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Comparison of Mechanical Strengths and Resistance to Acidic Conditions, Permeability and Resistance to Elevated Temperatures of Geopolymer Concrete and Conventional Concrete

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ABSTRACT

In recent years, geopolymers, as a new class of green cement binders, have gained significant attention as an environmental-friendly alternative to Portland Cement (PC) which can potentially reduce negative environmental impacts of PC production such as carbon dioxide (CO2) emissions, energy consumption, natural resources exhaustion and etc. Although the use of geopolymer cement to make concrete has significant environmental benefits, but the technical characteristics of geopolymer concrete should be studied and compared with conventional concrete. Hence, in this experimental study, several technical characteristics of geopolymer concrete including: compressive strength, indirect tensile strength, flexural strength, resistance to acidic conditions, water absorption capacity and resistance to elevated temperatures were studied and compared with conventional concrete. Summarizing the obtained results of this study indicated that geopolymer concrete in addition to major environmental advantages, also has better technical properties in comparison with conventional concrete and can be considered as an acceptable green alternative to conventional concrete.

Keywords:

Geopolymer concrete, Conventional concrete, Mechanical strengths, Resistance to acidic condition, Resistance to elevated temperatures, Permeability.

1. Introduction

Concrete is the most consumed material after water. As the demand for concrete rises, so does the consequent demand for Portland cement (PC), as the main component of concrete [1]. But production of PC has major environmental disadvantages, so that it is identified as one of the major sources of carbon dioxide (CO_2) emission and one of the most energy-intensive industry in the world [2]. Production of 1 ton of PC releases approximately 0.73-0.99 ton of CO_2 into the environment [3]. On the other hand, climate change due to global warming is currently one of the most significant environmental challenges. Greenhouse gas emissions is the main contributing factor to global warming, with CO_2 having the greatest share (65%) among other greenhouse gases. PC manufacturing is accounted for 7 to 10% of global CO_2 emissions [4]. Besides CO_2, the PC industry accounts for significant emissions of carbon monoxide (CO) and heavy metals [5]. Global PC production has continued to expand from 2568 Mt in 2006-4180 Mt in 2014. Furthermore, global PC production in 2020 was 4100 Mt and China with 2,100 Mt, India with 320 Mt, Vietnam with 95 Mt, the United States with 89 Mt and Egypt with 76 Mt were the top 5 countries in the ranking of the world's largest PC producers. Iran was the 7th largest producer of PC in the world with the production of 60 Mt in 2019. Therefore, it seems necessary to find an alternative to PC. In recent years, geopolymers have been introduced as environmentally friendly cementitious materials capable of reducing the negative environmental impacts associated with OPC [6]. In 1978, Davidovits introduced geopolymers as a new class of binders belonging to inorganic polymers [7]. Geopolymers are inorganic aluminosilicate substances comprised of two main constituents: a raw material rich in SiO_2 and Al_2O_3 and an alkaline activator solution [8]. The geopolymerization process involves a substantially fast chemical reaction under alkaline condition on Si-Al minerals, that results in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al bonds [9]. While, PC gel dominated by C-H-S bonds, which are obtained through the hydration reaction between water and PC. The alkaline activator solution playing an important role in the formation of crystalline structures of Si and Al, which is typically a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate (Na_2SiO_3) or potassium silicate (K_2SiO_3) [10]. The raw material, also known by other names such as aluminosilicate source, geopolymerization source and source material, plays the most important role in geopolymer cements and determines the technical properties of Geopolymer Concrete (GPC), as the supplier of Si and Al. The raw material, depending on required characteristics, cost and availability, can be of natural origin (e.g. Zeolite), synthetic (e.g. metakaolin) or waste materials (e.g. fly ash or Granulated Ground Blast Furnace Slag (GGBFS)) [11]. Fly ash is a by-product of the coal-fired power plant which can be one of the best raw-material candidates due to its proper structural nature. Fly ash is classified into two classes: C (high-calcium) and F (low-calcium). Metakaolin is another raw material obtained from calcinating Kaolin at 600–800 ˚C. GGBFS is a by-product of the steel industry, which due to its amorphous nature and its high content of glassy phase, GGBFS can be considered as a potential raw material for manufacturing of GPC. Although the use of geopolymer cement to make concrete has significant environmental benefits, but the technical characteristics of GPC should be studied and compared with conventional concrete. It provides a clear understanding of this type of concrete, which contributes to advances in the use of GPC. Hence, in this experimental study, the technical characteristics of GPC including: compressive strength,

tensile strength, flexural strength, resistance to acidic conditions, permeability and resistance to elevated temperatures were studied and compared with conventional concrete.

