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Fresh and Mechanical Properties of Fly Ash-Based Geopolymer Mortars Activated by Different Alkaline Solutions

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ABSTRACT

Geopolymer is considered to be an eco-friendly binder and replacement for ordinary Portland cement as it leads to a reduction in CO_2 emissions and energy saving. A strong alkaline solution is required to activate the silicon and aluminum present in the fly ash and setting additives. The main objectives of this work are to determine the effects of the alkaline solution type on the fresh and mechanical properties of alkali-activated fly ash (class F) based geopolymer mortar. Four different alkaline solutions were prepared. The first and the second solutions were made by mixing sodium silicate liquid with sodium hydroxide and with potassium hydroxide, respectively. For the other two solutions, potassium silicate liquid was used instead of sodium silicate liquid. The investigated parameters included molarity of NaOH and KOH (10M, 12M, 14M and 16M) as well as different ratios of alkaline solutions to the binder (0.40, 0.45 and 0.50), silicate to hydroxide solutions ratio (2, 2.5 and 3) and sand to fly ash ratio (1.5, 2.0 and 2.5). Test results revealed that the workability significantly increased by using potassium silicate with respect to sodium silicate. In addition to increasing the silicate to hydroxide ratio has a negative impact on the workability of potassium silicate-based geopolymer mortar prepared by NH or KH. In case of sodium silicate based geopolymer mortars, the concentration of NH or KH of 16M achieves the maximum compressive strength but the concentration of 14M was remarked in case of potassium silicate-based geopolymer.

Keywords: Geopolymer, Fly ash, Alkaline solutions, Binder, Activator, Fresh properties, Mechanical properties.

1. INTRODUCTION

The high contribution of the cement industry to CO_2 emissions is considered as one of the major contributors of global warming. That has inspired some scientists to look for solutions to minimize its effects. A feasible source material for the geopolymer binder can be any material that is rich in silicon (Si) and aluminum (Al) in an amorphous form. In the production of geopolymers, various mineral and industrial by-products have been used. The use of fly ash as part or complete substitute for cement in concrete is one of the promising alternatives. Since the invention of the geopolymer by Davidovits in 1979 [1], the complete replacement of cement has been possible. Geopolymers are a class of inorganic polymers formed by reacting silica-rich and alumina-rich solids such as fly ash with a high alkaline solution. Van Jaarsveld et al, (1997) suggested a model for geopolymerization process [2].

Theoretically, any material containing aluminum and silicon can be a solid source of aluminosilicate for geopolymerization. Low calcium Fly Ash (FA) is considered the main precursor in the geopolymer industry due to its high content of SiO_2 and Al_2O_3. The low-calcium

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fly ash (Class F) is the preferred source material to the high-calcium fly ash (Class C) [3-4]. A strong alkaline solution is required to activate the silicon and aluminum present in the fly ash and setting additives, that allows transforming glassy structure partially or totally into a very compacted composite [5]. Also, the activation process of fly ash binders is in general described well by the Bingham model [6]. The mechanical performance of geopolymers is highly influenced by the Si/Al ratio [7,8], hydroxide concentration [7], effectiveness of the geopolymerization reaction [9], type of alkali activator used [10], and curing conditions [11,12]. Geopolymers can exhibit different mechanical properties according to the materials employed or depending on their molar ratio.

The type of alkaline solution used to activate the silicon and alumina plays an important role of geopolymers properties. Silicate activation of low-calcium binders is usually achieved most effectively by the addition of dissolved alkali silicates to the solid precursor. Solid silicate sources have been trilled in fly ash-based binders but tend to give slow strength development [13, 14]. There are various ways of manipulating the composition of a sodium silicate solution, and each has a somewhat different effect on the binder structure. Moving from a hydroxide to a silicate solution tends to lead to a higher strength, lower porosity binder [15-18] up to a solution modulus, where the exact value of this optimum depends on the nature of the aluminosilicate precursor [19]. Generally, the geopolymer composites showed good fresh properties compared by the cementitious ones [20-26]. A sulphate and chloride attach of the geopolymer materials are of a great concern of the researchers. Thus, the geopolymer materials showed a significant performance to both of them [27-31]. On the other hand, the fire endurance of it is higher than of the ordinary cementitious Portland materials [32-36]. The highly fresh and mechanical properties of the geopolymer composites led to use it as a repair material [37-41] for the RC elements.

Many research studies were performed on the sodium-based geopolymer and to the best knowledge of the authors, the fresh and mechanical properties of potassium silicate-based geopolymer mortar have not been covered well. Thus, the purpose of this study is to compare the influence of the type of activating solution on the workability and mechanical properties of geopolymeric mortars. To this end, four fly ash (class F) based geopolymer mortars were developed with different alkaline-activating solutions by combining different materials, including sodium silicate (Na_2SiO_3), potassium silicate (K_2SiO_3), sodium hydroxide (NaOH), and potassium hydroxide (KOH). Also, various affecting parameters were studied.

2. EXPERIMENTAL WORK

2.1 Materials Properties

The experimental work includes numerous geopolymer (GP) mortar mixes containing a low-calcium fly ash class F according to ASTM C 618 [42] as a source of pozzolanic material, which is rich in silica and alumina with specific gravity and a specific surface area of 2.31 and 5000 cm^2/g, respectively. The used alkaline solutions were a combination of sodium hydroxide NaOH (NH), sodium silicate Na_2SiO_3 (NS), potassium hydroxide KOH (KH), and potassium silicate K_2SiO_3 (KS) as shown in **Fig. 1**. Four different molarities were examined 10M, 12M, 14M, and 16M. NaOH and KOH solids were dissolved in water to make the solution. This hydroxide solution was prepared 24 hours prior to use as shown in **Fig. 2**. Dissolving mass of NH or KH depends on concentration of solution expressed in terms of Molar (M). The desired concentration per liter could be obtained by multiplying the molecule of NaOH (40g) or KOH (56g) with the molar concentration. For instance, the concentration 14M of NaOH consists of 14×40 = 560g of NaOH solids per liter of the solution. Similarly, the concentration 14M of KOH is 784g of KOH solids per liter of the prepared solution. The mass of NH and KH solids per g of the solution for other concentrations were measured as shown in **Table 1**. River siliceous sand was selected as a fine aggregate in the experimental program for mortar complied to ECC-Appendix 3 (2007) with a specific gravity of 2.57, a fineness modulus of 2.5, and water absorption 0.90% and passed through sieve # 4 (4.75mm) is suitable to be used in casting GP mixes. The chemical composition of the used fly ash as determined by XRD as well as the properties of the used sand are shown in **Table 2**.

