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Very high strength (120 MPa) class F fly ash geopolymer mortar activated at different NaOH amount, heat curing temperature and heat curing duration

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HIGHLIGHTS

- Influence of activator concentration on geopolymer mortar compressive and tensile strength was investigated.
- Influence of heat curing temperature and duration on geopolymer mortar compressive and tensile strength were investigated.
- Very high compressive strength (120 MPa) and tensile strength (15 MPa) geopolymer were obtained.
- For a constant curing temperature, optimal activator content was existed for maximal strength.
- For a constant activator content, optimal temperature was existed for maximal strength.

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ABSTRACT

In this laboratory work, high compressive and flexural tensile strength of alkali activated fly ash geopolymer mortars were presented. Class F fly ash was used throughout the study. NaOH was used as alkali medium that provides high pH value. Also, the factors influencing the compressive and flexural tensile strength were investigated. A total of 216 fly ash geopolymer mortar samples were prepared. Heat curing temperature, heat curing duration and alkali (Na) concentration were chosen as the influencing parameters of strengths. Mortar mixture parameters were 3 and 1/3 for sand–binder ratio, and water–binder ratio, respectively. Na concentrations of the mortar mixtures were changed from 4% to 20% with 2% increment step. Heat curing temperatures were changed from 45 to 115 °C with 10 °C increment step. Heat curing durations were chosen as 24, 48 and 72 h. For each combination of influencing parameter, three prismatic specimens with 40 mm × 40 mm × 160 mm dimensions were prepared using a three-cell mortar cast. After heat curing period in a laboratory oven, the samples were left to cool down to room temperature, then compressive and flexural strengths were measured as described in its respective standard. Very high compressive and flexural tensile strength obtained, which were as high as 120 and 15 MPa respectively.

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1. Introduction

It is known that cement production is an energy intensive process that consumes enormous amount of energy, also production of cement is held responsible for CO_2 emission at about 7% into atmosphere. Production of a tone cement is responsible for a tone CO_2 emission during calcinations of calcareous materials, and burning coal or fuel to keep high temperatures in a rotary kiln [1,2].

Pressure of the lobby behind the environmental movements, consideration of savings energy and financial expenditure of cement strengthen using by-products binding materials (i.e., silica fume, ground granulated slag, fly ash, etc.) in concrete as cement replacement [3].

Nowadays, using by-products mineral admixtures (i.e., fly ash, slag or silica fume, etc.) in concrete as cement replacement is widespread in practice. In hardened and fresh phase, concrete properties were influenced by the use of fly ash in concrete, it improves workability, increases strength property, reduces drying shrinkage and temperature rise, and increases abrasion resistance of

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concrete. Also, the storage and disposal problems of fly ash is put away [4–6,3].

Atis [3] and Huang et al. [7] studied on the properties of concrete made with very high volume fly ash. They used class F fly ash in concrete mixture; they obtained satisfactory results from their laboratory work. Atis [3] replaced cement up to 70% fly ash by weight; however, Huang et al. [7] put a step further and used 80% fly ash as cement replacement in concrete. The target of these and the other researchers was to utilise fly ash in concrete as a cement replacement up to 100%. This target was achieved by using fly ash as geopolymeric materials.

Geopolymerisation is based on alumino-silica chain. It is a polymeric reaction that takes place between certain amount of alumina and silica in the presence of a strong alkaline solution (i.e., NaOH, KOH, water glass or their combination, etc.). Geopolymerisation is often referred as alkali activation, transforms the amorphous ingredients of materials into a composite that have strong binding property [8–11].

Class F fly ash is a by-product of thermal power plant that produce electricity. Fly ash contains an ample quantity of amorphous alumina and silica. Therefore, it is a suitable and a good source material for producing geopolymeric binder owing to its chemical compositions [12].

It is obvious that strong alkaline medium is necessary to activate amorphous phase of fly ash, alkaline medium plays a catalysing role in the geopolymerisation reaction. Therefore, concentration of activation materials plays an important role in the reaction. Alkaline medium dissolves the soluble amorphous classy content of fly ash ingredients in the first step of polymeric reaction to form geopolymer precursors and finally aluminosilicate material [13]. The higher alkali concentration increases amount of dissolved amorphous content of fly ash in the medium which is important for the following geopolymerisation reaction and mechanical properties of hardened geopolymer product [14,15]. Therefore, one of the important parameter that plays an important role in the geopolymerisation is concentration of alkaline medium.