2. Materials and Methods

2.1. Materials

Aluminosilicate sources used in this study included: Class C fly ash, GGBFS and metakaolin. The PC used was also type II. The X-Ray Fluorescence (XRF) chemical analysis of the aluminosilicate sources and PC is illustrated in Table 1 NaOH with 98% purity and liquid Na_2SiO_3 with SiO_2/Na_2O molar ratio of 2 were used to prepare the alkaline activator solution. Table 2 represents the chemical analysis of the Na_2SiO_3 and NaOH substances. Figure 1 depicts the three aluminosilicate sources and PC used in this study.

Metakaolin GGBFS Fly Ash PC

Figure 1: Aluminosilicate sources and PC used in this study

Table 1. XRF chemical analysis of the aluminosilicate sources and PC (weight %).

Chemical substance	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	Na_2O	MnO	Cl	TiO_2	SO_3	LOI
GGBFS	34.4	11.2	37	0.6	9.8	0.68	0.6	1.58	0.002	-	-	2.63
Fly Ash	70.7	21.1	1.13	3.90	0.77	1.09	0.26	0.05	-	0.92	-	2.45
Metakaolin	54.45	30.21	1.23	4.89	-	4.05	2.32	0.11	-	0.10	-	1.41
PC	21.31	4.61	63.2	3.6	2.4	0.6	0.4	-	0.43	-	1.97	2.05

Table 2. Chemical analysis of NaOH and Na_2SiO_3 solutions.

NaOH			Na_2SiO_3		
Chemical substance	**Result**	**Unit**	**Chemical substance**	**Result**	**Unit**
NaOH	98	%	SiO_2	30	%
Na_2CO_3	1	%	Na_2O	14.5	%
NaCl	200	ppm	Water	55.5	%
Fe	6	ppm			
SiO_2	15.7	ppm			

Aggregates with granular sizes of 7-10 mm was used as coarse aggregate (sand) and < 4 mm sized aggregates were used as fine aggregate. Fine and coarse aggregates were sieved according to ASTM C33 [12]. SSD specific gravity and water absorption tests were conducted on the coarse and fine aggregates using the ASTM C127 [13] and ASTM C128 [14] procedures, respectively, given in Table 3 The fineness modulus (using ASTM C136 [15]) and sand equivalent (using ASTM D2419 [16]) values of the fine aggregates were measured equal to 3.01 and 73, respectively.

Table 3. Specific gravity and Water absorption of aggregates.

Material	SSD Specific gravity (gr/cm^3)	Water absorption (%)
Coarse aggregates	2.62	1.3
Fine aggregates	2.59	3.2

2.2. Experimental Program

2.2.1. Mix Design

After performing the initial tests, the concrete mix design was selected. 3 mix designs for geopolymer concrete were set, using different aluminosilicate sources. Moreover, one mix design was considered for conventional concrete (to compare with GPC). In all mix designs, the weight ratio of alkaline activator/aluminosilicate source (in GPC) or water/cement (in PC concrete) was 0.6. Table 4 illustrates the mix design of specimens. To manufacturing specimens, initially the alkaline activator solution, constituting of NaOH (14M), Na_2SiO_3 are combined and allowed to cool for 24 hrs. In the mixing process, the aggregates and aluminosilicate sources (fly ash or GGBFS or metakaolin) were first dry mixed in the mixer for 3 minutes. Next, the alkaline activator solution was added and the concrete was mixed for a further 2 minutes. A similar method was used to make PC specimens.

Table 4. Mix design of specimens (kg/m3).

Mix design ID	Fly ash	GGBFS	Metakaolin	PC	NaOH	Na_2SiO_3	Water	Coarse aggregate	Fine aggregate
F	400	-	-	-	96	144	-	850	850
G	-	400	-	-	96	144	-	850	850
M	-	-	400	-	96	144	-	850	850
PC	-	-	-	400	-	-	240	850	850