Table 1: Mass required for preparing one liter of solution from NaOH and KOH

Required molarity	Mass of NaOH solid (g)	Mass of KOH solid (g)
1M	40	56
10M	400	560
12 M	480	672
14 M	560	784
16 M	640	896

Table 2: Properties of the used materials (fly ash and sand)

Chemical composition of the used fly ash			Properties of the used sand	
Oxide	**(%)**	**Limits**	**Property**	**Value**
Silicon dioxide (SiO_2)	60.28	--	Specific gravity	2.57
Aluminum oxide (Al_2O_3)	28.59	--	Unit weight (t/m^3)	1.72
Ferric oxide (Fe_2O_3)	4.99	--	Void ratio (%)	32.55
Total SiO_2 + Al_2O_3 + Fe_2O_3	93.86	70% min	Fineness modulus	2.5
Calcium oxide (CaO)	1.19	--	% clay and fine	2%
Phosphorus pent oxide (P_2O_5)	0.52	--	Water absorption %	0.90%
Sulphur trioxide (SO_3)	0.06	5.0% max	Specific gravity	2.57
Potassium oxide (K_2O)	1.09	--		
Titanium dioxide (TiO_2)	2.42	--		
Sodium oxide (Na_2O)	0.01	1.50% max		
Magnesium oxide (MgO)	0.27	--		
Loss on Ignition (LOI)	0.58	6.0% max		

2.2 Mortar Mix Proportions

Numerous mixtures of geopolymer mortar were proportioned to study the effect of different variables, which include the type of alkaline solution (four different alkaline solution were used), molarity of NaOH and KOH (10M, 12M, 14M, and 16M) and ratio of alkaline solution to binder (0.40, 0.45, and 0.50). A total of 28 GP mixes were investigated. The parametric study of GP mortar mixtures consists of two groups. Group 1 and group 2 consist of 16 GP and 12 GP mortar mixes, respectively. Group1 investigates the effect of type of alkaline solution with different concentrations of hydroxide solution. Group 2 studies the effect different alkaline solution ratios. Each mix had constant sand to fly ash ratio of 2.0 and silicate to hydroxide solution ratio of 2.50 and cured at 65°C for 48 hours. The details and mix proportions of the studied fly ash based geopolymer mixtures are tabulated in **Table 3**.

For potassium silicate-based GP mortar mixes, some additional parametric studies were performed by additional 12 mortar mixes. Where group 3 and group 4 tested the silicate to hydroxide ratio, sand to fly ash ratio, respectively. The alkaline solution in these mortar mixes was a mix of KS with each of NH and KH. Each mix had constant alkaline to fly ash ratio of 0.5 and constant molarity of NaOH or KOH of 14M and was cured at 65°C for 48 hours. The details of the additional mortar mixes are tabulated in **Table 4**.

2.3 Mixing, Casting and Curing Procedures for Mortar

The dry materials were first mixed by hand for 1 minute. Then, Hobart mixer with rotating blades was used for additional 4 minutes of dry mixing. Then the previously prepared alkaline solution was added to the dry mix and the mixing continued for another five minutes to finish the mixing process **(see Fig. 3a)**. The fresh mortar was cast and placed in the prepared oiled steel molds **(see Fig. 3b)**. The geopolymer specimens were compacted by vibration for 10 seconds on the vibrating table. The molds were left in open air for 24 hours as a rest period for all geopolymer specimens then were heated in an oven at 65°C for 48 hours. After that, the specimens were taken out from the oven, removed from their molds and left at room temperature until the test age as shown in **Fig. 3c**.

Table 3: Mix proportions of GP mortar mixtures

Group & Investigated parameters	Mix No	Mix ID	Alkaline solution	Molar	S/FA	Si/H	A/FA
G1 Type of alkaline solution + Molarity of hydroxide solution	1	NN-M10A0.5	NS/NH	10	2.0	2.5	0.50
	2	NN-M12A0.5	NS/NH	12	2.0	2.5	0.50
	3	NN-M14A0.5	NS/NH	14	2.0	2.5	0.50
	4	NN-M16A0.5	NS/NH	16	2.0	2.5	0.50
	5	NK-M10A0.5	NS/KH	10	2.0	2.5	0.50
	6	NK-M12A0.5	NS/KH	12	2.0	2.5	0.50
	7	NK-M14A0.5	NS/KH	14	2.0	2.5	0.50
	8	NK-M16A0.5	NS/KH	16	2.0	2.5	0.50
	9	KN- M10A0.5	KS/NH	10	2.0	2.5	0.50
	10	KN- M12A0.5	KS/NH	12	2.0	2.5	0.50
	11	KN- M14A0.5	KS/NH	14	2.0	2.5	0.50
	12	KN- M16A0.5	KS/NH	16	2.0	2.5	0.50
	13	KK- M10A0.5	KS/KH	10	2.0	2.5	0.50
	14	KK- M12A0.5	KS/KH	12	2.0	2.5	0.50
	15	KK- M14A0.5	KS/KH	14	2.0	2.5	0.50
	16	KK- M16A0.5	KS/KH	16	2.0	2.5	0.50
G2 Alkaline solution to binder ratio	17	NN-M14A0.4	NS/NH	14	2.0	2.5	0.40
	18	NN-M14A.45	NS/NH	14	2.0	2.5	0.45
	19	NN-M14A0.5	NS/NH	14	2.0	2.5	0.50
	20	NK-M14A0.4	NS/KH	14	2.0	2.5	0.40
	21	NK-M14A.45	NS/KH	14	2.0	2.5	0.45
	22	NK-M14A0.5	NS/KH	14	2.0	2.5	0.50
	23	KN- M14A0.4	KS/NH	14	2.0	2.5	0.40
	24	KN- M14A.45	KS/NH	14	2.0	2.5	0.45
	25	KN- M14A0.5	KS/NH	14	2.0	2.5	0.50
	26	KK- M14A0.4	KS/KH	14	2.0	2.5	0.40
	27	KK- M14A.45	KS/KH	14	2.0	2.5	0.45
	28	KK- M14A0.5	KS/KH	14	2.0	2.5	0.50

NS/NH : Sodium silicate + Sodium hydroxide
KS/NH : Potassium silicate + Sodium hydroxide
NS/KH : Sodium silicate + Potassium hydroxide
KS/KH : Potassium silicate + Potassium hydroxide
S/FA : Sand / Fly ash ratio
Si/H : Silicate / Hydroxide solutions ratio
A/FA : Alkaline / Fly ash ratio

Mortar mix ID
NN : NS/NH
NK : NS/KH
KN : KS/NH
KK : KS/KH
M : molarity of NH or KH
A : Alkaline to fly ash ratio

