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Evaluating the Impact of Inclusion Metakaolin and Silica Fume on the Green and Mechanical Properties of Low Calcium Fly Ash Concrete

Sarah Al-Qutaifi[1], Saleem Ethaib[2*], Yahya Resan Awei[2]

[1] Department of Reconstruction & Projects, University of Thi-Qar, Al-Nassiriya 64001, Iraq
[2] Department of Civil Engineering, College of Engineering, University of Thi-Qar, Al-Nassiriya 64001, Iraq

Corresponding Author Email: salem_eidt@yahoo.com

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ABSTRACT

Generally, low calcium fly ash concretes (FFACs) subjected to ambient temperatures exhibit low initial strengths. Thus, FFACs require higher temperatures to improve the monomer dissolutions, but that increases the energy consumption. Thus, this paper aims to evaluate the influence of the incorporation of different dosages of silica fume (SF) and metakaolin (MK) on the green and hardened properties of FFACs cured at room temperature of 21℃. Slump and air content tests were applied to evaluate the green characteristics of the designed geopolymer concrete mixes (GPCMs). The hardened properties of FFACs were assessed in terms of compressive, flexural, and splitting tensile strengths at different curing ages. Outcomes revealed that the slump and air content of GPCMs declined with improving SF or MK percentages. The 28 days flexural, compressive, and splitting tensile strengths of FFACs manufactured with the optimum dosages of 20% MK and 10% SF cured at 21℃ were evidently higher than those of FFACs (100% FFA) subjected to curing temperatures ranging from 10-to-50℃. Also, the strength enhancement of MK was relatively comparable to those of SF with less requirement for superplasticizers.

1. INTRODUCTION

Ordinary Portland Cement (OPC) is frequently utilized in building materials attained from lime oxides. OPC possesses several preferred mechanical and physical properties and the affordability and availability aspects [1]. However, the cement production process is tremendously energy-intensive and extremely harmful to the environment [2]. Specifically, OPC contributes to depleting the ozone layer by releasing high percentages of carbon dioxide emissions (CO_2) and other patterns of greenhouse gases [3]. Statistics indicated that 13500 million tons of carbon dioxide (CO_2) is globally resulted by the traditional cement production procedure. It approximately equals 7% of CO_2 annually [4]. Thus, in recent decades, massive research projects have been focused on developing sustainable and eco-friendly alternatives to OPC by using geopolymers or pozzolanic materials. Geopolymers (GPs) are cementitious materials utilized as additives or admixtures as wholly or partly substituting to OPC to manufacture high strength, and durable concretes [5, 6]. Fly ash (FA), metakaolin (MK), ground granulated blast furnace slag (GGBS), rice-husk ash (RHA), silica fume (SF), and red mud (RM) are some examples of geopolymer materials utilized in manufacturing concretes with superior properties. Some types of GPs have produced by-products as waste products such as silica fume (SF), rice-husk ash (RHA), fly ash (FA), red mud (RM), etc. Otherwise, they are made of industrial natural aluminosilicates i.e., metakaolin (MK). While, other geopolymer source materials can be found as natural minerals such as clays, kaolinite, etc. GPs are frequently produced from materials possessed alkali-activated aluminosilicates compounds without or with calcium elements [7]. According to alkali-activated aluminosilicate technology, geopolymers show lower energy consumptions and thus result in lower CO_2 compared to conventional cement (OPC).

Source materials and alkaline activators are the essential constituents in forming GPCs. Geopolymer source materials should be rich in silica (SiO_2) and alumina (Al_2O_3) [8]. Based on alumina (Al_2O_3) and silica (SiO_2) contents of GP source materials, it can be derived three patterns of 3D alumina-silicate structures, varying from semi-crystalline to the amorphous state [9]. The mechanical and physical properties of geopolymer concrete (GPCs) are highly dependent on Si/Al ratio and SiO_2 and Al_2O_3 contents [10]. Geopolymers involve a substantial influence on enhancing the chemical, physical, and hardened properties of concrete. More specifically, GPs contribute to producing concrete with higher early strength, lower permeability, more superior fire resistance, and higher acid resistance compared to those of OPCs [11]. Therefore, their usages in concretes as cementitious or additional materials have been promoted in modern civil engineering. [12].

