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Performance of geopolymer mortars prepared by different alkaline solutions under elevated temperature

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ABSTRACT

Fire has severe effects on concrete as it causes a significant deterioration in its properties. Geopolymers (GP) are considered as an emerging alternative binder to Portland-cement (OPC). This paper presents an investigation of the performance of fly ash (FA) based GP-mortars made with different alkaline solutions after exposure to elevated temperatures (200, 400, 600, and 800 °C). The main investigated parameters were the type of hydroxide (NaOH and KOH), type of silicate (Na₂SiO₃ and K₂SiO₃), molarity levels of NaOH, Na₂SiO₃/NaOH ratios, alkaline-solution to FA ratio and sand to FA ratio. Compressive, flexural, and indirect tensile strengths were measured before and after exposure to elevated temperatures. Moreover, SEM analysis was conducted on GP and OPC mortars. The results showed that performance of GP mortars containing Na₂SiO₃ with KOH was better than GP mixes that contained Na₂SiO₃ with NaOH or K₂SiO₃ with KOH after exposure to elevated temperatures. A higher loss rate in mechanical properties after exposure to 800 °C was observed as the NaOH molarity increased. Increasing Na₂SiO₃/NaOH ratio up to 2.5 caused an increase in the mechanical properties, while increasing that ratio from 2.5 to 3 caused higher loss in the mechanical properties of GP mortars. After exposure to 800 °C, sand to FA ratio of 2 and alkaline solution to FA ratio of 0.5 gave higher residual strengths than the other ratios. Behavior of GP mortar was found to be better than OPC mortar after exposure to elevated temperatures. SEM images showed that the structure of the GP mortar, after exposure to elevated temperatures, was denser than that of the OPC mortar. Empirical equations capable of predicting the residual mechanical properties of GP-mortars made using different alkaline solutions with good correlation have been proposed.

1 Introduction

Concrete is considered as the most widely used construction material due to its low cost, ease of fabrication, acceptable strength, good durability, good fire resistance, and no combustibility properties [1-3]. Ordinary Portland cement (OPC) is used

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in manufacturing concrete to provide its strength. OPC industry causes the emission of CO₂ because of the usage of fossil fuels and decomposition of limestone [4]. The ecological balance is affected by the calcination of limestone and ignition of fossil fuel as about one ton of CO₂ is released for every one ton of OPC manufacturing [5-7]. This reflects the impact of global warming [8] and resulted in noticeable environmental changes overall the world [9, 10]. Clear climate changes in many countries cause fires and droughts in some areas, requiring alternative materials for OPC. One of the recent methods to reduce CO₂ emission is the production of geopolymers [11].

Geopolymer concrete (GPC) has attracted considerable attention research during recent years due to its environment friendliness, early compressive strength, high mechanical properties, low permeability, excellent durability, and good fire resistance [12-14]. Geopolymer (GP) is an alternative binding agent that is formed by the reaction of aluminosilicate source material, such as fly ash (FA), metakaolin (MK), and ground granulated blast furnace slag (GGBFS), with an alkaline solution, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) and soluble silicates such as sodium silicate (Na₂SiO₃) or potassium silicate (K₂SiO₃) [13-15]. The alkaline hydroxide solution is necessary for the dissolution of aluminosilicate sources while silicate solution works as an alkaline activator, plasticizer, and binder [16, 17]. The dissolved Al₂O₃ and SiO₂ species undergo geopolymerization to form an amorphous alumina-silicate network with strength similar to or higher than that of OPC concrete [13, 18]. Recently, GP and GPC have become increasingly popular research areas because of their high mechanical properties [13, 19-22] and good durability properties [19, 23-24].

Fire is a major societal hazard which is associated with the built environment. Structural concrete members must satisfy appropriate fire safety requirements specified in building codes [25]. The performance of traditional concrete at elevated temperatures is necessary when evaluating the durability of concrete [26, 27]. When cement concrete is exposed to elevated temperatures, dehydration of cement paste occurs where the calcium hydroxide begins to decompose at 300-400 °C, while calcium carbonate decomposes at 700 °C and melts at 800 °C [26, 28]. The different thermal expansion between the cement matrix and the coarse aggregates also causes deterioration of concrete when exposed to high temperatures. When the temperature exceeds 500 °C, the compressive strength of concrete usually drops by 50% to 60% [29]. Increase in porosity, thermal creep, and thermal spalling are also of the most important effects of fire on concrete [30].

The behaviour of GP subjected to elevated temperatures is significantly studied nowadays [13, 31-33]. Previous studies on GP found that GP exhibited good resistance to elevated temperatures and good thermal stability because of its inorganic framework [34]. Rashad and Zeedan [35] concluded that the recorded relative residual compressive strengths of FA-based GP pastes made with low, medium, and high concentrations of sodium silicate reached 665.9%, 258.6%, and 70.5% after exposure to 1000 °C, respectively.

Sitarz et al. [36] studied the mechanical properties of FA-based GP mortar after exposure to elevated temperatures. Residual compressive strength values of GP mortar were 123%, 62%, and 42% of the initial values after exposure to 200 °C, 400 °C, and 600 °C, respectively. Saxena et al. [37] recorded compressive strength ranging from 12.8 to 34 MPa for GP mortars made with different raw materials (FA or GGBFS or calcined clay) after exposure to 800 °C.

Mathew and Joseph [38] and Junaid et al. [39] found that the residual compressive strengths of FA-based GPC after exposure to 600 °C and 800 °C were in the range of 53-54% and 57-58%. Kong and Sanjayan [40] and Zhang et al. [26] found that residual compressive strengths of FA-based GPC were about 41.5% and 56.3%, respectively after exposure to 800 °C. FA-based GPC was found to be better than OPC concrete when subjected to elevated temperatures [41]. Sarker et al. [42] compared the residual compressive strength of high and normal strength FA-based GPC with OPC concrete after exposure to elevated temperatures and it was found that the residual strength of the GPC after exposure to 400 °C, 650 °C, 800 °C, and 1000 °C is higher than that of OPC concrete.

The type of alkaline solution and its content in the GP system are significant in determining the room-temperature mechanical properties as well as the high-temperature properties [16]. The FA geopolymer paste containing potassium (K-based) activator exhibited higher residual compressive strengths than the sodium (Na-based) activator paste [43, 44]. Shaikh and Hosan [45] compared between using Na-based and K-based activators in steel fibre reinforced geopolymer concrete (SFRGC). Residual compressive strength of Na-based SFRGC and K-based SFRGC was 60% after exposure to 800 °C. Albadawy et al. [46] studied the effect of NaOH molarity, Na₂SiO₃/NaOH ratios, and alkaline solution/FA ratios on the compressive strength after exposure to 200 °C, 400 °C, 600 °C, 800 °C, and 1000 °C for 2 hrs. The results showed that when molarity=16, Na₂SiO₃/NaOH ratio=2.5, and alkaline to FA ratio=0.4 gave the highest compressive strength after exposure to 1000 °C.

Average percentage of mass loss for FA-based GPC cylinders was 2.86% after exposure to hydrocarbon fire test due to loss of moisture [47]. Hosan et al. [43] found that the mass loss of Na-based GP paste is slightly higher than that of K-based GP paste. Hager et al. [48] observed that the mass was released at the highest rate at a temperature of approximately 80 – 110 °C while between 200 °C and 400 °C, chemically bound water was released and dehydration began. Between 400 °C and 600 °C, dehydroxylation of hydroxyl groups occurred [45].

Exposure to elevated temperatures affects the microstructure of GP in many ways due to crystallization and sintering. It is widely acknowledged that variation in mechanical properties of geopolymers is mainly attributed to changes of inner microstructure. Lahoti et al [31] in their review discussed the microstructure changes in GP when exposed to elevated temperatures. Many studies used SEM analysis to study and understand the behaviour of OPC or GP systems when exposed to elevated temperatures at early ages [31, 42, 44, 49, 50].

Sarker et al. [42] found that the microstructure of GP specimens became denser with the increase of fire temperatures up to 1000 °C because more geopolymerization of FA has occurred. Zhang et al. [26] observed through the SEM analysis of ambient cured GPC that it has a large amount of unreacted FA than heat cured GPC. The amounts of unreacted FA particles were few after exposure to 800 °C. After exposure to 1000 °C, the microstructure has fewer impurities, and it reveals a smoother texture due to the melting, viscous flow and sintering of unreacted FA particles and amorphous aluminosilicate gels [26].

To the author's knowledge, rare studies were conducted to study and compare the influence of different alkaline solution types besides other parameters, like silicate to hydroxide ratio and alkaline solution to FA ratio, on the physical and mechanical behaviour of GP mortars after exposure to elevated temperatures [43–45]. It will be helpful to engineers in deciding the level of deterioration for GP-mortar cast with different alkaline solutions under fire. Moreover, several research have studied the behaviour of GP at the early ages, but limited studies were conducted to study the fire performance of GP at later ages as fire often occurs at long-term ages. This paper aims to study the performance of different GP mortars after exposure to elevated temperatures up to 800 °C at the age of one year. The main investigated parameters were the molarity level of NaOH, the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratios, the alkaline solution to FA ratios, and sand to FA ratios. Also, the effect of using KOH and K_2SiO_3 was studied.

2 Experimental Procedure

2.1 Materials

Low-calcium Fly Ash (FA), class F as specified in ASTM C618 [51], with a specific gravity of 2.4 was used in this study as the basic aluminosilicate material to manufacture geopolymer mixes. XRF test was performed on the FA to determine its chemical analysis as shown in Table 1.

Ordinary Portland cement (OPC) CEM1 42.5N, with a specific gravity of 3.15, complied with the requirements of EN 196-1 [52] was used. The initial and final setting times of the OPC were 95 and 220 minutes, respectively. OPC was used for the preparation of the control mortar mix to be compared with GP mortar. XRF test was performed on the OPC to determine its chemical analysis as shown in Table 1.

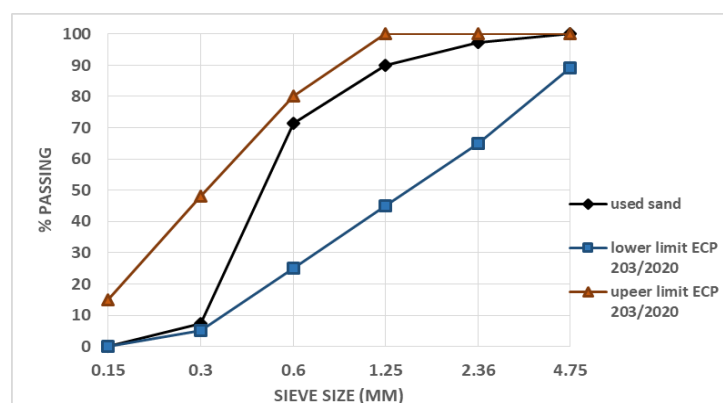
Alkaline activators in this investigation consisted of alkali silicate and hydroxide solutions. Grade D Sodium silicate (Na_2SiO_3) with specific gravity of 1.5 and containing SiO_2 = 29.4%, Na_2O = 14.7% and water=55.9%, was used in some mixes. Potassium silicate (K_2SiO_3) with a specific gravity of 1.32 and containing K_2O = 13%, SiO_2 = 27%, and water= 55%, was used in some GP mixes. Sodium hydroxide (NaOH) and Potassium hydroxide (KOH) were in pellets form with 98% and 90% purity, respectively. Hydroxide solutions were prepared with the required molarity by dissolving hydroxide pellets with tap water 24 h before mixing. Hydroxide solution and silicate solution were mixed 2 h before mixing.

The fine aggregate used in this study was medium well graded quartz sand, complied with ECP 203 [53] and ASTM C33 [54]. The physical properties of the used sand are shown in Table 2. Moreover, the grain size distribution curve of the used sand is presented in Fig. 1.

Potable tap water according to the requirements of ECP 203 [53], with a pH value of 7.5 was used for preparing the hydroxide solutions, mixing and curing of the OPC mortar mix.

Table 1 - Chemical composition of FA and OPC

Compound	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	K ₂ O	MgO	P ₂ O ₅	SO ₃	TiO ₂	LoI
Class F fly ash	60.30	27.57	4.95	1.19	0.01	1.08	0.24	0.52	0.04	2.31	0.55
Cement	23.00	5.25	3.15	64	0.44	0.15	-	-	3.01	-	5.1

**Fig. 1 – Grading of sand****Table 2 - Physical properties of the used sand**

Property	Value
Specific gravity	2.55
Unit weight t/m ³	1.75
Void ratio %	31.37
Fineness modulus	2.34
Clay and fine matter %	0.5
Water absorption %	0.9

2.2 Mix Proportions

To evaluate the effect of elevated temperatures on different FA-based GP mortars, 19 mixes were prepared (organized in 10 groups) as shown in Table 3. The first group investigated the effect of NaOH molarity (12M, 14M, and 16M), the second group investigated the effect of Na₂SiO₃ to NaOH ratios (2, 2.5, and 3), the third group investigated the effect of sand to FA ratios (1.5, 2, 2.5, and 3), and the fourth group investigated the effect of the alkaline solution to FA ratios (0.4, 0.5, and 0.6). To study the effect of elevated temperatures on GP mortars made with different alkaline solutions, groups 5, 6, 7, 8, and 9 were designed to compare between using Na₂SiO₃ with NaOH (NN mixes), Na₂SiO₃ with KOH (NK mixes) and K₂SiO₃ with KOH (KK mixes). Other parameters including silicate to hydroxide ratio, alkaline solution to FA ratio, and sand to FA ratio were also investigated in groups 5 to 9 as described in Table 3. Group 10 compared between GP and OPC mortars after exposure to elevated temperature. OPC mortar mix was designed to give a compressive strength of 42.5 MPa.

2.3 Mixing Procedure, Casting, and Curing of Specimens

Firstly, FA and sand were dry mixed together in a rotary mixer for 2 min to ensure homogeneity of the mixture. Then, the alkaline solution was added and mixed for another 4 min as shown in Fig. 2. After mixing, flow test of the fresh mortar was conducted to evaluate its consistency according to ASTM C1437 (2020) [55] as shown in Fig. 3. The specimen moulds were

cast, and the compaction was carried out on a vibrating table for 30 s as shown in Fig. 4. After that, the moulds were covered and kept at room temperature ($25 \pm 3^\circ\text{C}$ and $60 \pm 5\%$ RH) for 24 h as a rest period, then the specimens were heat cured at 60°C for 48 h, followed by air-dry curing for 24 h at an ambient temperature ($25 \pm 3^\circ\text{C}$ and $60 \pm 5\%$ RH) before stripping. After the curing period, the samples were de-moulded and left at room temperature ($25 \pm 3^\circ\text{C}$ and $60 \pm 5\%$ RH) until testing after one year. The mixing process used for OPC mortar was similar to the mixing of GP mortar. The OPC mortar was removed from moulds after 24 h and cured by immersing in tap water for 28 days, then OPC specimens were left open to room temperature ($25 \pm 3^\circ\text{C}$ and $60 \pm 5\%$ RH) up to testing after one year. For each mix, eighteen $40 \times 40 \times 160$ mm prisms were cast to evaluate the flexural and compressive strengths. Also, eighteen 50×100 mm cylinders were cast to evaluate the indirect tensile strength.

