Experimental Investigation of High Strength Geopolymer Concrete under Fire Resistance

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Abstract. Geopolymer concrete is an innovative material that is gaining popularity due to its superior performance and environmental sustainability. The objectives at the current work are to study the effect of slag content, the concentration of alkaline activators on the thermal resistance of geopolymer concrete (GPC). Three mixes of GPC were casted and tested. These mixes are devided into two groups, the first one consists of three mixes: each three slag contents were used 400 kg/m^3, tested; for each slag content three different activators percentages were tested; 8%, 10% and 12%. The second group consists of one mix: three different metakaolin replacement ratios were investigated 10%, 15% and 20% for each replacement ratio, two alkaline activators ratios were tested: 10% and 12% while the slag content kept constant for all group mixes at 400 kg/m^3. For comparison purposes, a control mix of OPC was casted and tested with cement content of 400 kg/m^3. The whole mixes were exposed to six different temperature 200°C, 300°C, 400°C, 600°C and 800°C for two hours duration. Compressive strength test were carried out after the heat exposure at 28 days age. The results indicated that within the limits of slag content and activator percentages used, the fire resistance increases as the slag content and activator percentages increases. The addition of metakaolin considerable improves the fire resistance of GPC up to 15% replacement ratio. Geopolymer concrete showed superior fire resistance compared to ordinary portland cement (OPC).

Keywords: Geopolymer, Composites, Fire Resistance, Efficiency, Thermal Resistance.

١. Introduction

Concrete is considered as the most material used in the world during the construction process while the main component used in the concrete is the Ordinary Portland Cement (OPC) as a bonding material. The cement manufacturing releases huge amount of CO_2 in the atmosphere and this leads to the greenhouse gas emission effect [١]. Cement production nearly Contributes ١٠٪ of the total CO_2 released in the atmosphere. In general, ordinary Portland cement concrete provides adequate thermal resistance. The ordinary portland cement concrete losses considerable percentage of its strength after exposure to fire [٢]. This may be attributed to physical and chemical reactions takes place during the temperature rise. As the temperature escalating, the Spalling of Concrete cover takes place and this may lead to direct exposure of steel reinforcement [٣]. The need of reducing the dependency on OPC as a main construction material due to its big role in global warming and because the huge power consumed in cement industry, encourage the researchers around the world to introduce an alternative for conventional concrete [٤]. Geopolymer Concrete attracts a great attention in the last two decades [١].
One of the main advantageous of geopolymer concrete is the materials used to produce it which are by products and sustainable materials [٥]. A wide variety of industrial and agricultural by products can be used as a precursor such as some of ground granulated blast furnace Slag (GGBFS), fly ash, rice husk ash and silica fume … etc. Natural materials such as metakaolin and bentonite can be used as a precursor to produce geopolymer concrete (GPC) [٦]. Geopolymer is an inorganic aluminosilicate compound produced by the polymerization process takes place as a physico-chemical reaction between the alumino Silicate precursor and alkaline activator such as sodium hydroxide and sodium silicate [٧]. Thermal

resistance to elevated temperatures is another advantage of geopolymer concrete. Chemical stability of geopolymer concrete made it an excellent alternative for conventional concrete when thermal resistance is a key requirement. Numerous researches were found in the literature concerning the thermal resistance of geopolymer Concrete [٨].
Most of the researches concentrate on fly ash and metakaolin based geopolymer. Since these two precursors showed high resistance to elevated temperatures [٩]. On the other hand, ground granulated blast furnace slag is the most promising precursor when speaking about compressive strength which is the most important concrete property. In Egypt, there is a resistance of lack of information regarding the thermal resistance of slag based geopolymer concrete produced using our local materials. Based on the above-mentioned discussion, there is great need to fill the gap of information concerning the Subject thermal resistance of slag based geopolymer concrete with local material. In year ٢٠٢٤, there was IOP Conf. Series [١٠]: Materials Science and Engineering ٩٥٥ to Performance studies on Geo polymer concrete the propose of this is to Strength development is significantly influenced by curing conditions, NaOH molarity, and mix design parameters[11].Geopolymer concrete shows promise as a sustainable alternative, though its tensile strength needs improvement Although in year 2024 there was Influence of coatings on residual strength of geopolymer concrete columns subjected to fire exposure and the propose is asses the performance of ceramic wool and high alumina cement coating on self-compacting geopolymer concrete (SCGC) columns subjected to ISO 834 fire exposure standards [12] However in year 2024 also International Postgraduate Conference on Materials, Minerals & Polymer And the propose is GPC shows increased compressive strength at 500c due to gepolymerization and the dens matrix of GPC provides superior structural integrity The propose of this study is to make geopolymer concrete with fire resistance with high strength instant of concrete and cement.