Some geopolymer-based materials require higher temperature levels to improve the monomer dissolutions. Consequently, that raises the energy consumption and then expands the greenhouse gas emission [13]. Several papers have revealed that the substitution of OPC by FA decreases the hydration heat and enhances the long-term strength owing to the effect of the pozzolanic reactions of FA. More specifically, the pozzolanic reaction of FA-based materials is highly slow at room temperature. Thus, concretes manufactured with fly ash (FA) exhibit high setting times and a consequential low early strength [14]. This issue can be addressed by incorporating specific percentages of calcium hydroxide constituents Ca $(OH)_2$. Particularly, those components possess high percentages of calcium (Ca), which enhances the setting times and initial strengths of FA-based concrete [15]. Additionally, the percentages of applied alkaline activators and the sodium hydroxide concentration have sizable effects on setting times and initial strengths of FA-based concretes. The inclusion of additional silicate into the GP system through incorporating some of GPs such as SF, MK, or GGBS can also improve the reactivity of pozzolanic materials, enhance the cement hydration, as well as the concrete strength growth [16]. Therefore, the current research paper aims to evaluate the influence of incorporating SF and MK on the green and hardened characteristics of low calcium fly ash concretes (FFACs) cured at room temperature of 21 ˚C. Moreover, the effect of different ranges of curing temperatures on the hardened properties of FFACs produced with 100%FFA has been inspected. The replacement percentages of low calcium fly ash (FFA) by SF or MK were 5%, 10%, 20%, and 30%. A combination of sodium hydroxide of 98% purity and 8 M concentration as well as sodium silicate solution (NaOH+D-Grade-Na_2SiO_3) were the applied alkaline activators. The green properties of FFACs have been assessed in terms of flowability and air content. While compression, three points bending, and splitting tensile strength tests have been applied to evaluate the hardened properties of FFACs produced with different percentages of additional materials (SF or MK) in addition to FFACs cured with different levels of temperatures.

2. THE EXPERIMENTAL PROCEDURE

2.1 Materials

Low-calcium fly ash (FFA) was utilized as the main cementitious material (Figure 2a). SF and MK were applied as a partial substitution of FFA (Figures 2b and 2c). Figure.1 demonstrates the particle size distribution of sand, FFA, MK, and SF. According to the X-ray Fluorescence analysis, the loss on ignition (LOI) and chemical of FFA, SF, as well as MK is revealed in Table 1. Fine aggregate (sand) was used with the maximum particle size of 4 mm (Figures 1 and 2c). The sand (S) used in producing all geopolymer concrete mixes (GPMs) had a specific gravity of 2.62 and water absorption of 1.4%. NaOH of 98% purity and D-Grade-Na_2SiO_3 were used as alkaline activators (Figures 2f and 2i). This type of alkaline activator is the most recommended solution with geopolymer concrete due to its beneficial chemical and physical properties, which can reflect positively on the concrete mechanical properties [17]. The chemical components of D-Grade sodium silicate (DSS) were 14.7 % Na_2O and 29.4 % SiO_2 by weight. Also, the specific gravity of D-Grade-sodium silicate was 1.5. NaOH was made with an 8 M concentration to attain balanced outcomes of flowability and strength. Especially, some previous studies have revealed that the increased NaOH concentrations can result in a decrease in the concrete mortar flowability but enhance the hardened concrete properties [18]. The utilized concentration of NaOH has been realized by melting its solid particles of 98% purity with water (Figure 2e). Sodium hydroxide concentration differs through changing the content of NaOH pellets and water depending on the required concentration [12]. In the current research paper, the weight ratio of sodium hydroxide-to-D-Grade sodium silicate solutions (NaOH/DSS) in preparing all geopolymer concrete mixes was selected as 1. It was selected based on previous literatures to achieve satisfactory results regarding to the workability and strength [11]. However, the optimum weight ratio of Na_2SiO_3/ NaOH is still a controversial issue among researchers. For instance, it has been reported that geopolymer concretes (GPCs) strength can be developed by decreasing the weight ratio of Na_2SiO_3/ NaOH [19]. While some findings have the opposite viewpoint regarding the effect of Na_2SiO_3/ NaOH weight ratio on the mechanical properties of GPC.

Table 1. Chemical and physical properties of FFA, MK, and SF

Chemical properties			
Chemicals	(FFA)%	(MK)%	(SF)%
AL_2O_3	25.55	45.22	0.68
SiO_2	51.22	51.13	92.81
CaO	4.31	0.05	0.41
MgO	1.46	—	1.72
Fe_2O_3	12.51	0.60	1.24
Na_2O	0.78	0.22	0.42
SO_3	0.23	—	—
K_2O	0.71	0.15	1.18
LOI	0.56	0.52	1.19
P_2O_5	0.89	—	—
Physical properties			
Color	Gray	White	Dark gray