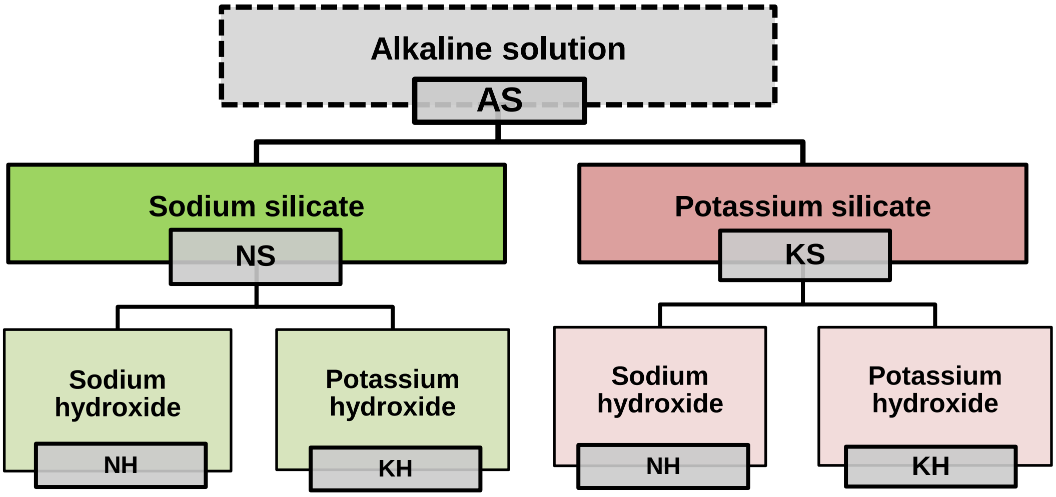


Fig. 1: Combinations of silicate and hydroxide solutions to prepare the alkaline activator

a) NaOH or KOH flakes b) NaOH or KOH solution c) Mixing both of silicate with hydroxide solution

Fig. 2: Preparing the alkaline solutions

2.4 Test Techniques and Procedures

2.4.1 Fresh Properties of Mortar Mixes

Flow Table Test was used to evaluate the flow percentage of the fresh GP mortars. Testing for the workability of the fresh mortar was done according to the ASTM C1437 [43].

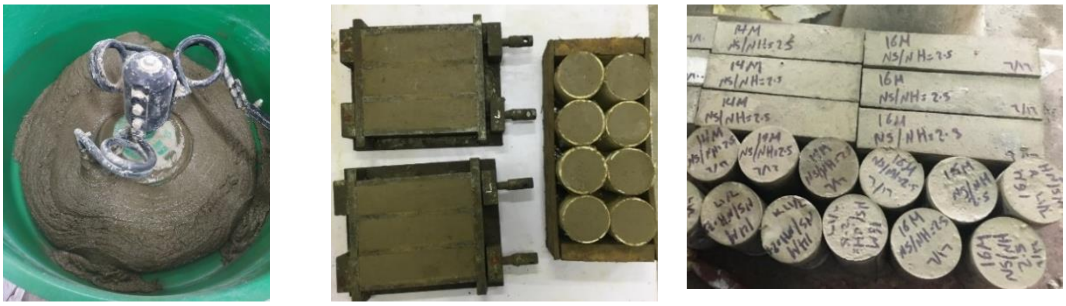
2.4.2 Mechanical properties

The flexural strength was determined using prismatic specimens of size 40×40×160 mm that were prepared. The flexure test was performed by a hydraulic machine with a capacity of 300 kN at the age of 7 and 28 days. Each prism was tested using a three-point loading (bending setup) to obtain the flexural strength. The compressive strength test was conducted by applying an axial load to the two halves resulted after the flexure test. The flexure and compression tests were performed according to EN 196-1 [44]. The compressive and flexural strength was calculated as the average results of three specimens from each mortar mix. The splitting tensile strength was performed according to ASTM C496/C [45], on cylindrical specimens of 50mm in diameter and 100mm in length, respectively.

Table 4: Mixes of Potassium silicate-based GP mortar

Group & Investigated parameters	Mix No	Mix ID	Alkaline solution	Molar	S/FA	Si/H	A/FA
G3 Silicate to hydroxide ratio	1	KN- M14S2Si2.0	KS/NH	14	2.0	2.0	0.50
	2	KN- M14S2Si2.5	KS/NH	14	2.0	2.5	0.50
	3	KN- M14S2Si3.0	KS/NH	14	2.0	3.0	0.50
	4	KK- M14S2Si2.0	KS/KH	14	2.0	2.0	0.50
	5	KK- M14S2Si2.5	KS/KH	14	2.0	2.5	0.50
	6	KK- M14S2Si3.0	KS/KH	14	2.0	3.0	0.50
G4 Sand to fly ash ratio	7	KN- M14S1.5Si2.5	KS/NH	14	1.5	2.5	0.50
	8	KN- M14S2Si2.50	KS/NH	14	2.0	2.5	0.50
	9	KN- M14S2.5Si2.5	KS/NH	14	2.5	2.5	0.50
	10	KK- M14S1.5Si2.5	KS/KH	14	1.5	2.5	0.50
	11	KK- M14S2Si2.50	KS/KH	14	2.0	2.5	0.50
	12	KK- M14S2.5Si2.5	KS/KH	14	2.5	2.5	0.50

Mortar mix ID **S** : refers to S/FA ratio
Si : refers to Si/H ratio



a) Mixing of GP mortar b) Geopolymer mortar after cast in molds c) Geopolymer mortar after heat curing

Fig. 3. Geopolymer mortar specimens

3. RESULTS AND DISCUSSIONS

3.1 Workability of GP mortar mixes

The type of the used alkaline solution and concentration of hydroxide solution, which depends on the dissolving mass of NaOH or KOH have a clear impact on the consistency of the geopolymer mortar mixes. The obtained results as shown in **Fig. 4** revealed that increasing molarity of the NH or KH solution leads to flow percentage reduction of all GP mortar mixes. These findings are more similar to that detected by Malkawi et al, 2016 and Mermerdaş et al, 2020 [46, 47]. For different types of alkaline solutions, the decrease in flow percentage from 10M to 16M in NN, NK, KN and KK mixes was 20%, 22.8%, 17.9%, and 15%, respectively. This can be attributed to the fact that increasing the concentration of NH or KH led to increase the viscosity of the solution. It can be clearly noticed that the values of the flow percentage of sodium silicate-based GP mortar mixes are less than potassium silicate-based GP mortar mixes at the same concentration of hydroxide solution. For 14M of NN, NK, KN, and KK mixes, the flow percentage were 57%, 91%, 113%, and 158% respectively. The reason for this can be attributed to the fact that the viscosity of sodium silicate is higher than that of potassium silicate. The highest flow percentage of the mixture is recorded with a combination of potassium silicate and potassium hydroxide. It is clear that the presence of potassium hydroxide either with sodium silicate or potassium silicate enhances the workability of the geopolymer mortar. The ratio of alkaline solution to fly ash has a direct effect on the flow percentage of GP mortar as shown in Fig. 5. For mixtures NN, NK, KN, and KK, increasing the A/FA from 0.40 to 0.50 led to increasing the workability by percentage of 33.3%, 50.5%, 58.8% and 38.4%, respectively.

For potassium silicate-based GP mortar mixes, it can be clearly noticed that increasing Si/H ratio resulted in reducing the flow percentage of the mortar. The flow percentage reduced by 35.17% and 25.6% for NK and KK mixes, respectively as shown in Fig. 6. These findings are more similar to that detected by (Görhan et al, 2014) [48] which concluded that increasing the silicate content led to a reduction of the workability. Also, it is clear that increasing the S/FA decreases the flow percentage by about 58.4% and 50% for NK and KK mixes, respectively as shown in Fig. 7. These data are parallel to that achieved by (Bhowmick et al, 2012) [49] who indicated that increasing the sand aggregate ratio decreases the flow and make the mortar very stiff and difficult to pack into the molds.