Studies have shown that temperature of curing medium is another parameter that has important role in geopolymerisation process [10,16]. For instance, particularly at ambient temperature polymerisation process of a fly ash-based geopolymer is very low, however, the rate of geopolymeric reaction increases with an increase in temperature of the curing medium [17,13,10,18,19].

Since geopolymerisation process is a chemical reaction, curing period also takes an important role in production of fly ash-based geopolymer [16,20,21].

A literature survey on the compressive strength (CS) of fly ash-based geopolymer concrete and mortar has been carried out. This is presented in the succeeding discussions.

Gorhan and Kurklu [17], studied the effect of alkali activator solution on the fly ash geopolymer mortar properties cured at 65 and 85 °C degree. NaOH solutions at different concentrations (3, 6 and 9 M) were used as activator, mortar samples prepared were cured up to 24 h at those given curing temperature, then, samples were stored at ambient room temperature until testing that took place at 7-day. They obtained 22 and 8 MPa, compressive and flexural tensile strength (FTS) respectively, from the mixture made with 6 M NaOH solutions and cured at temperature of 85 °C, for 24 h heat curing duration. They concluded that an increase in the curing temperature increased the strength property. Furthermore, they reported that 6 M NaOH concentration was an ideal alkaline medium to obtain the highest compressive strength. However, geopolymer mortar flexural strength showed contradictory trend depending on the curing temperature. For instance, the flexural strengths of samples cured at 65 °C for 2 and 5 h, decreased with an increase in the NaOH concentration. A different trend was reported for the mortars cured for 24 h. It was observed from their results that as the curing duration increases, the strength property increases in general.

Joseph and Mathew [22] investigated the effects of aggregate content on strength properties of geopolymer concrete made with fly ash. They used NaOH and water glass mixture solution as activator, fresh geopolymer mixture were kept in room temperature for 60 min prior to heat curing at 60–120 °C for up to 72 h. After heat curing period, samples were then de-moulded and kept in room temperature until testing time 3, 7 and 28 days. They reported 58, 4.95 and 4.51 MPa a compressive, flexural and splitting tensile strength obtained, respectively, from the mixture cured at 100 °C curing temperature for 24 h, and tested at 28 days.

Olivia and Nikraz [23] attempted to design the properties of fly ash geopolymer concrete using Taguchi method; they achieved CS in the order of 60 MPa. In the geopolymer mixture, they used 14 M NaOH solution with sodium silicate, sodium silicate to NaOH ratio was between 1.5 and 2.5, and sample were cured for 24 h heat curing duration at 75 °C.

Ryu et al. [24] investigated the strength properties of concrete made with alkali activated fly ash, they used NaOH and water glass as activator, and geopolymer concrete samples were cured for 24 h at 60 °C and further 55 days in laboratory condition. The highest compressive strength reported was in the order of 45 MPa.

Skvara et al. [25] studied on a low calcium Czeck fly ash obtained by burning brown coal; they activated brown coal fly ash using NaOH plus water glass. Samples cured at 80 °C for 12 h, developed 40 MPa compressive strength at 28 days.

Vora and Dave [26] carried out a parametric study on compressive strength of geopolymer concrete made with class F fly ash. Mixture of NaOH and water glass was used as activator; they reported that the highest compressive strength was in the order of 40 MPa.

Xin et al. [27] reported compressive and flexural tensile strength in the order of 60 and 6 MPa respectively, which were obtained from slag–fly ash geopolymeric material system.

Topcu et al. [28] reported that the highest compressive strength obtained from alkali activated coal bottom ash geopolymer cement was in the order of 25 MPa.

De Vargas [29] investigated compressive strength development of fly ash geopolymer system activated by combined NaOH and Ca $(OH)_2$ mixture, in the order of 30 MPa compressive strength was reported.

Somna et al. [13] reported compressive strength in the order of 25 MPa, they used 16 M alkali activator prepared by mixing NaOH with water glass, and geopolymer sample was cured at ambient temperature for 28 days.