2.2.2. Testing

In the preparation process of the specimens, after completion of material mixing, the GPC and PC specimens were molded. Each mix was batched to produce 3 cube specimens (100x100x100mm) for compressive testing. The prepared specimens were dry cured at 60℃ for 24 hours and then allowed to set at ambient temperature. Thereafter, compressive tests on 7- and 28-day specimens were conducted in accordance with BS1881: Part116 [17]. For tensile strength tests, 3 cylindrical specimens (300x150mm) were produced for each mix design and tested at 7- and 28 days according the indirect tensile strength testing method of ASTM C496 [18]. As for flexural tests, 3 beam specimens (500x100x100mm) were considered for each mix design and tested according to ASTM C293 [19] 3-point bending test protocol. Water absorption capacity of the GPC and PC specimens was studied following the ASTM C642 [20] procedures. For water absorption capacity, the 28-day specimens were initially placed in a 105 ˚C oven to reach a stable dry weight

and then weighted (m_0). The specimens were then placed in a water tank for 3 days. They were then taken out and after drying the surface water, were weighted again (m). The 3-day water absorption capacity (W) is calculated by Eq. (1):

$$W = \frac{m - mo}{mo} \times 100 \quad (1)$$

Also, to test the chemical resistance of GPC and PC specimens, the 28-day specimens were placed in a solution of water and sulfuric acid at pH equal to 1 for 28 days. Then, weight loss test was taken from specimens. Three 100×100×100 mm cube specimens for each of mix designs were considered to evaluate GPC and PC resistance to elevated temperatures. For elevated temperature testing, the 28- day specimens were placed in the oven subject to various elevated temperatures: 200, 400, 600 and 800 ˚C. Fifteen cube specimens were produced for each of the considered mix designs, where 12 specimens were subjected to elevated temperatures (3 specimens for each aforementioned temperature level) and 3 specimens were considered as control specimens (not subjected to elevated temperatures). The oven temperature was raised with a constant rate of 1 ˚C/minute. After reaching the considered temperature, the specimens were kept in the oven for 3h and then the oven was turned off to gradually cool down to ambient temperatures. The specimens were then removed from the oven and subjected to compressive strength testing. Fig. 2 presents GPC and PC specimens.

M G F PC

Figure 2. GPC and PC specimens.

3. Results and Discussions

3.1. Mechanical Strength

The 7- and 28-day compressive, tensile and flexural strengths of specimens are gathered in Figures 3-5. As it can be seen, the highest initial (7-day) and lateral (28-day) compressive strengths, equal to 80.7 and 88.5 MPa, respectively, were recorded for the mix G, in which the GGBFS was used as the aluminosilicate source. The lowest 7- and 28-day compressive strengths belonged to the mix PC (Portland cement), showing 22.8 and 32.5 MPa, respectively. The obtained results indicated that GPC specimens provided higher compressive strength than conventional concrete specimen (PC). So that the compressive strength of G, F and M specimens was approximately 172, 119 and 15% higher than PC specimen, respectively. It could be due to the stronger Si-O-Al bonds (GPC) than C-H-S bonds (PC), resulting in higher bond strength of GPC specimens than PC specimen. Consequently, GPC specimens showed higher mechanical strength than PC specimen.

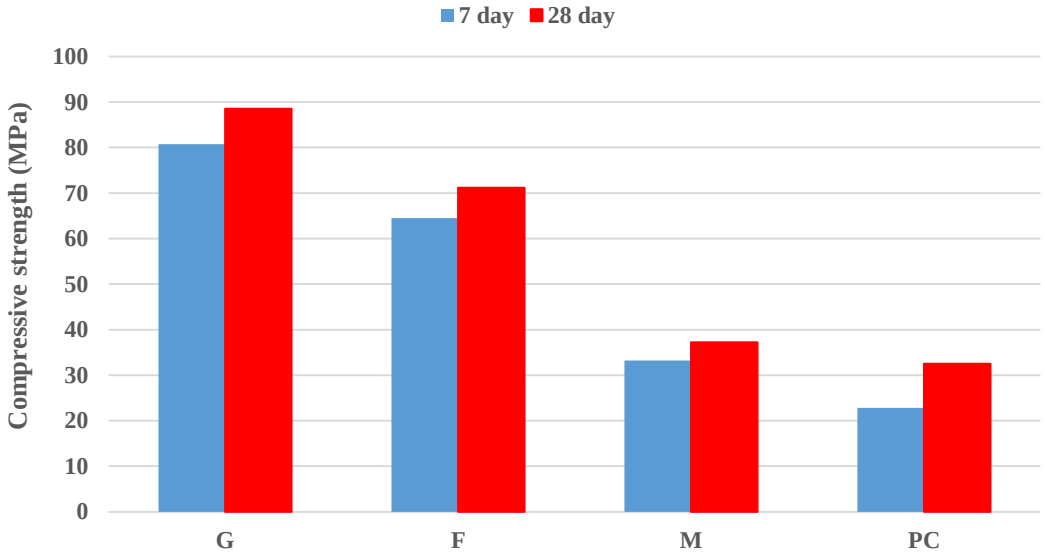

Figure 3. 7-day and 28-day compressive strengths of specimens.