Table 3 - Mix proportions of the investigated mixes (ratio by weight)

Group	Mix ID*	Binder	Investigated parameter	M**	Si type/ OH type	Si / OH	Sand / binder	A / FA* **	W/C* *** ratio	% Flow
Group 1	NN-Si2.5-S2/A0.5-12M	FA	Molarity	12	NS/NH	2.5	2	0.5	-	55
	NN-Si2.5-S2/A0.5-14M	FA		14	NS/NH	2.5	2	0.5	-	50
	NN-Si2.5-S2/A0.5-16M	FA		16	NS/NH	2.5	2	0.5	-	45
Group 2	NN-Si2-S2/A0.5-14M	FA	Silicate to hydroxide ratio	14	NS/NH	2	2	0.5	-	70
	NN-Si2.5-S2/A0.5-14M	FA		14	NS/NH	2.5	2	0.5	-	50
	NN-Si3-S2/A0.5-14M	FA		14	NS/NH	3	2	0.5	-	40
Group 3	NN-Si2.5-S1.5/A0.5-14M	FA	Sand to FA ratio	14	NS/NH	2.5	1.5	0.5	-	80
	NN-Si2.5-S2/A0.5-14M	FA		14	NS/NH	2.5	2	0.5	-	50
	NN-Si2.5-S2.5/A0.5-14M	FA		14	NS/NH	2.5	2.5	0.5	-	40
	NN-Si2.5-S3/A0.5-14M	FA		14	NS/NH	2.5	3	0.5	-	30
Group 4	NN-Si2.5-S2/A0.4-14M	FA	Alkaline solution to FA ratio	14	NS/NH	2.5	2	0.4	-	35
	NN-Si2.5-S2/A0.5-14M	FA		14	NS/NH	2.5	2	0.5	-	50
	NN-Si2.5-S2/A0.6-14M	FA		14	NS/NH	2.5	2	0.6	-	90
Group 5	NN-Si2.5-S2/A0.5-14M	FA	Alkaline solution type	14	NS/NH	2.5	2	0.5	-	50
	NK-Si2.5-S2/A0.5-14M	FA		14	NS/KH	2.5	2	0.5	-	100
	KK-Si2.5-S2/A0.5-14M	FA		14	KS/KH	2.5	2	0.5	-	150
Group 6	NN-Si3-S2/A0.5-14M	FA	Alkaline solution type (silicate to hydroxide ratio = 3)	14	NS/NH	3	2	0.5	-	40
	NK-Si3-S2/A0.5-14M	FA		14	NS/KH	3	2	0.5	-	100
	KK-Si3-S2/A0.5-14M	FA		14	KS/KH	3	2	0.5	-	150

Group 7	NN-Si2.5-S2/A0.4-14M	FA	Alkaline solution type (alkaline solution to FA ratio= 0.4)	14	NS/NH	2.5	2	0.4	-	35
	NK-Si2.5-S2/A0.4-14M	FA		14	NS/KH	2.5	2	0.4	-	80
	KK-Si2.5-S2/A0.4-14M	FA		14	KS/KH	2.5	2	0.4	-	110
Group 8	NN-Si2.5-S2.5/A0.5-14M	FA	Hydroxide type (sand to FA = 3)	14	NS/NH	2.5	2.5	0.5	-	40
	NK-Si2.5-S2.5/A0.5-14M	FA		14	NS/KH	2.5	2.5	0.5	-	60
Group 9	NN-Si2.5-S2/A0.6-14M	FA	Hydroxide type (alkaline solution to FA ratio= 0.6)	14	NS/NH	2.5	2	0.6	-	90
	NK-Si2.5-S2/A0.6-14M	FA		14	NS/KH	2.5	2	0.6	-	120
Group 10	NN-Si2.5-S3/A0.5-14M	FA	Comparing GP and OPC mortars	14	NS/NH	2.5	3	0.5	-	30
	OPC	cement		-	-	-	3	-	0.5	50

*The mix ID was designed to explain the type of used silicate and hydroxide solutions. Also mix proportions were mentioned in the ID. For example, mix NN-Si2.5-S2/A0.5-14M was made using Na₂SiO₃ and NaOH solutions (NN), Na₂SiO₃/NaOH ratio (Si) is 2.5, sand (S) to FA ratio is 2, alkaline solution (A) to FA ratio is 0.5 and the NaOH molarity (M) is 14.

**M is the molarity of hydroxide solution

*** A/FA is the alkaline solution to FA ratio

**** W/C is the water to cement ratio



Fig. 2 – Mixing GP mortars



Fig. 3 – Flow test of GP mortars



a) 40x40x160 mm prisms



b) 50x100 mm cylinders

Fig. 4 – Casting and vibrating the GP mortar mixes

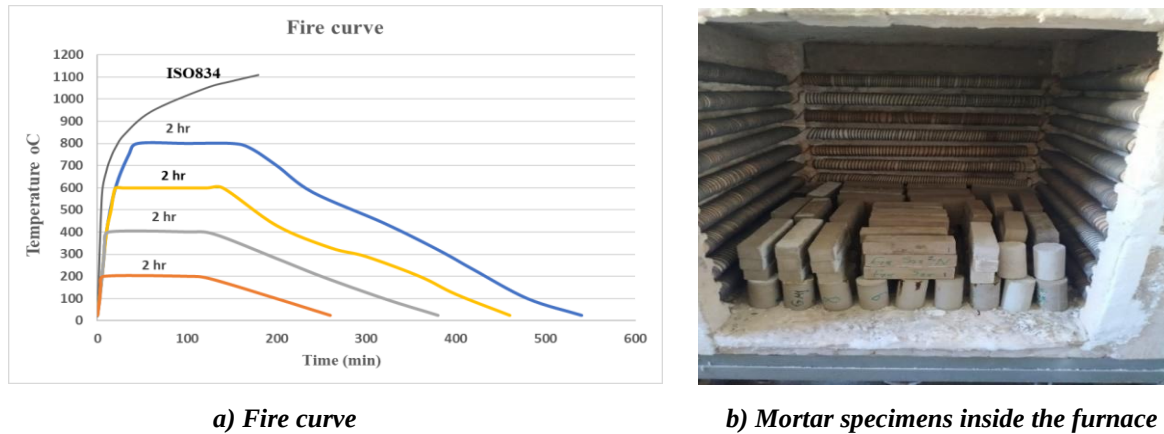


Fig. 5 – Heating of GP mortars

2.4 Elevated Temperature Exposure Regime

The specimens were exposed to elevated temperatures at the age of one year after casting. Specimens were heated in an electrical heater furnace. For each mix, three prisms and three cylinders were exposed to 200 °C, 400 °C, 600 °C, and 800 °C according to the fire rate shown in Fig. 5-a. The temperature was sustained at target temperature for 2 h before the specimens were allowed to cool naturally to room temperature inside the furnace. Fig. 5-b shows the specimens inside the furnace.

2.5 Physical and Mechanical Tests

Percentage of weight loss of GP mortar was measured for each mix by measuring average weight of three prisms before and after exposure to 200 °C, 400 °C, 600 °C, and 800 °C then substitution in Eq. 1 as follows:

$$\text{Percentage of weight loss} = \frac{(\text{Average weight before exposure} - \text{Average weight after exposure})}{(\text{Average weight before exposure})} \times 100 \quad (1)$$

Compressive, flexural, and indirect tensile strengths were measured before and after exposure to 200 °C, 400 °C, 600 °C, and 800 °C at the age of one year. Flexural strength was determined according to EN 196-1 [52] by taking the average strength of three prisms as shown in Fig. 6-a. Compressive strength was determined according to EN 196-1 [52] by taking the average strength of six half-prisms as shown in Fig. 6-b. Indirect tensile test was carried out according to ASTM C496 [56] by taking the average strength of three cylinders as shown in Fig. 6-c.

Scanning Electron Microscopy (SEM) was performed on 4 mixes of GP mortars and the OPC mortar mix to investigate the change in microstructure before and after exposure to 800 °C.

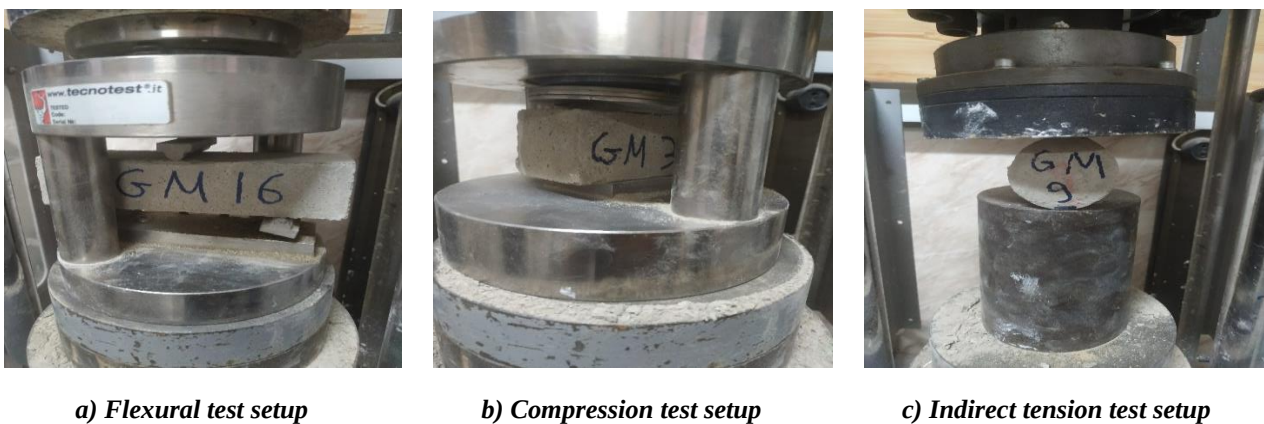


Fig. 6 - Mechanical properties setup for GP mortars

3 Results and Discussion

3.1 Physical Properties of GP Mortars

Figure 7 illustrates the percentage of mass loss of the GP and OPC mortar mixes. Generally, the percentages of mass loss of GP mortar mixes varied between 1.5% and 3.6% after exposure to 200 °C. These reductions are associated with water evaporation [46, 57]. Mass loss of GP happens in four parts: a) evaporation of water and hydroxyl groups, b) decomposition of GP components, such as calcium hydroxide, c) change phase to nepheline, and d) the stage that the weight losses become unchanged [58].

At 400 °C, the percentage of mass loss remarkably increased for GP mortar mixes. Ranjbar et al. [58] indicated that this loss happens due to the beginning of de-hydroxylation of $\text{Al}_2(\text{OH})_3$ at 285 °C and dehydration of chemically bounded water at above 300 °C. Also, the weight loss at about 400 °C may be caused by energy release, the loss of OH groups during the phase change and the decomposition of sodium carbonate formed by atmospheric carbonation of unreacted NaOH [58]. At 600 °C and 800 °C, the percentage of mass loss increased slightly due to the beginning of melting [48].

Mix NN-Si2.5-S2/A0.5-14M recorded the least mass loss value at different elevated temperatures as shown in Fig. 7-a. Increasing sand/FA ratio and alkaline solution/FA ratio adversely affected the mass loss values. GP mortar mix NN-Si2.5-S3/A0.5-14M was more stable than OPC mortar where the mass loss of OPC and GP mortars after exposure to 800 °C reached 8.1% and 4.95%, respectively.

Taking into consideration the type of alkaline solution, using K-based solution is better than using Na-based solutions as shown in Fig. 7-b. This result is compatible with Hosan et al. [43] as it was concluded that the mass loss in using Na-based solutions in GP paste was higher than in using K-based solutions.

3.2 Mechanical Properties of GP Mortars

Compressive, flexural, and indirect tensile strengths of GP mortar mixes were measured as the mechanical properties at ambient temperature and after exposure to elevated temperatures at the age of one year. Generally, it was observed that all strengths started to decrease gradually after exposure to 200 °C, 400 °C, 600 °C, and 800 °C. Contrary to what was mentioned in some other studies where compressive strength of GP mortars or concrete was increased after exposure to 200 °C and 400 °C [42, 44, 46]. This increase was interpreted as due to the completion of the geopolymerization process as specimens were exposed to elevated temperatures at early ages, 7 or 28 days.

In this research, specimens were exposed to elevated temperatures at the age of 365 days. Thus, the geopolymerization process has been fully completed and this will be explained through the SEM analysis. The change in physical and mechanical properties are discussed below.

3.2.1 Compressive strength

3.2.1.1 Effect of Sodium Hydroxide Molarity

Compressive strength of GP mortar mixes of group 1 at ambient temperature and after exposure to elevated temperatures are presented in Fig. 8-a. Increasing molarity of NaOH enhanced the compressive strength for the unexposed specimens where mix NN-Si2.5-S2/A0.5-16M recorded a compressive strength higher than that of mix NN-Si2.5-S2/A0.5-12M by about 12.8%.

These results are compatible with Ghazy et al. [59]. Compressive strength of all mixes decreased gradually with increasing the elevated temperatures as presented in Fig. 8-a. After exposure to 200 °C and 400 °C, residual compressive strength for mix NN-Si2.5-S2/A0.5-14M was about 93.5% and 79%, respectively. After exposure to 800 °C, residual compressive strength of mixes NN-Si2.5-S2/A0.5-12M, NN-Si2.5-S2/A0.5-14M, and NN-Si2.5-S2/A0.5-16M was about 36.3%, 38.8%, and 28.5%, respectively. Increasing molarity of NaOH from 12 to 16 M negatively affected the residual compressive strength. Shaikh and Vimonsatit [41] observed that the rate of loss of compressive strength after 600 °C is high in GPC containing high molarity of NaOH.