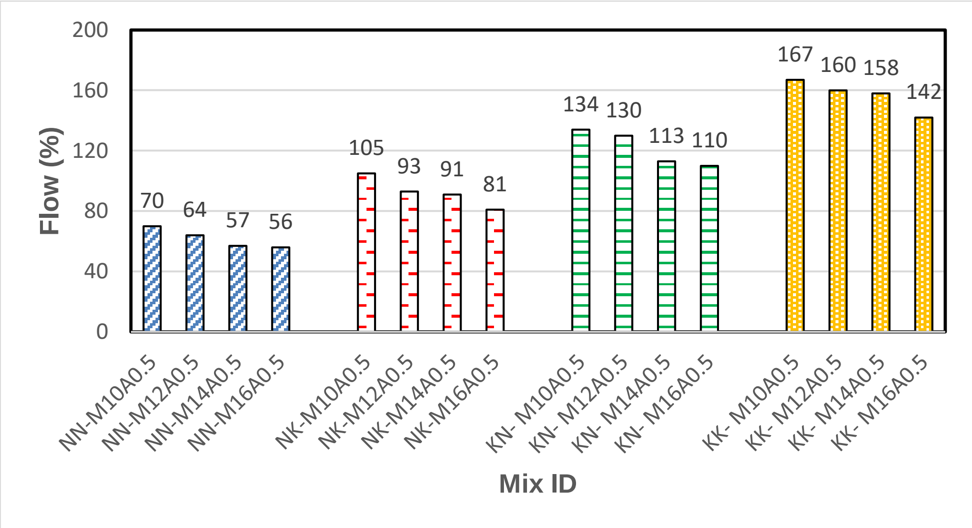


Fig. 4: Flow test results of GP mortar mixes with different types of alkaline solution and variable molarities

3.2 Compressive strength of GP mortar

The studied parameters were included type of alkaline solution, molarity of NaOH and KOH, and ratio of alkaline solution to binder. Moreover, the effect of silicate to hydroxide solution ratio and sand to fly ash ratio were studied. Compressive strength test results of the studied GP mortar mixes are presented as following.

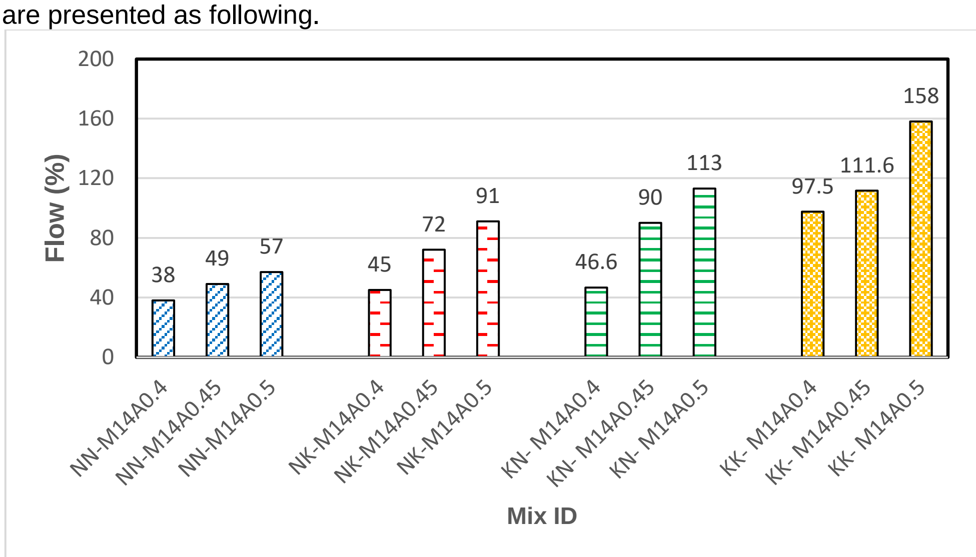


Fig. 5: Flow test results of GP mortar mixes with different A/FA ratios

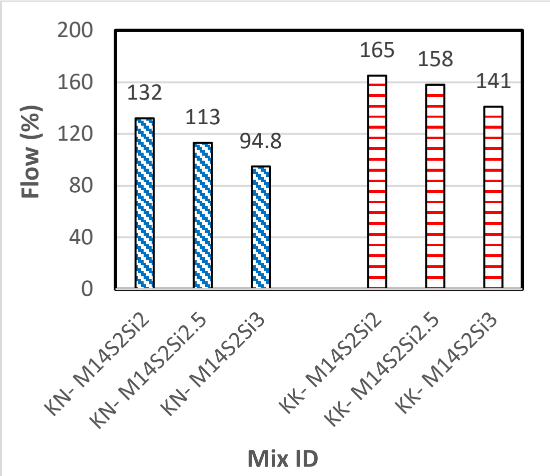


Fig. 6: Flow test results of GP mortar mixes with different Si/H

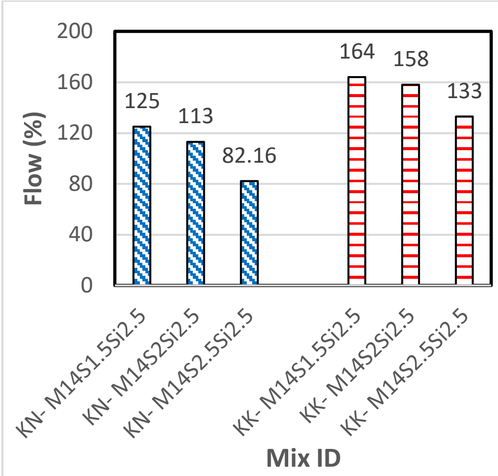


Fig. 7: Flow test results of GP mortar mixes with different S/FA ratios

3.2.1 Effect of different types of alkaline solutions with variable molarities

The obtained results as shown Fig. 8 revealed that increasing molarity of NH or KH in sodium or potassium silicate-based GP mortar mixes (NN, NK, KN, and KK) enhances the compressive strength of mortar mixes at 7 and 28 days. For sodium silicate-based GP mortar mixes, increasing molarity of NH or KH from 10M to 16M leads to increase in the compressive strength while for potassium silicate-based GP mortar (KN and KK) increased up to 14M only. After this molarity level, a reduction in compressive strength was noticed at 7 and 28 days. It is clear that the compressive strength results are very close at 14M at 7 and 28 days for the four investigated alkaline solutions. For instance, the compressive strength was 51.3, 53.8, 52.65, and 45.8 for NN, NK, KN, and KK mixes at concentration of 14M for NH and KH solution, respectively at 7 days age. In addition, it is clearly noticed that the values of the compressive strength of sodium silicate-based GP mortar (NN and NK) mixes were higher than potassium silicate-based GP (KN and KK) mixes at 7 and 28 days.

