



# Factors Influencing the Compressive Strength and Permeability of Geopolymer Concrete Based on Granulated Ground Blast Furnace Slag Cured at Ambient Condition

Sarvenaz Moradikhou<sup>1</sup>, Amir Bahador Moradikhou<sup>2\*</sup>

<sup>1</sup> M. Sc. of Chemical Engineering, Department of Chemical Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran

<sup>\*2</sup> Ph.D. candidate in Engineering and Construction Management, Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

(amirbahador.moradikhou@srbiau.ac.ir)

(Date of received: 10/09/2021, Date of accepted: 26/11/2021)

## ABSTRACT

In recent years, geopolymers, as a new class of green cement binders, have been considered as an environmental-friendly alternative to Ordinary Portland Cement (OPC) which can potentially reduce negative environmental impacts of OPC. Geopolymers are inorganic alumina-silicate materials produced from raw materials in combination with an alkaline activator solution. The alkaline activator solution as one of pillar of the geopolymerization process, playing an important role in the formation of crystalline structures of Si and Al. Therefore, it seems necessary to study the impact of various alkaline activator solutions on the mechanical strength of Geopolymer Concrete (GPC). On the other hand, in most pervious research, high temperature curing condition have been studied. Hence, in this research, granulated ground blast furnace slag and ambient curing condition were used to make GPC. The obtained results indicated that in ambient curing condition, using sodium hydroxide and sodium silicate, results in higher compressive strength as well as, lower permeability compared to potassium-based (potassium hydroxide and potassium silicate) and combination of sodium and potassium-based alkaline activator solutions. Moreover, simultaneous inclusion of NaOH and KOH led to decline the compressive strength. Furthermore, the obtained results indicated that increasing the NaOH and KOH concentration resulted in higher compressive strength. The optimal SiO<sub>2</sub>/Na<sub>2</sub>O ratio was 2 in the case of using 14M NaOH solution and 2.5 in the case of using 10M NaOH solution.

## Keywords:

Geopolymer concrete, Granulated ground blast furnace slag, Compressive strength, resistance to acidic condition



## 1. Introduction

Pollution and climate change due to global warming have become the most significant environmental concerns worldwide [1]. Greenhouse gas emissions is the main contributing factor to global warming, with carbon dioxide ( $\text{CO}_2$ ) having the greatest share (65%) among other greenhouse gases [2]. The production process of Ordinary Portland Cement (OPC) is identified as one of the major sources of  $\text{CO}_2$  emission and energy consumption. OPC production accounts for approximately 5% of global energy consumption. Furthermore, Production of 1 ton of OPC releases approximately 1 ton of  $\text{CO}_2$  into the environment [3] and consumes 1.5 tons of raw materials [4]. Therefore, it seems necessary to find an alternative to OPC. In recent years, geopolymers have been introduced as a new cementitious material and green alternative to OPC which can potentially reduce negative environmental impacts of OPC [5]. Geopolymers were first developed by Davidovits, as a new family of binders of inorganic origin. Geopolymers are inorganic aluminosilicate materials produced from raw materials, rich in silica ( $\text{SiO}_2$ ) and alumina ( $\text{Al}_2\text{O}_3$ ), in combination with an alkaline activator solution [6-8]. The geopolymerization process involves a substantially fast chemical reaction under alkaline condition on Si-Al minerals, that results in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al bonds [9,10]. Regarding civil engineering applications, Geopolymer Concrete (GPC) has showed enhanced physical and mechanical properties over conventional concrete, e.g. higher mechanical strength and rapid hardening [11-14], higher resistance to elevated temperatures and fire [11,15-17], enhanced durability [18], lower permeability, improved resistance to solvents and acids [11,19], and lower creep effects [20]. The aluminosilicate source, also known by other names such as raw material, geopolymerization source and source material, plays the most important role in geopolymer cements, as the supplier of Si and Al. The aluminosilicate source, depending on required characteristics, cost and availability, can be of natural origin (e.g. zeolite), synthetic (e.g. metakaolin) or waste materials (e.g. fly ash or granulated ground blast furnace slag (GGBFS)) [1,21]. However, Usage of industrial by-products such as GGBFS in GPC not only helps to reduce environmental pollution, but also alleviates storage costs of these materials. GGBFS can be one of the best aluminosilicate source candidates due to its proper structural nature [1]. In this research, GGBFS was used as an aluminosilicate source to make GPC specimens. The alkaline activator solution is one of the two main constituents of geopolymers, playing a significant role in the formation of Al and Si crystals, and is normally chosen based on Na and K (solvent alkali metals) solutions. The most convenient alkali solution used in geopolymerization is a compound solution of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) or potassium silicate ( $\text{K}_2\text{SiO}_3$ ) [22,23]. Considering the important role of alkaline activator solution in geopolymer cement, it seems necessary to study the role and effectiveness of different alkaline activator solutions. In consequence, various research has been done by researchers in this field, some of which are briefly discussed below. In early research on geopolymers by Davidovits [24, 25], NaOH or KOH solution without silicate solution was used as the alkaline activator solution. They concluded that in this type of alkaline activator solution, KOH provides better results. While Palomo et al [19] compared NaOH and KOH in alkaline activators without silicate solution and concluded that using NaOH subjects to better results. Cheng et al [15] found in their research that alkaline activator solution plays an important role in the polymerization reaction and adding a silicate solution such as  $\text{Na}_2\text{SiO}_3$  or  $\text{K}_2\text{SiO}_3$  to NaOH or KOH solution can help increase the



reaction rate and achieve better results. They also found that using a solution of NaOH and  $\text{Na}_2\text{SiO}_3$  had better results than by means of a solution of KOH and  $\text{K}_2\text{SiO}_3$ . Rashed [4] decided in a study on geopolymers that in general, in most cases, the compressive strength of GPC is increased through enhancing the concentration of NaOH solution to a certain concentration. In a study on metakaolin-based GPC, Moradikhou et al [1] used a combination of NaOH and  $\text{Na}_2\text{SiO}_3$  as an alkaline activator solution and concluded that increasing the concentration of NaOH to 14M subjects to enhance the compressive strength of concrete. However, further proliferation in concentration up to 16M causes no significant change in compressive strength. This is while, in a similar study, Patel et al [26] concluded that increasing the concentration of NaOH solution to 12M in metakaolin-based GPC increases the compressive strength, and increasing the concentration to more than 12M decreases the compressive strength. Regarding the weight ratio of silicate to hydroxide solution, Hardjito et al [27] mulled over the GPC based on Class F fly ash and reported that the optimal weight ratio of  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  solution was equal to 2.5 when using NaOH solution with a concentration of 14M. While Moradikhou et al [21] did the similar study on GPC based on class F fly ash and determined that the optimal weight ratio of  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  solution in the case of 14M NaOH solution is 1.5. According to the aforementioned points, sodium-based alkaline activator solutions have been used in most articles and studies and several research on sodium-based alkaline solutions and effective parameters of alkaline activator solution on compressive strength of GPC such as NaOH solution concentration,  $\text{Na}_2\text{SiO}_3$  solution concentration, the ratio of  $\text{Si}_2\text{O}$  to  $\text{Na}_2\text{O}$  in  $\text{Na}_2\text{SiO}_3$  solution, the weight ratio of  $\text{Na}_2\text{SiO}_3$  solution to NaOH solution, as well as the optimization of these parameters have been implemented. Henceforth, they pave the way for more research. However, very little research has been done on KOH solution, combination of NaOH and KOH solution, study of relevant parameters and their optimization, as well as comparison of these three different alkaline activator solutions. On the other hand, GPC are cured at temperatures of 60-90 ° C for 4-24 hours in most studies. Processing at ambient temperature changes the results of GPC mechanical strengths because, for example, the rate of reactivity, the rate of dissolution of alumino-silicate sources in alkaline activator solution vary at different temperatures. Considering the fact that in practice the use of concrete and mortar is done in ambient conditions and curing in the oven is only for the laboratory, the study of the role of different alkaline solutions in ambient temperature conditions (actual use conditions) is particularly significant. Therefore, this study tried to investigate the manufacturing of GPC by considering the practical cases in real conditions. Since the results of previous research in this field are contradictory and in addition, previous research has not considered the practical conditions of using GPC, such research is a step forward in the practical use of GPC in infrastructure construction