٢. Experimental program

٢,١. Material used

Slag, metakaolin, cement, and sodium hydroxide are considered innovative materials as shown in figs. ١, ٢, ٣, and ٤ respectively that used to produce GPC as shown in Fig.٥.

Fig.١ Slag

Fig.٢ Metakaolin Powder

Fig.٣ Cement Bag

Fig.٤ Sodium Hydroxide

Fig.٥ GPC Samples

These proposed materials that used to produce different samples of GPC are used in design mix with its allowable properties as shown in Table 1.

Table 1. The properties of the proposed materials.

Materials	**Prosperities**
Slag	fine grey powder produced by grinding a ground-granulated blast furnace Indian slag, the specific gravity of slag was 2.9.
Metakaolin	pozzolanic material produced by calcining Kaolinite at high temperature.
Cement	Beni Suef CEM I (52.5) cement was used in control mix, the specific gravity of cement equal 3.15.
Sodium Hydroxide	highly soluble in water, the specific gravity of the used Sod. Hydr.is 0.9.
Sodium Silicate	A thick liquid sodium silicate, the specific gravity of Sod. Silicate is 1.2.
sand	Natural clean sand was used as fine aggregate, the fineness modulus of the used sand was 2.89, while its specific gravity was 2.5.
Coarse Aggregates	Clean crushed dolomite with maximum aggregate size of 20mm, the specific gravity of the used dolomite was 2.6.

٢,٢. Superplasticizer

A naphthalene sulphonates - with synthetic polymer- (Adicrete PVF) was used in this research. This kind of superplasticizer allows mixing water condensate de-foamed admixture, the chemical & physical properties of the used superplasticizer are shown in Table ٢, this type of superplasticizer was chosen for its electrostatical behaviour as shown in Fig.٦.

Table ٢. Chemical and Physical Characteristics of Adecrete BVF.

Cement	SiO٢	Al٢O٣	Cao	Fe٢O٣	MgO	Na٢O	K٢O	SO٣	LOI
Constituents%	٢٠,١	٥,٣٢	٦١,٧	٣,٦١	٢,٣٩	٠,٣٧	٠,١٣	٢,٨٧	≤ ٠,٠١

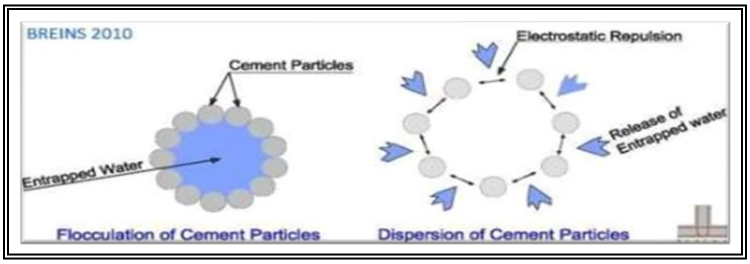

Fig.٦ Schematic representation of a mode of action of naphthalene sulphonate

٢,٣. Samples Preparation

By knowing the specific gravity of each material, the absolute volume equation can used to determine the quantity of aggregate needed in each mix. For example, design of stage ١ mixes will be shown in detail as follows:

$$\mathbf{1000} = \frac{\mathbf{S}}{SG_s} + \frac{\mathbf{SP}}{SG_{sp}} + \frac{\mathbf{W}}{SG_w} + \frac{\mathbf{S.S}}{SG_{s.s}} + \frac{\mathbf{S.H}}{SG_{S.H}} + \frac{\mathbf{Agg.}}{SG_{agg}}$$

