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RESEARCH

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Enhancing class F fly ash geopolymer concrete performance using lime and steam curing

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Abstract

Background: Producing fly ash geopolymer concrete (FGPC) which can be cured by air, water, or steam instead of thermal curing without decreasing its mechanical properties will facilitate using FGPC in cast-in situ applications and precast concrete industry. Furthermore, it will decrease the consumed energy in FGPC production. This research attempts to achieve this goal by investigating the efficacy of supplementing class F FGPC with lime while using different curing processes to generate lime-fly ash geopolymer concrete (L-FGPC) that could be a feasible alternative to ordinary FGPC.

Methods: The studied variables included lime content, molarity of sodium hydroxide (NaOH), additional water content, curing type, and moisture of aggregates. The comparative criteria were setting times of fresh concrete, mechanical properties of hardened concrete, and voids ratio. SEM and X-ray diffraction tests were used to validate test results.

Conclusions: Steam curing generated the best mechanical properties of L-FGPC. Using 2% lime content with steam-cured L-FGPC yielded proper setting times and the best mechanical properties. Microstructure tests revealed compact microstructure and decreased voids ratio upon using 2% lime content in L-FGPC. Increasing molarity of NaOH, decreasing additional water content, and decreasing moisture of aggregates enhanced L-FGPC's mechanical properties.

Keywords: Fly ash geopolymer concrete, Lime, Setting properties, Mechanical properties, SEM, X-ray diffraction

Introduction

Geopolymer concrete is one of the major steps to reduce the use of cement concrete that greatly increases pollution [1, 2]. Fly ash which is deemed as a waste material is one of the binding materials of geopolymer concrete [3]. Geopolymer concrete is joined with the name of J. Davidovits who created this bonding system [1, 4–11]. He found that an alkaline solution (e.g., sodium hydroxide mixed with sodium silicate) with aluminum-(Al) and silicon (Si)-based materials can react to produce a hard-bonding material. He called it geopolymers as the chemical reaction is a polymerization process for materials of geological origin. Some researchers named it alkali-activated aluminosilicate binders

[12]. Geopolymerization process generates an alkali aluminosilicate gel (N-A-S–H) with a highly cross-linked pseudo-zeolitic structure [13–16].

Thermal curing is found to accelerate the polymerization process [17]. In the geopolymerization process of geopolymer concrete, water is given out during the chemical reaction, and this water tends to evaporate as the specimens were thermally cured [3]. Likewise, the drying shrinkage turns out to be negligible due to the minor quantity of water in the pores of the concrete. On the other hand, Temuujin et al. [18] stated that this hypothesis of the higher water evaporation for elevated temperature cured samples has not been confirmed. For very good geopolymerization, the curing temperatures should be between 40 and 85 °C, and it depends on duration of curing. Microstructural analysis revealed that higher temperature is vital in accelerating the polymerization reaction of geopolymer concrete with a powerful bonding between the aggregate and geopolymer paste and thus strengthened micro crack path which later yield significance improvement in strength of concrete specimens [19]. Thermally cured low-calcium fly ash geopolymer concrete has a high early strength, good durability to sulfate and acid attack [20, 21], low creep [22], and low-drying shrinkage [23]. Steam curing reduced efflorescence in geopolymer concrete at elevated temperature of 65 °C and above causing strength enhancements of the geopolymer concrete due to the generation of more alkali aluminosilicate gel from the starting material [24].

Hardjito et al. [3] studied the effect of fly ash content, water content, ratio of sodium silicate to sodium hydroxide, and duration of heat curing on the properties of FGPC. They confirmed that the elastic properties of hardened fly ash-based geopolymer concrete are like those of ordinary Portland cement concrete. Geopolymers with high alkali content show a very low expansion due to alkali silica reaction compared with normal Portland cement concrete [25]. Jaarsveld et al. [26] stated that alkali metal content (sodium oxide and potassium oxide), particle size, metal content (aluminum oxide, silicon oxide, ferritin oxide, etc.), calcium oxide content, amorphous content, and morphology and origin of fly ash influence geopolymer properties. They stated that the content of calcium affects strength development. Other researchers [27, 28] presented that using fly ash with significant calcium content (e.g., class C fly ash) could interfere with the polymerization process and alters the microstructure. At the same time, the extremely short setting times of class C fly ash, when activated with conventional alkaline silicate solution, increase the difficulty of using it in industrial applications [29, 30]. Thus, low-calcium fly ash (i.e., class F according to ASTM C618) was recommended to be used. On the other hand, class F fly ash produces fly ash geopolymer concrete (FGPC) which sets slowly and tardily develops strength in ambient condition decreasing its applicability to be used in cast-in situ applications [31]. Adding calcium to geopolymer systems showed reduction in their setting times at ambient temperature [18]; however, most of specimens with added calcium showed degradation in their mechanical properties when thermally cured [18, 28]. On the other hand, Temuujin et al. [32] used two radioactive fly ashes with high Cao content (14–30 wt%) for the preparation of alkali-activated geopolymers by only 8 M NaOH solution. They produced pastes that set up to 10 h achieving good compressive strengths (up to 32 MPa) when thermally cured at 70 °C for 22 h.