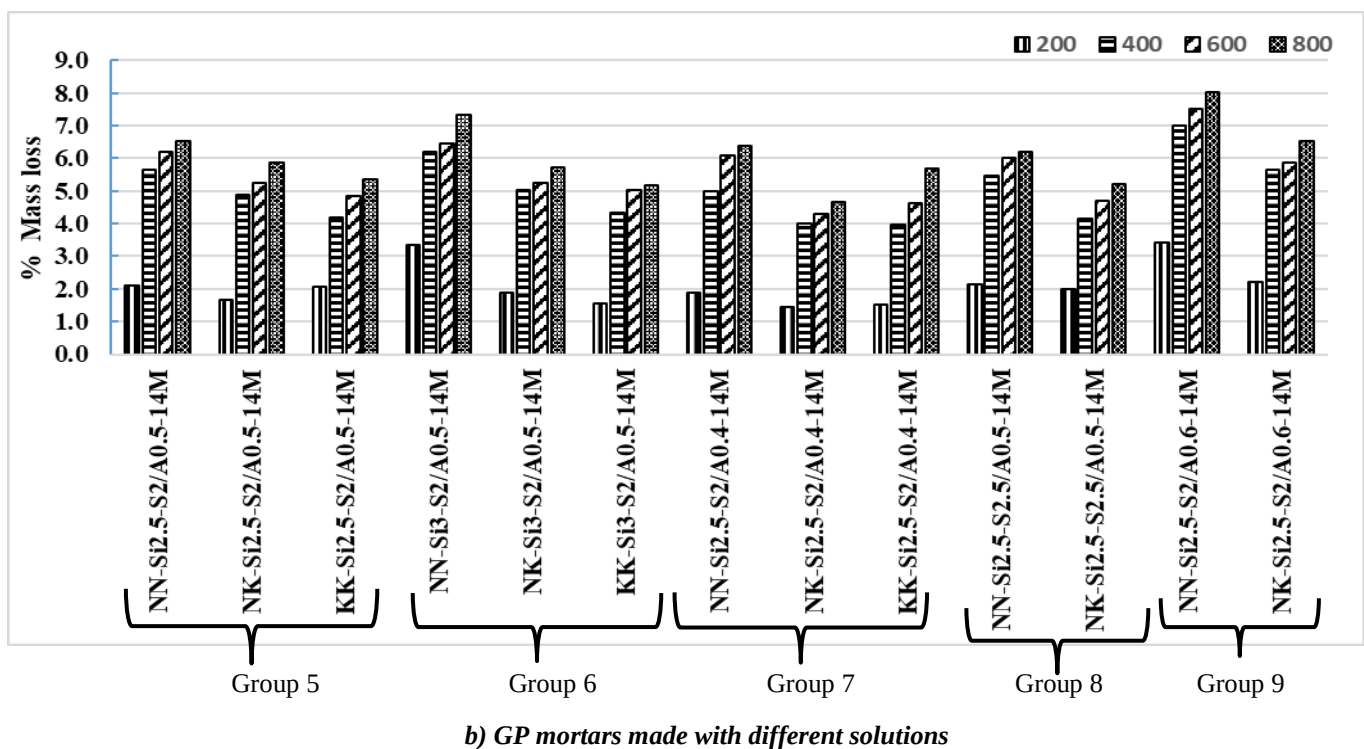
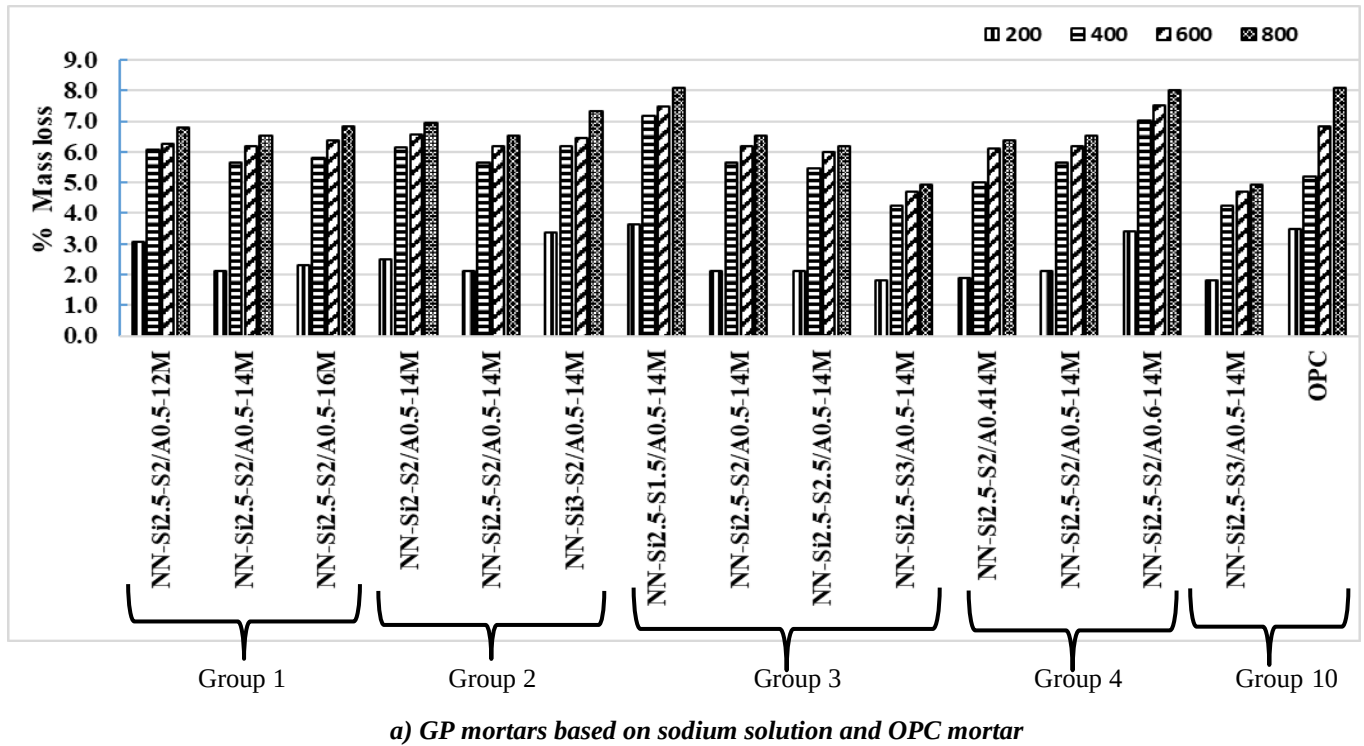


Fig. 7 – Mass loss of different GP and OPC mortars after exposure to elevated temperatures

3.2.1.2 Effect of Sodium Silicate to Sodium Hydroxide Solution Ratio

Figure 8-a presents the compressive strength of GP mortar mixes of group 2. At ambient temperature, increasing the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio from 2 in mix NN-Si2-S2/A0.5-14M to 2.5 in mix NN-Si2.5-S2/A0.5-14M caused increase in the compressive strength by about 13.26%. On the other hand, increasing that ratio from 2.5 to 3 in mix NN-Si3-S2/A0.5-14M caused decrease in compressive strength by about 10.4%. After exposure to 200 °C and 400 °C, residual compressive strength of mix NN-Si2.5-S2/A0.5-14M was 93.5% and 79%, respectively. After exposure to 800 °C, residual compressive strength of mix NN-Si2.5-S2/A0.5-14M was 38.8% while it was 36.6% and 31.8% for mixes NN-Si3-S2/A0.5-14M and NN-Si2-S2/A0.5-

14M, respectively. Increasing the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio from 2.5 to 3 negatively affected the compressive strength either before or after exposure to elevated temperatures. Albadawy et al. [46] reported that when the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio is more than 2.5 the compressive strength tended to decrease as the dissolved precursors tend to form zeolites which are weaker in compressive strength

3.2.1.3 Effect of sand to FA Ratio

Figure 8-a shows the compressive strength of GP mortar mixes of group 3 where the mortar mixes contained sand to FA ratios of 1.5, 2, 2.5 and 3. Mix NN-Si2.5-S2/A0.5-14M had the maximum compressive strength for the unexposed specimens as it recorded 70.13 MPa. Increasing sand/FA ratio from 1.5 to 2 resulted in increasing the compressive strength either before or after exposure to elevated temperature. On the other hand, increasing the sand/FA ratio from 2 to 2.5 and 3 caused a decrease in compressive strength either before or after exposure to elevated temperature. After exposure to 800 °C, residual compressive strength of mixes NN-Si2.5-S1.5/A0.5-14M, NN-Si2.5-S2/A0.5-14M, NN-Si2.5-S2.5/A0.5-14M and, NN-Si2.5-S3/A0.5-14M were 23%, 27%, 20.4% and, 20.7% respectively.

3.2.1.4 Effect of alkaline solution to FA Ratio

Compressive strength of GP mixes of group 4 is also shown in Fig. 8-a. For the unexposed specimens, increasing alkaline solution to FA ratio (A/FA) from 0.4 to 0.5 led to a slight increase in compressive strength by 2%. This increase is a result of more geopolymerization of FA particles. On the other hand, increasing A/FA ratio from 0.4 to 0.6 led to decrease in compressive strength by 13%. After exposure to 200 °C, the residual compressive strengths were about 95.5%, 93.5% and 76% for mixes NN-Si2.5-S2/A0.4-14M, NN-Si2.5-S2/A0.5-14M and NN-Si2.5-S2/A0.6-14M, respectively. After exposure to 400 °C, 600 °C and 800 °C, it was noticed that as the A/FA ratio increases, the compressive strength decreases with increasing the exposure temperature. This trend was expected as increasing the alkaline solution ratio leads to more pores in the structure of GP mortars [46].

3.2.1.5 Comparing of Geopolymer and OPC Mortar Mixes

Figure 8-a shows the compressive strength of GP and OPC mortar mixes. The behavior of GP mortar before and after exposure to elevated temperatures was clearly better than OPC mortar and this is compatible with Shaikh and Vimonsatit [41] and Albadawy et al. [46]. After exposure to 800 °C, residual compressive strength of mix NN-Si2.5-S3/A0.5-14M and OPC mortar mix were 37.4% and 24.4% respectively.

3.2.1.6 Comparing Geopolymer Mortar Mixes with Different Alkaline Solution Types

Figure 8-b shows the compressive strength of GP mortar mixes made with different alkaline solutions in groups 5, 6, and 7. For group 5, unexposed specimens of mix NN-Si2.5-S2/A0.5-14M recorded a compressive strength of 70.1 MPa, while mix KK-Si2.5-S2/A0.5-14M recorded 50.3 MPa. Ghazy et al. [59] also reported that compressive strength of NN and NK mixes are higher than KK mix. After exposure to 200 °C, compressive strength of mixes NN-Si2.5-S2/A0.5-14M and NK-Si2.5-S2/A0.5-14M decreased by about 6.5% and 11%, respectively while compressive strength of mix KK-Si2.5-S2/A0.5-14M decreased by only 1.5%. After exposure to 400 °C, 600 °C, and 800 °C, the compressive strength decreased gradually. After exposure to 800 °C, residual compressive strength of mix NK-Si2.5-S2/A0.5-14M was 54% compared to 38.8% and 48.7% for mixes NN-Si2.5-S2/A0.5-14M and KK-Si2.5-S2/A0.5-14M, respectively. GP mortar mixes containing potassium exhibited less strength loss after exposure to elevated temperature. Lahoti et al. [44] also found that K-based and Na-K based GP were more stable than Na-based GP under elevated temperatures up to 900 °C.

In group5, another comparison of using different solutions but with silicate to hydroxide solution ratio of 3 can be discussed. At ambient temperature, compressive strength of NN and NK GP mixes was higher than KK-based GP mortar by about 57%. After exposure to 800 °C, GP mortar mixes containing K exhibited less strength loss as the residual compressive strength of mixes NN-Si3-S2/A0.5-14M, NK-Si3-S2/A0.5-14M and, KK-Si3-S2/A0.5-14M were 36.6%, 47.5% and, 63.7% respectively. Comparing group 5 with group 6 in Fig. 8-b, increasing the silicate to hydroxide solution ratio from 2.5 to 3 negatively affected the compressive strength values for mixes NN-Si3-S2/A0.5-14M and KK-Si3-S2/A0.5-14M either before or after exposure to elevated temperatures. For mix NK-Si3-S2/A0.5-14M, the effect was noticeable.