Where :
S……Weight of slag in kg used in ١ $m^{٣}$ of concrete.
SG_s….Specific gravity of slag.
SP…..Weight of superplasticizer used in ١ $m^{٣}$ of concrete.
SG…….Specific gravity of superplasticizer.
W……Weight of water used in ١ $m^{٣}$ of concrete.
SG_w ...Specific gravity of water.
S.S…..Weight of sodium silicate used in ١ $m^{٣}$ of concrete.
$SG_{S.S}$ ..Specific gravity of sodium silicate.
S.H…..Weight of sodium hydroxide used in ١ $m^{٣}$ of concrete.
$S.G_{S.H}$ ..Specific gravity of sodium hydroxide.
Agg…..weight of aggregate used in ١ $m^{٣}$ of concrete.
SG_{agg} ...Specific gravity of aggregate.

٢,٣,١. General steps to calculate the amount of mix design.

a. Calculate the total amount of Sodium oxide.
Na٢O = ٨٪ of total binder content.
Na٢O = ٠,٠٨ x ٣٥٠ = ٢٨ kg.

b. Calculate total amount of sodium silicate
Modulus of activator ratio Ms (SiO٢ / Na٢O) = ١

$$\frac{\mathbf{SiO_2}}{\mathbf{Na_2O}} = \mathbf{1}$$ → SiO٢ = Na٢O = ٤٠ kg.

S.S $= \frac{\mathbf{28}}{\mathbf{0.317}} = \mathbf{88.33\ kg}$

c.Calculate amount of Na٢O in sodium silicate.
Na٢O in S.S = ٨٨,٣٣ x ٠,١٢ = ١٠,٥ kg.

d.Calculate Na٢O needed.
Na٢O needed = ٢٨ – ١٠,٥ = ١٧,٥ kg.

e. Calculate the total amount of NaOH
NaOH = $\frac{\mathbf{17.5}}{\mathbf{0.6025}}$ =٢٩,٠٤ kg

f. Extra water calculations
Water in S.S = ٨٨,٣ x ٠,٥٦٢٥ = ٤٩,٦٦ kg.
Water in NaOH = ٢٩,٠٤ x ٠,٣٩٧٥ = ١١,٥ kg
Total amount of water = w/b x total binder content = ٠,٤ x ٣٥٠ = ١٤٠ liters
Extra water needed = Total amount of water – water in S.S – water in NaOH
= ١٤٠ – (٢٩,٦ + ١١,٥) = ٩٨,٩ liters.
Using the absolute volume equation, the total amount of agg. is calculated as follows:

$$\mathbf{1000} = \frac{\mathbf{350}}{\mathbf{2.8}} + \frac{\mathbf{0.4x350}}{\mathbf{1.18}} + \frac{\mathbf{98.9}}{\mathbf{1}} + \frac{\mathbf{88.33}}{\mathbf{1.2}} + \frac{\mathbf{29.04}}{\mathbf{0.8}} + \frac{\mathbf{Agg.}}{\mathbf{2.6}}$$

Agg. = ١٧٠١ kg, using C/F ratio of ١,٥
Sand = ٥٩٦ kg.
Coarse agg. = ١١٠٥ kg.

Three slag content (S٤٠٠) were used and tested in this experimental program as
Shown in Table 3.

Table ٣. Simple of golypolymer concrete mix design.