## **2. Materials and Methods**

### ***2-1-Materials***

Table 1 summarizes the physical and chemical properties of the GGBFS used. NaOH with 98% purity, KOH with 90% purity, liquid  $\text{Na}_2\text{SiO}_3$  and liquid  $\text{K}_2\text{SiO}_3$ , were used to prepare the alkaline activator solutions. The chemical analysis of these 4 substances is illustrated in Table 2. The aggregates were obtained from quarries around Tehran. Aggregates with granular sizes of 7-10 mm was used as coarse aggregate (sand), and < 4.75 mm sized aggregates were used as fine aggregate. Fine and coarse aggregates were sieved according to ASTM C33 [28]. SSD specific gravity and



water absorption tests were conducted on the coarse and fine aggregates using the ASTM C127 [29] and ASTM C128 [30] procedures, respectively, and gathered in Table 3. The fineness modulus (using ASTM C136 [31]) and sand equivalent (using ASTM D2419 [32]) values of the fine aggregates were measured equal to 3.01 and 73, respectively. To reduce water content and improve workability of concrete, polycarboxylate-based Super Plasticizer (SP) with a specific gravity of  $1.1 \text{ g/cm}^3$ , was incorporated. Water consumption was also tap water in Tehran.

**Table 1. Chemical properties of GGBFS used.**

Content	Result	Unit
SiO <sub>2</sub>	34.4	%
Al <sub>2</sub> O <sub>3</sub>	11.2	%
CaO	37.2	%
Fe <sub>2</sub> O <sub>3</sub>	0.6	%
MgO	9.8	%
K <sub>2</sub> O	0.62	%
Na <sub>2</sub> O	0.68	%
MnO	1.58	%
SO <sub>3</sub>	1.2	%
Cl	0.02	%
L.O.I	0.5	%
SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	3.07	-

**Table 2. Chemical analysis of NaOH, KOH, Na<sub>2</sub>SiO<sub>3</sub> and K<sub>2</sub>SiO<sub>3</sub> solutions.**

NaOH			KOH			Na <sub>2</sub> SiO <sub>3</sub>			K <sub>2</sub> SiO <sub>3</sub>		
Chemical substance	Result	Unit	Chemical substance	Result	Unit	Chemical substance	Result	Unit	Chemical substance	Result	Unit
NaOH	98	%	KOH	90.7	%	SiO <sub>2</sub>	30.00	%	SiO <sub>2</sub>	30.50	%
Na <sub>2</sub> CO <sub>3</sub>	1	%	K <sub>2</sub> CO <sub>3</sub>	0.2	%	Na <sub>2</sub> O	14.50	%	K <sub>2</sub> O	14.50	%
NaCl	200	PPm	NaCl	0.006	%	Water	55.50	%	Water	55	%
Fe	6	PPm	Fe	0.2	PPm	ROM*	2.06	-	ROM**	2.1	-
SiO <sub>2</sub>	15.7	PPm	NaOH	0.6	%	Appearance	Clear liquid		Appearance	Clear liquid	
Appearance	White flake		Appearance	White flake		*ROM: ratio of model (SiO <sub>2</sub> /Na <sub>2</sub> O)			**ROM: ratio of model (SiO <sub>2</sub> /K <sub>2</sub> O)		

**Table 3. Specific gravity and Water absorption of aggregates.**

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



## 2-2- Mix design

### 2-2-1- Alkaline activator type

In this section, in order to investigate the effect of alkaline activator solution type on GPC compressive strength, 4 different types of alkaline activator solution were inspected, including:

1-NN:  $\text{Na}_2\text{SiO}_3$  ( $\text{SiO}_2/\text{Na}_2\text{O}$  ratio = 2) + NaOH 10M

2-NK:  $\text{Na}_2\text{SiO}_3$  ( $\text{SiO}_2/\text{Na}_2\text{O}$  ratio = 2) + KOH 10M

3-KN:  $\text{K}_2\text{SiO}_3$  ( $\text{SiO}_2/\text{Na}_2\text{O}$  ratio = 2) + NaOH 10M

4-KK:  $\text{K}_2\text{SiO}_3$  ( $\text{SiO}_2/\text{Na}_2\text{O}$  ratio = 2) + KOH 10M

In this regard, 3 mix designs were prepared which are indicated in Table 4. To manufacture GPC specimens, initially, the alkaline activator solution, constituting of NaOH, KOH,  $\text{Na}_2\text{SiO}_3$ ,  $\text{K}_2\text{SiO}_3$ , SP and the extra water (according to each mix design) are combined and allowed to cool for 24 hrs. In the mixing process, the aggregates and GGBFS were first dry mixed in the mixer for 3 minutes. Next, the alkaline activator solution was added and the concrete was mixed for a further 2 minutes. Subsequently, three compressive (100x100x100 mm cubes) specimens (for each mix design) were molded and vibrated for 10 seconds on a vibrating table. Thus, the specimens were allowed to rest at laboratory ambient temperature. The specimens were subjected to the 7- and 28-day compressive strength test according to BS1881: Part116 [34].

**Table 4. Mix designs related to the type of alkaline activator ( $\text{kg}/\text{m}^3$ ).**

Mix ID	GGBFS	NaOH 10M	KOH 10M	$\text{Na}_2\text{SiO}_3$	$\text{K}_2\text{SiO}_3$	Fine aggregates	Coarse aggregates	SP	Extra water
NN	400	80	-	120	-	860	860	6	10
NK	400	80	-	120	-	860	860	6	10
KN	400	-	80	-	120	860	860	6	10
KK	400	-	80	-	120	860	860	6	10

### 2-2-2- Concentration of NaOH and KOH

In this section, in order to investigate the effect of NaOH and KOH solutions on GPC compressive strength based on GGBFS and optimization of this parameter, 8 mix designs were set, as detailed in Table 5. It should be note that based on the results from previous sections,  $\text{NaOH}+\text{Na}_2\text{SiO}_3$  and  $\text{KOH}+\text{K}_2\text{SiO}_3$  were selected as alkaline activator solutions. Similar compressive specimen production and testing procedure as Section 2-2-1 is followed.



**Table 5. Mix designs related to NaOH and KOH concentration (kg/m<sup>3</sup>).**

Mix ID	GGBFS	NaOH	KOH	Na <sub>2</sub> SiO <sub>3</sub>	K <sub>2</sub> SiO <sub>3</sub>	Fine aggregates	Coarse aggregates	SP	Extra water	NaOH concentration (M)	KOH concentration (M)
N10	400	80	-	120	-	860	860	6	10	10	-
N12	400	80	-	120	-	860	860	6	10	12	-
N14	400	80	-	120	-	860	860	6	10	14	-
N16	400	80	-	120	-	860	860	6	10	16	-
K10	400	-	80	-	120	860	860	6	10	-	10
K12	400	-	80	-	120	860	860	6	10	-	12
K14	400	-	80	-	120	860	860	6	10	-	14
K16	400	-	80	-	120	860	860	6	10	-	16

### 2-2-3- Concentration of NaOH and KOH

In this section, the effect of different combinations of NaOH and KOH solutions on the compressive strength of GPC based on GGBFS was scrutinized. In this regard, 7 mix designs were set up, which are shown in Table 6. It should be noted that because Na<sub>2</sub>SiO<sub>3</sub> is cheaper and more available than K<sub>2</sub>SiO<sub>3</sub> and existence of Na<sub>2</sub>SiO<sub>3</sub> with different SiO<sub>2</sub>/Na<sub>2</sub>O ratios as well as according to the results obtained from the previous sections, Na<sub>2</sub>SiO<sub>3</sub> was used as the silicate solution in the continuation of the research. GPC specimens were made and tested exactly as in the previous sections.