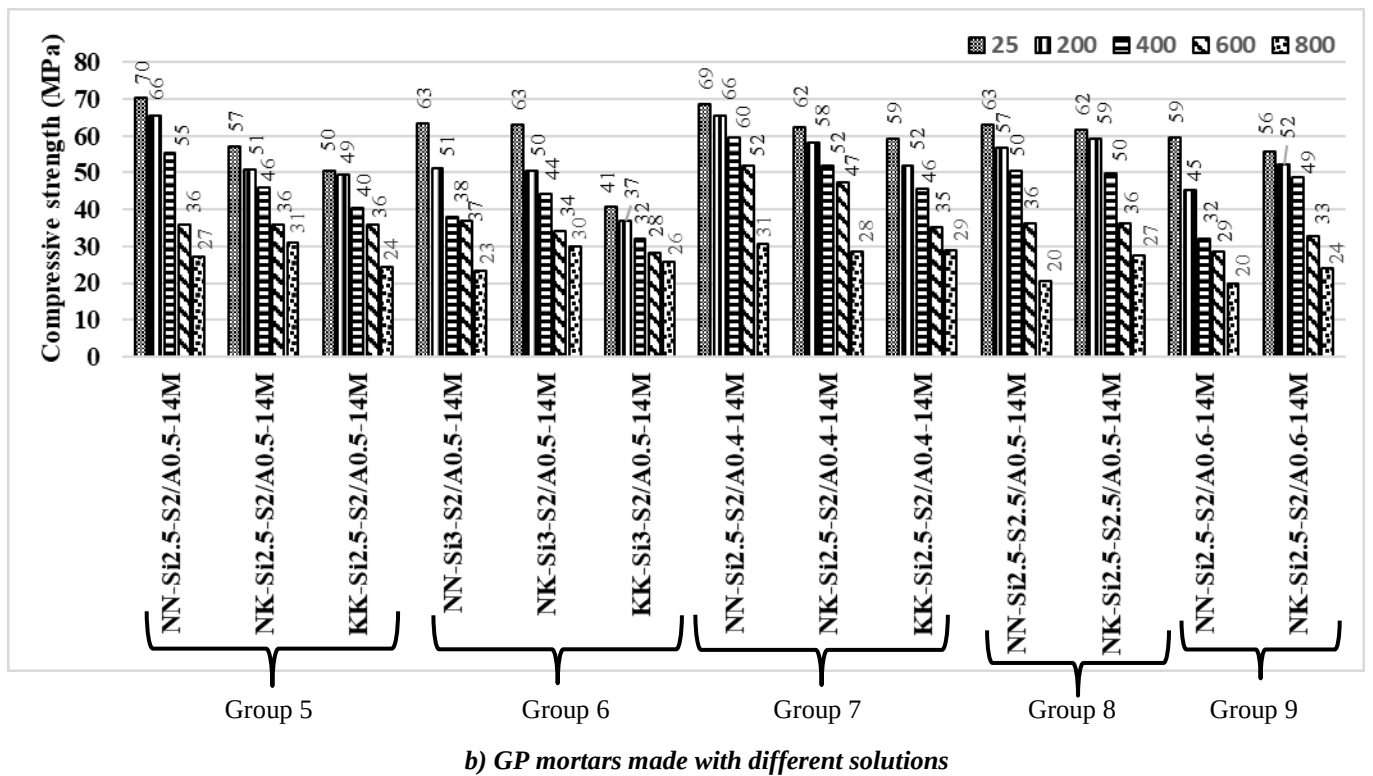
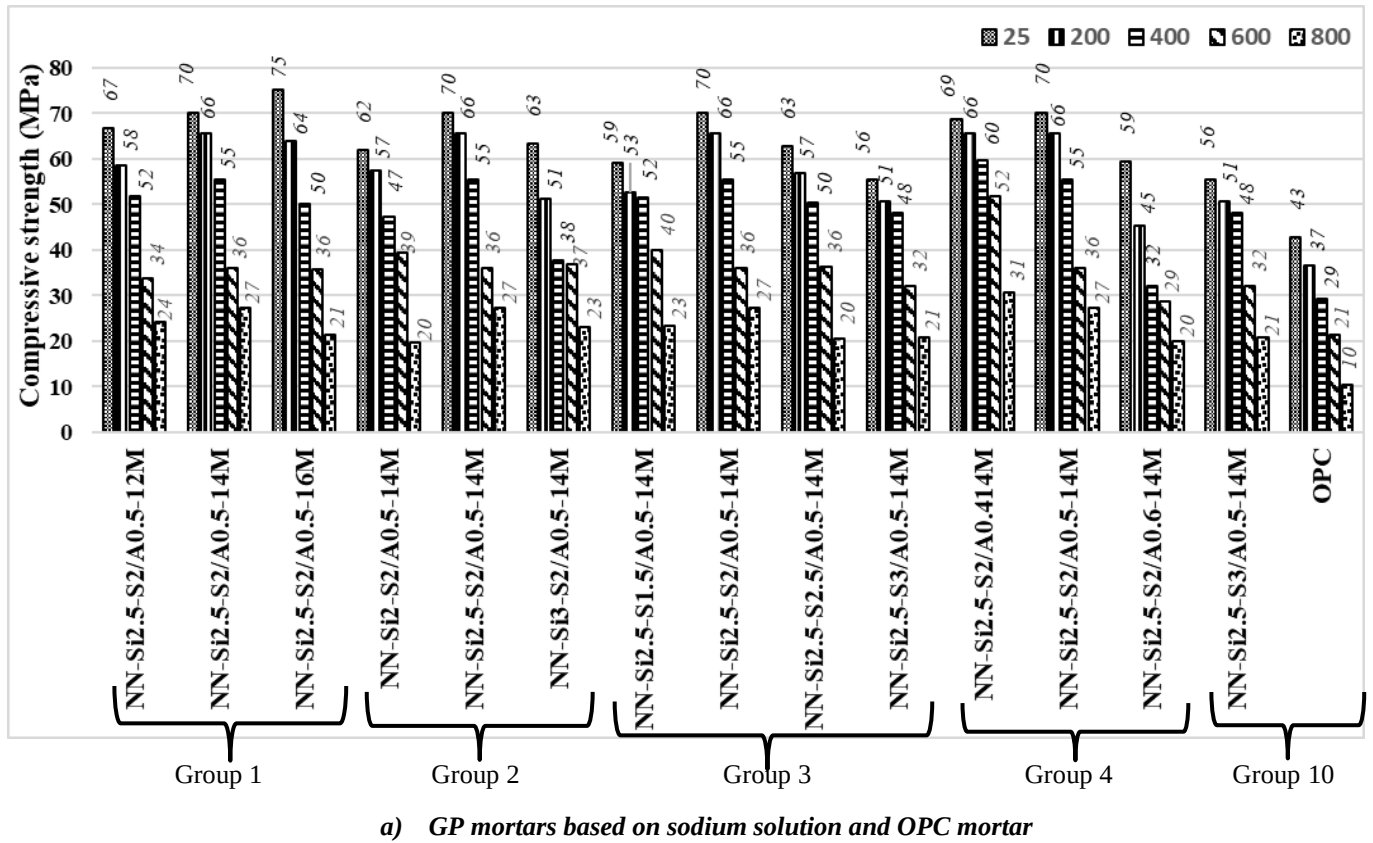


Fig. 8 – Compressive strength of the investigated GP mortars as affected by elevated temperatures

Figure 8-b shows the compressive strength of GP mortar mixes of group 7. At ambient temperature, Mix NN-Si2.5-S2/A0.4-14M recorded the maximum compressive strength when compared to mixes NK-Si2.5-S2/A0.4-14M and KK-Si2.5-S2/A0.4-

14M. after exposure to 800 °C, residual compressive strength of the three mixes was convergent as it was in the range of 44.5–49%.

The compressive strength of mixes in groups 8 and 9 is also shown in Fig. 8-b. Compressive strength of mixes NK-Si2.5-S2.5/A0.5-14M and NK-Si2.5-S2/A0.6-14M were higher than those of mixes NN-Si2.5-S2.5/A0.5-14M and NN-Si2.5-S2/A0.6-14M, respectively especially after exposure to elevated temperature. These results from groups 5 to 9 show that the behavior of GP mortars containing Na₂SiO₃ with KOH is better than using other solutions in agreement with Lahoti et al. [44].

3.2.2 Flexural strength

3.2.2.1 Effect of Sodium Hydroxide Molarity

Figure 9-a shows the flexural strength of GP mortar of group 1. For the unexposed specimens, increasing molarity of NaOH from 12 to 16 lead to an increase in flexural strength by 16.7%. Ghazy et al. [59] also reported that increasing NaOH molarity up to 16 leads to an increase in flexural strength for NN mixes. Flexural strength of the three mixes was decreased by about 17–20% after exposure to 200 °C.

After exposure to 400 °C, the residual flexural strength was 43%, 70% and 56% for mixes NN-Si2.5-S2/A0.5-12M, NN-Si2.5-S2/A0.5-14M and NN-Si2.5-S2/A0.5-16M, respectively. After exposure to 600 °C and 800 °C, the flexural strengths kept decreasing and the residual flexural strength of mixes NN-Si2.5-S2/A0.5-14M and NN-Si2.5-S2/A0.5-16M were 24% and 13.8% after exposure to 800 °C, respectively.

3.2.2.2 Effect of Sodium Silicate to Sodium Hydroxide Solution Ratio

Increasing Na₂SiO₃/NaOH ratio from 2 to 2.5 led to increasing the flexural strength before exposure to elevated temperatures as shown in Fig. 9-a. On the other hand, increasing Na₂SiO₃/NaOH ratio from 2.5 to 3 led to decreasing the flexural strength. After exposure to 200 °C, residual flexural strength of mixes NN-Si2.5-S2/A0.5-14M and NN-Si3-S2/A0.5-14M was 83% and 93% respectively.

After exposure to 400 °C, 600 °C, and 800 °C, the residual flexural strength of GP mortar mix with Na₂SiO₃/NaOH of 2.5 was higher than GP mortar mix with Na₂SiO₃/NaOH of 3. After exposure to 800 °C, residual flexural strength of mixes NN-Si2.5-S2/A0.5-14M and NN-Si3-S2/A0.5-14M was 24% and 16% respectively. These results are compatible with the compressive strength results.

3.2.2.3 Effect of sand to FA Ratio

Figure 9-a shows the flexural strength of GP mortar mixes of group 3. Unexposed specimens of mix NN-Si2.5-S2/A0.5-14M had the highest flexural strength. Increasing sand/FA ratio from 1.5 to 2 resulted in increasing the flexural strength either before or after exposure to elevated temperature.

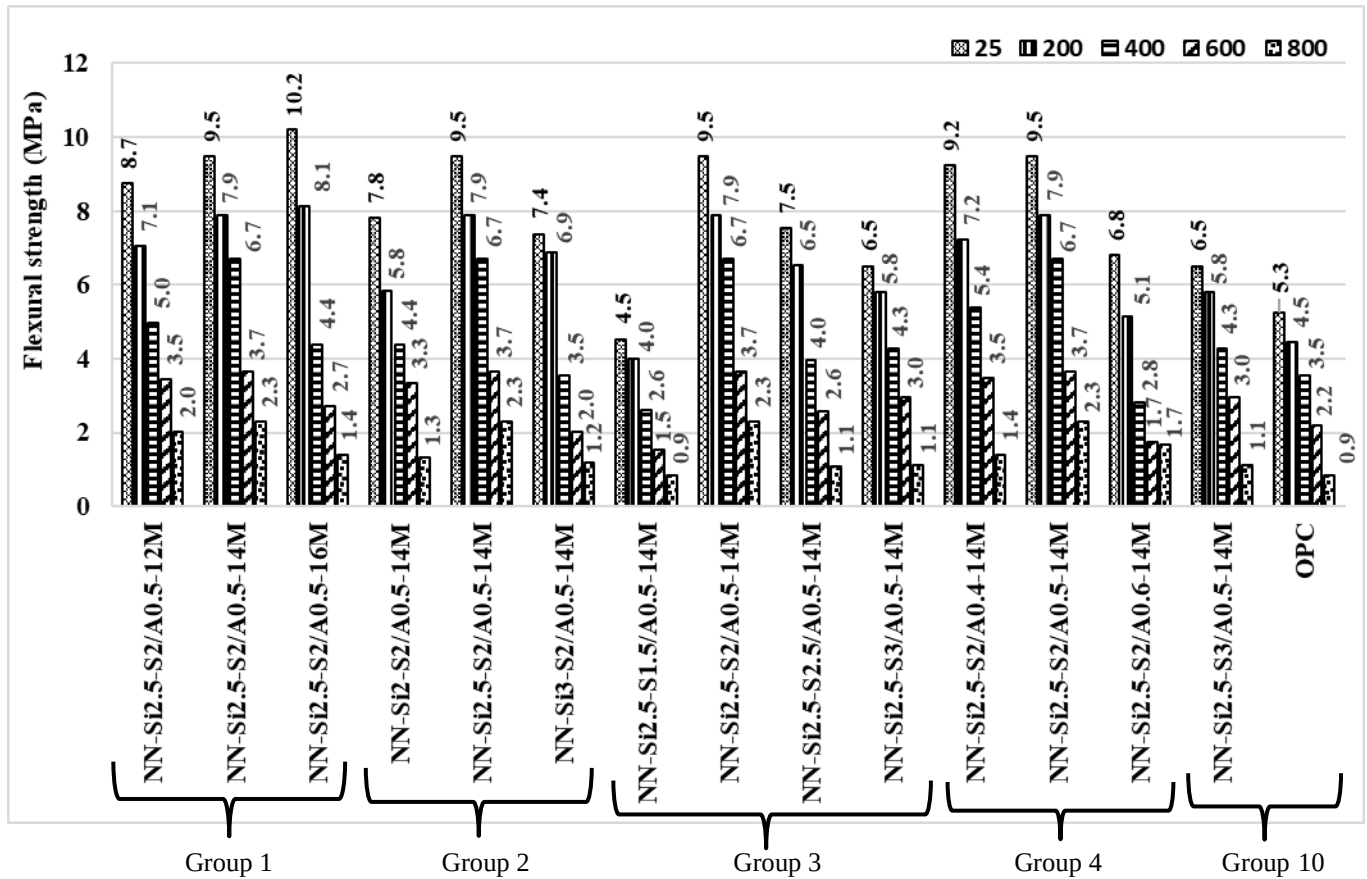
On the other hand, increasing the sand/FA ratio from 2 to 2.5 and 3 caused decrease in flexural strength either before or after exposure to elevated temperature. After exposure to 800 °C, residual flexural strength of mix NN-Si2.5-S2/A0.5-14M was 24%, while it was 14.5% and 17% for mixes NN-Si2.5-S2.5/A0.5-14M and NN-Si2.5-S3/A0.5-14M, respectively.

3.2.2.4 Effect of Alkaline Solution to Fly Ash Ratio

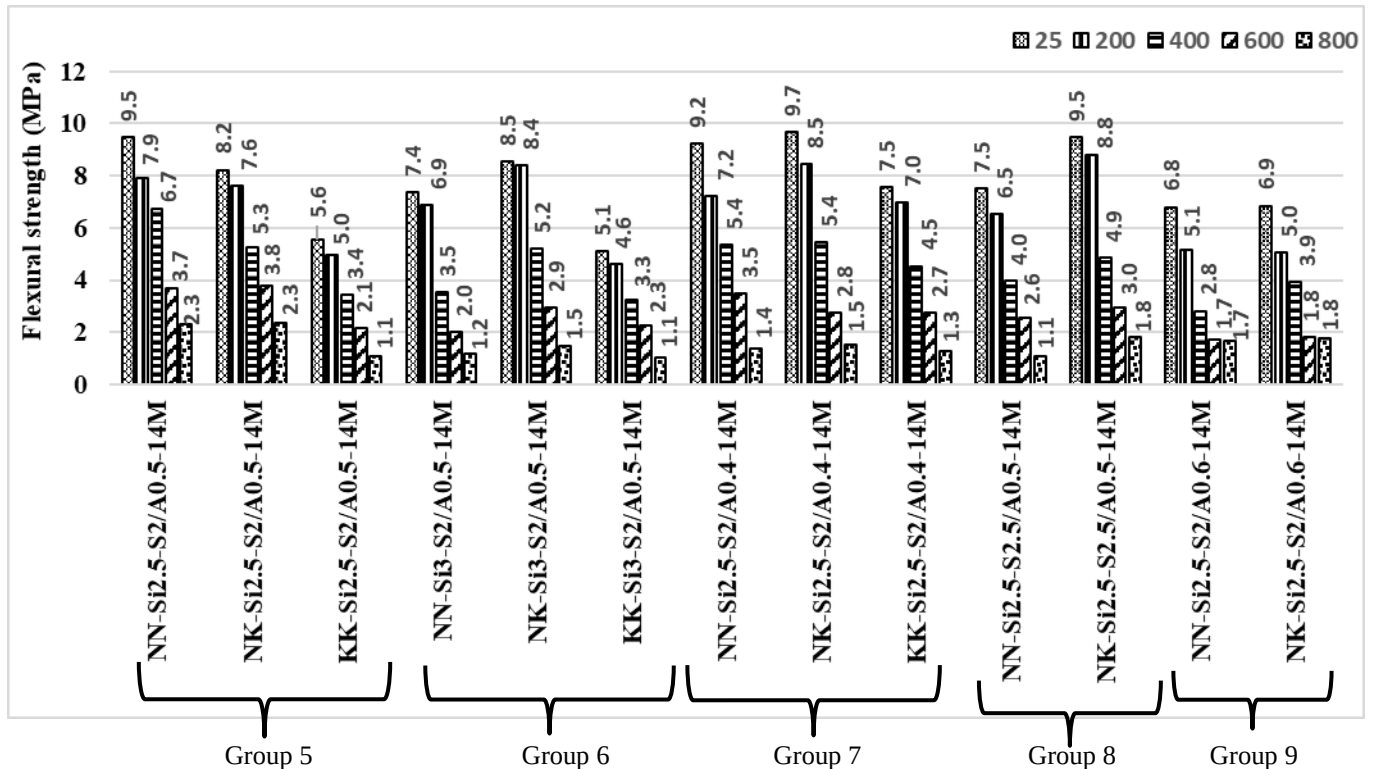
Flexural strength of GP mortar mixes in group 4 is presented in Fig. 9-a. For the unexposed specimens, mix NN-Si2.5-S2/A0.6-14M recorded the lowest value of flexural strength as it has the highest A/FA ratio. With increasing the elevated temperature, the flexural strength decreased gradually for the three mixes. After exposure to 800 °C, mix NN-Si2.5-S2/A0.5-14M recorded a flexural strength value of 2.29 MPa which is higher than the flexural strength of mixes NN-Si2.5-S2/A0.4-14M and NN-Si2.5-S2/A0.6-14M.