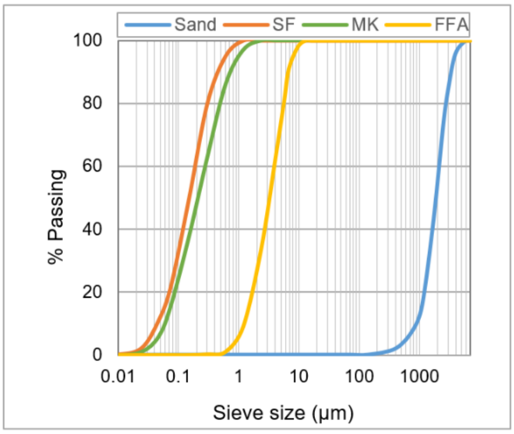

Figure 1. Particle size distribution of FA, MK, SF, and sand

Figure 2. a. FFA, b.MK, c. SF, d. Sand, e. Solid particles of NaOH, f. NaOH, i. D-Grade-Na_2SiO_3

2.2 Geopolymer concrete mixes

The experimental program of this paper included nine geopolymer concrete mixes (GPCMs) in total. One reference concrete mixture (GPFA) was excluded from additional materials (SF and MK). At the same time, the rest of the geopolymer concrete mixes involved different percentages of silica fume (SF) or metakaolin (MK). All concrete mixes have been prepared with FFA as a primary cementitious material, sand (S) with 4 mm maximum particle size, and alkaline activators (ALAC) of D-grade-sodium silicate solutions (DSS) as well as sodium hydroxide (NaOH). NaOH was prepared with 8 M based on the previous papers to attain satisfying outcomes of the workability and strength [12]. In this study, GPCMs have been manufactured with the constant water/FFA, cementitious materials/sand, and ALAC/cementitious materials ratios of 0.21, 0.36, and 0.35, respectively. GPCMs have also been prepared with constant NaOH/D-Grade-Na_2SiO_3 of 1. MK and SF were applied into FFA mixtures with different substitution ratios of 5%, 10%, 20%, and 30%. Table 2 includes the proportion of the utilized geopolymer concrete mixes.

Table 2. Details of mix design

Mix ID	FFA	SF	MK	DSS	NaOH	SP
	Unit content (kg/m^3)					
GPFA	500	0	0	88	88	3
GPSF5%	475	25	0	88	88	5
GPSF10%	450	50	0	88	88	5
GPSF20%	400	100	0	88	88	5
GPSF30%	350	150	0	88	88	5
GPMK5%	475	0	25	88	88	4
GPMK10%	450	0	50	88	88	4
GPMK20%	400	0	100	88	88	4
GPMK30%	350	0	150	88	88	4

2.3 Specimens preparations & testing procedure

The experimental procedure of this paper included two groups of geopolymer concrete specimens (GPCSs). The first group involved several GPCSs used to assess the impact of including different dosages of SF and MK on the hardened properties of FFACs cured at 21 ˚C room temperature. The second group of GPCSs was utilized to determine the optimum elevated curing temperature for geopolymer concrete produced with 100 % fly ash. For more clarification, Table 3 includes the details of the second group of GPCSs manufactured with the reference concrete mixture (GPFA). The preparation procedure of GPCSs started with preparing moulds. Next, the dry mixing procedure was applied to solid constituents, such as geopolymer materials if any used, and fine aggregate (sand), and it was run for 2 min. Then, the wet mixing process started with adding alkaline activators and water gradually to the dry mixture in the electrical mixing machine (Figure 3a). It was lasted for 5 min. to achieve a homogenous paste with suitable consistency. Throughout the wet mixing process, the applied alkaline solutions begin binding un-reacted constituents i.e., sand to form geopolymer concrete mortar (GPCM). The dry and wet mixing procedures were implemented in ambient temperature of 21℃. Then, the prepared GPCMs have been applied to the specified standard moulds. Next, GPCSs were compacted by using the vibrant electrical table. The vibrating process was lasted for 3 min. to attain a high compaction level, place concrete mortar properly in the utilized mould, and reduce air voids in concrete mortar. Then, GPC specimens were put inside plastic cover for 1 day at the ambient temperature of 21℃ to save their moisture level and avoid passive reaction between the green geopolymer concrete specimens (GPCSs) and particles that existed in the air. After that, the first group of GPCSs was demoulded and cured under ambient temperature till the specified testing day. While the second group of GPCSs, was demoulded and subjected to different ranges of elevated temperatures of 10, 20,30, 40, 50, 60,70, 80, and 90℃ for 12hr. After that, they were left in room temperature until the testing day.