Mixes	Slag (Kg)	S.P. (Kg)	Water (Kg)	Sand (Kg)	C. Agg. (Kg)	S.S (Kg)	NaOH (Kg)	M.K
S٤٠٠-٨	٤٠٠	١٦	٩٠,١٢	٥٧١,٥٥	١٠٦١,٤٥	١٠٠,٩	٣٣,٠٣	---
S٤٠٠-١٠	٤٠٠	١٦	٧٢,٦١	٥٥٨,٩	١٠٣٨	١٢٦,٢	٤١,٢٦	---
S٤٠٠-١٢	٤٠٠	١٦	٥٥,١٥	٥٤٦,٤٦	١٠١٤,٥	١٥١,٤٢	٤٩,٥	---

These three mixes in order to investigate the effect of adding metakaolin as a slag supplement, a group with slag content ٤٠٠ kg/m٣ was chosen. Three different percentages of metakaolin as supplemented, i.e., ١٠٪, ١٥٪ and ٢٠٪ by w.t of slag. For each supplement percentage, two activator contents were used (١٠٪ &١٢٪). This group contains three mixes. In order to compare the effect of high resistance on the behaviour of geopolymer concrete mixes with the ordinary portland cement concrete, a control mix of OPC with cement content of ٤٠٠ kg/m³ was mixed and tested.

٢,٤. Mixing Procedures

Sand, Coarse aggregate and Slag (or Slag + Metakaolin) were mixed dry first in the mixer for ٢ minutes. The alkaline solution was prepared by adding sodium hydroxide to sodium silicate and mixing together for ١٥ min., then the water was added. Finally, the superplasticizer was added to the solution. The alkaline solution then added gradually during mixing. The mixing process takes about another ٢ minutes to reach homogeneous mix.

٢,٥. Casting Procedure

eighteen moulds ١٠x١٠x١٠ cm were used to cast eighteen concrete cube samples for each mix. After casting the concrete into the moulds, the moulds were comparted using the vibrating table as shown in Fig.٧.

Fig. ٧ The vibrating table

٢,٦ Curing

All specimens were cured in room temperature until the date of testing.

٢,٧. Thermal Exposure Regime

In order to measure the resistance of geopolymer concrete to thermal exposure, ٣ concrete cubes were tested in room temperature (control or reference samples), for each mix ٣ concrete cubes, for each temperature, were exposed to the following five different temperatures:٢٠٠°C, ٣٠٠°C, ٤٠٠°C, ٦٠٠°C, and ٨٠٠°C. The mix design of normal concrete is showed in Table ٤.

Table ٤. The mix design of normal concrete.

Material	Cement	Sand	Dol size ١٤ mm	Dol size ٢٥mm	Total water	Admixture (HG١)	Fiber glass
Weight	٤٠٠	٦٨٠	٥٦٠	٥٨٠	١٩٠	٦	٠,٩
٠,٠٤	١٦,٠٠٠	٢٧,٢٠٠	٢٢,٤٠٠	٢٣,٢٠٠	٧,٦٠٠	٠,٢٤٠	٠,٠٣٦

٣. Results and discussion:

٣,١. Effect of temperature on OPC:

The results show that the original compressive strength (٥٠٠kg/cm_2) decreases gradually as the heat temperature increases. Increasing the heat temperature to ٢٠٠°C leads to ٧,٢٤٪ decrease in compressive strength. Exposing the OPC to ٣٠٠ °C, ٤٠٠ °C and ٦٠٠ °C yields to decrease in compressive strength by ١٨٪, ٢٤,٢٪ and ٥٦٪ respectively. Reaching the exposed temperature to ٨٠٠°C the concrete compressive strength significantly decreased to nearly one third of the original compressive strength as shown in fig.٨.