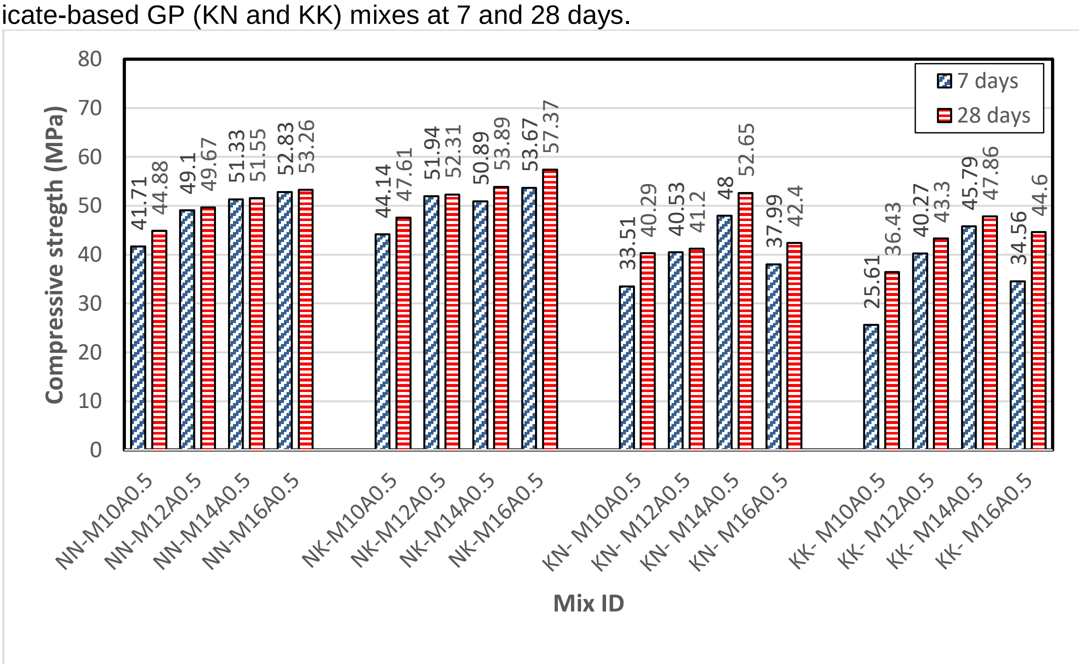


Fig. 8: Compressive strength test results of different types of alkaline solution with variable molarities GP mortar mixes

3.2.2 Effect of different alkaline solution to binder ratios

The effect of different A/FA ratios on the compressive strength of GP mortar mixes were observed through three different ratios. The increasing in A/FA ratio leads to a decrease in the compressive strength at 7 and 28 days, as shown in **Fig. 9**. Of course, the concept here is similar to the w/c ratio and its effect. It was clearly noticed that increasing A/FA from 0.4 to 0.5 led to a decrease of the compressive strength by percentages of 11.2%, 8.93%, 22.5%, and 17.7% of NN, NK, KN, and KK mixes at age of 7 days, respectively. The compressive strength of potassium silicate-based GP mortar (KN and KK) mixes was found to be more affected by changing A/FA ratio.

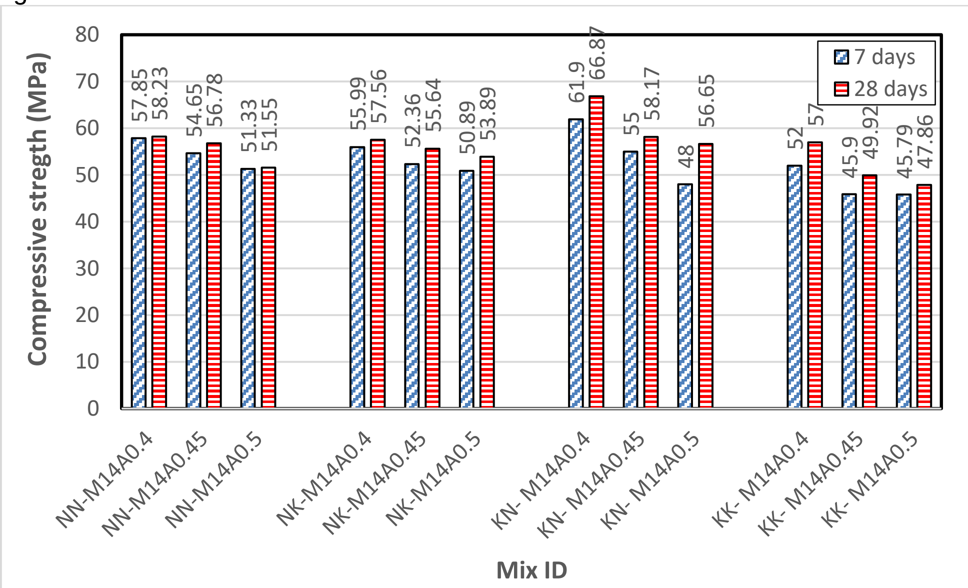
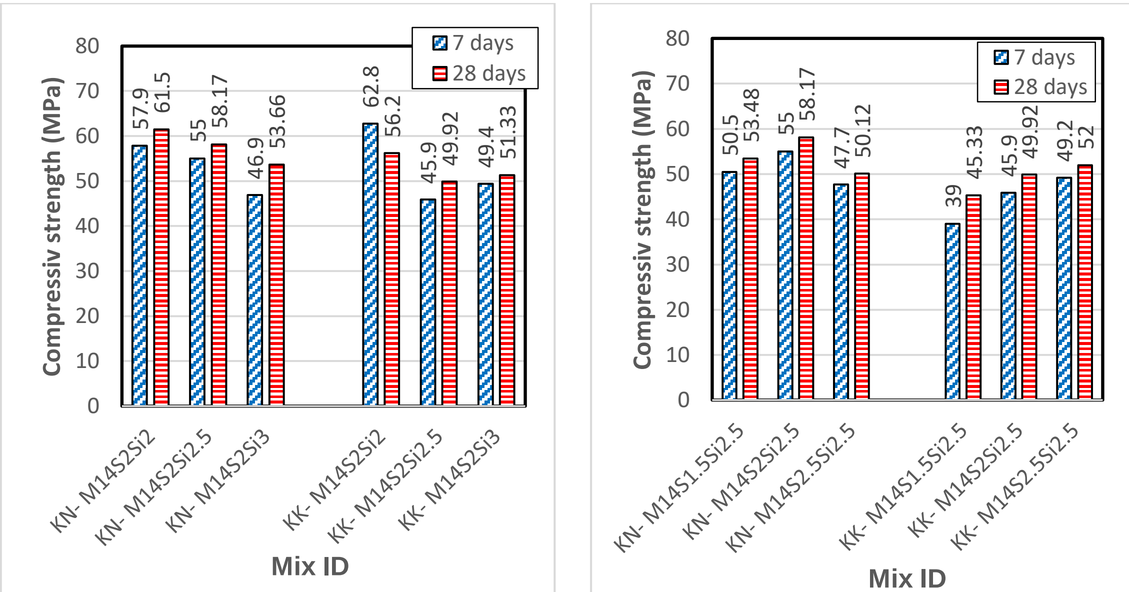


Fig. 9: Compressive strength test results of GP mortar mixes with different A/FA ratios



a) Si/H ratios b) S/FA ratios

Fig. 10: Effect of Si/H and S/FA ratios on compressive strength of NK and KK mixes