**Table 6. Mix designs related to NaOH / KOH ratio (kg/m<sup>3</sup>).**

Mix ID	GGBFS	NaOH 10M	KOH 10M	Na <sub>2</sub> SiO <sub>3</sub>	Fine aggregates	Coarse aggregates	SP	Extra water	NaOH/KOH ratio
N100	400	80	-	120	860	860	6	10	100/0
N80K20	400	64	16	120	860	860	6	10	80/20
N60K40	400	67	45	120	860	860	6	10	60/40
N50K50	400	40	40	120	860	860	6	10	50/50
N40K60	400	45	67	120	860	860	6	10	40/60
N20K80	400	20	90	120	860	860	6	10	20/80
K100	400	-	80	120	860	860	6	10	0/100

### 2-2-4- SiO<sub>2</sub>/Na<sub>2</sub>O weight ratio of Na<sub>2</sub>SiO<sub>3</sub> solution

In this part, the effect of SiO<sub>2</sub>/Na<sub>2</sub>O weight ratio of Na<sub>2</sub>SiO<sub>3</sub> solution on compressive strength of GPC based on GGBFS was studied. In this regard, NaOH solution and 3 types of Na<sub>2</sub>SiO<sub>3</sub> solution with SiO<sub>2</sub>/Na<sub>2</sub>O ratios equal to 2, 2.5 and 3 were used. Similarly, in order to simultaneously dissect the effect of NaOH solution concentration and SiO<sub>2</sub>/Na<sub>2</sub>O ratio of Na<sub>2</sub>SiO<sub>3</sub> solution, 2 concentrations of 10 and 14M were considered for NaOH solution. Hence, 6 mix designs were selected, which are indicated in Table 7. Similar compressive specimen production and testing procedure as pervious sections, is followed. Figure 1 represents GPC specimens.



**Table 7. Mix designs related to SiO<sub>2</sub>/Na<sub>2</sub>O ratio (kg/m<sup>3</sup>).**

Mix ID	GGBFS	NaOH	Na <sub>2</sub> SiO <sub>3</sub>	Fine aggregates	Coarse aggregates	SP	Extra water	SiO <sub>2</sub> /Na <sub>2</sub> O ratio of Na <sub>2</sub> SiO <sub>3</sub>	NaOH concentration (M)
N2-10	400	80	120	860	860	6	10	2	10
N2-14	400	80	120	860	860	6	10	2.5	14
N2.5-10	400	80	120	860	860	6	10	3	10
N2.5-14	400	80	120	860	860	6	10	2	14
N3-10	400	80	120	860	860	6	10	2.5	10
N3-14	400	80	120	860	860	6	10	3	14



**Figure 1.** Images of fresh GPC specimens.

#### **2-2-5- Water absorption and weight loss under acidic condition**

In last part of research, the effect of alkaline activator type on weight loss under acidic condition and water absorption of GPC specimens, were studied. Water absorption capacity of the GPC specimens was studied following the ASTM C642 [35] procedures. Hence, 3 compressive cube specimens were considered for N, NaK and K mix designs (Table 8). The 28-day specimens after the production process similar to section 2-2-1, were initially placed in a 105 °C oven to reach a stable dry weight and then weighted ( $m_0$ ). The specimens were then placed in a water tank for 3 days. They were then taken out and after drying the surface water, were weighted again ( $m$ ). The 3-day water absorption capacity ( $W$ ) is calculated by Eq. (1):

$$W = \frac{m - m_0}{m_0} \times 100 \quad (1)$$

Also, to test the chemical resistance of GPC specimens, the 28-day specimens of N, NaK and K mix designs were placed in a solution of water and sulfuric acid at pH equal to 1 for 28 days. Then, weight loss test was taken from specimens.



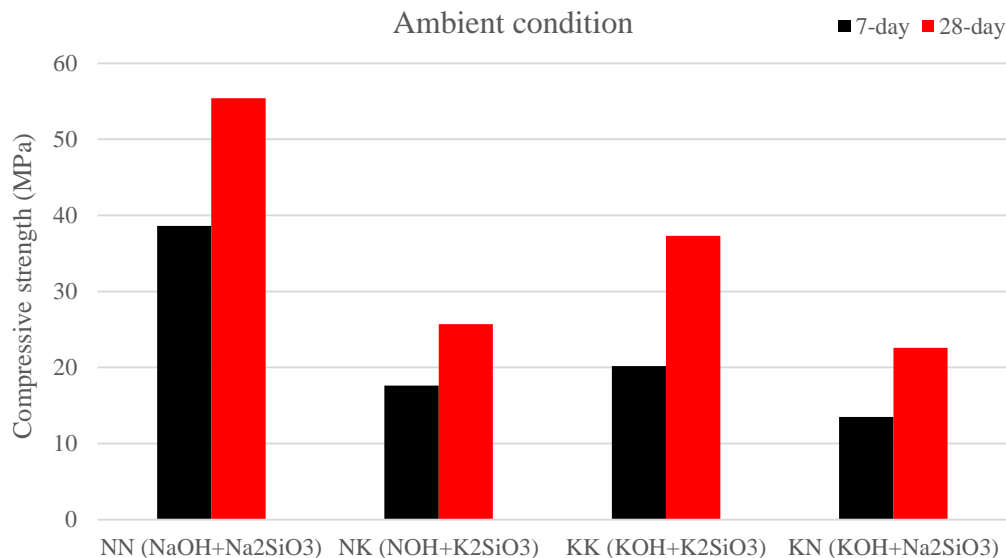
**Table 8. Mix designs related to the Water absorption and weight loss under acidic condition ( $\text{kg/m}^3$ ).**

Mix ID	GGBFS	NaOH 10M	KOH 10M	$\text{Na}_2\text{SiO}_3$	$\text{K}_2\text{SiO}_3$	Fine aggregates	Coarse aggregates	SP	Extra water
N	400	80	-	120	-	860	860	6	10
NaK	400	40	40	120	-	860	860	6	10
K	400	-	80	-	120	860	860	6	10

### 3. Results and Discussion

#### 3-1- Effect of alkaline activator solution type on compressive strength of GPC

Figure 2 shows the effect of alkaline activator solution type on the mean compressive strength of GPC specimens. The 7- and 28-day compressive strength of NN specimen, which was made of NaOH and  $\text{Na}_2\text{SiO}_3$  solution, was measured as 38.6 and 55.4 MPa, respectively. The 7-day and 28-day compressive strengths of the KK ( $\text{KOH}+\text{K}_2\text{SiO}_3$ ) specimen, were 20.2 and 37.3 MPa, respectively. According to the results, the specimen made with Na-based activating solution ( $\text{NaOH}+\text{Na}_2\text{SiO}_3$ ), offered a much higher compressive strength than the specimen made with K-based activator solution ( $\text{KOH}+\text{K}_2\text{SiO}_3$ ) so that the use of Na-based activator resulted in maximum compressive strength.



**Figure 2.** Effect of alkaline activator type on 7 and 28-day compressive strength of GPC.

Table 9 shows the changes in the early strength (the level of strength obtained at 7-days) of the specimens. The results revealed that the use of Na-based activator solution upsurges early strength. Na-based specimen obtained a higher percentage of its final strength (28 days) at 7 days of age compared to the specimen made with K-based solution. Moreover, the early strength of KN and NK specimens improved in comparison with K-based specimen but were less than Na-based specimen.