The effect of the inclusion of various percentages of MK and SF on the green properties of fly ash concrete has been assessed in terms of the workability and the air content. The flowability of different geopolymer concrete mixes (GPCMs) have been determined by applying slump tests according to ASTM C143/C143M through utilizing flow table motorized machine (Figure 3b) [20]. The air content of GPCMs was performed based on ASTM C138/C138M (Figure 3c) [21]. Whereas the impact of incorporating different percentages of SF or MK on the hardened characteristics of FFACs cured at surrounding room temperature have been assessed in term of the compressive strength at 7, 14, 28, and 91 days, in addition to the 28 days flexural and splitting tensile strengths. Compression and splitting tensile strength tests were performed according to ASTM C39/C39M and ASTM C496/C96M, respectively (Figure 3d, and Figure 3e [22, 23]. Three-point bending tests were applied in accordance to ASTM C1609/C1609 M. (Figure 3f) [24].

Table 3. Details of GPCSs produced with GPFA

GPCSs ID	GPCMs ID	Pre-oven curing delay time(hr.)	Oven-Curing delay Time(hr.)	curing temperature (C˚)
FACS1	GPFA	24	12	10
FACS2	GPFA	24	12	20
FACS3	GPFA	24	12	30
FACS4	GPFA	24	12	40
FACS5	GPFA	24	12	50
FACS6	GPFA	24	12	60
FACS7	GPFA	24	12	70
FACS8	GPFA	24	12	80
FACS9	GPFA	24	12	90

Figure 3. a. Electrical mixing machine, b. Flow table moterized machine, c. Concrete air meter, d. Concrete speciemen under compression test, e. Spliting tensile strength test, f. Three-point bending test

3. RESULT AND DISCUSSION

3.1 Fresh properties

The slump test and air content outcomes of the designed geopolymer concrete mixes (GPCMs) of this paper are represented in Figure 4 and Figure 5, respectively. It was observed that the flowability of GPCMs were highly influenced by the applied additional materials and their percentages. More specifically, the incorporation of SF led to lower slump values and higher superplasticizers (SP) percentages compared to the reference concrete mixture (GPFA) as seen in Figure 4 and Table 2. For example, the slump results of GPCMs manufactured with 5%, 10%, 20%, and 30% SF were lower by 29%, 44%, 63%, and 85% than that manufactured with GPFA. While concrete mortars made with MK showed higher workability and lower SP dosages in comparison with those of GPCMs prepared with the same dosages of SF (Table 2 and Figure 4). The current paper findings also indicated that the slump values of GPCMs decreased with improving the percentages of applied additional materials (MK or SF). Therefore, the current paper findings agree with some previous papers that incorporating supplementary materials results in a decrease in the concrete mortar workability [25, 26]. Particularly, the physical and chemical properties of MK and SF can stand beyond the reduction in the concrete mortar workability. More specifically, silica fume is characterized by its higher specific surface area, rougher surface texture, and more irregular shape than those of MK and FA [27, 28]. Consequently, the reactivity of silica fume-based material (SFBM) can be higher than those of metakaolin and low calcium fly ash. Consequently, silica fume requires more activator solution, SP, or additional water demands for the chemical reaction of geopolymer constituents [25, 26]. While it was frequently reported in the previous literatures that fly ash involves particles with a spherical shape, which eliminate the friction against the mortar flowability [27-29]. Therefore, FFA decreases the need of high SP dosage demanded to adjust the concrete mortar workability. Comparable outcomes were stated by several previous papers for FFA [30, 31]. Thus, the addition of MK may be considered more economical in terms of SP dosages and high-range water reductions.

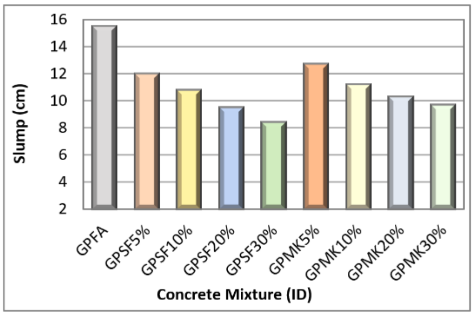

Figure 4. Slump test results

The results of this paper also showed that the incorporations of SF and MK into geopolymer concrete mixes eliminated the air content of GPCMs compared to that of the reference mixture (GPFA). Particularly, the addition of pozzolanic materials into concrete mixes contributes in reducing the concrete permeability through enhancing the bond strength between reacted and un-reacted materials (cementitious constitution and aggregates) [32]. It was also noticed that the air content of GPCMs was depended on the type of the applied additional material and its percentages. For instance, geopolymer concrete mixtures prepared with 30%SF and 30%MK have recorded the lowest air content results in comparison with GPCMs manufactured with lower dosages of MK and SF, as seen in Figure 5.

