were tested also to determine the compressive strength for each fire duration.

3. Results and Discussion

The compressive strength of the GC cylinders and failure load of the tested specimens with the corresponding considered variables are listed in Table 3. The behavior of the GC columns was investigated in terms of failure loads and the crack pattern and failure mode.

3.1. The GC Compressive Strength

The average of three cylinders was taken to determine the compressive strength at different periods of fire. It was found that with 10 and 15 min. exposure to fire, the compressive strength increased by 5.3 % and 9 %, respectively. There is 16 % reduction in strength for 20 min. fire period as compared to the control specimen with no exposure to fire; the gain in strength can be attributed to the evaporation of water causes voids reduction in GC in addition to the change in microstructure of the material.

3.2. Effect of Fire Exposure Duration

Nine of the tested columns were subjected to different periods of time (10, 15, 20 minutes time for models). For a certain cover thickness, there is an increase in the ultimate failure load in relation to 10 and 15 min. exposure period. A drop in load carrying capacity of the columns when they subjected to 20 min. fire duration Fig. 2. It can be observed that the maximum reduction in strength occurs in column C4 equals to 27 % of the original strength. The maximum gain in strength is 12 % for the exposure duration of 15 min in C11, Fig. 4.

3.3. Effect of Cover Thickness

Three values of cover thickness were selected as (15, 25, and 35 mm) for the columns. The ultimate failure load values versus the cover thickness have the same trend at all exposure periods especially at fire periods 10 and 15 min. However, at the greatest value of fire duration, larger influence of the cover thickness can be noticed on the load carrying capacity Fig. 3. There is no significant effect of increasing the cover thickness from 15 to 25 mm on enhancing the load carrying capacity of the columns. The percentage difference of strength between columns of 15 and 25 mm exposed to fire less than 20 min. equals to 1 %, but increasing the cover thickness to 35 mm improves the column strength by an average value of 5 % at same fire period. When the exposure duration increased to 20 min., increasing the cover from 15 to 35mm enhance the load carrying capacity by 13 %. The confinement of the column according to the largest reduction of GC compressive strength at 20 min. Fig. 5.

Table 1. Description of Columns Specimens Sets.

Cover Thickness (mm)	Duration of Exposure (minutes)			
	0	10	15	20
15	C1	C2	C3	C4
25	C5	C6	C7	C8
35	C9	C10	C11	C12

Table 2. Proportion of Geopolymer Concrete Mixtures in kg/m^3

Metakaolin	Sand	Gravel	Alkaline Activator	Water	Superplasticizer
400	720	1100	180	40	12

Table 3. Proportion of Geopolymer Concrete Mixtures in kg/m^3

Column No.	Exposure Duration min.	Cover Thickness mm	GC Compressive Strength, f'c, MPa	Ultimate Failure Load, Pu, kN	Pu)Col to Pu)Control
C1	0	15	28.6	554	1.00
C2	10	15	30.1	587	1.06
C3	15	15	31.2	596	1.08
C4	20	15	24	402	0.73
C5	0	25	28.6	556	1.00
C6	10	25	30.1	592	1.06
C7	15	25	31.2	599	1.08
C8	20	25	24	411	0.74
C9	0	35	28.6	559	1.00
C10	10	35	30.1	613	1.10
C11	15	35	31.2	626	1.12
C12	20	35	24	474	0.85

3.4. Cracks Pattern and Spalling

All fire exposed GC column experienced a change in color, which is considered an indication for the column deterioration intense. The color was not uniform along the specimens. Three colors can be distinguished, grey, dark grey and light pink as the duration of fire exposure increases to (10, 15 and 20 minitus). The applied concentrated load caused a compression failure for the tested columns. Fig. 6 illustrates the placement of specimens that the whole column surface area was subjected to fire and the columns failure after test. Vertical cracks were observed and extended as the loading increased until reaching to failure. However, for columns exposed to fire for 10 and 15 min., no cover spalling accrued which reflected the improvement in the load carrying capacity. After 20 min. of fire exposure, wide cracks was formed and extended resulted in crushing of the GC which lead to cover spalling of some areas along the surface area of the columns. C4, which is the column with 15 mm, cover thickness and exposed to fire for 20 min. had the greatest degree of damage that explained the maximum drop in strength among the other specimens. The differential of the thermal ingredient induced by the difference between the temperature of column surface and its core causes the cover spalling [27]. The increase in temperature affects the strength of the unconfined cover and hence reduce the compression force contributed by the cover to resist the applied axial force. In general, the MK- based GC columns have better performance as compared to the OPC reinforced concrete columns.

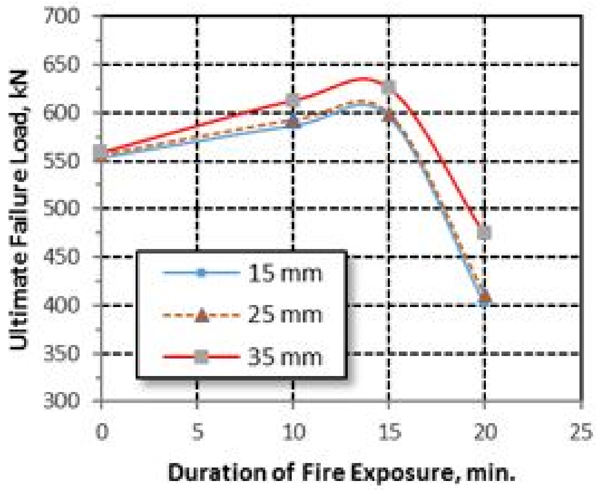

Fig. 2. Effect of Fire Exposure Duration on the Columns Failure Load.