3.2.3 Effect of Si/H and S/FA ratios on potassium silicate-based GP mortar mixes

Effect of different Si/H and S/FA ratios on potassium silicate-based GP mortar mixes was as shown in **Fig. 10**. For KN mixes, increasing Si/H ratio from 2.0 to 3.0 leads to a decrease of the compressive strength by percentages of 18.9% and 12.7% at age of 7 and 28 days, respectively. For KK mixes, increasing Si/H ratio from 2.0 to 2.50 caused a decrease in the compressive strengths by percentages of 26.9% and 11.2% after 7 and 28 days, respectively. But raising Si/H ratio from 2.5 to 3.0 caused a reduction in the compressive strengths by percentage of 8% and 2.8% after 7 and 28 days, respectively. Also, increasing S/FA ratio from 1.5 to 2.0 in NK mix leads to an increase in the compressive strength by percentages of 10% and 8% after age of 7 and 28 days, respectively. After increasing the S/FA ratio from 2.0 to 2.5, the compressive strength decreased by percentages of 13.3% and 13.75 % after age of 7 and 28 days, respectively. For KK mix, increasing the S/FA from 1.5 to 2.5 ratio leads to increase by percentage of 21.2% after age of 7 days and by percentage of 9.3% after age of 28 days.

3.3 Flexural strength of GP mortar

The studied parameters were included type of alkaline solution (four different alkaline solution were used), molarity of NaOH and KOH (10M, 12M, 14M, and 16M), ratio of alkaline solution to binder (0.40, 0.45, and 0.50). The effect of silicate to hydroxide solution ratio (2.0, 2.5, and 3.0) and sand to fly ash ratio (1.5, 2.0, and 2.5) were studied. Flexure strength test results of the studied GP mortar mixes are presented as following.

3.3.1 Effect of different types of alkaline solution with variable molarities

The results plotted in **Fig. 11** shows that increasing molarity of NH or KH in sodium silicate-based GP mortar mixes (NN and NK) leads to increase of the flexural strength up to 16M. Such finding coincides with that obtained by (Ghazy et al., 2017) [50]. But for potassium silicate-based GP mortar mixes, increasing molarity of NH or KH leads to increase the flexural strength up to 14M only then a reduction in flexural strength was recorded up to 16M. The increase of flexural strength from 10M to 14M was by percentages of 51.33%, 13.9%, 33.7%, and 44.4% at age of 7 days and by 26.4%, 10.4%, 25.4%, and 41% at age of 28 days for NN, NK, KN, and KK mixes, respectively. The decrease in flexural strength from 14M to 16M was by percentages of 13.4% and 18.1% for KN and KK mixes, respectively at age of 7 days and by percentages of 26.1% and 15.1%, respectively at age of 28 days.

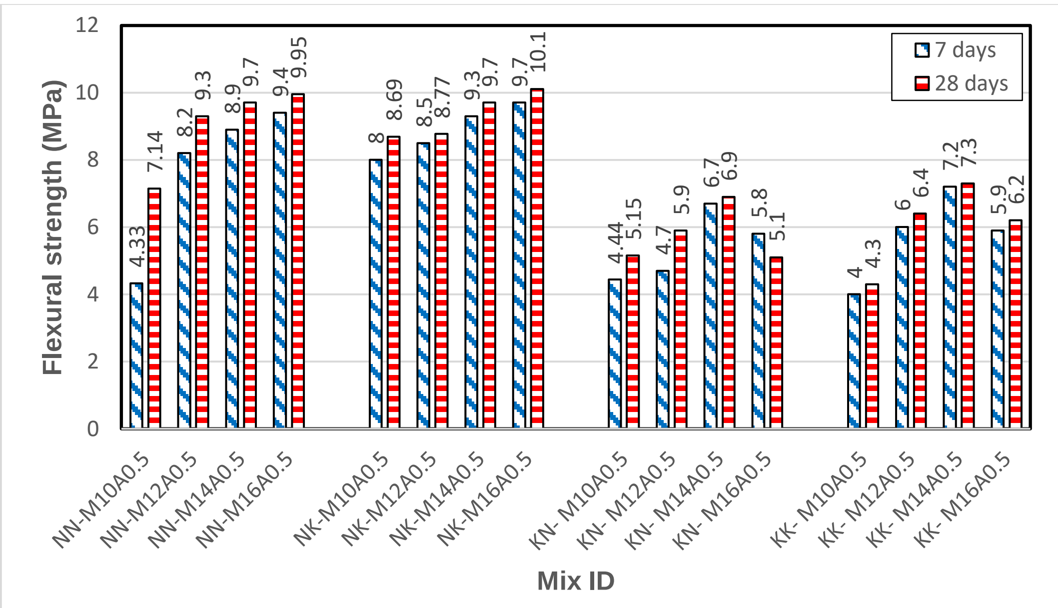


Fig. 11: Flexure test results of different alkaline solution and molarities of GP mortars

3.3.2 Effect of different alkaline solution to binder ratios

The effect of different A/FA ratios on the flexural strength of GP mortar mixes for constant ratios S/FA as 2.0 and Si/H as 2.50 and molarity of NH and KH as 14M can be observed by comparing three ratios of 0.4, 0.45, and 0.5 for all GP mortar mixes. **Fig. 12** shows that increasing the A/FA ratio leads to a direct decrease in the flexure strength at 7 and 28 days. For instance, the flexural strength of NN, NK, KN, and KK mixes decreases by percentages of 6.3%, 10.2% to 2.2%, and 5.2%, respectively after age of 7 days and by percentages of 6.3%, 11.6%, 28.1%, and 7.5%, respectively after age of 28 days.

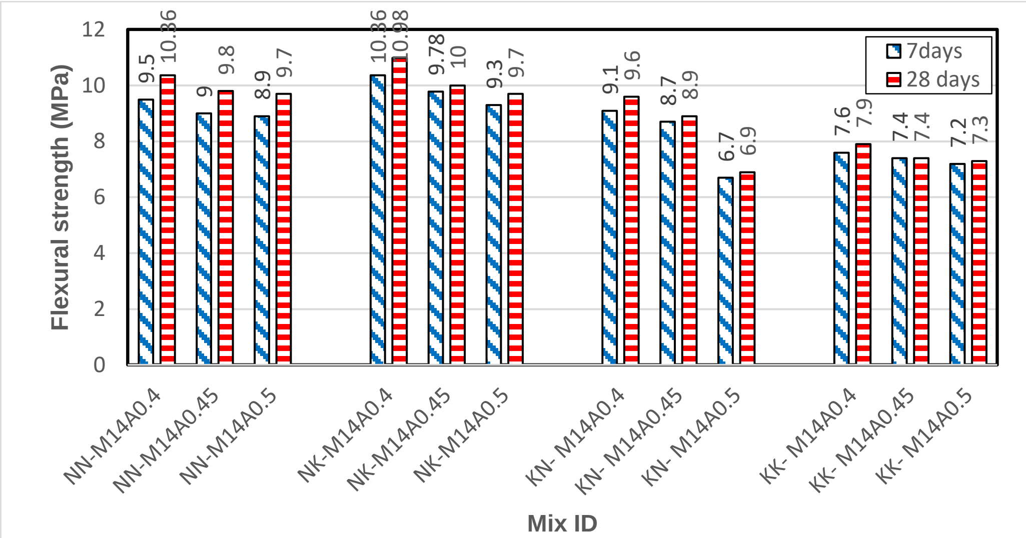
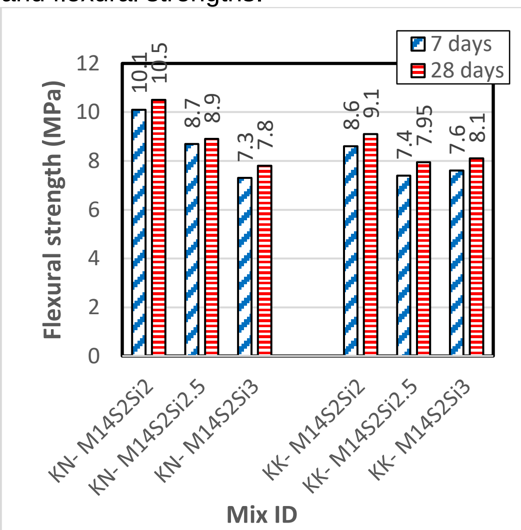