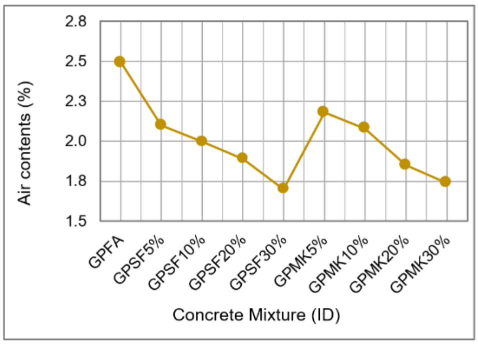

Figure 5. Air content results

3.2 Geopolymer concrete strength

3.2.1 Compressive strength

Figure 6 demonstrates the compressive strength development of geopolymer concrete samples (GPCSs) manufactured with different percentages of SF and MK at different curing ages. According to the current paper results, it was indicated that GPCSs, included different percentages of additions (MK or SF), exhibited higher compressive strengths compared to those produced with the reference mixture (GPFA) especially at early curing ages. It was also noticed that the compressive strength development was highly depended on the applied supplementary material dosages and the design curing ages. For instance, GPCSs manufactured with GPSF10% and GPSF5% exhibited higher compressive strength results particularly at initial curing ages in comparison with those produced with GPSF20%, GPSF30%, and GPFA, respectively (Figure 6). However, some papers have different findings regarding to the optimum additional percentage of SF. For instance, it was revealed that the inclusion of more than SF5% into concrete mixes involves detrimental effects on the concrete strength because it increases the porosity of concrete structure [33]. Particularly, it was stated that the high silicon dioxide content (SiO_2) existed in SF can impede the polymerization process. Other researchers asserted that sodium oxide, demanded for completed dissolution, may highly be unavailable in activator liquid with improving silica fume dosage. Thus, some unreacted supplementary materials remains in the delivered GP gel, which may rise the porosity of concrete and then decrease the concrete strength [34]. Therefore, several studies have restricted the percentages of the additional materials into concrete mixtures depending on the utilized mineral admixture [35, 36]. Correspondingly, GPCSs included metakaolin (MK) showed higher compressive strength results than those of the reference mixture (GPFA) at all testing ages. Paper findings indicated that the addition of GPMK20% led to the highest compressive strength values compared to other utilized dosages of MK (Figure 6). Similar findings regarding to the optimum replacement percentages of MK was reported in some previous papers [3, 37]. However, some findings have different results about the optimum replacement percentages of metakaolin. For instance, it was revealed that the enhancement in the concrete pore structure increases with improving the substitution percentages of MK up to at least 20% as partial replacement of the cement weight [38, 39]. While, other researchers indicated that the optimal replacement dosages of MK is 15% by the cement weight [40]. According to the current paper results, it was observed that the compressive strength values of GPCSs, manufactured with MK20%, cured at room temperature of 21 ˚C, were approximately equivalent to those of SF10% as seen in Figure 6. The current findings also stated that the effect of SF and MK on promoting the concrete compressive strength were more noticeable particularly in the early curing stages. Particularly, the chemical and physical characteristics of the applied additions contribute to generate a denser geopolymer structure due to the presence of nano-dimension of amorphous silicon dioxide (SiO_2), which fill the concrete pores. Thus, the incorporation of additions (SF or MK) is mainly beneficial during the early curing ages. After 28 days of curing, the addition of MK20% does not contribute to significant strength development. While concrete specimens produced with FFA and cured at ambient temperature exhibited low compressive strengths at early stages. This may highly refer to the high particle size in addition to the chemical component of used FFA which can delay the gepolymerization process. Specifically, the silicon and aluminum contents as well as the fineness of the utilized cementitious materials include significant effects on accelerating the hydration process and improving the concrete strength at the initial curing stages. Thus, it is expected that concretes produced with 100 % fly ash contains more voids due to the incomplete gepolymerization reaction. However, it was noticed that the 91 days compressive strength results of GPCSs manufactured with GPFA and cured at ambient temperature were slightly lower than those produced with SF and MK (Figure 6). This may attribute to the continuity of the chemical interactions of fly ash particles.