3.2.2.5 Comparing GP and OPC Mortars

Figure 9-a shows the flexural strength of GP and OPC mortars before and after exposure to elevated temperatures. Once again, behaviour of GP mortar mix is better than OPC mortar mix either before or after exposure to elevated temperatures. Flexural strength of mix NN-Si2.5-S3/A0.5-14M and OPC mortar was 1.12 and 0.85 MPa after exposure to 800 °C, respectively.



a) GP mortars based on sodium solution and OPC mortar



b) GP mortars made with different solutions

Fig. 9 – Flexural strength of the investigated GP mortars as affected by elevated temperatures

3.2.2.6 Comparing GP Mortar mixes with Different Alkaline Solution Types

Figure 9-b show the flexural strength of GP mortar mixes made with different alkaline solutions in groups 5-9. Using mix of Na_2SiO_3 and NaOH solution in control group (group 5) gave the highest flexural strength value at ambient temperature. After exposure to elevated temperatures, the flexural strength decreased whatever the type of the solution.

After exposure to 400 °C, flexural strength of mixes NN-Si2.5-S2/A0.5-14M, NK-Si2.5-S2/A0.5-14M and, KK-Si2.5-S2/A0.5-14M decreased to 70.7%, 63.9% and 61.9% of the original strength, respectively. After exposure to 800 °C, residual flexural strengths of mixes NN-Si2.5-S2/A0.5-14M, NK-Si2.5-S2/A0.5-14M, and KK-Si2.5-S2/A0.5-14M were 24%, 28.5% and, 19.4% respectively. Using KOH enhanced the behaviour of GP mortars under elevated temperatures.

In group 6; mix NK-Si3-S2/A0.5-14M recorded higher values of flexural strength either before or after exposure to elevated temperatures as shown in Fig. 9-b. Flexural strengths of mixes NN-Si3-S2/A0.5-14M, NK-Si3-S2/A0.5-14M and KK-Si3-S2/A0.5-14M after exposure to 800 °C were 1.17, 1.46 and 1.05 MPa, respectively. Comparing groups 5 and 6, increasing silicate to hydroxide ratio from 2.5 to 3 negatively affected the flexural strength whatever the type of alkaline solution.

For group 7; mix NK-Si2.5-S2/A0.4-14M recorded the highest flexural strength at ambient temperature as shown in Fig. 9-b. After exposure to 200 °C and 400 °C, residual flexural strengths of mix KK-Si2.5-S2/A0.4-14M were 92% and 60%, while it was 87.6% and 56.4% for mix NK-Si2.5-S2/A0.4-14M, respectively.

After exposure to 800 °C, residual flexural strengths of the three mixes were similar. Comparing groups 5 and 7, initial flexural strength of GP mortar mixes with A/FA ratio of 0.4 was higher than that of GP mortar mixes with A/FA ratio of 0.5. With the exposure to elevated temperatures of 200 °C, 400 °C, 600 °C and, 800 °C, the percentage of residual flexural strength of GP mortar mixes with A/FA ratio of 0.5 was higher than that of GP mortar mixes with A/FA ratio of 0.4 as more geopolymerization occurred.

Figure 9-b shows that flexural strength of GP mortar mix NK-Si2.5-S2.5/A0.5-14M is higher than that of mix NN-Si2.5-S2.5/A0.5-14M before and after exposure to elevated temperatures. Residual flexural strength of mix NK-Si2.5-S2.5/A0.5-14M after exposure to 800 °C was about 19.3%, while it was 14.3% for mix NN-Si2.5-S2.5/A0.5-14M.

Figure 9-b shows the flexural strength of GP mortar mixes NN-Si2.5-S2/A0.6-14M and NK-Si2.5-S2/A0.6-14M. Flexural strength of the two mixes was approximately the same before exposure to elevated temperatures.

After exposure to 400 °C, the flexural strength of mix NK-Si2.5-S2/A0.6-14M was higher than that of mix NN-Si2.5-S2/A0.6-14M. After exposure to 800 °C, residual flexural strength of mix NK-Si2.5-S2/A0.6-14M was 25.7% while it was 24.7% for mix NN-Si2.5-S2/A0.6-14M.

3.2.3 Indirect tensile strength

3.2.3.1 Effect of Sodium Hydroxide Molarity

Indirect tensile strength values of GP mortar mixes of group1 are shown in Fig. 10-a. In accordance with compressive and flexural strength results, unexposed specimens of mix NN-Si2.5-S2/A0.5-16M recorded the highest indirect tensile strength.

After exposure to elevated temperatures, indirect tensile strength decreased gradually. Residual indirect tensile strength of mix NN-Si2.5-S2/A0.5-14M was 40.5% and 24% while it was 32.4% and 20.1% for mix NN-Si2.5-S2/A0.5-16M of the unexposed state after exposure to 600 and 800 °C, respectively.

3.2.3.2 Effect of Sodium Silicate to Sodium Hydroxide Solutions Ratio

Indirect tensile strengths of GP mortar mixes in group 2 are shown in Fig. 10-a. Unexposed specimens of mix NN-Si2.5-S2/A0.5-14M recorded the highest indirect tensile strength compared to mixes NN-Si2-S2/A0.5-14M and NN-Si3-S2/A0.5-14M.

After exposure to elevated temperatures, indirect tensile strength decreased slightly and reached about 65.6%, 68.5% and 67% of the original strength for mixes NN-Si2-S2/A0.5-14M, NN-Si2.5-S2/A0.5-14M, and NN-Si3-S2/A0.5-14M after exposure to 400 °C, respectively. After exposure to 800 °C, residual indirect tensile strength of mix NN-Si2.5-S2/A0.5-14M was 24%. Increasing Na_2SiO_3 to NaOH ratio from 2 to 2.5 was more effective than the increase from 2.5 to 3.

3.2.3.3 Effect of sand to FA Ratio

Increasing sand/FA ratio from 1.5 to 2 led to an increase in the indirect tensile strength before and after exposure to elevated temperatures as shown in Fig. 10-a. On the other hand, increasing sand to FA ratio from 2 to 2.5 caused a decrease in the indirect tensile strength. Increasing that ratio from 2.5 to 3 has no significant effect on indirect tensile strength. Percentage of residual indirect tensile strength of mix NN-Si2.5-S2/A0.5-14M is about 24% of the original strength after exposure to 800 °C.

3.2.3.4 Effect of Alkaline solution to FA Ratio

Increasing A/FA ratio from 0.4 to 0.5 had a slight effect on the indirect tensile strength either before or after exposure to elevated temperatures as shown in Fig. 10-a. Increasing A/FA ratio from 0.5 to 0.6 caused a decrease in the indirect tensile strength due to the increase in the pores of the GP microstructure.

3.2.3.5 Comparing Between Geopolymer and OPC Mortars

Figure 10-a shows the indirect tensile strength of GP mortar mix NN-Si2.5-S3/A0.5-14M and OPC mortar. The indirect tensile strength of unexposed GP mortar specimens is higher than that of OPC mortar by 157.8%. After exposure to 200 °C, 400 °C, 600 °C, and 800 °C, indirect tensile strengths decreased gradually for both GP and OPC mortars. After exposure to 800 °C, the indirect tensile strengths of GP mortar mix NN-Si2.5-S3/A0.5-14M and OPC mortar were 1.12 and 0.7 MPa, respectively.

3.2.3.6 Comparing Geopolymer Mortar Mixes with Different Alkaline Solution Types

Fig. 10-b shows the indirect tensile strength for control mixes made with different alkaline solutions, group 5. For the unexposed specimens, mix NN-Si2.5-S2/A0.5-14M recorded the highest indirect tensile strength followed by mix NK-Si2.5-S2/A0.5-14M and mix KK-Si2.5-S2/A0.5-14M, respectively.

After exposure to elevated temperatures, the indirect tensile strength was gradually decreased. After exposure to 800 °C, residual indirect tensile strength of mix NK-Si2.5-S2/A0.5-14M, NN-Si2.5-S2/A0.5-14M, and KK-Si2.5-S2/A0.5-14M were 33.9%, 24% and 25%, respectively.

Indirect tensile strengths of unheated GP mortar mixes of group 6 were 4.98, 4.8, and 3.27 MPa for mixes NN-Si3-S2/A0.5-14M, NK-Si3-S2/A0.5-14M, and KK-Si3-S2/A0.5-14M, respectively as shown in Fig 10-b. After exposure to 400 °C, the indirect tensile strengths for mixes NN-Si3-S2/A0.5-14M, NK-Si3-S2/A0.5-14M, and KK-Si3-S2/A0.5-14M were decreased to about 67%, 66%, and 57% respectively. After exposure to 600 and 800 °C, the decreasing rate of mix NN-Si3-S2/A0.5-14M was higher than that of mix NK-Si3-S2/A0.5-14M. Comparing the results of this group with group 5, increasing silicate to hydroxide ratio from 2.5 to 3, whatever type of solution, caused a decrease in the indirect tensile strength.

Figure 10-b shows the indirect tensile strength of GP mortar mixes of group 7. At ambient temperature and after exposure to 200 and 400 °C, the indirect tensile strength values of mixes NN-Si2.5-S2/A0.4-14M and NK-Si2.5-S2/A0.4-14M were convergent.

After exposure to 600 °C and 800 °C, mix NK-Si2.5-S2/A0.4-14M recorded indirect tensile strength higher than that of mix NN-Si2.5-S2/A0.4-14M. Mix KK-Si2.5-S2/A0.4-14M recorded the lowest values of indirect tensile strength either before or after exposure to elevated temperature. Decreasing A/FA ratio from 0.5 to 0.4 caused a slight increase in the indirect tensile strength

Figure 10-b shows the indirect tensile strength of mixes NN-Si2.5-S2.5/A0.5-14M and NK-Si2.5-S2.5/A0.5-14M in groups 8. After exposure to 200 °C, indirect tensile strength of mix NK-Si2.5-S2.5/A0.5-14M was higher than that of mix NN-Si2.5-S2.5/A0.5-14M by 2.7%.

After exposure to 800 °C, percentage of the indirect tensile strength of mix NK-Si2.5-S2.5/A0.5-14M was 34% while it was 27.8% for mix NN-Si2.5-S2.5/A0.5-14M.

Figure 10-b shows the indirect tensile strength of mixes NN-Si2.5-S2/A0.6-14M and NK-Si2.5-S2/A0.6-14M in group 9. Changing the type of hydroxide did not have a clear effect on the indirect tensile strength up to exposure to 600 °C.

After exposure to 800 °C, the percentages of residual indirect tensile strength for mixes NN-Si2.5-S2/A0.6-14M and NK-Si2.5-S2/A0.6-14M were 21% and 25%, respectively.