**Table 9. Effect of alkaline activator solution type on lateral and early strength of GPC.**

Mix ID	Alkaline activator type	28-day compressive strength (MPa)	28-day strength above NN mix (%)	Level of 28-day strength obtained at 7-days (early strength) (%)	Early strength above NN mix (%)
NN	NaOH + Na <sub>2</sub> SiO <sub>3</sub>	55.4±0.8	-	70	-
NK	NaOH + K <sub>2</sub> SiO <sub>3</sub>	25.7±0.9	-53	68	-3
KK	KOH + K <sub>2</sub> SiO <sub>3</sub>	37.3±1	-33	54	-23
KN	KOH + Na <sub>2</sub> SiO <sub>3</sub>	22.6±0.7	-59	59	-16

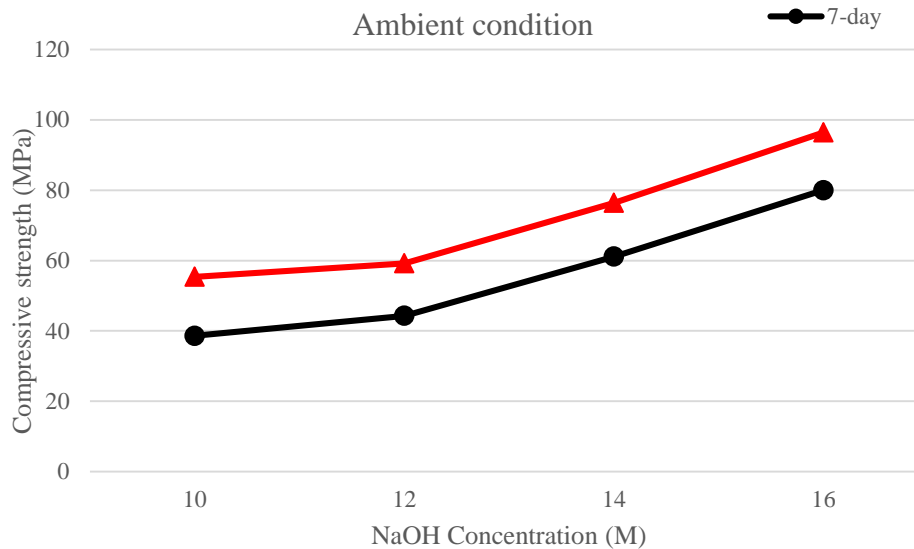
These results may be related to differences in the mechanism of reactions of Na and K. The mechanism of action of alkaline activator solution breaks the structure of silica and alumina of alumin-silicate source, forms silicon and aluminum ions and makes geopolymer gel, within 3 stages of dissolution, partial orientation of the mobile precursor and reloading of particles from the initial solid phase are implemented [36, 37]. The type of alkaline activator plays a very important role in the development of the geopolymer production process. In most previous studies in this regard, high temperature curing conditions (60-90 °C) have been practiced to process GPC specimens. The researchers concluded that potassium leads to the formation of larger oligomer silicates due to its larger atomic radius, which Al(OH)<sup>4+</sup> prefers and attaches to. Therefore, more geopolymer is formed in the case of using K-based activator solution, subjects to the formation of a stronger and more compact system than Na-based activator solution [38], which results in lower 3- and 7-day compressive strength, slower hardening and higher 28-day compressive [23]. On the other hand, in Na-based activator solution, NaOH has the ability to dissolve more minerals in concentrations similar to KOH and NaOH. This leads to a higher reaction rate of Na<sup>+</sup> compared to K<sup>+</sup> [39,40]. Attributable to the same high rate of reaction Na<sup>+</sup>, in the case of using Na-based activator, higher 7-day compressive strength and faster hardening than K-based, obtained [1]. However, it should be noted that these results are achieved in the case of curing at high temperatures and providing the necessary energy. In this study, ambient temperature conditions are used and as can be seen, the results of this study are different from the previous ones. This could be due to Less Active K<sup>+</sup> for the sake of the larger ionic size of K<sup>+</sup> compared to Na<sup>+</sup> [39] as well as the lower solubility of Si and Al in K-based activator solution than Na-based at similar molar concentrations [40]. Therefore, more energy is needed in the case of using K-based activator, so the use of ambient temperature conditions in this study did not provide the essential energy for effective K<sup>+</sup> activity. As a result, the specimen made with K-based activator provided both lower lateral compressive strength and lower early strength compared to Na-based activator. In fact, for this reason the early compressive strength of the specimen increased by replacing part of K<sup>+</sup> with Na<sup>+</sup> in the NK, KN specimens. According to the results obtained from this section, two alkaline activator solutions (NaOH+Na<sub>2</sub>SiO<sub>3</sub>) and (KOH+Na<sub>2</sub>SiO<sub>3</sub>) were selected to continue the research process.

### **3-2- Effect of NaOH and KOH concentration on compressive strength of GPC**

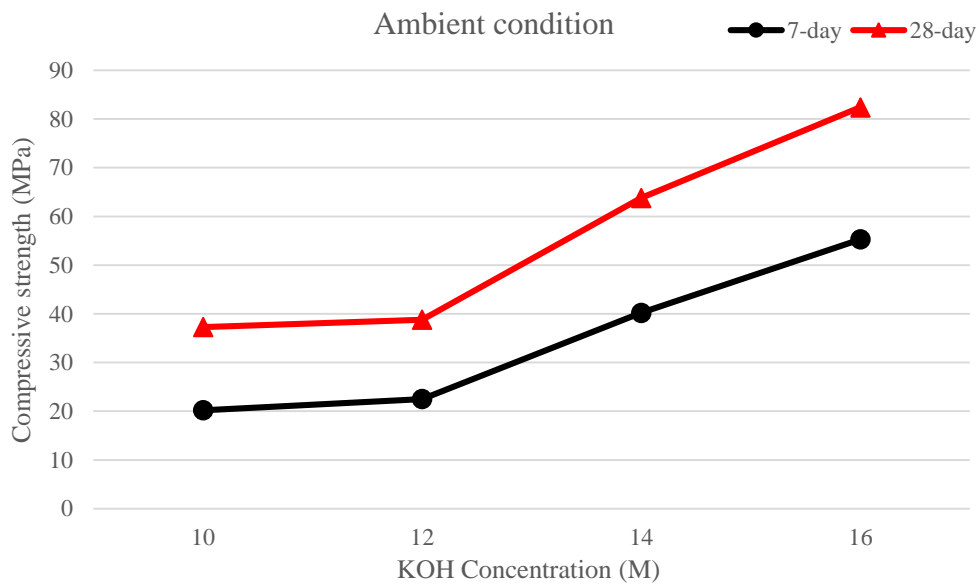
The results of the study of the effect of NaOH solution concentration on compressive strength are presented in Figure 3 and the results of this experiment for KOH solution are divulged in Figure 4. According to the results of Na-based activator, the lowest 7- and 28-day compressive strength were 38.6 and 55.4 MPa, related to 10M NaOH. Through increasing the concentration of NaOH solution from 10 to 16M, the 7- and 28-day compressive strength also increased. The results were similar for KOH solution. The lowest compressive strengths of 7 and 28 days were measured in



10M KOH solution at 20.2 and 37.3 MPa. By increasing the concentration of KOH solution to 16M, the compressive strength increased and reached its maximum value. Increasing the molar concentration of hydroxide solutions increases the pH. Also, more amounts of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> of aluminosilicate source are dissolved in the alkaline activator solution, resulting in formation higher amounts of geopolymer gel, leading to higher compressive strength [41]. Consequently, the compressive strength also increased significantly through growing the concentration of NaOH and KOH solutions to 16M.



**Figure 3.** Effect of NaOH concentration on 7 and 28-day compressive strength of GPC.



**Figure 4.** Effect of KOH concentration on 7 and 28-day compressive strength of GPC



On the other hand, an increasing trend in the acquisition of early strength of GPC was observed by increasing in the concentration of NaOH and KOH solutions (Tables 10 and 11). This could be related to acceleration of the geopolymerization process with NaOH and KOH solutions concentration [2]. It should be considered that the results obtained from this section are different from some of the results of previous research. Esparham et al [1] scrutinized the role of NaOH solution concentration on GPC compressive strength. The researchers used a combination of NaOH and Na<sub>2</sub>SiO<sub>3</sub> solution as the alkaline activator solution and concluded that increasing the concentration of NaOH solution to 12 mol improves the compressive strength, but further increasing the concentration to 14 mol decreases the compressive strength. The researchers used 80 °C curing conditions to process the specimens, which could be the main reason for the difference in results. Patel et al [42] obtained similar results. In another study, Esparham et al [2] also premeditated the effect of the concentration of NaOH solution on the compressive strength of GPC. They also used heat curing regime at 90 °C to curing the specimens and concluded that increasing the concentration from 10 to 14M increased the compressive strength by 23%, but no significant change in compressive strength was detected with a further increase in concentration from 14 to 16M.