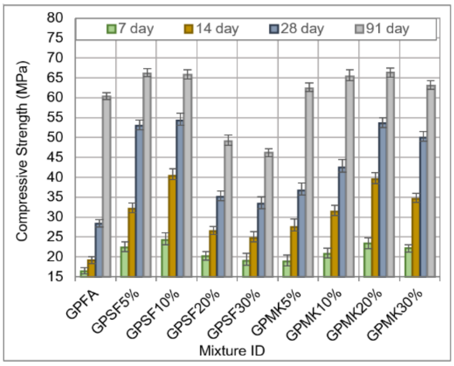

Figure 6. Compressive strength results of GPCSs

3.2.2 Splitting tensile and Flexural Strengths

Figures 7 and 8 represent the results of 28 days splitting tensile strength and flexural strength of different concrete mixes, respectively. The 28 flexural and splitting tensile strengths of GPCSs comprising SF or MK had approximately same the compressive strength pattern. More particularly, paper results revealed that GPCSs, involved additional materials, showed higher splitting tensile and flexural strengths in comparison with that of the reference mixture (GPFA). For instance, the incorporation of MK20% and SF10% led to higher 28 days concrete flexural and splitting tensile strengths developments up to 23% and 20%, respectively, in comparison with those manufactured with GPFA. More specifically, the addition of supplementary materials (MK, SF, FA, etc.) into concrete admixtures improves a concrete matrix structure by enhancing the bond between unreacted materials and cement paste [41]. Particularly, the bonding strength improvement of GPCSs is mostly resulted via the calcium hydroxide modification, which is formed on aggregates, into hydrated calcium silicate in reactive supplementary materials [1, 42]. Consequently, the concrete permeability highly decreases and then that enhance the performance of GPCs.

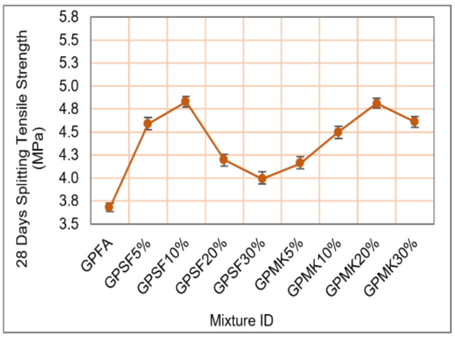

Figure 7. Splitting tensile strength results of GPCSs

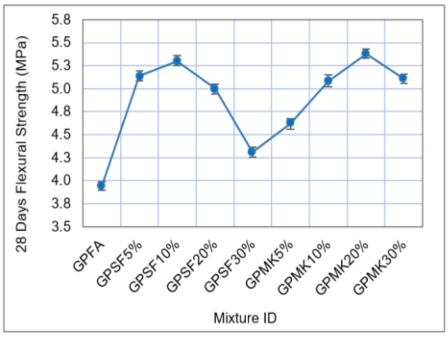

Figure 8. Flexural strength results of GPCSs

3.2.3 Concrete strength developments at different curing temperatures

This test involved several fly ash concrete specimens (FACSs), prepared with 100% low calcium fly ash (GPFA). Each three FACSs have been cured at 10°C, 20°C, 30°C, 40°C, 50°C, 60°C, 70°C, 80°C, and 90°C, respectively, for delay time of 12 hr. Figure 9 demonstrates the compressive strength results of FACSs subjected to different ranges of curing temperatures as mentioned previously. Figures 10 and 11 show the 28 days splitting tensile and flexural strengths of FACSs cured at different temperatures levels ranged from 10-to-90°C. The effects of elevated curing temperature on fly ash-based concretes have been discussed in the several previous findings. The current paper results confirm the previous findings that elevated temperatures induce the chemical reactions of FA-based geopolymer and enhance the hardened properties of GPC. However, controversial findings have been reported regarding to the optimum curing temperature and its delay time. Some researchers have indicated that 60°Cfor 48 hr. delay time is the optimum curing condition for FA based geopolymer [43]. While other findings asserted that the target compressive strength of FA concrete (FAC) is realized at 60°C for 24 hr. [17, 44]. Paya et al. indicated that the optimum 28 days compressive strength of FAC can be attained at 40°C curing temperature [45]. According to the current paper results, the optimum 28 days compressive, splitting tensile, and flexural strengths of 58.9, 4.5, and 5 MPa were obtained from FACSs subjected to elevated temperature of 70°C.