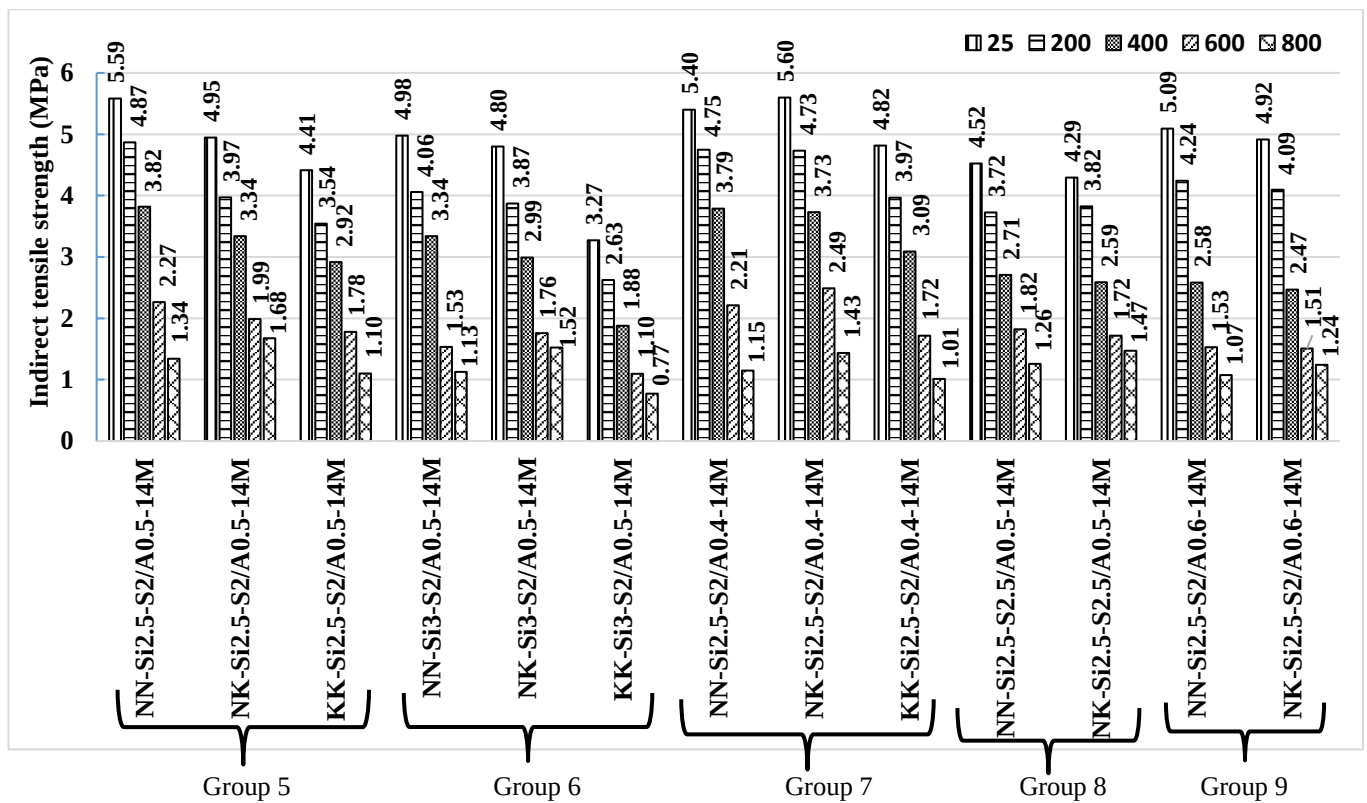
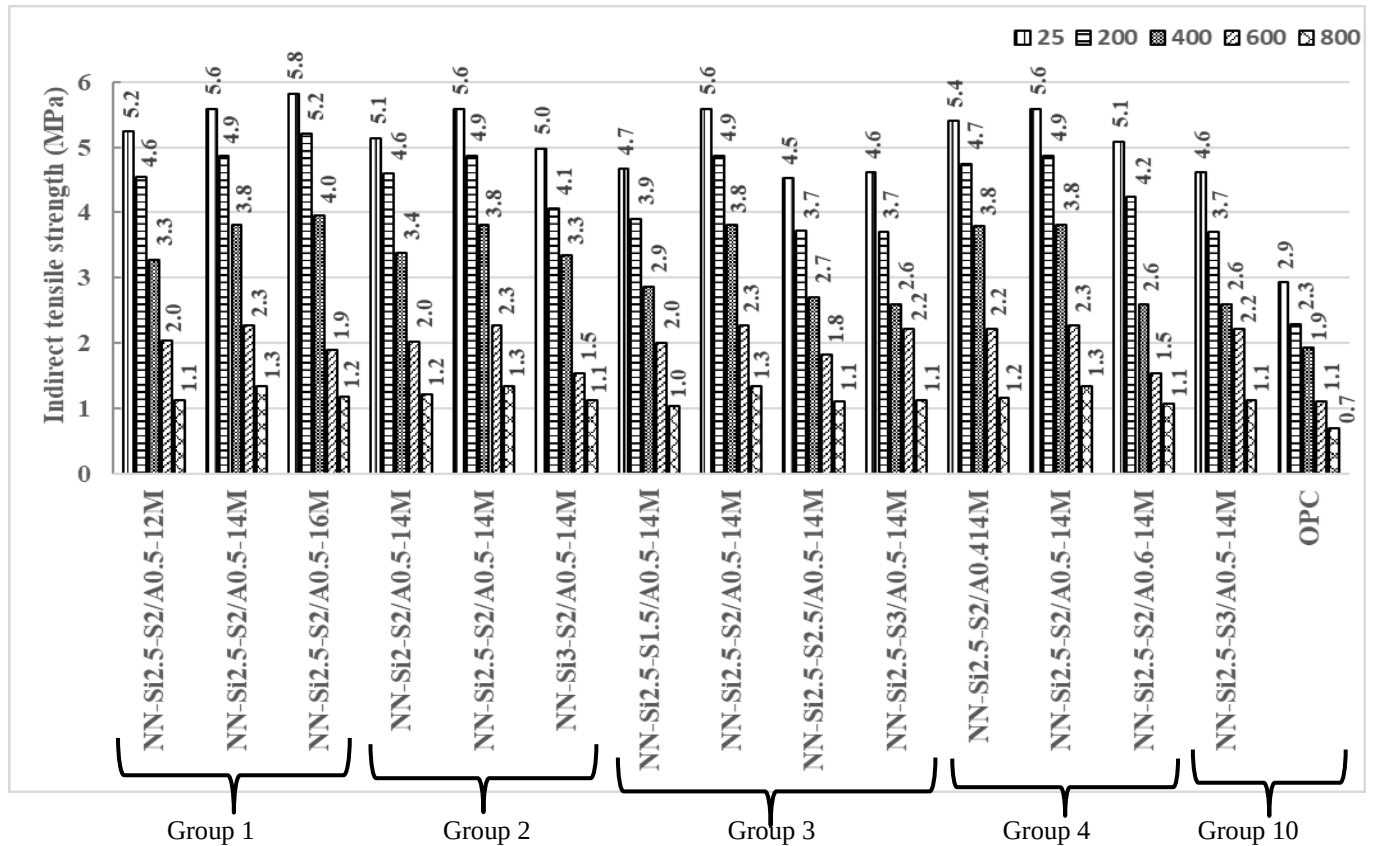


Fig. 10 – Indirect tensile strength of the investigated GP mortars as affected by elevated temperatures

3.3 Proposing empirical equations to predict the residual mechanical properties of geopolymer mortar after fire

Empirical equations to predict the residual mechanical properties of GP mortar at various elevated temperatures are very useful in the design of GP mortars at fire. To the authors' knowledge, there is no available models to predict the mechanical properties of GP mortars at elevated temperatures, especially in case of using different alkaline solutions. Figures 11-a to 11-c show the residual compressive strength of mixes NN-Si2.5-S2/A0.5-14M, NK-Si2.5-S2/A0.5-14M, and KK-Si2.5-S2/A0.5-14M after exposure to elevated temperatures.

A linear relationship is observed between residual compressive strength and the elevated temperatures with a high correlation coefficient R^2 exceeding 0.9 but with different slopes and different intersects parts. The linear equation of any mix is in the formula $f_c/T / f_c = A - B \cdot T$, where A is a constant that presents the intersecting part of the vertical axis as well as the initial strength, B is a constant that presents the slope of the linear relationship between residual strength and elevated temperatures as well as the degradation rate of strength with temperature. These constants were found to be dependent on the alkaline solution type.

All GP mortars were having the same trend but with different values of A and B . Also, the residual flexure and indirect tensile strengths were found to have a linear relationship. Average values of the constants A_1 and B_1 for compressive strength, A_2 and B_2 for flexural strength, and A_3 and B_3 for indirect tensile strength were taken for each type of the used alkaline solution as shown in Table 4.

Empirical equations can be proposed as given in Eq. (2), Eq. (3), and Eq. (4) for compressive, flexural, and indirect tensile strengths of GP mortars made with different alkaline solutions, respectively. Moreover, to investigate the accuracy of the introduced equations, the actual vs predicted values of the compressive, flexural, and indirect tensile strengths were plotted in Figure 12. Three lines including the line of perfect values as well as two lines shifted $\pm 20\%$ from the perfect line are drawn. It can be seen from the figures that the most of data points are lying between the two reference lines within $\pm 20\%$ bound.

$$F'_{cT} = F_c (A_1 - B_1 \cdot T) \quad (2)$$

$$F'_{fT} = F_f (A_2 - B_2 \cdot T) \quad (3)$$

$$F'_{tT} = F_t (A_3 - B_3 \cdot T) \quad (4)$$

where, F'_{cT} = compressive strength at elevated temperature, T (MPa)

F_c = compressive strength at ambient temperature (MPa)

F'_{fT} = flexural strength at elevated temperature, T (MPa)

F_f = flexural strength at ambient temperature (MPa)

F'_{tT} = indirect tensile strength at elevated temperature, T (MPa)

F_t = indirect tensile strength at ambient temperature (MPa)

T = elevated temperature value ($^{\circ}\text{C}$)

A_1 = 1.0447 in case of NN-based solution; = 1.0404 in case of NK-based solution; and = 1.029 in case of KK-based solution

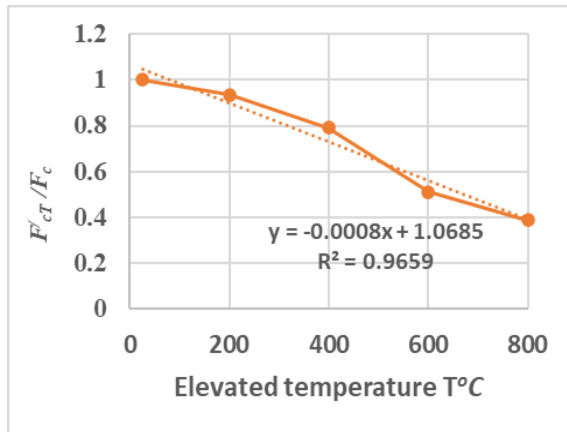
A_2 = 1.0201 in case of NN-based solution; = 1.0464 in case of NK-based solution; and = 1.0661 in case of KK-based solution

A_3 = 1.0375 in case of NN-based solution; = 1.0123 in case of NK-based solution; and = 1.0177 in case of KK-based solution

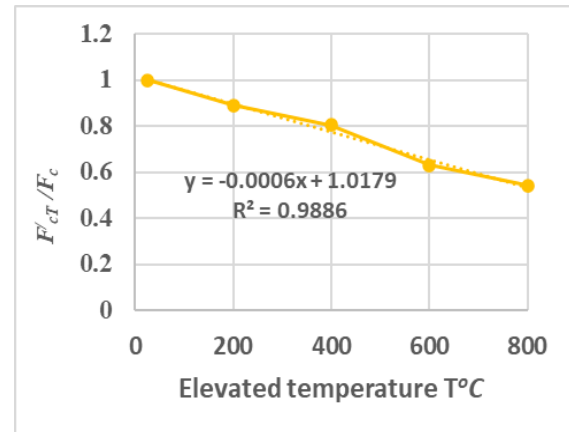
B_1 = 0.00081 in case of NN-based solution; = 0.0007 in case of NK-based solution; and = 0.00063 in case of KK-based solution

B_2 = 0.00108 in case of NN-based solution; = 0.0011 in case of NK or KK-based solution

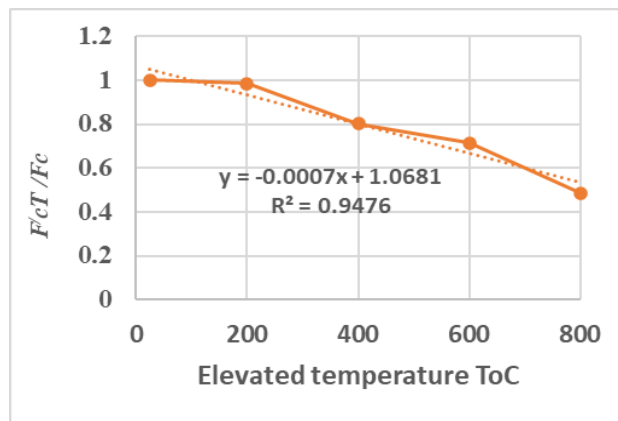
B_3 = 0.00105 in case of NN-based solution; = 0.00094 in case of NK-based solution; and = 0.00103 in case of KK-based solution.



a) Mix NN-Si2.5-S2/A0.5-14M

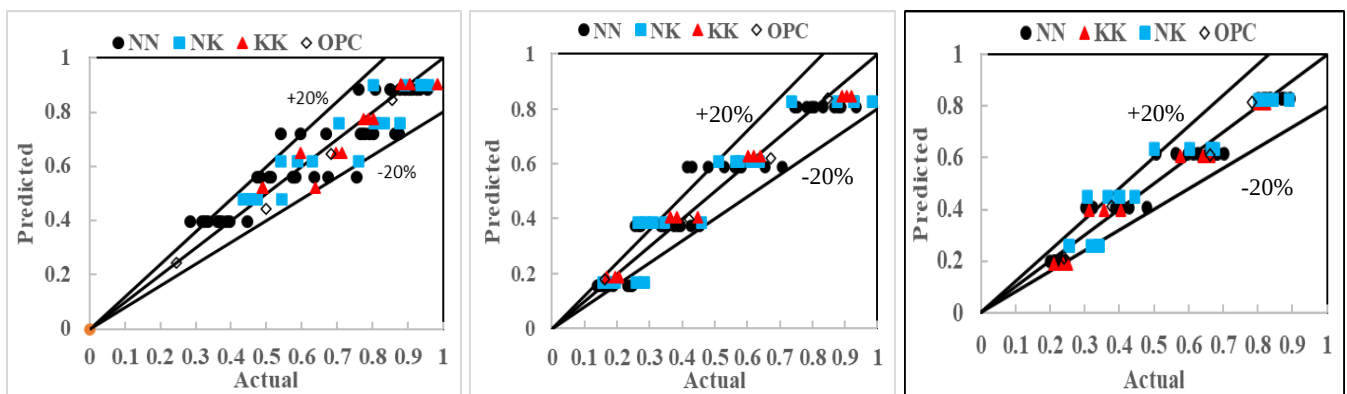


b) Mix NK-Si2.5-S2/A0.5-14M



c) Mix KK-Si2.5-S2/A0.5-14M

Fig. 11 - Residual compressive strength ratio of GP mortars made with different alkaline solutions



a) Compressive strength

b) Flexural strength

c) Indirect tensile strength

Fig. 12 - Actual and predicted values of mechanical strengths of NN, NK and KK GP mortars

3.4 Visual inspection of geopolymer and OPC mortar mixes

Figures 13 shows some GP and OPC mortar specimens after exposure to 600 and 800 °C, respectively. Up to 600 °C no cracks or color change were observed in the GP or OPC specimens' surface. After exposure to 800 °C, GP mortar specimens suffered from some little surface cracks due to the evaporation of free water from pores, contraction of pores and development of cracks that resulted in overall shrinkage of the GP mortar specimens [44]. On the other hand, OPC specimens have many wide surface cracks. Color changed from gray to light red in GP mortars. This change of color may be attributed to oxidation of iron in the FA [60]. Lahoti et al. [44] observed that after 900 °C, the GP paste samples turn reddish-brown. It was observed that the NK and KK-based GP mixes exhibited slightly more reddish color than the NN-based mix. This observation was also recorded by Shaikh and Hosan [45].

Table 4. Constant values of the linear relationship between strengths and elevated temperatures.