**Table 10. Effect of NaOH concentration on lateral and early strength of GPC.**

NaOH concentration	28-day compressive strength (MPa)	28-day strength above 10 M (%)	Level of 28-day strength obtained at 7-days (early strength) (%)	Early strength above 10M (%)
10M	55.4±0.8	-	70	-
12M	59.2±0.9	+7	75	+7
14M	76.4±0.8	+38	79	+13
16M	96.4±1.1	+74	83	+19

**Table 11. Effect of KOH concentration on lateral and early strength of GPC.**

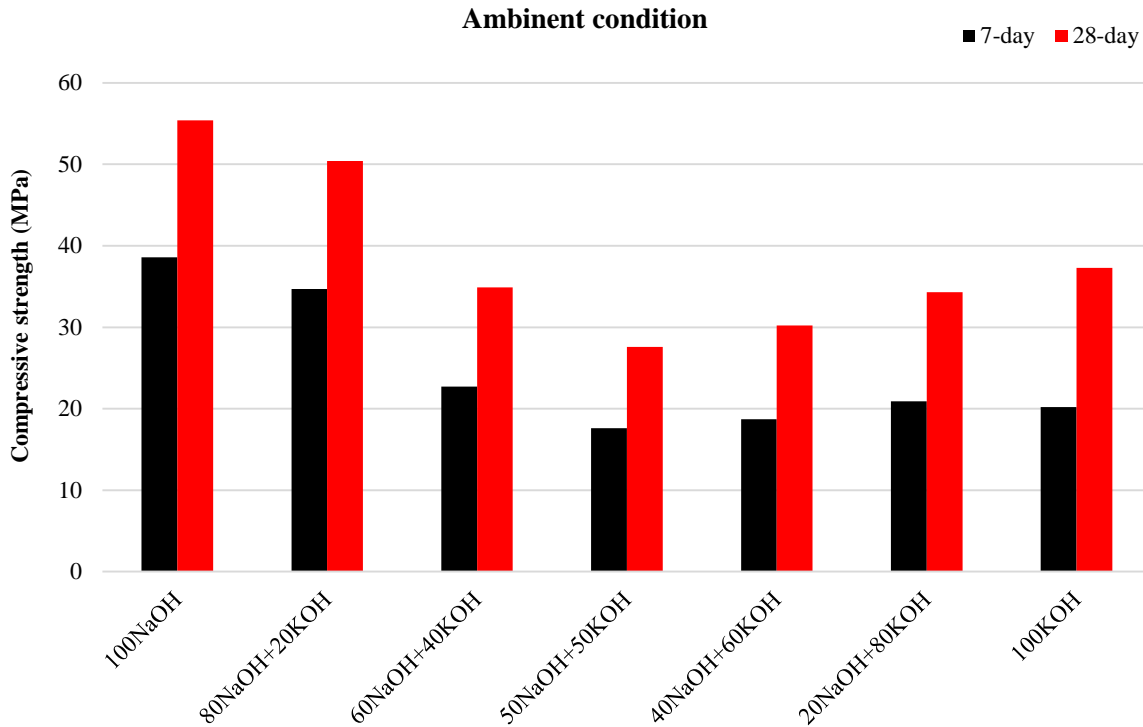
KOH concentration	28-day compressive strength (MPa)	28-day strength above 10 M (%)	Level of 28-day strength obtained at 7-days (early strength) (%)	Early strength above 10M (%)
10M	37.3±1	-	54	-
12M	38.8±0.6	+4	58	+8
14M	63.8±0.8	+71	63	+17
16M	82.4±0.6	+121	67	+24

### 3-3- Effect of combination of NaOH and KOH on compressive strength of GPC

The obtained results for the effect of the combination of NaOH and KOH solutions on the compressive strength of GPC specimens, are presented in Figure 5. The results demonstrated that the combination of NaOH and KOH solutions reduced the compressive strength of the specimens compared to both 100% NaOH and 100% KOH solution, and the higher the replacement percentage, the lower the compressive strength was measured (Table 11). Thus, the lowest 7-and 28-day compressive strength was observed in the specimen made of 50% NaOH solution and 50% KOH solution at the rate of 17.6 and 27.6 MPa. These results can also be due to differences in the mechanisms of Na and K. As mentioned in Section 3.1, KOH tends to perform a condensation reaction and the formation of large oligomer silicates due to the larger atomic radius, while NaOH is capable of dissolving more inorganic components than KOH, which leads to faster reaction rate for Na<sup>+</sup> than for K<sup>+</sup>. The high reactivity of Na<sup>+</sup> could not be balanced with the tendency of K<sup>+</sup> towards condensation reaction [40]. This can well explain the declining trend of the compressive



strength of GPC by increasing the substitution level of NaOH and KOH from 20 to 50%; that is, by increasing the substitution level, the interference in the reactivity of  $\text{Na}^+$  and  $\text{K}^+$  would increase.



**Figure 5.** Effect of combination of NaOH and KOH on 7 and 28-day compressive strength of GPC.

On the other hand, it can be seen that in specimens where the amount of NaOH solution is predominant (NaOH solution content  $\geq 50\%$ ) according to Table 12, adding KOH solution not only lessens the compressive strength of the specimens compared to 100% NaOH solution, but also diminishes the early strength. Nonetheless, the results are the opposite. In specimens with a predominant amount of KOH solution (KOH solution  $\geq 50\%$ ), the addition of NaOH solution increases the early strength of the specimens to a 100% KOH solution, and as the percentage of NaOH increases, the early strength of the specimens also upsurges, which can also lead to the differences in Na and K reaction maps are related.