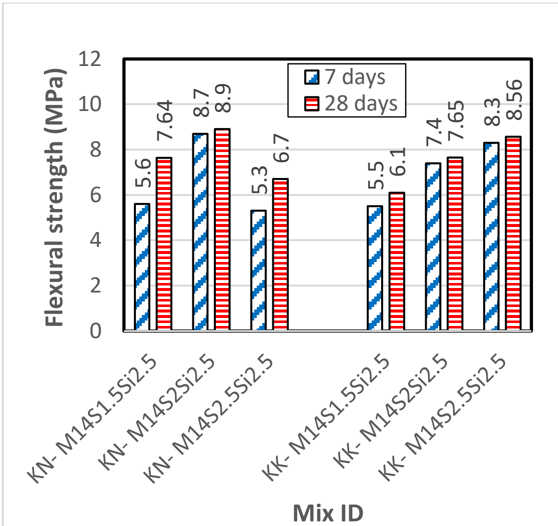
Fig. 12: Flexure test results of different A/FA of GP mortar mixes

3.3.3 Effect of Si/H and S/FA ratios on potassium silicate-based GP mortar mixes

The effect of Si/H ratio of KN and KK mixes can be observed by comparing the results of three different ratios of 2.0, 2.50, and 3.0 as shown in **Fig. 13**. For KN mix, it is clear that increasing Si/H ratio from 2.0 to 3.0 leads to a decrease on the flexural strength by percentage of 25.7% after 28 days. For KK mixes, increasing Si/H ratio from 2.0 to 2.50 caused a decrease in the flexural strength by percentage of 13.9% and 12.6% after 7 and 28 days, respectively. But increasing Si/H ratio from 2.5 to 3.0 caused a slightly increase in the flexural strength by percentages of 2.6% and 1.9% after 7 and 28 days, respectively. For KK mixes, Increasing S/FA ratio from 1.5 to 2.5 leads to a remarkable increase in flexural strength. For KN mixes, Increasing S/FA ratio from 1.5 to 2.0 leads to an increase in the flexural strength after age of 7 and 28 days. But increasing the ratio from 2.0 to 2.50 decreases the flexural strength. It can be concluded that the effect of SI/H and S/FA ratios showed the same trend of the compressive and flexural strengths.



a) Si/H ratios



b) S/FA ratios

Fig. 13: Effect of different Si/H and S/FA ratios on flexural strength of NK and KK geopolymer mortar mixes

3.4 Splitting tensile strength of GP mortar

The studied parameters were included type of alkaline solution (four different alkaline solution were used), molarity of NaOH and KOH (10M, 12M, 14M, and 16M), ratio of alkaline solution to binder (0.40, 0.45, and 0.50). The effect of silicate to hydroxide solution ratio (2.0, 2.5, and 3.0) and sand to fly ash ratio (1.5, 2.0, and 2.5) were studied Splitting tensile strength test results of the studied GP mortar mixes are presented as following.

3.4.1 Effect of different types of alkaline solution with variable molarities

The findings in **Fig. 14** indicated that increasing the concentration of NH or KH leads to increase the splitting tensile strength. The effect of molarity can be observed by comparing the tensile strength of mixes containing NH and KH with molarity of 10M, 12M, 14M, and 16M. In general, increasing the molarity of NH or KH enhances the splitting tensile strength. For mixes containing sodium silicate, increasing the molarity from 10M to 16M increases the tensile strength of NN and KK by percentages of 35.7% and 13.76%, respectively after age of 7 days. But for mixes containing potassium silicate, the splitting tensile strength increased up to 14M only for KN and KK by percentages of 28.7% and 14.5%, respectively after age of 7 days and then decreased after this level of molarity up to 16M by percentages of 25.2% and 13.5% for KN and KK, respectively after age of 7 days.

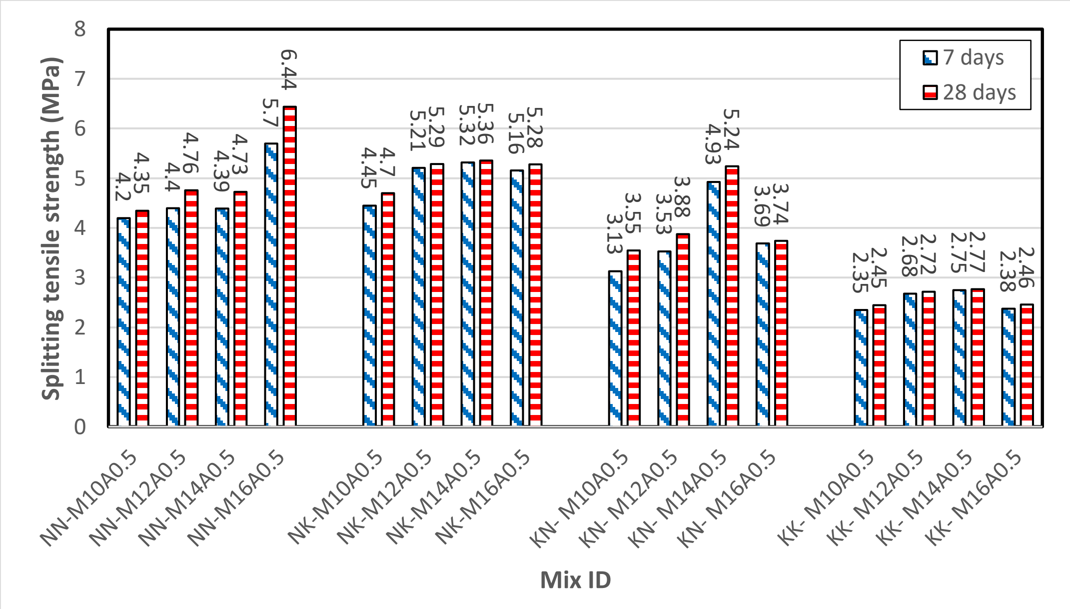


Fig. 14: Splitting tensile test results of different alkaline solutions and molarities of GP mortars

3.4.2 Effect of different alkaline solution to binder ratios

The obtained results as shown in **Fig. 15** revealed that increasing A/FA ratio leads to decrease the splitting tensile strength for all the GP mortar mixes at constant ratios of S/FA (2.0), Si/H (2.50) and molarity of 14M. Increasing the A/FA ratio from 0.4 to 0.5 leads to a direct reduction in the splitting tensile strength by percentages of 23.9%, 3.3%, 26.4%, and 48.5% for NN, NK, KN, and KK after age of 7 days and by percentages of 19%, 12.13%, 24.6%, and 49.8% after age of 28 days. It is clear that, KN mix is the less affected by increasing the alkaline solution ratio. In contrast, KK mix recorded a significant decrease in the splitting tensile strength due to the increase in the ratio of the solution.