Geopolymer concrete requires various procedures before and after casting which hinders its practical application and necessitates the development of alternative approaches.

Thus, this study aims to investigate the effect of adding low lime contents to class F fly ash on the concrete setting times and the different geopolymer concrete mechanical properties (including concrete compressive strength, concrete splitting tensile strength, and concrete modulus of elasticity) while using different curing processes to generate lime-fly ash geopolymer concrete (L-FGPC) that could be a feasible alternative to ordinary FGPC and could enhance its mechanical properties. Several other variables were studied such as molarity of sodium hydroxide, additional water content, and moisture of the used aggregates. One of the main goals of this study is to produce a FGPC which can be used in cast-in situ applications and precast concrete industry by decreasing the setting time of fresh concrete to be comparable to the traditional concrete setting times. Furthermore, one of the key objectives is to produce a FGPC which can be cured by air, water, or steam instead of thermal curing without decreasing the traditional FGPC strength which facilitate using FGPC in industry and decrease the consumed energy in FGPC production.

Methods/experimental

Aim of the study

This experimental program aimed to overcome the obstacles causing delays to use class F (low calcium) FGPC in practical applications. The long setting times of fresh concrete and the use of thermal curing to achieve the required concrete mechanical properties are the major difficulties facing FGPC production in cast-in situ applications and precast concrete industry. This study attempts to add a small amount of lime to the FGPC mix to decrease the long setting time of fresh concrete and to create FGPC which can be cured by air, water, or steam instead of thermal curing to save the required energy for curing in FGPC production. Thus, an investigation was conducted to find the optimal required lime content in the FGPC mix and the finest curing practice to achieve the best behavior for fresh and hardened fly ash geopolymer concrete.

Materials

Siliceous sand of 2.5 modulus of fineness and crushed hard limestone of 9.5 mm maximum aggregate size meet the requirements of ASTM C83 were used. Class F fly ash with chemical composition of (SiO_2 56.76%, Al_2O_3 32.49%, Fe_2O_3 8.83%, CaO 1.09%, K_2O 0.28%, Na_2O 0.17%, MgO 0.02%, SO_3 0.01%, Cl 0.02%, and loss of ignition of 0.2%), meeting ASTM 618 with 5% retained on sieve 750 μm and with 2.25 specific gravity, was used as a source of alumina and silica for geopolymer concrete. The alkaline solution was a mix of NaOH solution and sodium silicate solution using a mixing ratio of 1:2 by weight. NaOH was in a pellet form with a 98% purity. The solution was prepared 24 h before casting. Type F high range water-reducing material (ASTM C 494) with naphthalene formaldehyde sulfonate chemical base was used. Lime with 2.49 specific gravity and with 95% passing from sieve 750 μm was used. The calcium hydroxide Ca (OH)2 of the used lime was 93.8%. Sodium silicate solution was colorless with specific gravity of 1.5 and total solid content of 46%.

Test variables

The studied variables were the lime content (used as an additive), molarity of NaOH, additional water content, curing type, and moisture of aggregates. The lime content was varied between 0%, 1%, 2%, 3%, 4%, and 6% of fly ash weight. Molarity of NaOH changed between 8, 12, and 16. Additional water contents of 5%, 7.5%, 10%, and 13.5% of the fly ash weight were studied. Different curing types were studied. Specimens were cured in water up to testing date, cured in temperature of 70 °C for 48 h in the oven, cured in steam without pressure for 48 h at almost 65 °C in a steam-curing chamber, and cured in air (i.e., cured at ambient temperature). Finally, moisture of the used aggregates (i.e., water contents of the used aggregates) of 0.0% (oven dried), 0.5%, 1.5%, and 2.5% of aggregate weight were considered.