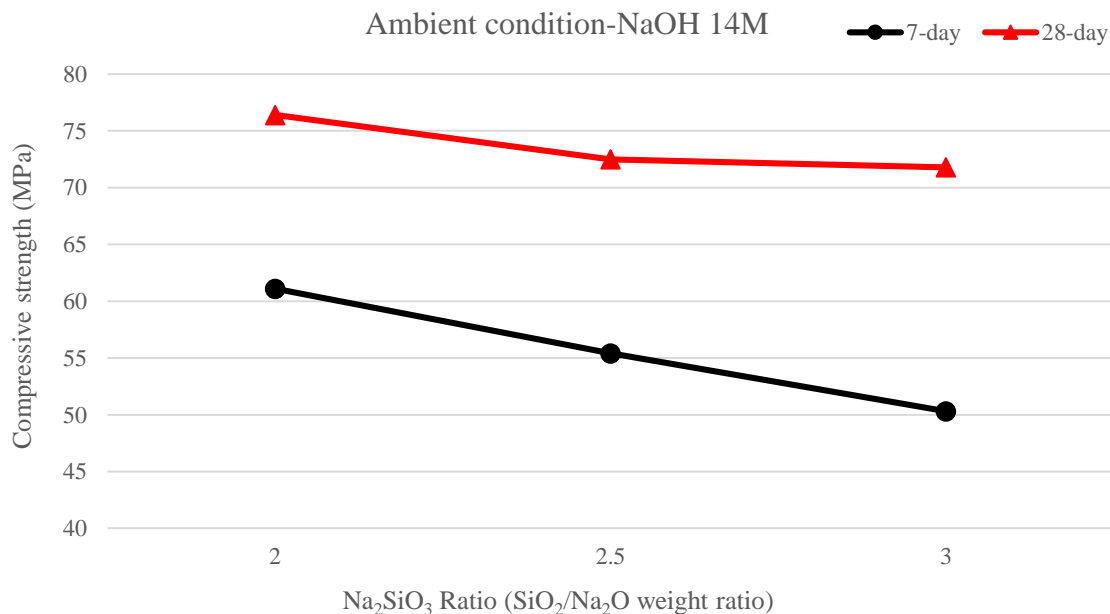


**Table 12. Effect of NaOH and KOH combination on lateral and early strength of GPC.**

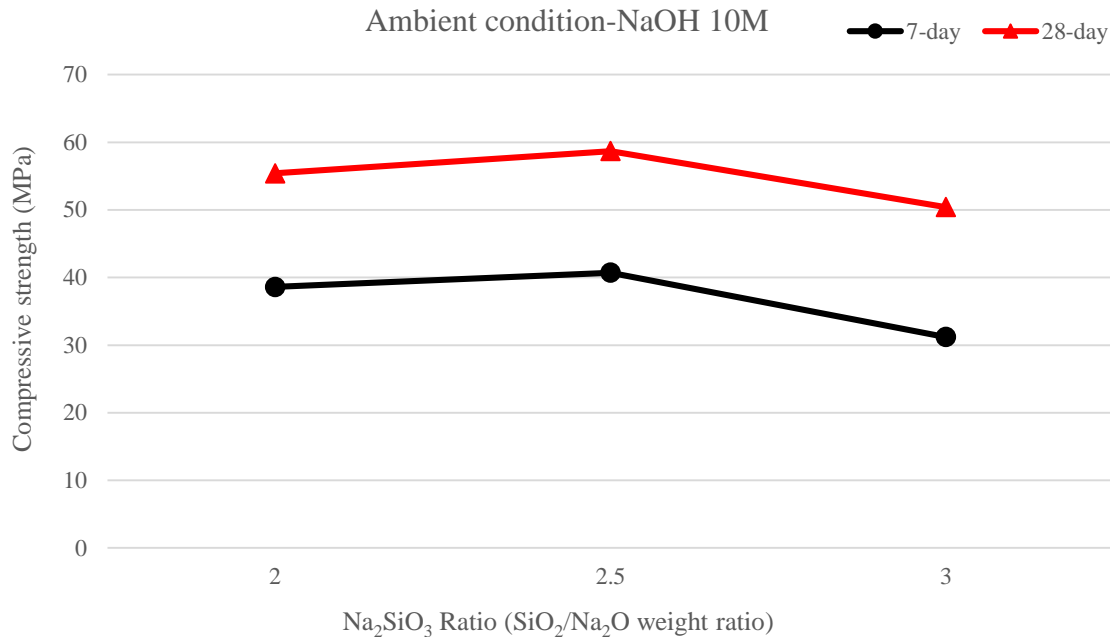
NaOH/KOH ratio	28-day compressive strength (MPa)	28-day strength above 100% NaOH (%)	Level of 28-day strength obtained at 7-days (early strength) (%)	Early strength above 100% NaOH (%)
100%NaOH	55.4±0.8	-	70	-
80%NaOH+20%KOH	50.4±0.9	-9	69	-2
60%NaOH+40%KOH	34.9±0.7	-37	65	-7
50%NaOH+50%KOH	27.6±0.8	-50	64	-9
NaOH/KOH ratio	28-day compressive strength (MPa)	28-day strength above 100% KOH (%)	Level of 28-day strength obtained at 7-days (early strength) (%)	Early strength above 100% KOH (%)
100%KOH	37.3±1	-	59	-
80%KOH+20%NaOH	34.3±0.6	-8	61	+3
60%KOH+40%NaOH	30.2±0.9	-19	62	+5
50%KOH+50%NaOH	27.6±0.8	-26	64	+8

### 3-4- Effect of the weight ratio of $\text{SiO}_2/\text{Na}_2\text{O}$ of $\text{Na}_2\text{SiO}_3$ solution on compressive strength of GPC

The results of the compressive strength test using 14M NaOH in Figure 6 and 10M NaOH are presented in Figure 7. The results indicate that the highest 7- and 28-day compressive strength was obtained in  $\text{Na}_2\text{SiO}_3$  solution with weight ratio of  $\text{SiO}_2/\text{Na}_2\text{O} = 2$  in the case of using 14M NaOH solution (61.1 and 76.4 MPa). Increasing the  $\text{SiO}_2/\text{Na}_2\text{O}$  ratio of  $\text{Na}_2\text{SiO}_3$  solution to 2.5 and 3 reduced the compressive strength by 4 and 5%, respectively. In the case of using 10M NaOH solution, the 7- and 28-day compressive strength of the specimen made with  $\text{Na}_2\text{SiO}_3$  solution with  $\text{SiO}_2/\text{Na}_2\text{O} = 2$  were 38.6 and 55.4 MPa, respectively. Unlike the use of 14M NaOH solution, increasing the  $\text{SiO}_2/\text{Na}_2\text{O}$  ratio of  $\text{Na}_2\text{SiO}_3$  solution to 2.5 increased the compressive strength by approximately 6% and achieved the maximum compressive strength at 7 and 28 days (40.7 and 58.7 MPa). By further increasing the  $\text{SiO}_2/\text{Na}_2\text{O}$  ratio of  $\text{Na}_2\text{SiO}_3$  solution to 3, the compressive strength decreased by roughly 9% compared to the optimal state (2.5).



**Figure 6.** Effect of  $\text{SiO}_2/\text{Na}_2\text{O}$  of  $\text{Na}_2\text{SiO}_3$  solution on compressive strength of GPC (NaOH concentration=14M).



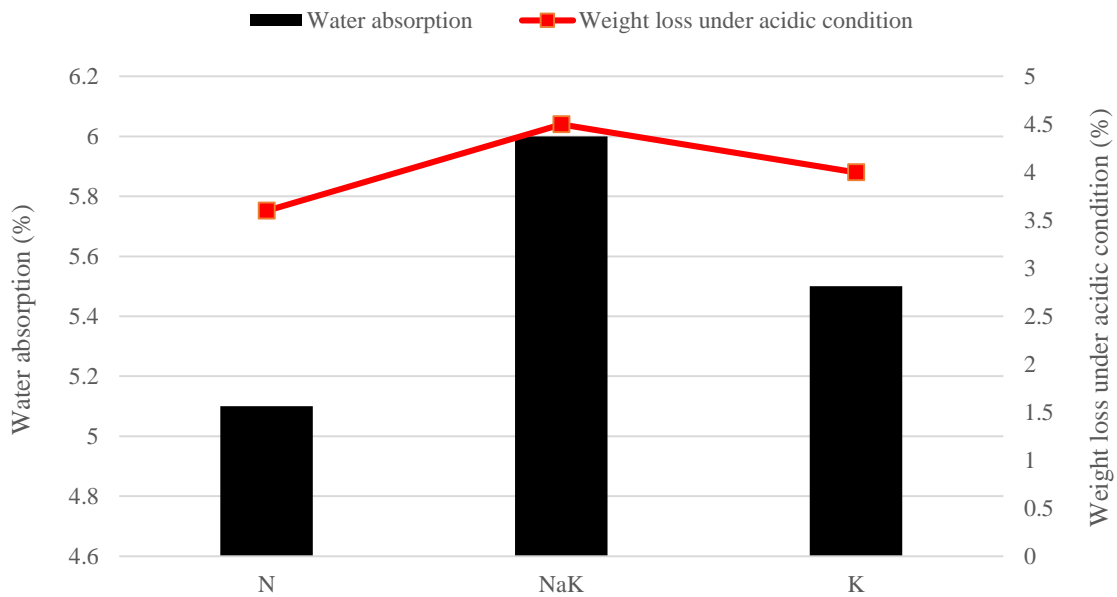
**Figure 7.** Effect of SiO<sub>2</sub>/Na<sub>2</sub>O of Na<sub>2</sub>SiO<sub>3</sub> solution on compressive strength of GPC (NaOH concentration=10M).

The role of alkaline activator solution, especially NaOH or KOH, is to dissolve Si and Al in the alumino-silicate source, produce SiO<sub>4</sub> and AlO<sub>4</sub> and yield a geopolymer gel. Adding a silicate solution such as Na<sub>2</sub>SiO<sub>3</sub> or K<sub>2</sub>SiO<sub>3</sub> to the alkaline activator solution increases the amount of SiO<sub>4</sub> and the geopolymerization reaction rate, due to the presence of soluble Si. Consequently, it improves the compressive strength of GPC. Meanwhile, adding a small amount (less than the optimal ratio) of soluble Si and accordingly lowering the amount of SiO<sub>4</sub> reduces the compressive strength. On the other hand, adding an extra amount (more than the optimal ratio) also reduces the compressive strength because the amounts of SiO<sub>4</sub> are produced in this case excessive, whereas the amount of AlO<sub>4</sub> in the composition is constant (or limited) [38, 43]. As a result, the compressive strength decreases as the Si/Al ratio deviates from the optimal range. But the optimal amount of Si in solution can depend on several factors, the first one is the SiO<sub>2</sub>/Na<sub>2</sub>O ratio of Na<sub>2</sub>SiO<sub>3</sub> solution. Naturally, Na<sub>2</sub>SiO<sub>3</sub> solution with higher SiO<sub>2</sub>/Na<sub>2</sub>O ratio has higher amounts of SiO<sub>2</sub> as well as soluble Si. The next factor that can affect the optimal SiO<sub>2</sub>/Na<sub>2</sub>O ratio of Na<sub>2</sub>SiO<sub>3</sub> solution is the concentration of NaOH solution. As observed in the previous sections, the degree of dissolution of the Si presented in alumino-silicate source is directly related to the concentration of NaOH solution. The use of higher concentrations of NaOH solution increases the solubility of Si of the alumino-silicate source and produces higher amounts of soluble Si. In this case, the use of Na<sub>2</sub>SiO<sub>3</sub> solution with high SiO<sub>2</sub>/Na<sub>2</sub>O beard can lead to a decrease in compressive strength due to excessive increment of soluble Si. In fact, this issue can be the reason for the difference in the results of optimizing the SiO<sub>2</sub>/Na<sub>2</sub>O ratio of Na<sub>2</sub>SiO<sub>3</sub> solution in two states of NaOH 10M and 14M in this study. The results of this study presented that in the case of using 10M NaOH solution, the optimal amount of SiO<sub>2</sub>/Na<sub>2</sub>O is 2.5 and it is 2 in the case of using 14M NaOH solution.