Furthermore, strength gaining (early strength) of the GPC specimens after 7 days of curing was better than that of PC specimen. GPC specimens gained approximately 90% of their 28-day compressive strength in 7 days. Whereas, the rate of strength gaining of the mix PC after 7 days of curing was around 70%. The main difference between geopolymer cement and PC is in the formation and hardening mechanism of these two types of cement. In PC, a hydration reaction occurs. Hydration of PC basically lasts up to a month and is completed in a year. But the mechanism of formation and hardening of geopolymer cement occurs through a geopolymerizatoin reaction in a short time and under severe alkaline conditions, during which the geopolymer binder forms and hardens in a much shorter time than PC. Indeed, this is why the process of hardening and gaining strength of GPC is greater than PC concrete. Similar to the compressive strength test, GPC specimens provided greater tensile and flexural strengths in comparison with PC specimens. The 28- flexural strengths of G, F, M and PC mix designs was 9.8, 7.9, 4.2 and 3.7 MPa, respectively. G, F and M specimens showed approximately 165, 113 and 14% higher flexural strength compare to PC specimen, respectively. The highest 7- and 28- day tensile strengths were measured in G specimen (6 and 6.8 MPa, respectively), and the PC specimen showed the lowest 7- and 28-day tensile strengths (1.7 and 2.6 MPa, respectively) among all specimens. Tensile strength of G, F and M specimens was approximately 161, 111 and 8% higher than PC specimen, respectively.

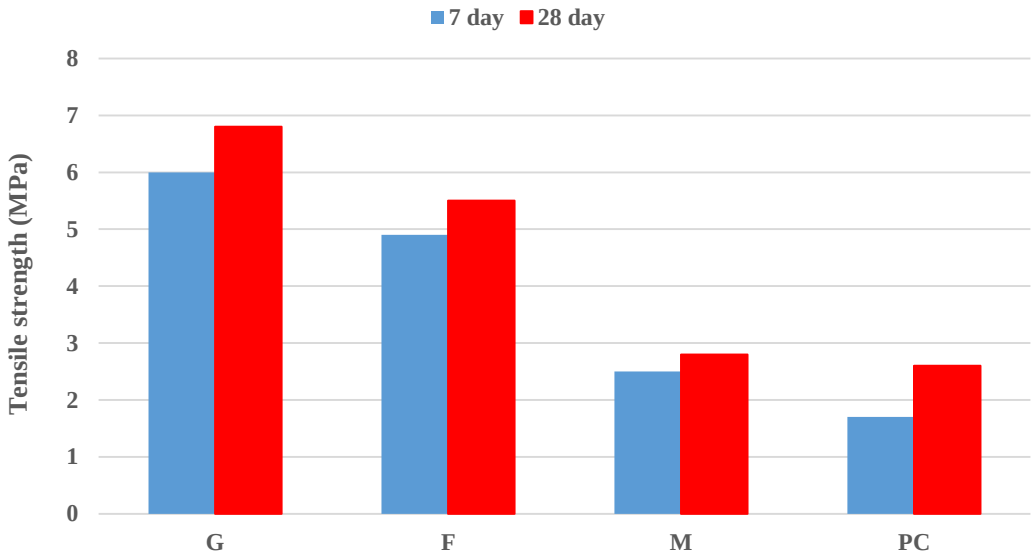

Figure 4. 7-day and 28-day tensile strengths of specimens.