The aim of this study is to exploit full potential of geopolymeric and binding properties of class F fly ash and produce high strength mortar, a parametric study was carried out to achieve this purpose. Amount of NaOH or molarity, activation temperature, and heat curing period were chosen as the influencing parameters. Nine different amount of NaOH, and three different heat curing periods and eight different temperatures were considered. Due to high amount of data, in this study, only compressive and flexural tensile strength of fly ash geopolymer mortar were presented and discussed, durability related properties of high strength class F fly ash geopolymer mortar are going to be discussed in another paper.

2. Properties of materials used

2.1. Fly ash

Fly ash was supplied from ISKEN-Iskenderun Energy Production Plant located in Sugozu village of Yumurtalik county of Adana, which is a southern city of Turkey. Chemical compositions of class F fly ash used were presented in Table 1. Since its total value of $SiO_2 + Al_2O_3 + Fe_2O_3$, is higher than 70% and CaO amount is less than

Table 1
Chemical compositions of fly ash (%).

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	Na_2O	Free CaO	Cl^-	LOI
Fly ash	61.81	19.54	7.01	1.77	0.31	2.43	0.07	0.04	2.20

10%, present fly ash is classified as class F type and low lime fly ash according to ASTM C618 [30] specification. Specific gravity of fly ash was 2.390 and its remaining on 45 μm sieve was 12%.

2.2. Standard sand

Rilem Cembureau Standard sand complied with TSE EN 196-1 [31] specification was used in the production of mortar mixtures. Sieve analysis of standard sand and limits of standard specifications were presented in Table 2. Sieve analysis results are found to be in agreement with the limits of standard.

2.3. Activator

In the laboratory experiment, as an alkali activator sodium hydroxide (NaOH) with more than 97% purity was used. Molecular weight of activator is 40 g/mol. The amount of Na_2CO_3 in activator was less than 1%. Chlore and SO_4 amount in activator were less than 0.01%. Al and Fe contents of activator were less than 0.002%.

2.4. Water

A drinking tap water taken from the city water supply system was used as mixing water.

3. Experimental program

Cement free mortar mixtures made with fly ash used as binder were produced using standard sand, drinking tap water and NaOH as activator. In the mortar mixture, sand/fly ash ratio and water/fly ash ratio were kept constant as 3 and 1/3, respectively. Sodium concentration parameter was changed form 4% to 20% with 2% increment step in weigh basis. Sodium concentration is taken into account in this study, therefore, additional water that comes within NaOH is considered and determined; and then, that amount is reduced from mixing water to keep water/fly ash ratio at 1/3.

Fresh fly ash geopolymer mixture were prepared using different amount of activator concentration, then, they were subjected to eight different heat curing temperatures for three different heat curing duration. Heat curing temperatures were changed from 45 to 115 °C with 10 °C increment step. Heat curing durations were 24, 48 and 72 h.

In preparation of fresh geopolymer mortar mixture, first, NaOH was solved in water; the water–NaOH mixture was rested in laboratory to cool down its temperature. Then, alkali–water solution was put in a Hobart mixture. Sequentially, fly ash was put in the mixer, and alkali solution and fly ash mixed in slow mode for 30 s, and then the sand was poured for 30 s while mixture was running in slow mode. Next, the mixing was continued in fast mode for 30 s, and then the mixer was stopped and held for 15 s automatically, followed by further mixing for 60 s in fast mode. Finally, the freshly mixed mortar was taken from the mixer, fed into specimen moulds and vibrated in two layers until to obtain full compaction.

Three prismatic specimens with 40 mm × 40 mm × 160 mm dimensions were prepared from fresh fly ash geopolymer mixture for the strength measurements using the mixture composition presented in Table 3, the compositions were standardised for a three-cell mould.

After preparing prism specimens using three-cell mould, the mould with fresh mixture of fly ash geopolymer made with a certain Na concentration were put in an oven with a specified temperature for a desired heat curing duration. After heat curing duration, the samples were removed from the oven, then, de-moulded and left in the laboratory condition for an about 30 min to cool down the samples so that testing to be carried out.

For each hardened fly ash geopolymer mortar mixture, flexural tensile strength measurements were carried out using three prismatic specimens by performing a third point loading test described in TS EN 1015-11 [32]. The compressive strength measurements were carried out according to relevant standard TS EN 1015-11 [32], using six broken pieces of the prismatic specimens obtained from flexure test. Average of three specimens and average of six specimens were used for a data point for flexural tensile and compressive strength test, respectively.