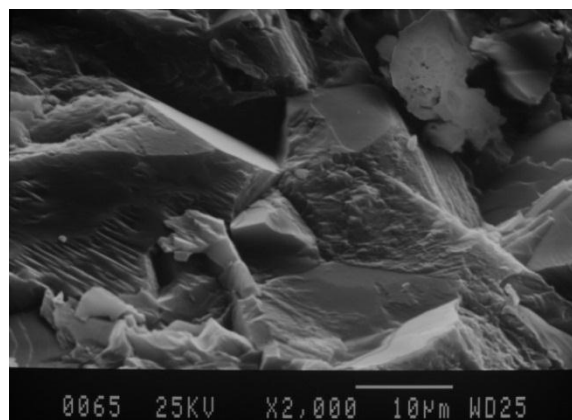


### 3-5- Effect of alkaline activator type on water absorption and weight loss under acidic condition of GPC

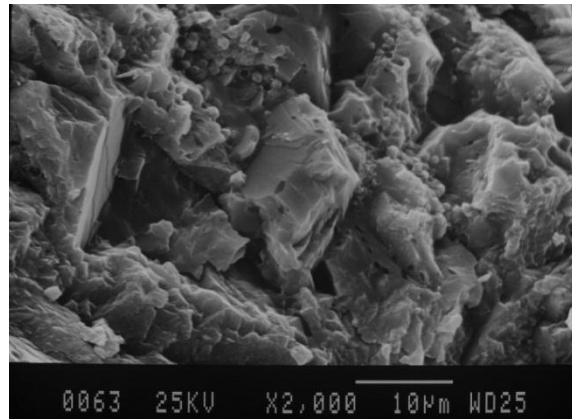
Figure 8 illustrates the results of water absorption and weight loss under acidic condition tests of GPC specimens. Also, the SEM analyze images of GPC specimens are represented in Figure 15. The water absorption capacity of N, NaK and K mix designs were measured approximately 5.1, 6 and 5.5%, respectively. Also, weight loss under acidic condition N, NaK and K mix designs were measured approximately 3.6, 4.5 and 4%, respectively. By observing the results of Figure 8, as well as Figure 9, water absorption capacity and weight loss in acidic condition of N mix design were less compared to other specimens, mainly due to higher density of the geopolymeric matrix structure in this mix design.



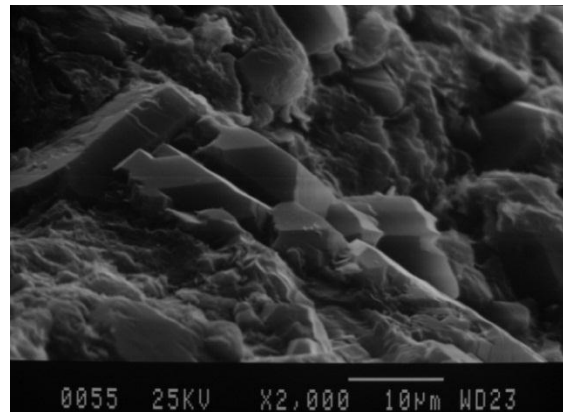
**Figure 8.** Water absorption and weight loss under acidic condition of N, NaK and K mix designs.



(a)



(b)



(c)

Figure 9. SEM analyze of N (a), NaK (b) and K (c) mix designs.

#### 4. Conclusions

In this comprehensive experimental study, the role of different alkaline solutions type, some parameters related to alkaline solution and curing conditions on compressive strengths and also, resistance to acidic condition and water absorption of GPC based on GGBFS, were deliberated. The following conclusions can be drawn based on results of the current experimental studies:

1- The type of alkaline activator solution is one of the parameters affecting the compressive strength of GPC. At ambient temperature, the use of Na-based activator ( $\text{NaOH} + \text{Na}_2\text{SiO}_3$ ) leads to greater lateral compressive strength and early strength than the K-based activator ( $\text{KOH} + \text{K}_2\text{SiO}_3$ ) due to the higher reactivity of  $\text{Na}^+$  compare to  $\text{K}^+$  and higher dissolution of Si and Al in NaOH solution in comparison with KOH solution.

2- In addition, the concentration of NaOH and KOH solutions potentially affects the compressive strength of GPC. Increasing the concentration from 10 to 16M cusses a 77% improvement in GPC compressive strength (in the case of using NaOH solution) and 132% (in the case of using KOH solution) as a result of the rise in dissolution of Si and Al (presented in fly ash) by the alkaline activator solution.





3-Using the combination of NaOH and KOH solutions reduces the compressive strength of GPC because of the interference of the reactive affinity of  $\text{Na}^+$  and  $\text{K}^+$ . Moreover, increasing the replacement ratio of NaOH and KOH solutions from 20-80 to 50-50 %, significantly diminished the compressive strength.

4- The  $\text{SiO}_2/\text{Na}_2\text{O}$  ratio of  $\text{Na}_2\text{SiO}_3$  solution is another parameter influencing compressive strength of GPC. The optimal amount depends on various factors, including the concentration of the hydroxide solution. The optimal  $\text{SiO}_2/\text{Na}_2\text{O}$  ratio of  $\text{Na}_2\text{SiO}_3$  solution is 2 in the case of using 14M NaOH solution and 2.5 in the case of using 10M NaOH solution.

5- The use of Na-based activator solution to make GPC, leads to the formation of a denser geopolymer matrix than K-based activator, resulting in lower water absorption and weight loss under acidic condition.

### **Acknowledgments**

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

### **5. References**

- [1]- Esparham, A., Moradikhou, A. B., Kazemi Andalib, F. and Jamshidi Avanaki, M., 2021, **Strength characteristics of granulated ground blast furnace slag-based geopolymer concrete**, *Advances in Concrete Construction*, 11(3), 219-229.
- [2]- Esparham, A., Moradikhou, A. B. and Jamshidi Avanaki, M., 2020, **Effect of Various Alkaline Activator Solutions on Compressive Strength of Fly Ash-Based Geopolymer Concrete**, *Journal of civil Engineering and Materials Application*, 4(2), 115-123.
- [3]- Moradikhou, A. B. and Esparham, A., 2021, **Water Absorption, Density, Mechanical Strengths and High-temperature Resistance of Metakaolin-based Geopolymer Concrete Reinforced with Hybrid Polyolefin and Simple Polypropylene Fibers**, *Advance Researches in Civil Engineering*, 3(2), 1-15.
- [4]- Rashad, A. M., 2013, **A comprehensive overview about the influence of different additives on the properties of alkali-activated slag – A guide for Civil Engineer**, *Construction and Building Materials*, 47, 29-55.
- [5]- Moradikhou, A. B. and Ravanshadnia, M., 2021, **Evaluation of CO<sub>2</sub> Emissions Reduction Strategies in the Iranian Cement Industry**, *Journal of Civil Engineering and Materials Application*, 5(3), 1-13.
- [6]- Moradikhou, A. B., Esparham, A. and Avanaki, M. J., 2019, **Effect of Hybrid Fibers on Water absorption and Mechanical Strengths of Geopolymer Concrete based on Blast Furnace Slag**, *Journal of civil Engineering and Materials Application*, 3(4), 195-211.
- [7]- DeSilva, P., Sagoe-Crenstil, K. and Sirivivatnanon, V., 2007, **Kinetics of geopolymerization: role of  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$** , *Cement and Concrete Research*, 37(4), 512-518.
- [8]- Neupane, K., Chalmers, D. and Kidd, P., 2018, **High-Strength Geopolymer Concrete-Properties, Advantages and Challenges**, *Advances in Materials*, 7(2), 15-25.
- [9]- Görhan, G. and Kürklü, G., 2014, **The influence of the NaOH solution on the properties of the fly ash-based geopolymer mortar cured at different temperatures**, *Composites Part B: Engineering*, 58, 371-377.