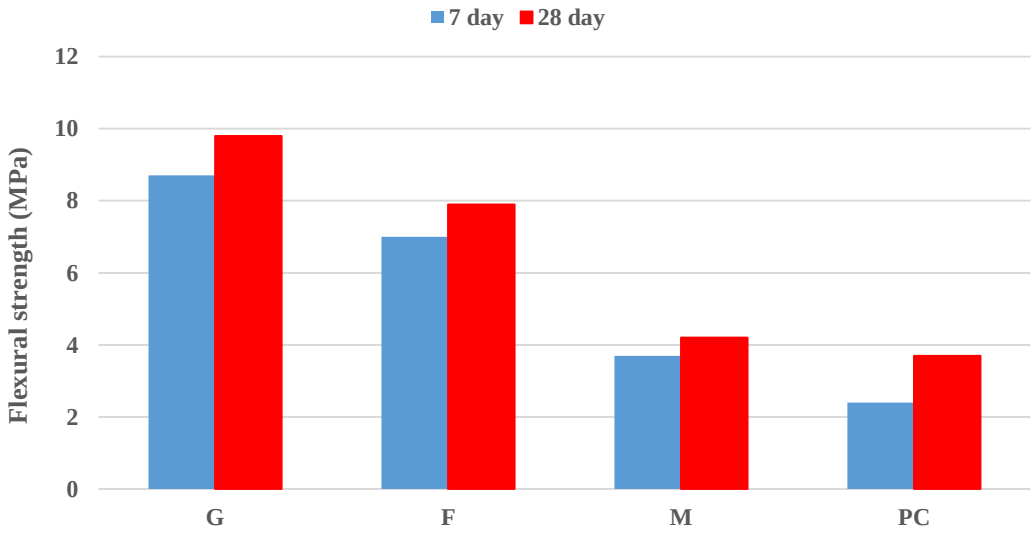

Figure 5. 7-day and 28-day flexural strengths of specimens.

3.2. Resistance to Acidic Conditions and Permeability

Figure 6 illustrates the results of water absorption and weight loss under acidic condition tests of GPC and PC specimens. The water absorption capacity of G, F, M and PC mix designs were calculated approximately 5.1, 5.5, 4.7 and 5%, respectively. Moreover, weight loss under acidic condition of G, F, M and PC mix designs were measured approximately 5.1, 5.5, 4.7 and 5%, respectively. By observing the results of fig 6, water absorption capacity and weight loss in acidic condition of GPC specimens were less compared to PC specimen, mainly due to higher density of the geopolymeric matrix structure in these mix designs. Therefore, it can be concluded that the

permeability of GPC is less than PC concrete and also the resistance to acidic conditions of GPC is higher than PC concrete.

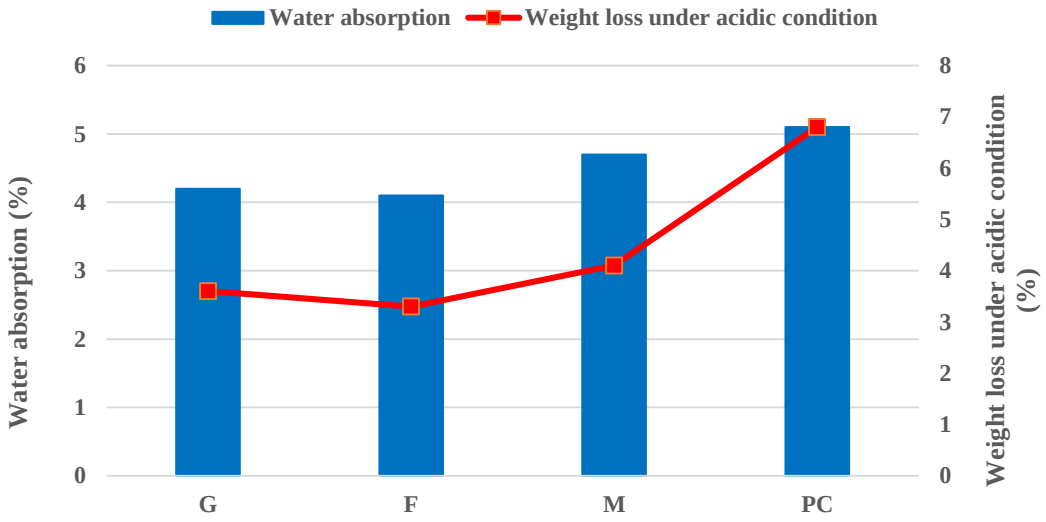

Figure 6. Water absorption and weight loss under acidic condition of specimens.