Mix ID	Compressive strength			Flexural strength			Indirect tensile strength		
	A ₁	B ₁	R ²	A ₂	B ₂	R ²	A ₃	B ₃	R ²
NN-Si2.5-S2/A0.5-14M	1.047	0.0008	0.9659	1.0047	0.001	0.9805	1.0465	0.0011	0.99
NN-Si2.5-S2/A0.5-12M	1.0685	0.0008	0.9766	1.0415	0.001	0.993	1.0534	0.0011	0.9947
NN-Si2.5-S2A/0.5-16M	1.0304	0.0009	0.9995	0.9941	0.0012	0.9649	1.0707	0.0011	0.9725
NN-Si2-S2/A0.5-14M	1.0743	0.0009	0.9478	0.9905	0.001	0.9858	1.0578	0.001	0.9884
NN-Si3-S2/A0.5-14M	0.9799	0.0008	0.9501	1.0563	0.0012	0.9456	1.0306	0.0011	0.969
NN-Si2.5-S2.5/A0.5-14M	1.0648	0.0007	0.9593	1.0474	0.0011	0.9867	1.0279	0.001	0.9966
NN-Si2.5-S1.5/A0.5-14M	1.0707	0.0009	0.8995	1.0418	0.0011	0.9855	1.0149	0.001	0.9993
NN-Si2.5-S3/A0.5-14M	1.0767	0.0008	0.9316	1.0688	0.0011	0.9877	0.9981	0.0009	0.9818
NN-Si2.5-S2/A0.4-14M	1.0783	0.0007	0.8841	1.0147	0.0011	0.9988	1.0661	0.0011	0.9857
NN-Si2.5-S2/A0.6-14M	0.9568	0.0008	0.948	0.949	0.001	0.9057	1.0086	0.0011	0.9678
Average	1.04474	0.00081	0.946	1.0201	0.00108	0.973	1.0375	0.00105	0.985
KK-Si2.5-S2/A0.5-14M	1.0681	0.0007	0.9476	1.0585	0.0011	0.9913	1.0178	0.001	0.993
KK-Si3-S2/A0.5-14M	0.9997	0.0005	0.9867	1.0662	0.0011	0.989	1.0039	0.001	0.984
KK-Si2.5-S2/A0.4-14M	1.0193	0.0007	0.9937	1.0737	0.0011	0.9828	1.0315	0.0011	0.9923
Average	1.0290	0.00063	0.976	1.0661	0.0011	0.988	1.0177	0.00103	0.99
NK-Si2.5-S2/A0.5-14M	1.0179	0.0006	0.9886	1.0572	0.001	0.9825	1.001	0.0009	0.9724
NK-Si3-S2/A0.5-14M	0.9758	0.0007	0.9687	1.1015	0.0012	0.96	1.0054	0.0009	0.9697
NK-Si2.5-S2.5/A0.5-14M	1.0605	0.0006	0.9695	1.05	0.0012	0.9544	1.0352	0.001	0.9602
NK-Si2.5-S2/A0.4-14M	1.069	0.0008	0.8998	1.0513	0.0011	0.981	1.0221	0.0009	0.9984
NK-Si2.5-S2/A0.6-14M	1.0788	0.0008	0.9285	0.9719	0.001	0.9428	0.9976	0.001	0.9507
Average	1.0404	0.0007	0.951	1.0464	0.0011	0.964	1.0123	0.00094	0.97
OPC	1.045	0.001	0.992	1.0583	0.0011	0.99	1.0127	0.001	0.9862

3.5 Microstructure of geopolymer and OPC mortar mixes (SEM analysis)

The microstructure of GP and OPC mortars at ambient temperature are shown in Fig. 14. At the age of 28 days, it is observed that all GP mortar samples have some unreacted FA particles. Zhang et al. [61] found that FA geopolymers were loose in microstructure and contained a large number of spherical unreacted FA and a small amount of voids at room temperature. The percentage of the unreacted particles in mixes NK-Si2.5-S2/A0.5-14M and KK-Si2.5-S2/A0.5-14M were less than that in mix NN-Si2.5-S2/A0.5-14M, which indicates that the use of KOH led to better geopolymerization.

Figures 14-d and 14-g of mixes NK-Si2.5-S2/A0.5-14M and KK-Si2.5-S2/A0.5-14M show some small micro-cracks in the dense matrix resulted from water evaporation during preparation and curing process. The semi-sphered surface was the gap between unreacted particles and GP binder. It can be seen that some unreacted particles were surrounded by needle or stripe-shaped substances due to high concentration of alkaline solution [34].

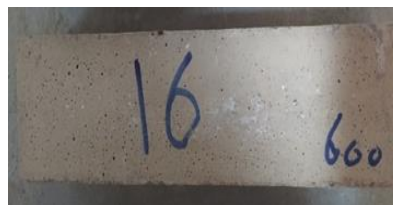
At the age of 365 days, few unreacted FA particles were observed which means that further geopolymerisation have been occurred. This observation explains the reduction in mechanical properties of GP mortars after exposure to different elevated temperatures as no more geopolymerisation will take place.

For the OPC mortar it can be seen in Fig. 14-j that a needle-like structure is visible, which indicates the presence of ettringite. Also, portlandite (plate-like shape) and CSH (sheet-like structure), which are the major hydration products, are shown in Fig. 14-j.

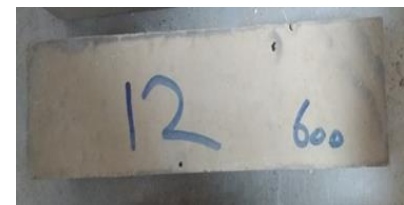
After exposure to 800 °C, an increase in pore size was observed in the microstructure of different GP mortars. The pores within the GP mortars started to connect, and no unreacted FA particles were observed. The structure of GP mortars became loose and honeycomb-shaped as shown in Figs. 14-f and 14-i. Similar behaviour was observed by Jiang et al. [34] and Razak et al. [62]. For the OPC specimen, the matrix started to crumble and disintegrate. Heavy damage to the specimen was observed after the exposure to 800 °C, as shown in Fig. 14-k, due to the complete dehydration.



a) NN-Si2.5-S2/A0.5-14M, 600 °C



b) NK-Si2.5-S2/A0.5-14M, 600 °C



c) KK-Si2.5-S2/A0.5-14M, 600 °C



d) NN-Si2.5-S2/A0.5-14M, 800 °C



e) NK-Si2.5-S2/A0.5-14M, 800 °C



f) KK-Si2.5-S2/A0.5-14M, 800 °C

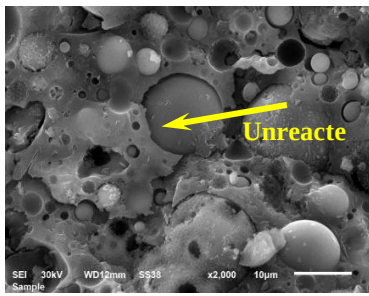


g) OPC, 600 °C

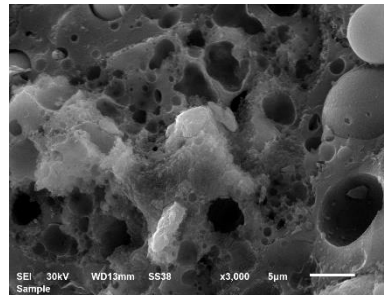


h) OPC, 600 °C

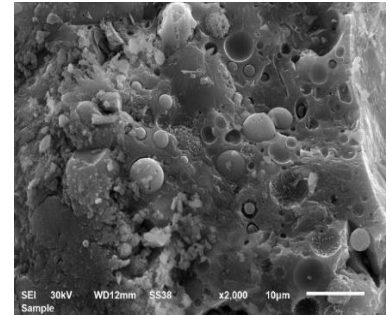
Fig. 13 - Images of geopolymer and OPC mortars after exposure to 600 °C and 800 °C



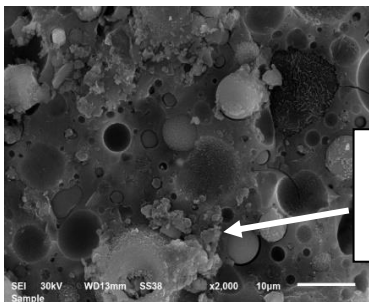
a) *NN-Si_{2.5}-S₂/A0.5-14M at ambient temperature (28 days age).*



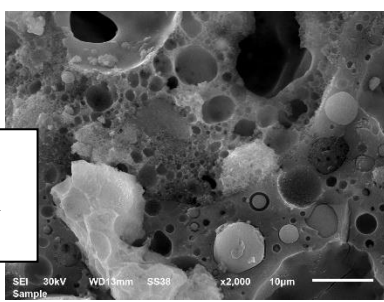
b) *NN-Si_{2.5}-S₂/A0.5-14M at ambient temperature (365 days age).*



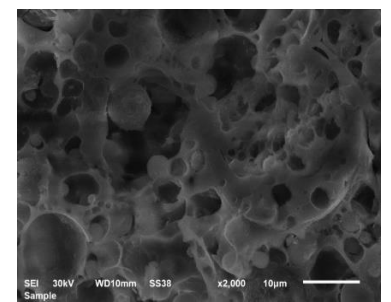
c) *NN-Si_{2.5}-S₂/A0.5-14M, 800°C.*



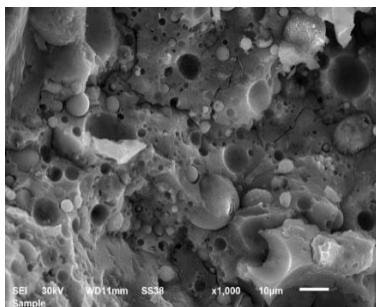
a) *NK-Si_{2.5}-S₂/A0.5-14M at ambient temperature (28 days age).*



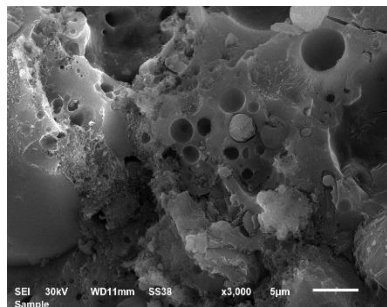
b) *NK-Si_{2.5}-S₂/A0.5-14M at ambient temperature (365 days age).*



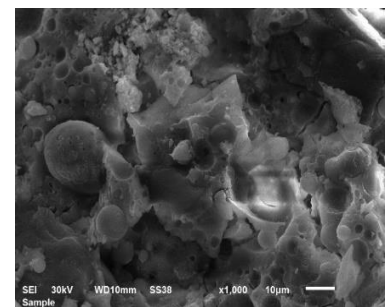
c) *NK-Si_{2.5}-S₂/A0.5-14M, 800°C.*



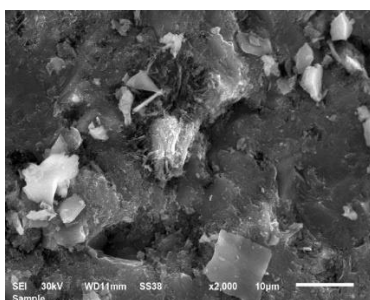
a) *KK-Si_{2.5}-S₂/A0.5-14M at ambient temperature (28 days age).*



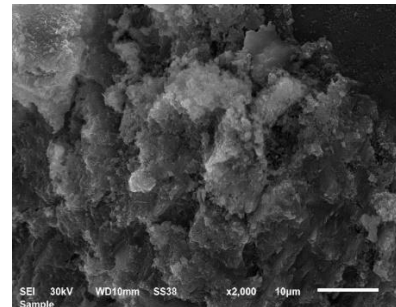
b) *KK-Si_{2.5}-S₂/A0.5-14M at ambient temperature (365 days age).*



c) *KK-Si_{2.5}-S₂/A0.5-14, 800°C.*



b) *OPC at ambient temperature.*



c) *OPC, 800°C.*

Fig. 14 - SEM micrographs of GP and OPC mortars before and after exposure to elevated temperatures

4 Conclusions

Fly ash (FA) based geopolymer (GP) mortars were exposed to elevated temperatures at 200 °C, 400 °C, 600 °C, and 800 °C. Physical properties, including mass loss, and mechanical properties, including compressive, flexural, and indirect tensile strengths, were studied. The investigated parameters included the effect of NaOH molarity, Na₂SiO₃ to NaOH solution ratio, alkaline solution to FA ratio, and sand to FA ratio. Also, the effect of using different alkaline solutions including mixing Na₂SiO₃ with NaOH, Na₂SiO₃ with KOH and K₂SiO₃ with KOH were studied. Based on the results, the following conclusions can be drawn:

As the NaOH molarity increases, the compressive strength of unheated GP mortar increased as well. On the other hand, Higher loss rate in compressive strength after exposure to 600 °C was observed as the NaOH molarity increased. After exposure to 800 °C, residual compressive strength of GP mortar mixes with NaOH molarity of 12, 14, and 16 were 36.3%, 38.8%, and 28.5%, respectively. Increasing Na₂SiO₃/NaOH ratio from 2 to 2.5 caused increase in the mechanical properties while increasing that ratio from 2.5 to 3 negatively affected the mechanical properties of GP mortars either before or after exposure to elevated temperatures. After exposure to 800 °C, residual compressive, flexural, and indirect tensile strengths of GP mix containing Na₂SiO₃/NaOH ratio of 2 were 38.8%, 24.2%, and 24.1%, respectively. Increasing sand to FA ratio from 1.5 to 2 resulted in increasing the mechanical properties either before or after exposure to elevated temperature. On the other hand, increasing that ratio from 2 to 2.5 and 3 caused decrease in the mechanical properties. Increasing the alkaline solution to FA ratio from 0.4 to 0.5 have no significant effect on the mechanical properties while increasing that ratio from 0.5 to 0.6 lead to decreasing the mechanical properties either before or after exposure to elevated temperatures. Taking into consideration the alkaline solution type, using Na₂SiO₃ with KOH or K₂SiO₃ with KOH gave lesser values of the studied mechanical properties than that of using Na₂SiO₃ with NaOH at ambient temperature. But after exposure to elevated temperature, the behaviour of GP mortar mixes containing Na₂SiO₃ and KOH was better than that containing Na₂SiO₃ and NaOH. Residual compressive strength values of GP mixes containing NN, NK, and KK solutions after exposure to 800 °C were 38.8.2%, 54.2%, and 48.7% MPa, respectively. Empirical equations capable of predicting the residual compressive, flexural, and indirect tensile strengths of GP mortars made with different alkaline solutions were proposed with high correlation. The SEM images of GP mortars showed that fewer unreacted FA particles at the age of 365 days than at the age of 28 days. Using KOH led to more geopolymerization of FA particles than using NaOH. After exposure to 800 °C, loose microstructure and increase in pore size were observed. The OPC mortar endured heavy damage due to dehydration. Behaviour of GP mortar was found to be better than OPC mortar either before or after exposure to elevated temperatures. More studies are still needed to investigate the thermal properties as well as elevated temperature endurance of GP composites. Moreover, structural behaviour of various GP concrete structural elements as affected by elevated temperatures, whether using practical or theoretical studies, needs to be applied for a comprehensive understanding of the behaviour of GP concrete.