- [10]- Gao, K., Lin, K.-L., Wang, D., Hwang, C.-L., Anh Tuan, B. L., Shiu, H.-S. and Cheng, T.-W., 2013, **Effect of nano-SiO<sub>2</sub> on the alkali-activated characteristics of metakaolin-based geopolymers**, *Construction and Building Materials*, 48, 441-447.
- [11]- Moradikhou, A. B. and Safehian, M., 2021, **Comparison of Mechanical Strengths and Resistance to Acidic Conditions, Permeability and Resistance to Elevated Temperatures of Geopolymer Concrete and Conventional Concrete**, *Advance Researches in Civil Engineering*, 3(2), 27-37.
- [12]- Bagheri, A. and Nazari, A., 2014, **Compressive strength of high strength class C fly ash-based geopolymers with reactive granulated blast furnace slag aggregates designed by Taguchi method**, *Materials & Design (1980-2015)*, 54, 483-490.
- [13]- Karakoç, M. B., Türkmen, İ., Maras, M. M., Kantarci, F., Demirbogça, R. and Uğur Toprak, M., 2014, **Mechanical properties and setting time of ferrochrome slag based geopolymer paste and mortar**, *Construction and Building Materials*, 72(Supplement C), 283–292.
- [14]- Karthik, A., Sudalaimani, K. and Vijaya Kumar, C. T., 2017, **Investigation on mechanical properties of fly ash-ground granulated blast furnace slag based self-curing bio-geopolymer concrete**, *Construction and Building Materials*, 157(Supplement C), 338–349.
- [15]- Cheng, T. W. and Chiu, J. P., 2003, **Fire-resistant geopolymer produced by granulated blast furnace slag**, *Minerals Engineering*, 16(3), 205-210.
- [16]- Sarker, P. K., Kelly, S. and Yao, Z., 2014, **Effect of fire exposure on cracking, spalling and residual strength of fly ash geopolymer concrete**, *Materials & Design*, 63, 584-592.
- [17]- Sakkas, K., Panyas, D., Nomikos, P. P. and Sofianos, A. I., 2014, **Potassium based geopolymer for passive fire protection of concrete tunnels linings**, *Tunnelling and Underground Space Technology*, 43, 148-156.
- [18]- Lee, W. K. W. and van Deventer, J. S. J., 2002, **The effects of inorganic salt contamination on the strength and durability of geopolymers**, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 211(2), 115-126.
- [19]- Palomo, A., Blanco-Varela, M. T., Granizo, M., Puertas, F., Vazquez, T. and Grutzeck, M., 1999, **Chemical stability of cementitious materials based on metakaolin**, *Cement and Concrete Research*, 29(7), 997-1004.
- [20]- Zhang, M., Guo, H., El-Korchi, T., Zhang, G. and Tao, M., 2013, **Experimental feasibility study of geopolymer as the next-generation soil stabilizer**, *Construction and Building Materials*, 47, 1468-1478.
- [21]- Moradikhou, A. B., Hosseini, M. H., Mousavi Kashi, A., Emami, F. and Esparham, A., 2020, **Effect of Simple and Hybrid Polymer Fibers on Mechanical Strengths and High-temperature Resistance of Metakaolin-based Geopolymer Concrete**, *Modares Civil Engineering journal*, 20(2), 147-161.
- [22]- Hardjito, D., Wallah, S. E., Sumajouw, D. M. J. and Rangan, B. V., 2004, **On the Development of Fly Ash-Based Geopolymer Concrete**, *ACI Materials Journal*, 101(6), 467-472.
- [23]- Esparham, A. and Moradikhou, A. B., 2021, **A Novel Type of Alkaline Activator for Geopolymer Concrete Based on Class C Fly Ash**, *Advance Researches in Civil Engineering*, 3(1), 1-13.
- [24]- Davidovits, J., 1988, **Soft Mineralurgy and Geopolymers**, *Geopolymer '88*, 1, 19-23.
- [25]- Davidovits, J., 1991, **Geopolymers: Inorganic Polymeric New Materials**, *Journal of Thermal Analysis*, 37, 1633-1656.
- [26]- Patel, Y. J. and Shah, N., 2018, **Development of self-compacting geopolymer concrete as a sustainable construction material**, *Sustainable Environment Research*, 28(6), 412-421.



- [27]- Hardjito, D., Wallah, S. E., Sumajouw, D. M. and Rangan, B., 2004, **Factors influencing the compressive strength of fly ash-based geopolymer concrete**, *Civil engineering dimension*, 6(2), 88-93.
- [28]- ASTM C33 / C33M-18, 2018, **Standard Specification for Concrete Aggregates**, ASTM International, West Conshohocken, PA, 2018.
- [29]- ASTM C127-15, 2015, **Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate**, ASTM International, West Conshohocken, PA, 2015.
- [30]- ASTM C128-15, 2015, **Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate**, ASTM International, West Conshohocken, PA, 2015.
- [31]- ASTM C136 / C136M-14, 2014, **Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates**, ASTM International, West Conshohocken, PA, 2014.
- [32]- ASTM D2419-14, 2014, **Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate**, ASTM International, West Conshohocken, PA, 2014.
- [33]- Hardjito, D. and Rangan, B. V., 2005, **Development and properties of low-calcium fly ash-based geopolymer concrete**, Curtin University, Perth, Australia.
- [34]- British Standards Institution, 1983, **Testing Concrete: Method for Determination of the Compressive Strength of Concrete Cubes**, BS1881: Part116: 1983, London.
- [35]- ASTM C642-13, 2013, **Standard Test Method for Density, Absorption, and Voids in Hardened Concrete**, ASTM International, West Conshohocken, PA, 2013.
- [36]- Davidovits, J., 1999, **Chemistry of Geopolymeric Systems**, Terminology In: Proceedings of 99 International Conference, eds. Joseph Davidovits, R. Davidovits & C. James, France,
- [37]- Duxson, P., Provis, J. L., Lukey, G. C. and van Deventer, J. S. J., 2007, **The role of inorganic polymer technology in the development of 'green concrete'**, *Cement and Concrete Research*, 37(12), 1590-1597.
- [38]- Komnitsas, K., Zaharaki, D. and Perdikatsis, V., 2009, **Effect of synthesis parameters on the compressive strength of low-calcium ferronickel slag inorganic polymers**, *Journal of Hazardous Materials*, 161(2), 760-768.
- [39]- Xu, H. and Van Deventer, J. S. J., 2000, **The geopolymerisation of alumino-silicate minerals**, *International Journal of Mineral Processing*, 59(3), 247-266.
- [40]- Panagiotopoulou, C., Kakali, G., Tsivilis, S., Perraki, T. and Perraki, M., 2010, **Synthesis and Characterisation of Slag Based Geopolymers**, *Materials Science Forum*, 636-637, 155-160.
- [41]- van Jaarsveld, J. G. S., van Deventer, J. S. J. and Lukey, G. C., 2003, **The characterisation of source materials in fly ash-based geopolymers**, *Materials Letters*, 57(7), 1272-1280.
- [42]- Moradikhou, A. B., Esparham, A. and Jamshidi Avanaki, M., 2020, **Physical & mechanical properties of fiber reinforced metakaolin-based geopolymer concrete**, *Construction and Building Materials*, 251, 118965.
- [43]- Patel, Y. J. and Shah, N., 2018, **Study on Workability and Hardened Properties of Self Compacted Geopolymer Concrete Cured at Ambient Temperature**, *Indian Journal of Science and Technology*, 11(1), 45-52.