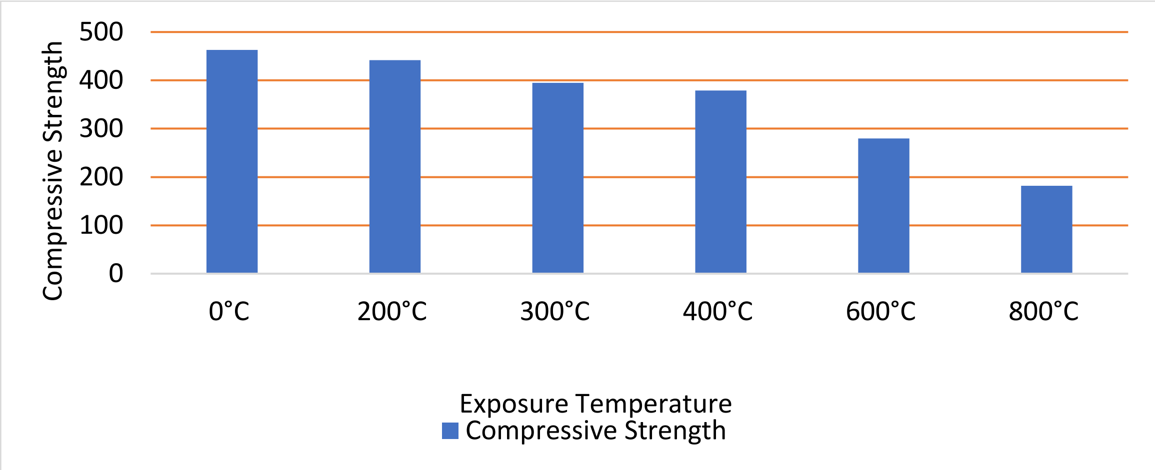

Fig. ٨ Effect exposure temperature on the compressive strength of ordinary portland concrete

It is obvious that the compressive strength of OPC decreases as the exposed heat temperature increases. The comp. str. of OPC decreases by ٤,٧٥٪, ١٤,٧٪,١٨,١٪,٣٤٪ and ٥٢٪ as the exposed heat temperature increases by ٢٠٠°C, ٣٠٠°C, ٤٠٠°C, ٦٠٠°C and ٨٠٠°C respectively. In contrary, the compressive strength of geopolymer concrete increases as the exposed heat temperature increases up to ٣٠٠°C as mentioned earlier. The comp. str. of GPC increases by ٤,٤٪ and ١٠,٦٪ as the exposed heat increases to ٢٠٠°C and ٣٠٠°C respectively. At ٤٠٠°C exposure the compressive strength returns back as original one. At ٦٠٠°C and ٨٠٠°C heat exposure, the compressive strength decreases by ١٧٪ and ٤٦٪ respectively. It is worth mentioning that although the original compressive strength of GPC was less than the original one of OPC by about ٢٦,٨٪. Its strength after exposure to ٨٠٠°C was higher than that of OPC by ٢٠٪ by the comparison between the effect of heating temperatures on the comp. str. of both geopolymer concrete (S٤٠٠-٨) and OPC as shown in Fig. ٩.