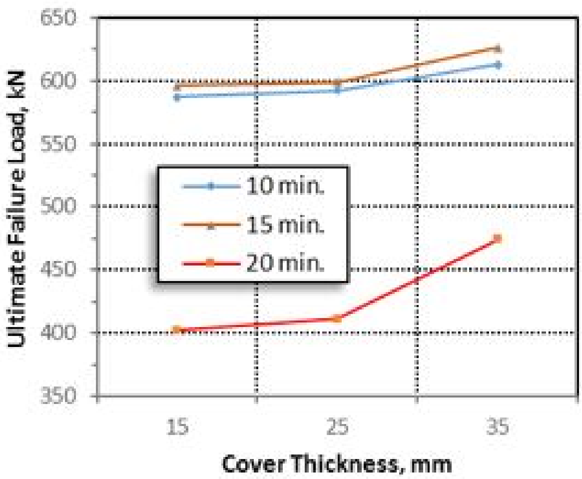

Fig. 3. Effect of Cover Thickness on the Columns Failure Load.

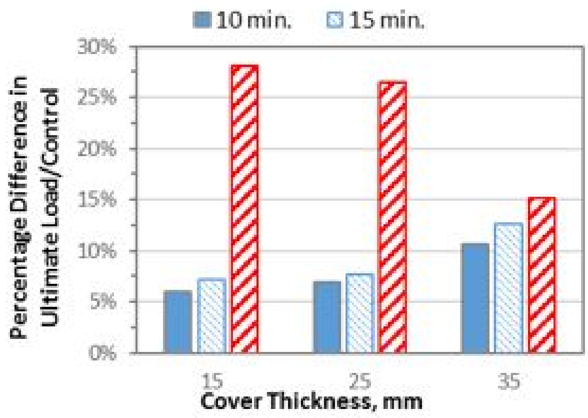

Fig. 4. Fire Exposure Duration vs the Columns Failure Load.

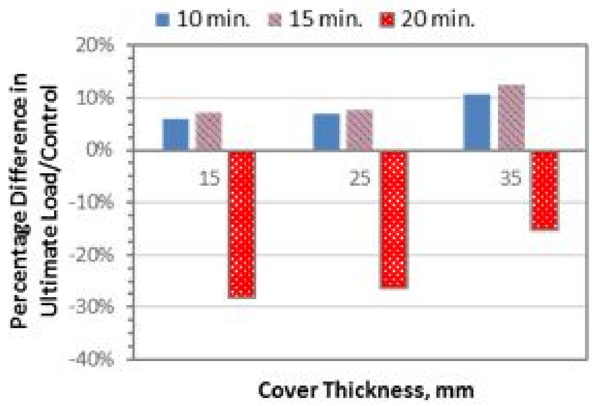

Fig. 5. Cover Thickness vs Difference in the Columns Failure Load.

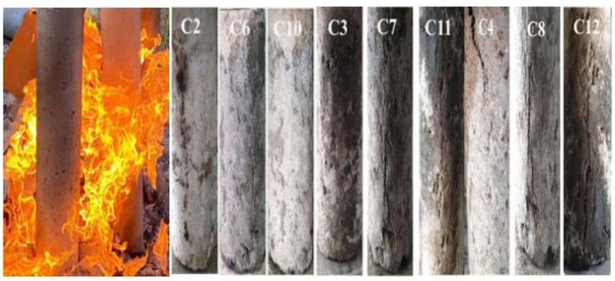

Fig. 6. Columns during fire exposure and Failure of the tested columns.

4. Conclusions

Based on the experimental results of the tested columns exposed to fire, the following conclusions can be drawn:

1. The load carrying capacity of the columns improved with the exposure to fire at periods of (10 and 15 min.) for a certain cover thickness, ranged from (6 - 12 %).

High reduction in the strength was determined after 20 min. of fire exposure equal to 28 % of the initial capacity for the column with 15 mm cover thickness.

2. The change in cover thickness from 15 to 25 cm has no significant effect on the load carrying capacity of the columns subjected to different fire periods, which found to be 2 % as maximum.

   Increasing the thickness to 35 mm greatly influenced the fire resistance; it increases the strength value up to 13 % as compared to smallest cover thickness.

3. Three main colors were distinguished for the columns as indication of the column damage. The general failure mode of the columns was compression failure, the thermal effect in addition to the applied static concentrated load caused vertical cracks with no spalling at fire duration less than 20 min. The spalling occurred in the specimens at 20 min. fire exposure for three specimens with the different cover thickness especially for 15 mm thickness. The unconfined cover experienced loss in strength due to fire, which reflected on the total load carrying capacity.

5. Acknowledgment

Great sincere appreciation to the College of Engineering, Mustansiriya University, for the facilitation of this research that its staff has shown.

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