Statements and Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

- [1]- W. Li, X. Lin, D.W. Bao, Y.M. Xie, A review of formwork systems for modern concrete construction. In Structures 8 (2022) 52-63. Elsevier. DOI: 10.1016/j.istruc.2022.01.089
- [2]- F.P. Glasser, J. Marchand, E. Samson, Durability of concrete—Degradation phenomena involving detrimental chemical reactions. Cement and Concrete Research. 38(2) (2008) 226-246. DOI: 10.1016/j.cemconres.2007.09.015
- [3]- Y.L. Li, X.L. Zhao, R.S.Raman, S. Al-Saadi, Thermal and mechanical properties of alkali-activated slag paste, mortar and concrete utilising seawater and sea sand. Construction and Building Materials 159 (2018) 704-724. DOI: 10.1016/j.conbuildmat.2017.10.104
- [4]- E. Ekinici, Y. Kazancoglu, S.K. Mangla, Using system dynamics to assess the environmental management of cement

- industry in streaming data context. *Science of the total environment* 715 (2020) 136948. <https://doi.org/10.1016/j.scitotenv.2020.136948>
- [5]- B. Patil, M. Veerendra Kumar, H. Narendra, Durability studies on sustainable geopolymer concrete. *International Research Journal of Engineering and Technology (IRJET)* 2(4) (2015) 671-7.
- [6]- Z.G. Ralli, S.J. Pantazopoulou, State of the art on geopolymer concrete. *International Journal of Structural Integrity* 12(4) (2020). DOI:10.1108/IJSI-05-2020-0050.
- [7]- S.A. Zareei, F. Ameri, F. Dorostkar, M. Ahmadi, Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: Evaluating durability and mechanical properties. *Case studies in construction materials* 7 (2017) 73-81. <https://doi.org/10.1016/j.cscm.2017.05.001>
- [8]- T.R. Naik, Sustainability of concrete construction. *Practice Periodical on Structural Design and Construction* 2 (2008) 98-103.
- [9]- A.T. Damanabi, M. Servatan, S. Mazinani, A.G. Olabi, Z. Zhang, Potential of tri-reforming process and membrane technology for improving ammonia production and CO₂ reduction. *Science of the Total Environment* 664 (2019) 567-75. <https://doi.org/10.1016/j.scitotenv.2019.01.391>
- [10]- T. Wilberforce, A. Baroutaji, B. Soudan, A.H. Al-Alami, A.G. Olabi, Outlook of carbon capture technology and challenges. *Science of the total environment* 657 (2019) 56-72. <https://doi.org/10.1016/j.scitotenv.2018.11.424>
- [11]- R. Bajpai, K. Choudhary, A. Srivastava, K.S. Sangwan, M. Singh, Environmental impact assessment of fly ash and silica fume based geopolymer concrete. *Journal of Cleaner Production* 254 (2020) 120147. <https://doi.org/10.1016/j.jclepro.2020.120147>
- [12]- R. He, N. Dai, Z. Wang, Thermal and mechanical properties of geopolymers exposed to high temperature: A literature review. *Advances in Civil Engineering* (2020). <https://doi.org/10.1155/2020/7532703>
- [13]- N. Shehata, E.T. Sayed, M.A. Abdelkareem, Recent progress in environmentally friendly geopolymers: A review. *Science of The Total Environment* 762 (2021)143166. <https://doi.org/10.1016/j.scitotenv.2020.143166>
- [14]- N.B. Singh, B. Middendorf, Geopolymers as an alternative to Portland cement: An overview. *Construction and Building Materials* 237 (2020) 117455. <https://doi.org/10.1016/j.conbuildmat.2019.117455>
- [15]- B. Singh, G. Ishwarya, M. Gupta, S.K.Bhattacharyya, (2015) Geopolymer concrete: A review of some recent developments. *Construction and building materials* 85 (2015) 78-90. <https://doi.org/10.1016/j.conbuildmat.2015.03.036>
- [16]- I.H. Aziz, M.M. Al Bakri Abdullah, H.C. Yong, L.Y. Ming, K. Hussin, A. Surleva, E.A. Azimi, Manufacturing parameters influencing fire resistance of geopolymers: A review. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 233(4) (2019) 721-33. <https://doi.org/10.1177/1464420716668203>
- [17]- M.A. Mohd, K.N. I, Review on fly ash-based geopolymer concrete without Portland Cement. *Journal of engineering and technology research* 3(1) (2011) 1-4.
- [18]- W.K. Part, M. Ramli, C.B. Cheah, An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products. *Construction and Building Materials* 77 (2015) 370-95. <https://doi.org/10.1016/j.conbuildmat.2014.12.065>
- [19]- A. Hassan, M. Arif, M. Shariq, Use of geopolymer concrete for a cleaner and sustainable environment—A review of mechanical properties and microstructure. *Journal of cleaner production* 223 (2019) 704-28. <https://doi.org/10.1016/j.jclepro.2019.03.051>
- [20]- Z. Kubba, G.F. Huseien, A.R. Sam, K.W. Shah, M.A. Asaad, M. Ismail, M.M. Tahir, J. Mirza, Impact of curing temperatures and alkaline activators on compressive strength and porosity of ternary blended geopolymer mortars. *Case Studies in Construction Materials* 9 (2018) e00205. <https://doi.org/10.1016/j.cscm.2018.e00205>
- [21]- M.A. Abd-Elaty, M.F. Ghazy, O.H. Khalifa, Mechanical and thermal properties of fibrous rubberized geopolymer mortar. *Construction and Building Materials* 354 (2022) 129192. <https://doi.org/10.1016/j.conbuildmat.2022.129192>
- [22]- C. Ganesh, M. Muthukannan, Investigation on the glass fiber reinforced geopolymer concrete made of M-sand. *Journal of Materials and Engineering Structures «JMES»* 6(4) (2019) 501-12.
- [23]- T. Lingyu, H. Dongpo, Z. Jianing, W. Hongguang, Durability of geopolymers and geopolymer concretes: A review. *Reviews on Advanced Materials Science* 60(1) (2021) 1-14. <https://doi.org/10.1515/rams-2021-0002>
- [24]- M.F. Ghazy, M.A. Abd Elaty, M. Taman, M.E. Eissa, Durability performance of geopolymer ferrocement panels prepared by different alkaline activators. In *Structures* 38 (2022) 168-183. Elsevier. <https://doi.org/10.1016/j.istruc.2022.01.087>

- [25]- V. Kodur, Properties of concrete at elevated temperatures. *International Scholarly Research Notices* (2014). <https://doi.org/10.1155/2014/468510>
- [26]- H. Zhang, L. Li, C. Yuan, Q. Wang, P.K. Sarker, X. Shi, Deterioration of ambient-cured and heat-cured fly ash geopolymer concrete by high temperature exposure and prediction of its residual compressive strength. *Construction and Building Materials* 262 (2020) 120924. <https://doi.org/10.1016/j.conbuildmat.2020.120924>
- [27]- M.F. Ghazy, M.A. Abd Elaty, N.M. Zalhaf, Mechanical Properties of HPC Incorporating Fly Ash and Ground Granulated Blast Furnace Slag After Exposure to High Temperatures. *Periodica Polytechnica Civil Engineering* (2022). <https://doi.org/10.3311/PPci.19751>
- [28]- L. Li, L. Shi, Q. Wang, Y. Liu, J. Dong, H. Zhang, G. Zhang, A review on the recovery of fire-damaged concrete with post-fire-curing. *Construction and Building Materials* 237 (2020) 117564. <https://doi.org/10.1016/j.conbuildmat.2019.117564>
- [29]- I. Hager, Behaviour of cement concrete at high temperature. *Bulletin of the Polish Academy of Sciences: Technical Sciences*. (1) (2013).
- [30]- D.A. Krishna, R.S. Priyadarsini, S. Narayanan, Effect of elevated temperatures on the mechanical properties of concrete. *Procedia Structural Integrity* 14 (2019) 384-94. <https://doi.org/10.1016/j.prostr.2019.05.047>
- [31]- M. Lahoti, K.H. Tan, E.H. Yang, A critical review of geopolymer properties for structural fire-resistance applications. *Construction and Building Materials* 221 (2019) 514-26. <https://doi.org/10.1016/j.conbuildmat.2019.06.076>
- [32]- S. Luhar, D. Nicolaides, I. Luhar, Fire resistance behaviour of geopolymer concrete: An overview. *Buildings* 11(3) (2021) 82. <https://doi.org/10.3390/buildings11030082>
- [33]- B.A. Tayeh, A.M. Zeyad, I.S. Agwa, M. Amin, Effect of elevated temperatures on mechanical properties of lightweight geopolymer concrete. *Case Studies in Construction Materials* 15 (2021) e00673. <https://doi.org/10.1016/j.cscm.2021.e00673>
- [34]- X. Jiang, Y. Zhang, R. Xiao, P. Polaczyk, M. Zhang, W. Hu, Y. Bai, B. Huang, A comparative study on geopolymers synthesized by different classes of fly ash after exposure to elevated temperatures. *Journal of Cleaner Production* 270 (2020) 122500. <https://doi.org/10.1016/j.jclepro.2020.122500>
- [35]- A.M. Rashad, S.R. Zeedan SR, The effect of activator concentration on the residual strength of alkali-activated fly ash pastes subjected to thermal load. *Construction and Building Materials* 25(7) (2011) 3098-107. <https://doi.org/10.1016/j.conbuildmat.2010.12.044>
- [36]- M. Sitarz, I. Hager, J. Kochanek, Effect of High temperature on mechanical properties of geopolymer mortar. In *MATEC Web of Conferences Vol. 163* (2018) p. 06004. EDP Sciences. <https://doi.org/10.1051/mateconf/201816306004>
- [37]- S.K. Saxena, M. Kumar, N.B. Singh, Fire resistant properties of alumino silicate geopolymer cement mortars. *Materials Today: Proceedings* 4(4) (2017) 5605-12. <https://doi.org/10.1016/j.matpr.2017.06.018>
- [38]- G. Mathew, B. Joseph, Flexural behaviour of geopolymer concrete beams exposed to elevated temperatures. *Journal of Building Engineering* 15 (2018) 311-7. <https://doi.org/10.1016/j.jobe.2017.09.009>
- [39]- M.T. Junaid, A. Khennane, O. Kayali, Investigation into the Effect of the Duration of Exposure on the Behaviour of GPC at Elevated Temperatures. In *MATEC Web of Conferences* 11 (2014) 01003. EDP Sciences. <https://doi.org/10.1051/mateconf/20141101003>
- [40]- D.L. Kong, J.G. Sanjayan, Effect of elevated temperatures on geopolymer paste, mortar and concrete. *Cement and concrete research* 40(2) (2010) 334-9. <https://doi.org/10.1016/j.cemconres.2009.10.017>
- [41]- F.U. Shaikh, V. Vimonsatit, Compressive strength of fly - ash - based geopolymer concrete at elevated temperatures. *Fire and materials* 39(2) (2015) 174-88. <https://doi.org/10.1002/fam.2240>
- [42]- P.K. Sarker, S. Kelly, Z. Yao, Effect of fire exposure on cracking, spalling and residual strength of fly ash geopolymer concrete. *Materials & Design* 63 (2014) 584-92. <https://doi.org/10.1016/j.matdes.2014.06.059>
- [43]- A. Hosan, S. Haque, F. Shaikh, Compressive behaviour of sodium and potassium activators synthesized fly ash geopolymer at elevated temperatures: a comparative study. *Journal of Building Engineering* 8 (2016) 123-30. <https://doi.org/10.1016/j.jobe.2016.10.005>
- [44]- M. Lahoti, K.K. Wong, K.H. Tan, E.H. Yang, Effect of alkali cation type on strength endurance of fly ash geopolymers subject to high temperature exposure. *Materials & Design* 154 (2018) 8-19. <https://doi.org/10.1016/j.matdes.2018.05.023>
- [45]- F.U. Shaikh, A. Hosan, Mechanical properties of steel fiber reinforced geopolymer concretes at elevated temperatures. *Construction and building materials* 114 (2016) 15-28. <https://doi.org/10.1016/j.conbuildmat.2016.03.158>

-
- [46]- A.M. Albadawy, M.A. Abd Elaty, M.H. Taman, Performance of geopolymer mortars subjected to elevated temperatures. *MEJ. Mansoura Engineering Journal* 42(1) (2017) 12-20. DOI: 10.21608/BFEMU.2020.97655
 - [47]- A.M. Ali, J. Sanjayan, M. Guerrieri, Performance of geopolymer high strength concrete wall panels and cylinders when exposed to a hydrocarbon fire. *Construction and Building Materials* 137 (2017) 195-207. <https://doi.org/10.1016/j.conbuildmat.2017.01.099>
 - [48]- I. Hager, M. Sitarz, K. Mróz, Fly-ash based geopolymer mortar for high-temperature application–Effect of slag addition. *Journal of Cleaner Production* 316 (2021) 128168. <https://doi.org/10.1016/j.jclepro.2021.128168>
 - [49]- R.D. Abd El Hafez, A.R. Ahmad, M.A. Khafaga, F.A. Refaie, Effect of exposure to elevated temperatures on geopolymer concrete properties. *International Journal of Civil Engineering and Technology* 10(10) (2019).
 - [50]- Y. Zhang, D. Yan, N. Han, Y. Ao, S. Chen, H. Ye, H. Fazli, T.N. Ye, Effects of activator types on degradation mechanisms of metakaolin geopolymer mortars exposed to high temperature. *Journal of Materials in Civil Engineering* 32(12) (2020) 04020369. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003457](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003457)
 - [51]- ASTM, Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, American Society for Testing and Materials, 2019. 10.1520/ c0618-19
 - [52]- BS.EN, Methods of testing cement - part 1: Determination of strength, British Standard., 2016. 10.3403/00483082u.
 - [53]- Egyptian Code of Practice 203, “Basics of Design and regulations of Construction of Reinforced Concrete Structures: Appendix III, Guide for Testing of Concrete Materials
 - [54]- ASTM, Standard specification for concrete aggregates, American Society of Testing Materials, 2018. 10.1520/c0033_c0033m-16e01
 - [55]- ASTM, Standard test method for flow of hydraulic cement mortar, American Society of Testing Materials, 2020. 10.1520/c1437-20
 - [56]- ASTM, Standard test method for splitting tensile strength of cylindrical concrete specimens, American Society of Testing Materials, 2017. 10.1520/c0496_c0496m- 17.
 - [57]- K.M. Klima, K. Schollbach, H.J. Brouwers, Q. Yu, Thermal and fire resistance of Class F fly ash based geopolymers–a review. *Construction and Building Materials* 323 (2022) 126529. <https://doi.org/10.1016/j.conbuildmat.2022.126529>
 - [58]- N Ranjbar, M. Mehrali, U.J. Alengaram, H.S. Metselaar, M.Z. Jumaat, Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar under elevated temperatures. *Construction and building materials* 65 (2014) 114-21. <https://doi.org/10.1016/j.conbuildmat.2014.04.064>
 - [59]- M. Ghazy, M.A. Abd Elaty, M. Taman, M. Eissa, Fresh and Mechanical Properties of Fly Ash-Based Geopolymer Mortars Activated by Different Alkaline Solutions. *International Journal of Advances in Structural and Geotechnical Engineering* 3(01) (2022) 24-39.
 - [60]- W.D. Rickard, R. Williams, J. Temuujin, A. Van Riessen, Assessing the suitability of three Australian fly ashes as an aluminosilicate source for geopolymers in high temperature applications. *Materials Science and Engineering: A* 528(9) (2011) 3390-7. <https://doi.org/10.1016/j.msea.2011.01.005>
 - [61]- H.Y. Zhang, V. Kodur, B. Wu, L. Cao, S.L. Qi, Comparative thermal and mechanical performance of geopolymers derived from metakaolin and fly ash. *Journal of Materials in Civil Engineering* 28(2) (2016) 04015092.
 - [62]- S.N. Razak, N. Shafiq, L. Guillaumat, S.A. Farhan, V.K. Lohana, Fire-Exposed Fly-Ash-Based Geopolymer Concrete: Effects of Burning Temperature on Mechanical and Microstructural Properties. *Materials* 15(5) (2022) 1884. <https://doi.org/10.3390/ma15051884>