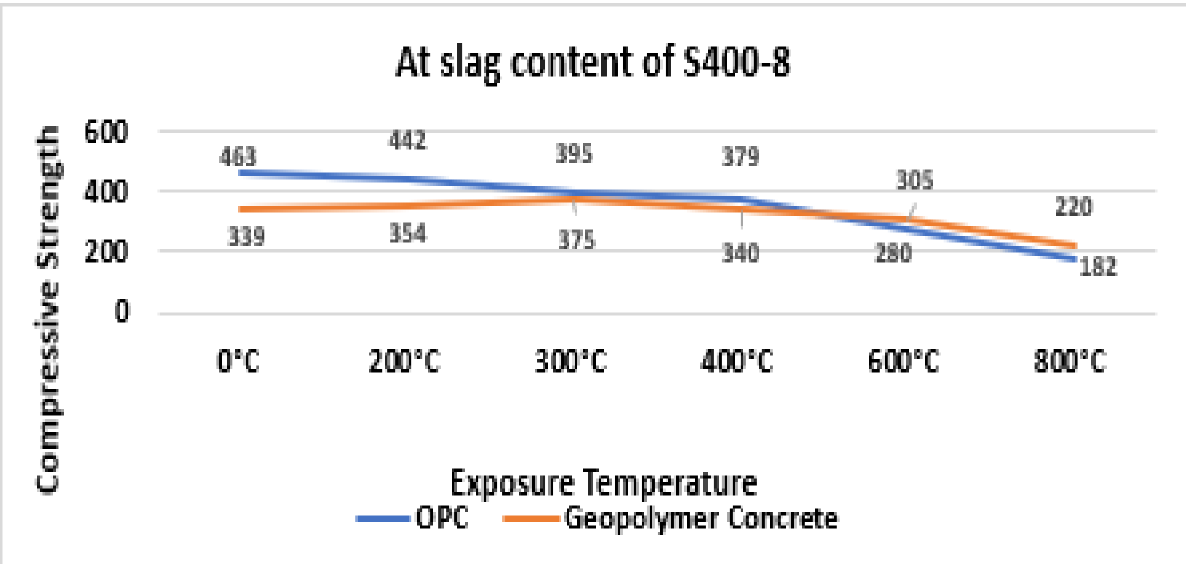

Fig. ٩ Effect exposure temperature on the compressive strength of ordinary portland concrete

The influence of exposure temperature on the compressive strength of both OPC and geopolymer concrete with ١٠٪ activator. The same trend as above was observed. The compressive strength of OPC decreases as the exposure temperature increases by ٤٪, ١٤٪, ١٨٪, ٣٩٪ and ٦٠,٦٪ as the exposure temperature increases to ٢٠٠°C, ٣٠٠°C, ٤٠٠°C, ٦٠٠°C and ٨٠٠°C respectively. Meanwhile the geopolymer concrete compressive strength showed increase in strength up to ٣٠٠°C by ٢٠,٤٪ then the compressive strength tends to decrease after exposure to ٦٠٠°C by ١١٪ only and by ٣١٪ after exposure to ٨٠٠°C. Although the original compressive strength of the GPC was less than that of OPC by ٢٤,٨٪, one can find that after exposure to ٨٠٠°C, the compressive strength of GPC was higher than that of OPC by ٣٠,٢٪ as shown in Fig. ١٠.

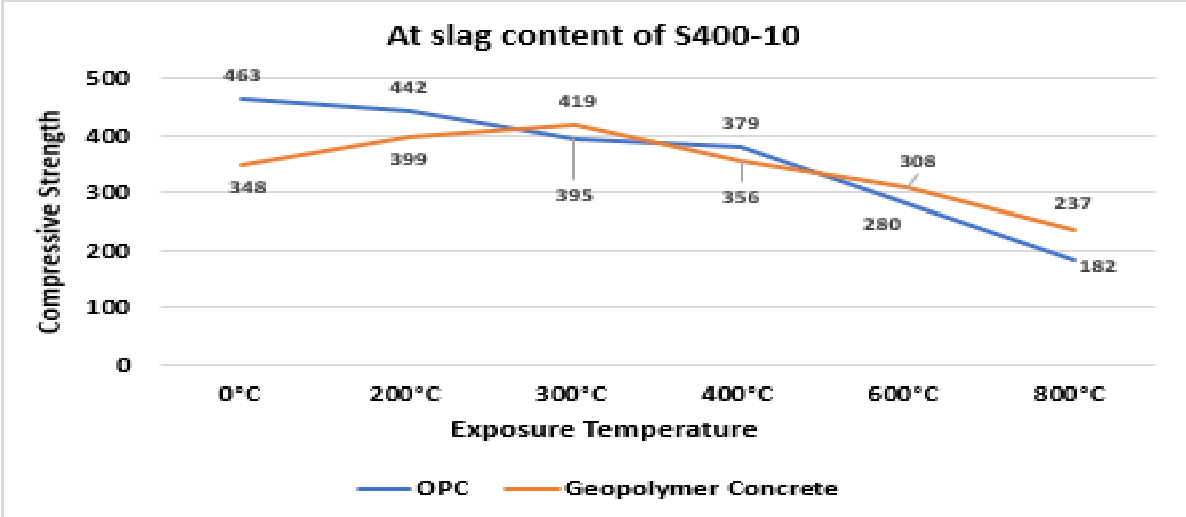

Fig.١٠ Effect exposure temperature on the compressive strength of ordinary portland concrete

The effect at exposure temperature on the compressive strength of both OPC and GPC with ١٢٪ activator concentration. As discussed above the OPC shows slight increase until ٣٠٠°C then significant strength loss takes place after exposure to ٤٠٠°C. The comp. str. of GPC at room temperature was less than OPC by ٢١,٢٪ while after exposure to ٨٠٠°C the GPC compressive strength was higher than that of OPC by ٤٩,٤٪ as shown in Fig. ١١.