Table 2
Gradation of sand used and values of standard limits.

Diameter of sand grain (mm)	0.08	0.16	0.5	1.0	1.6	2.0
Remaining (%)	99	87	72	34	6	0
Limits of specification (%)	99 ± 1	87 ± 5	67 ± 5	33 ± 5	7 ± 5	0

Table 3
Mixture compositions made with different activator concentration.

Sand (g)	Total water (g)	Fly ash (g)
1350	150	450

4. Results and discussions

4.1. Compressive strength

Compressive strengths (CS) of fly ash geopolymer mortar made with Na content that varies from 4% to 20%, and cured at heat curing temperatures that change from 45 to 115 °C for 24, 48 and 72 h are presented in Tables 4–6, respectively.

It can be seen from Tables 4–6 that geopolymer mortar containing different amount of Na content and cured at 45 °C heat curing provided no CS after 24, 48 and 72 h heat curing.

Considering of all heat curing duration case, Tables 4–6 show that the available lowest CS in the order of 1.2 MPa, the highest CS is in the order of 120 MPa. The available lowest CS is obtained from geopolymer mortar containing 4% of Na content at 55 °C heat curing. The highest CS is obtained from geopolymer mortar containing 14% Na content at 115 °C heat curing and for 24 h duration. Regardless of the activator content, heat curing temperature and heat curing duration, the average value of CSs is about 45 MPa. Standard deviation for each compressive strength data point is

Table 4
Compressive strength of geopolymer mortar at 24 h heat curing (MPa).

Na (%) →	4	6	8	10	12	14	16	18	20
45 °C	0	0	0	0	0	0	0	0	0
55 °C	1.6	5.5	7.3	8.4	8.6	3	3	1.2	0
65 °C	3.6	10.6	17.8	22.6	22.8	10.6	6.5	6.5	4.5
75 °C	10.5	13.3	21.3	28.7	29.7	34.3	32.7	18.7	10.7
85 °C	13.2	14.1	23.3	34.9	36.5	38.8	35.8	34.5	30.3
95 °C	17.3	27.7	28.4	32	42.6	70.6	61.5	51	43.6
105 °C	12.6	15.4	17.6	41	56.2	113	112.2	110.7	104.3
115 °C	0	0	0	61.4	73	120	110.5	106.1	88.9

Table 5
Compressive strength of geopolymer mortar at 48 h heat curing (MPa).

Na (%) →	4	6	8	10	12	14	16	18	20
45 °C	0	0	0	0	0	0	0	0	0
55 °C	6	13.2	19	19.7	19.8	8.4	5.2	2.4	2.3
65 °C	9.5	21.8	28	45	48.3	36.3	34.5	29.8	17.2
75 °C	18.1	24.3	35.5	62.7	62.9	63.9	59.1	54	50.3
85 °C	20.5	25.2	40	55.6	62.2	71.6	62.7	58.4	56.1
95 °C	21.4	27.9	45.6	59.5	72.7	99.1	84.6	82.5	74.2
105 °C	14.4	16.9	25.2	46.2	72.5	107.5	100.5	100.3	99.9
115 °C	0	0	0	59.2	69.1	117.4	109.6	100.3	88.6

Table 6
Compressive strength of geopolymer mortar at 72 h heat curing (MPa).

Na (%) →	4	6	8	10	12	14	16	18	20
45 °C	0	0	0	0	0	0	0	0	0
55 °C	7.8	20.2	28.9	38.4	39.5	10.5	8.6	7.7	5
65 °C	14.7	22	36.1	55.1	57	59.2	47.4	46.7	35.1
75 °C	20.1	26.4	38.1	68.1	68.7	60.1	53.2	52.1	46.8
85 °C	20.6	27.1	41.6	68.8	69.8	69.9	60.4	56.1	54
95 °C	21.7	28.3	47.1	70.8	71.1	80.8	80.8	78.5	73.5
105 °C	15.3	17.5	29.7	58.3	69.5	90.4	88.2	84.6	83.6
115 °C	0	0	0	56.7	68.7	108.4	106.7	100	85.6

calculated and average standard deviations are found to be in the order of 5%, highest standard deviation was about 10%.