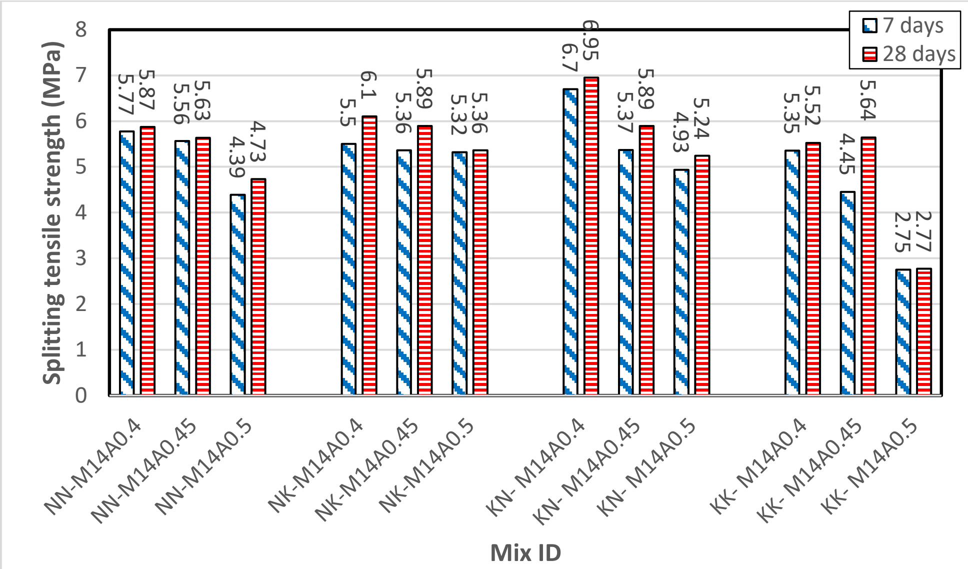
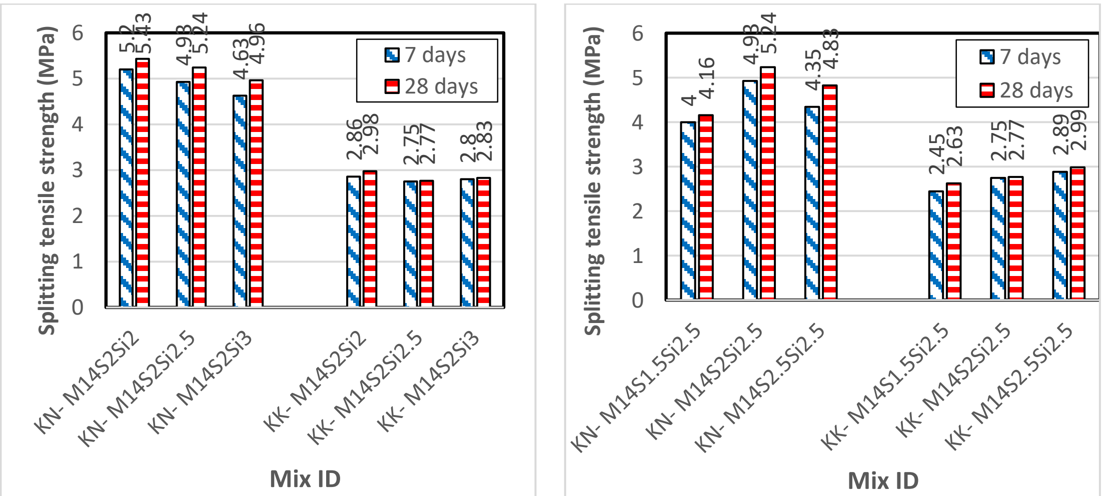


Fig. 15: Splitting tensile test results of different A/FA of GP mortars

3.4.3 Effect of Si/H and S/FA ratios on potassium silicate-based GP mortar mixes

The results are plotted in Fig. 16. For KN mixes, increasing Si/H ratio from 2.0 to 3.0 leads to decreasing of the splitting tensile strength by percentage of 10.9% and 8.7% at age of 7 and 28 days, respectively. For KK mixes, increasing Si/H ratio from 2.0 to 2.50 caused a decrease in the splitting tensile strength by percentage of 3.8% and 7% after 7 and 28 days, respectively. But increasing Si/H ratio from 2.5 to 3.0 caused an increase in the splitting tensile strength by percentage of 1.8% and 2.12% after 7 and 28 days, respectively. It was clear that increasing S/FA ratio from 1.5 to 2.0 in NK mix leads to an increase in the splitting tensile strength by percentages of 18.8% and 20.6% after age of 7 and 28 days. But increasing the S/FA ratio from 2.0 to 2.5, the splitting tensile strength decreased by percentages of 11.8% and 11.6 % after age of 7 and 28 days. For KK mix, increasing the S/FA from 1.5 to 2.5 ratio leads to an increase in the splitting tensile strength by percentage of 15.2% after age of 7 days and by percentage of 12.1% after age of 28 days.



a) Si/H ratios b) S/FA ratios

Fig. 16: Effect of different Si/H and S/FA ratios on splitting tensile strength of NK and KK geopolymer mortar mixes

4. CONCLUSIONS

Based on the current experimental investigation and the analysis of the obtained results, the following conclusions can be drawn,

- Increasing the concentration of the hydroxide solution reduces the workability of all geopolymer mortar mixes.
- The presence of potassium silicate or potassium hydroxide in fly ash geopolymer mortar generally enhances the workability
- The highest flow percentage of fly ash based-geopolymer mortar is recorded by a mixture of KS+KH solutions which is highly recommended for production of self-compacting geopolymer mixes.
- Increasing the silicate to hydroxide ratio and sand to fly ash ratio has a negative impact on the workability of potassium silicate-based geopolymer mortar prepared by NH or KH.
- In case of sodium silicate-based geopolymer mortars, the concentration of NH or KH of 16M achieves the maximum compressive strength.
- On the other hand, in case of potassium silicate-based geopolymer mortars, the concentration of NH or KH of 14M achieves the maximum compressive strengths.
- In case of fly ash based-geopolymer mortar mixes containing a mixture of KS with KH, increasing the sand to fly ash ratio enhances the compressive strength.

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