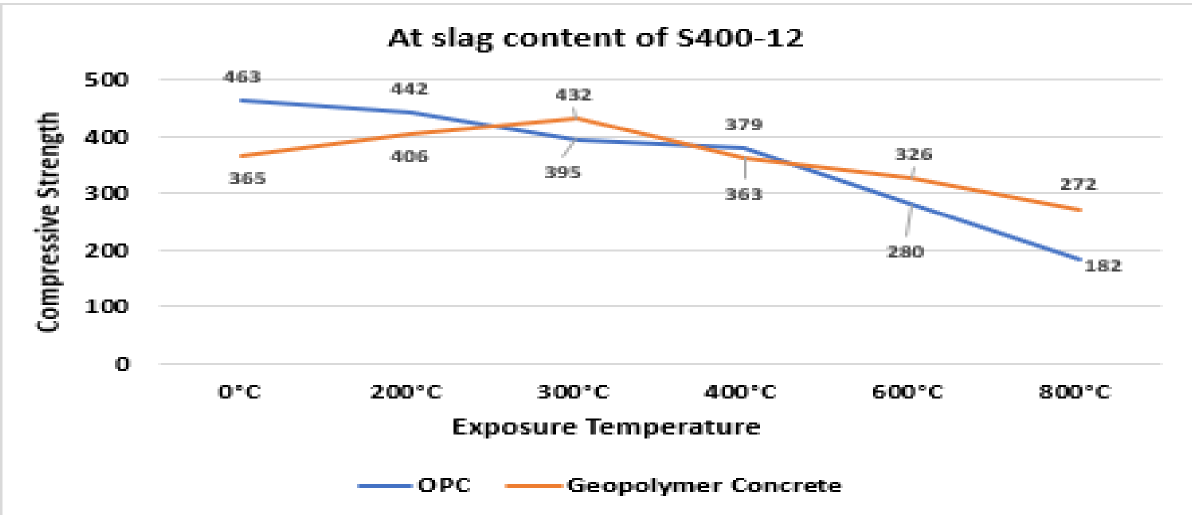

Fig.١١ Effect exposure temperature on the compressive strength of ordinary portland concrete

٤. Conclusion

It is possible to draw the conclusion that geopolymer concrete exhibits better heat resistance than regular Portland concrete based on the facts and discussion above:

١. Increasing the slag content significantly improves the heat resistance of geopolymer concrete within the range of slag content studied in this study.

٢. The compressive strength of geopolymer concrete is significantly increased by thermal **exposure** up to ٣٠٠°C. This rise could be as much as ٣٣٪. This rise can be the result of improving GPC's polymerization process.

٣. The compressive strength of GPC gradually decreases at temperatures beyond ٤٠٠°C.

٤. GPC's compressive strength is greatly impacted by thermal exposure to ٨٠٠°C. The remaining strength could be as much as ٥٠٪ of its initial value. Deboned alumino-silicate and calcium alumino-silicate hydrate may be the cause of this.٥. Within the range of activator percentages tested in this thesis, increasing the activator percentage increases the compressive strength of the GPC, and consequently enhances the thermal resistance of GPC. Increasing the activator percentage positively leads to increase the calcium alumino silicate hydrates bond tees.

٦. The significance of increasing the activator percentage is highly observative for the mixes with ٣٥٠ kg/m³ and ٤٠٠ kg/m³ slag content. For rich slag mixes with ٤٥٠ kg/ m³, the significance of increasing the activator percentage decreases to enhance the thermal resistance of GPC.

٧. Geopolymer Concrete has excellent thermal resistance properties compared with conventional ordinary portland cement concrete.

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