Similar findings regarding to the optimum oven curing temperature for FAC was reported in some previous papers [11, 46]. Paper results also presented that the compressive strength variations of FACSs subjected to 70 ˚C between designed testing ages were insignificant as shown in Figure 9. Basically, it is agreed that elevated temperatures can stimulate the chemical reactions between geopolymer based materials and enhance the concrete strength. Also, the sufficient application of elevated temperature ensures the continuity of the geopolymer reaction and that can reflect positively on the concrete compressive strength. However, it is expected that the optimal elevated temperature may differ between FACSs, if the delay time of the applied elevated temperature was inconstant. It is also expected that the optimum elevated curing temperatures can vary between concrete specimens used for different tests. Particularly, the difference between GPC specimens' dimensions can result in dissimilar surface to volume ratios between testing specimens. More specifically, specimens with high surface/ volume ratio are more exposed to evaporation than those of low surface/ volume ratio [47]. Paper results also showed that any increase in the oven curing temperatures beyond 70 ˚C resulted in a reduction the concrete strengths as seen in Figures 9, 10, and 11, respectively. For instance, the 28 days compressive, splitting tensile, and flexural strengths of FACSs subjected to 80 ˚C was lower by 12%, 9%, and 8% compared to those cured at 70 ˚C. While 90 ˚C curing temperature has resulted in the highest reductions in the 28 days compressive strength, flexure strength, and splitting tensile strength of 35%, 28%, and 30%, respectively, compared to those of 70 ˚C. More specifically, under excessive elevated temperatures, geopolymer concrete can experience a significant moisture loss. Consequently, that can reflect passively on the continuity of the geopolymerization process. Thus, GPC compressive strength can deteriorate because of unbounded materials resulted by the extreme evaporation.

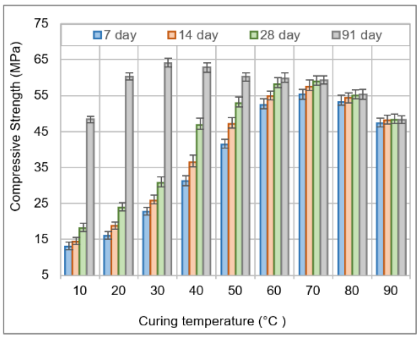

Figure 9. Compressive strength of FACSs cured at different temperatures

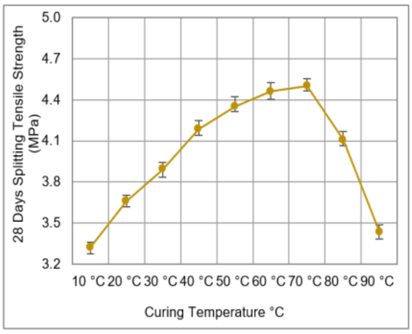

Figure 10. Splitting tensile strength of FACSs cured at different level of temperatures

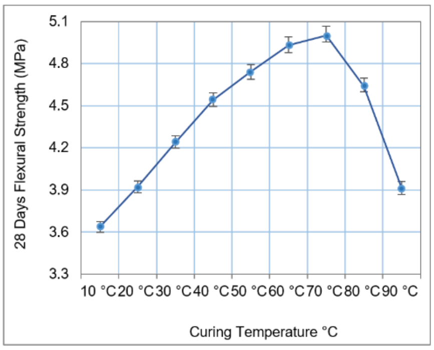

Figure 11. Flexural strength results of FACSs cured at different temperatures

However, it was also observed that the concrete strength developments of FACSs subjected to elevated temperatures ranged from 40 to 50 ˚C were rapid and inconstant particularly at early testing ages as seen in Figures 9, 10, and 11. While concrete strengths of FACSs cured at 10 °C involved the lowest compressive, flexural, and splitting tensile strengths as shown in Figures 9, 10, and 11). This may attribute to that low curing temperatures can hinder the continuity of the geopolymerization process.

3.2.4 Concrete strength variations

According to the current paper findings, the promoting effect of metakaolin and silica fume on the fly ash concrete strength is more noticeable at early hydration ages. For instance, the results of 28 days compressive, splitting tensile, and flexural strengths of GPCSs included the optimum dosages of additives (20% MK or 10% SF) cured at 21 ˚C were evidently higher than those of FACSs subjected to curing temperatures ranging from 10-to-50 ˚C as shown in Figures 12 and 13. This may refer to that SF and MK possess high content of silica and alumina, which can promote the geopolymerisation process and enhance the bonding strength, as well as the structure of interfacial transition zone. Additionally, the strength development of GPCSs may highly belong to the filling effect of SF and MK particles. Particularly, SF and MK involve small particle size with rough surface texture, and irregular shape. Thus, the utilized supplementary materials tend to fill voids between FA particles and accelerate the pozzolanic reaction of FA. As a result, that can improve the paste packing density and then hardened concrete properties [48].

However, the 91 days compressive strength of FACSs cured at higher temperatures of 30, 40, and 50 ˚C were comparable to those of GPCSs involved MK or SF cured at 21 ˚C. This highly refers to the continuity of geopolymer reaction of fly ash-based material. Whereas, the 7 days compressive strengths of FACSs cured at higher temperatures ranged from 40-to-50 ˚C were higher than those of GPCSs involved 20% MK and 10% SF cured at ambient temperatures of 21 ˚C. This can attribute to the beneficial influence of higher curing temperatures on promoting the geopolymerization process as well as the monomer dissolution of FFA. However, the 14 days compressive strengths of FACSs subjected to curing temperatures of 30 ˚C and 40 ˚C were lower by 13% and 10% than those included 10% SF and 20% MK. Thus, the current paper finding confirms that the higher temperature at early curing ages contributes to improve the compressive strengths of GPCs. Particularly, the early elevated curing temperatures can stimulate the pozzolanic reaction of geopolymer based materials.