Tables 4–6 also shows that as heat curing temperatures increases at a particular Na content, CS increases up to a heat curing temperature point, and then decreases after that temperature point. This is valid up to 8% Na concentration for 24 h curing duration (see Table 4). However, it is valid up to 12% Na concentration for 48 h curing duration (see Table 5). For other Na concentration either a clear optimal region or plateau is existed, thus, the authors believe that there would be an optimal point existed in optimal region and plateau-like region.

Similarly, for a particular heat curing temperature, an increase in Na content of geopolymer mixtures causes an increase in CS up to a certain content of Na, and then decreases after that certain point. This observation is in agreement with published results by Gorhan and Kurklu [17]. The decrease in compressive strength after optimal Na concentration was attributed to an increase in the coagulation of silica [14,17].

In addition, an interesting observation was made for 115 °C heat curing that geopolymer mortar containing up to 8% Na content did not developed CS after 24 h of heat curing (see Table 4). The same discussions and findings can be made for the same mixtures subjected to longer heat curing time for 48 and 72 h (see Tables 5 and 6).

A comparison between Tables 4 and 5 shows that when heat curing duration increases from 24 to 48 h, CS of geopolymer mortar increases in general. Error bars determined as standard deviation for each data points support this finding. This finding is also found to be in agreement with published results by Gorhan and Kurklu [17].

Furthermore, another comparison made between Tables 5 and 6 shows that when heat curing duration increases from 48 and 72 h, CS of geopolymer mortar increases but not as much increase as observed from 24 to 48 h case. It is observed from present data, that increase was higher for lower heat curing temperatures than 75 °C, and it is lower for higher heat curing temperatures than 75 °C.

It can also be concluded that for geopolymer mortar containing higher Na content than 12% or higher, and for higher heat curing temperature than 95 °C, 24 h heat curing duration is appropriate. However, for some cases medium heat curing temperature and medium Na content, 48 h of heat curing is appropriate. Similarly, for some cases lower heat curing temperature and lower Na content, 72 h of heat curing or higher is appropriate.

As previously mentioned that geopolymer mortar made with different Na content and cured at 45 °C heat curing temperature for 24, 48 and 72 h duration gave no CS. It is known that at ambient temperature polymerisation process of a fly ash based geopolymer was very low, thus, it can be concluded that 72 h heat curing time is not sufficient, longer curing time (i.e., 96 h or more) is needed to obtain CS for 45 °C temperature or lower. This is proved with a further small laboratory experiment, after finding no CS, the samples made with 14% NaOH were cured for longer time up to 7 days at 45 °C. After 96 h of curing, 2.5 MPa CS was obtained. Furthermore, at seven days curing, 6.4 MPa CS was obtained.

As also previously mentioned that geopolymer mortar made with up to 8% Na content and cured at 115 °C heat curing temperature for 24, 48 and 72 h durations gave no CS. This may be attributed to that 115 °C heat curing temperature evaporates the available water immediately in the mixture before permitting the dissolution of silica of fly ash in alkali medium, thus resulting no CS. Contrary to this, for higher Na concentration high compressive strengths were obtained. It is known that boiling point of NaOH solution increases with the increase in NaOH concentration, thus, boiling points temperature and evaporation is directly related. Thus, higher Na concentrations suppress the evaporation of water and allow more time to dissolve the silica of fly ash in alkali medium.

Apart from these findings from the laboratory study, some recommendation was made based on CS of geopolymer mortar results. As can be seen from Tables 4–6 that a variety of compressive strengths, was presented. These values were dependent on Na content, heat curing temperature and heat curing duration. When it is summarised, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70 75, 80, 85, 90, 95, 100, 105, 110, 115 and 120 MPa compressive strength and values can be observed from these tables. It can be concluded that geopolymeric materials with its compressive strength property can accommodate itself among construction materials. For example building bricks blocks can be produced using alkali activated fly ash geopolymer mortar and concrete, furthermore paving stone, kerb stone, tiles or similar materials can be produced using alkali activated fly ash geopolymer binder. Prefabricated building materials with an appropriate compressive strength can be produced using alkali activated fly ash geopolymer binder. Alkali activation does not only convert fly ash into a binder, but also helps the environment by providing disposal of fly ash, therefore, new appropriate areas can be promoted for use of such an environment friendly materials.

4.2. Flexural tensile strength

Flexural tensile strengths (FTSs) of fly ash geopolymer mortar made with Na content that varies from 4% to 20%, and cured at temperature that change from 45 to 115 °C for 24, 48 and 72 h are presented in Tables 7–9, respectively.