3.3. Resistance to Elevated Temperatures

Fig. 7 displays the mean compressive strength of the GPC and PC specimens after subjected to various elevated temperatures. Changes in compressive strength of the heat subjected specimens compared to corresponding nonexposed ones are gathered in Table 5. The compressive strength of GPC specimens showed increase at 200 and 400 ˚C, i.e. around 13.6 and 6.6% respectively, and decrease at 600 and 800 ˚C (around 2 and 13% respectively) compared to PC specimen. As observed in past research [4], GPC composites tend to show compressive strength increase when subject to temperatures of around 200–400 ˚C, due to dissolve and polycondensation of unreacted aluminosilicate compounds, resulting in higher matrix density and subsequent rise in compressive strength. Geopolymers have shown to maintain molecular stability up to 600 ˚C, but at 800 ˚C, difference in thermal resistance of the aggregates and geopolymeric matrix at contact regions, results in the formation and propagation of micro cracks and thus reduction of compressive strength [21]. On the other hand, the compressive strength of the concrete sample decreased slightly in the temperature range of 0-200 ° C. Further increase in temperature from 200 °C to 400 °C resulted in a 35% reduction of compressive strength. Moreover, the compressive strength of PC specimen dropped considerably between temperatures of 400-800 °C, so that the PC specimen was destroyed at 600 °C. This compressive strength deterioration is attributed to the $Ca(OH)_2$ decomposition that occurs at about 400-500 °C. Summarizing the results obtained from this section, it can be concluded that the elevated temperatures resistance of GPC is significantly higher than PC concrete.

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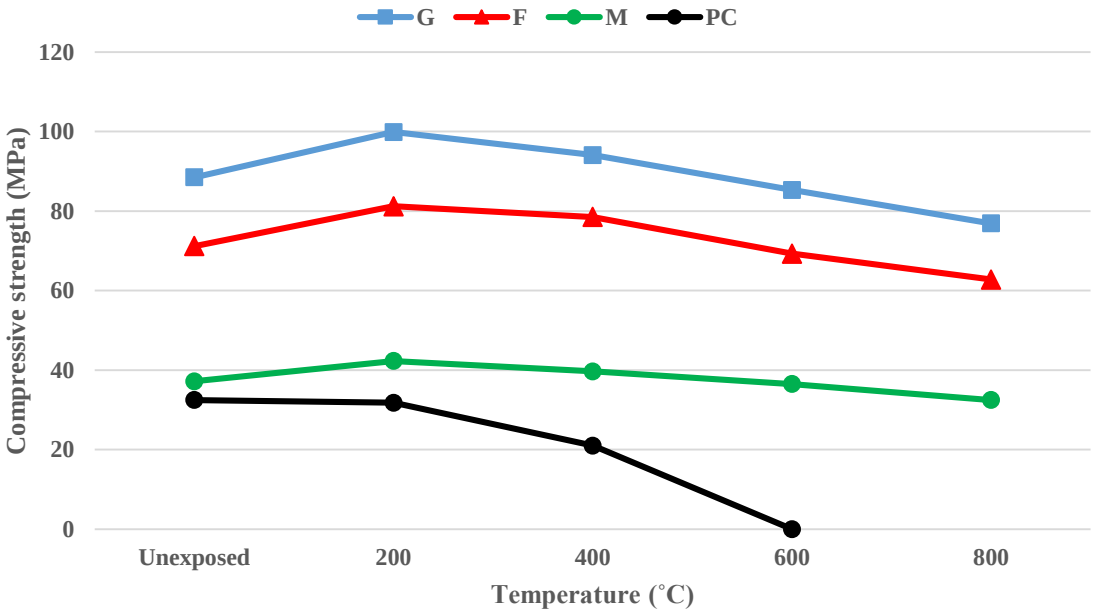

Figure 7. Mean compressive strength of specimens subjected to elevated temperatures.

Table 5. Change in specimen compressive strength (%) subject to elevated temperatures.

Mix ID	Temperature			
	200°C	400°C	600°C	800°C
G	+12.89	+6.35	-3.61	-13.11
F	+14.12	+7.24	-1.89	-11.73
M	+13.70	+6.64	-2.73	-12.50
PC	-2.26	-35.15	-100	-100

4. Conclusion

In this experimental study, several technical properties of geopolymer concrete were studied and compared with conventional concrete. The obtained results indicated that geopolymer concrete provided higher compressive, tensile and flexural strengths as well as faster hardening than conventional concrete. Furthermore, the permeability of geoplymer concrete is less than conventional concrete and also, the resistance to acidic conditions of geoplymer concrete is higher than conventional concrete. Hence, it can be concluded that the geopolymer concrete offers better chemical resistance than conventional concrete. Moreover, the elevated temperatures resistance of geopolymer concrete is significantly higher than conventional concrete, so that geopolymer concrete is almost stable up to 800 °C. Summarizing the results of this study showed that geopolymer concrete in addition to major environmental advantages, also has better technical properties in comparison with conventional concrete and can be considered as an acceptable green alternative to conventional concrete.

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