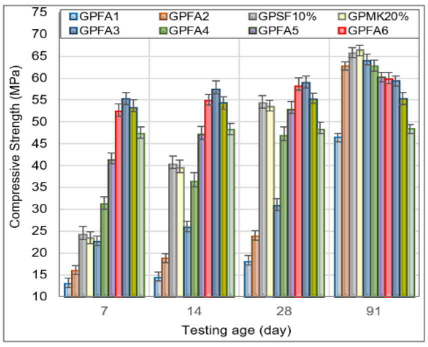

Figure 12. Compressive strengths of FACSs and GPCSs involved additives

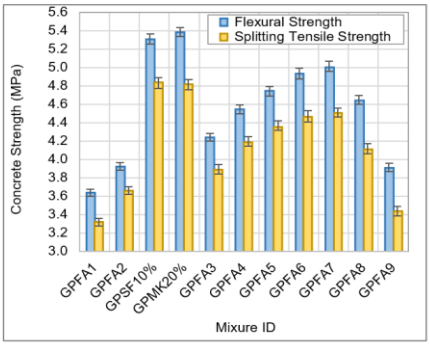

Figure 13. Splitting tensile and flexural strengths of FACSs and GPCSs involved additives

However, the paper results demonstrated that the outcomes of the late-age compressive strengths of FACSs subjected to higher curing temperatures of 70, 60, and 50℃were lower than those of 20, 30, and 40 ˚C as shown in Figure 12. Additionally, applying elevated temperature to cure fly ash based concrete causes a significant energy consumption and then increases greenhouse gas emissions [13]. Thus, the results of the current paper promote the addition of supplementary materials into FFA concrete to enhance the concrete strength and eliminate the need to the elevated temperature demand required for increasing the monomer dissolution of FFA.

4. CONCLUSION

Low calcium fly ash concrete cured at ambient temperature exhibits high setting time and low initial strengths. Consequently, FFAC necessitates elevated temperatures to improve the monomer dissolutions and the structure of the interfacial transition zone. Accordingly, that raises the energy consumption and carbon dioxides emissions. Thus, in the current research paper, the effects of metakaolin (MK) as well as silica fume (SF) on the green and hardened properties of low calcium fly ash concrete (FFAC) were assessed. Also, the impacts of different curing temperatures ranged from 10 - to - 90℃ on the compressive, flexural, and splitting tensile strengths of FFAC were investigated. According to the paper findings, the conclusions of this paper are as listed below:

- The addition of SF or MK into FFA based geopolymer declines the flowability and air content of FAC paste, and this reduction increases with improving the additional material dosage.
- Fly ash concretes (FACs) involved 10%SF results in higher compressive, flexural, and splitting tensile strengths in comparison with those of reference mix (100% FFA) and other incorporated percentages of SF.
- The addition of 20% MK into FACs results in superior compressive, flexural, as well as splitting tensile strengths in comparison with control specimen and other involved dosages of MK.
- The promoting effects of MK and SF on the compressive strength of FACs are more noticeable in early curing ages.
- The optimum elevated temperature curing conditions of the current investigation for FFACs is 70 ˚C for delay time of 12 hr.
- Elevated curing temperatures contribute to develop initial compressive strengths of FACs. While the late-age compressive strengths of FACs cured at elevated temperatures of 70℃, 60℃, and 50℃ are lower than those subjected to curing temperatures of 20℃, 30℃, and 40℃.
- The 28 days compressive, flexural, and splitting tensile strengths of GPCs manufactured with optimum dosages of 20% MK, or 10% SF cured at 21 ˚C were evidently higher than those of FACSs cured at 30, 40, and 50℃.
- The compressive, splitting tensile, flexural strengths improvements of 20% MK are relatively comparable to those of 10% SF with less requirement of SP. Thus, metakaolin can be alternative material to silica fume in practical constructions where high strength is specified.

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NOMENCLATURE

GPs	Geopolymers
FAA	Low calcium fly ash
SF	Silic Fume
MK	Metakaolin
NaOH	Sodium hydroxide solution
DSS	D-Grade sodium silicate
SP	Superplasticisers
FFACs	Low calcium fly ash concretes
GPCMs	Geopolymer concrete mixes
OPC	Ordinary Portland Cement
Al_2O_3	Alumina
S	Sand
ALAC	alkaline activators