It can be seen from Tables 7–9 that geopolymer mortar containing different amount of Na content and cured at 45 °C heat curing provided no FTS (as observed in CS case) after 24, 48 and 72 h heat curing.

Considering of all heat curing duration case, Tables 7–9 show that the available lowest FTS is in the order of 1 MPa, the highest FTS is in the order of 15 MPa. The available lowest FTS is obtained from geopolymer mortar containing 4% of Na content at 105 °C heat curing. The highest FTS is obtained from geopolymer mortar containing 14% Na content at 115 °C heat curing for 24 h duration. Regardless of the activator content, heat curing temperature and heat curing duration, the average value of FTSs is about 8 MPa. Standard deviation for each flexural tensile strength data point is

Table 7
Flexural tensile strength of geopolymer mortar at 24 h heat curing (MPa).

Na (%) →	4	6	8	10	12	14	16	18	20
45 °C	0	0	0	0	0	0	0	0	0
55 °C	1.7	2.3	2.3	2.4	2.5	1.3	1	1	0
65 °C	1.9	2.5	3.1	4.1	5.9	3.8	2.8	2.5	1.6
75 °C	2.5	3.2	4	5.2	6.3	7.4	8.6	8.9	7.2
85 °C	2.7	3.9	4.1	5.7	6.3	8.5	9.3	9.8	9.8
95 °C	2.9	5.9	6.9	7	8	11.2	10.1	11.5	11.4
105 °C	0.6	3.6	5	7	10.3	14.6	14.4	14.3	13.7
115 °C	0	0	0	6.9	11.8	14.9	14.3	14.2	14.2

Table 8
Flexural tensile strength of geopolymer mortar at 48 h heat curing (MPa).

Na (%) →	4	6	8	10	12	14	16	18	20
45 °C	0	0	0	0	0	0	0	0	0
55 °C	2.6	4.3	4.3	5.3	5.7	3	1.9	1.3	1.3
65 °C	3.4	4.5	5.8	7	9.5	8.8	10.1	7.5	7.3
75 °C	5.1	6.8	7.7	8.4	10.3	13.2	12.6	12.3	9.6
85 °C	4.4	4.7	8.2	8.6	11.1	13.3	13.1	12.4	10.7
95 °C	4.4	6.1	8.9	9.1	10.5	13.5	12.6	12.4	12.4
105 °C	1.2	4.6	7.2	8.2	10.8	13.5	13.6	13.8	12.8
115 °C	0	0	0	6.8	8.3	13.8	13.8	13.9	13.6

Table 9
Flexral tensile strength of geopolymer mortar at 72 h heat curing (MPa).

Na (%) →	4	6	8	10	12	14	16	18	20
45 °C	0	0	0	0	0	0	0	0	0
55 °C	3.2	4.6	5.8	7.7	9.9	3.4	2.9	2.9	2.1
65 °C	3.4	5.3	7.4	10.3	11.8	12.2	11.5	11.4	9.1
75 °C	5.2	7.3	8.3	10.3	12.3	12.9	11.8	11.7	11.3
85 °C	5.8	7.3	8.6	10.3	12.6	12.5	12.3	11.7	11.6
95 °C	6.6	7.3	9.3	10.5	12.7	12.7	12.1	11.8	11.6
105 °C	1.6	6.2	7.6	9	8.5	12.7	12.5	12.3	12.1
115 °C	0	0	0	6.8	8.2	13.1	12.9	12.8	12.8

calculated and average standard deviations are found to be in the order of 6%, highest standard deviation was about 11%.

Tables 7–9 also shows that as heat curing temperatures increases at a particular Na content, FTS increases up to a heat curing temperature point, and then decreases after that temperature point. This is valid up to 8% Na concentration for 24 h curing duration (see Table 7). However, it is valid up to 12% Na concentration for 48 h curing duration (see Table 8). For other Na concentration either a clear optimal region or plateau-like region is existed, thus, the authors believe that there would be an optimal point existed in optimal region or plateau-like region.

Similarly, for a particular heat curing temperature, an increase in Na content of geopolymer mixtures causes an increase in FTS up to a certain content of Na, and then decreases after that certain point. The decrease in FTS after optimal Na concentration could be attributed to an increase in the coagulation of silica [14,17].

An interesting observation was made for 115 °C heat curing; geopolymer mortar containing up to 8% Na content did not developed FTS after 24 h of heat curing. As made in compressive strength discussions, the same discussions and findings can be made for the same mixtures subjected to longer heat curing time for 48 and 72 h (see Tables 8 and 9).

A comparison between Tables 7 and 8 shows that when heat curing time increases from 24 to 48 h, FTS of geopolymer mortar increases in general. Error bars determined as standard deviation for each data points support this finding.

Furthermore, another comparison made between Tables 8 and 9 shows that when heat curing time increases from 48 to 72 h, FTS of geopolymer mortar increases for lower temperature and lower Na concentration. However, it reaches to a plateau with the increase in temperature and Na concentration.

It can also be concluded from FTS results that for geopolymer mortar containing higher Na content than 12% or higher, and for higher heat curing temperature than 95 °C, 24 h heat curing duration is appropriate. However, for some cases medium heat curing temperature and medium Na content, 48 h of heat curing is appropriate. Similarly, for some cases lower heat curing temperature and lower Na content, 72 h of heat curing or higher is appropriate.

As previously mentioned that geopolymer mortar made with different Na content and cured at 45 °C heat curing temperature for 24, 48 and 72 h gave no FTS. This is explained again with slower geopolymerisation of fly ash at lower temperature, thus, it can be concluded that 72 h heat curing time is not sufficient, longer curing time is needed to obtain FTS.

As also previously mentioned that geopolymer mortar made with up to 8% Na content and cured at 115 °C heat curing temperature for 24, 48 and 72 h gave no FTS. This may be attributed to that 115 °C heat curing temperatures evaporate the available water immediately in the mixture before permitting the dissolution of silica of fly ash in alkali medium resulting no FTS. Contrary to this, for higher Na concentration high flexural tensile strengths were obtained. It is known that boiling points of NaOH solution increases with the increase in NaOH concentration, thus, boiling points temperature and evaporation is directly related. Thus, higher Na concentrations suppress the evaporation of water and allow more time to dissolve the silica of fly ash in alkali medium.

Similar recommendation as made in CS case can also be made for FTS case based on FTS results obtained from the laboratory study. As can be seen from Tables 7–9 that a variety of FTSs are presented, these values were dependent on Na content, heat curing temperature and heat curing duration. When it is summarised, 1–15 MPa, FTS values can be observed from these tables. Materials with such a wide FTS category can be employed in different areas of use. It should be noted that 15 MPa for FTS is a respectable value for such a brittle material, i.e., concrete.

5. Conclusions

Based on compressive and flexural tensile strength measurement of geopolymer mortar made with class F fly ash, the following conclusions were made:

(1) This study has shown that it is possible to obtain a very high compressive and flexural tensile strength from fly ash geopolymer mortar mixture. For instance, 120 MPa CS and 15 MPa FTS are obtained from fly ash geopolymer mixture activated with14% NaOH, and cured at 115 °C for 24 h.
(2) As the alkali activator concentration increases in the geopolymer mortar mixture, the compressive and flexural tensile strengths increase up to an optimal point that also depends on heat curing temperature. However, this conclusion is weak and not very clear for very high curing temperature.
(3) When the geopolymer mortar mixture subjected to heat curing process, the compressive and flexural tensile strength increase as the heat curing temperature increases up to an optimal point that also depends on Na concentration. However, this conclusion is weak and not very clear for very high Na concentration.
(4) As the heat curing duration, for a geopolymer mixture, prolongs; the flexural tensile and compressive strength increase in comparison to short curing duration. The order of increase in strengths depends on curing temperature and Na concentration.
(5) For low heat curing temperature, 72 h of heat curing can be sufficient, however, for high heat curing temperature 24 h of heat curing can be sufficient.
(6) For very high heat curing temperature, no strength development was observed for geopolymer mixture containing up to 8% activator concentration.
(7) Fly ash geopolymer mortar mixtures cured at 45 °C temperature did not develop proper strength even after 72 h curing duration; this proved that geopolymerisation process of class F fly ash is slower at certain temperature (i.e., 45 °C) and lower.
(8) Current class F fly ash can be used in the production of geopolymeric concrete or mortar as a construction material.
(9) The strength results show that development of higher strength than those present one is possible by using the present fly ash.

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