Concrete mixes

The previously mentioned test variables were considered through the studied concrete mixes. A total of 400 kg/m^3 of fly ash, 53.34 kg/m^3 of NaOH solution, 106.68 kg/m^3 of sodium silicate solution, and 12 kg/m^3 of type F high range water-reducing material were constant proportions in all investigated concrete mixes. Table 1 shows the variable proportions of these mixes. The alkaline solution to fly ash content was kept constant by 40%. The mix design was obtained using absolute volume mix design method.

Preparing specimens

First, the alkaline solution was prepared as follows: the calculated amount of NaOH powder was dissolved in a calculated amount of water to obtain NaOH solution with the required molarity. This NaOH solution was left to cool for 2 h, and then, it was mixed with sodium silicate solution with 1:2 ratio by weight, respectively, to produce the required alkaline solution. This alkaline solution was left for 24 h before the concrete mixing.

The common way to develop geopolymer concrete as per Hardjito and Rangan (2005) [3] was used. Lime was added and mixed with fly ash to form the binder material. Then, the binder material was dry mixed with the aggregates for 3 min. Finally, water, alkali solution, and super-plasticizer were added to the mixer and wet mixed for 4 min. Materials were added by weight in the mixture, and an 80-l capacity tilting concrete mixer with speed of 30 RPM was used. Specimens were casted and left at room temperature until demolding which was after 48 h for FGPC and after 24 h for lime-fly ash geopolymer concrete (L-FGPC). Curing was conducted just after demolding depending on the studied curing type as per Table 1.

Testing of specimens

Slump and setting times according to ASTM C 143 and ASTM C 403, respectively, were recorded for fresh concrete. Compressive strength tests using cubes of 70.07 mm size (BS, 1881), and splitting tensile strength and modulus of elasticity using cylinders of 100 mm × 200 mm size (ASTM C 469), were used to evaluate the mechanical properties of the hardened concrete. Void ratios were calculated according to ASTM C642. Scanning electron microscope (SEM) and X-ray diffraction tests were used to investigate the

Table 1 Concrete mix proportions and test results

Mix name	Lime	Additional water	NaOH molarity	Coarse agg	Sand	Moisture of agg[a]	Curing type	Initial setting time	Final setting time	7 days fcu[c]	28 days fcu[c]	fspt [d]	Voids ratio
	% of fly ash	Total % of fly ash		kg/m^3	kg/m^3	kg/m^3	s, t, a, or w[b]	(h)	(h)	(MPa)	(MPa)	(MPa)	%
M1	0	10	16	852.5	852.5	0[a]	s	4	36	12	21.6	1.27	10.2
M2	2	10	16	848.3	848.3	0	s	1.5	7	39	42.2	3.05	7.1
M3	4	10	16	844.1	844.1	0	s	0.67	3.5	31.8	35.2	2.9	9.1
M4	6	10	16	839.9	839.9	0	s	0.42	3	33	34	2.81	10.4
M5	3	10	16	846.2	846.2	0	s	1	4.25	32	35.9	2.91	10.3
M6	1	10	16	850.4	850.4	0	s	2.67	24	22	25.6	2.07	11.4
M7	0	10	16	852.5	852.5	0	t	4	36	23.5	27	2	8.5
M8	0	10	16	852.5	852.5	0	a	4	36	14	19		4.9
M9	0	10	16	852.5	852.5	0	w	4	36	6.6	10.4		5
M10	2	10	16	848.3	848.3	0	t	1.5	7	22.2	22.6		9.8
M11	2	10	16	848.3	848.3	0	a	1.5	7	14.2	17.6		6.5
M12	2	10	16	848.3	848.3	0	w	1.5	7	12.3	15.6		9.4
M13	4	10	16	844.1	844.1	0	t	0.67	3.5	15.49	17.6		10.1
M14	4	10	16	844.1	844.1	0	a	0.67	3.5	17.6	20.8		7.7
M15	4	10	16	844.1	844.1	0	w	0.67	3.5	18.2	21.2		12.1
M16	6	10	16	839.9	839.9	0	t	0.42	3	16	10.2		12
M17	6	10	16	839.9	839.9	0	a	0.42	3	15.1	18		8.3
M18	6	10	16	839.9	839.9	0	w	0.42	3	17.3	20		12.7
M19	3	10	16	846.2	846.2	0	t	1	4.25	18.4	20		10.3
M20	3	10	16	846.2	846.2	0	a	1	4.25	15.2	18.6		7.7
M21	3	10	16	846.2	846.2	0	w	1	4.25	14.6	18.4		13.6
M22	1	10	16	850.4	850.4	0	t	2.67	24	22.3	25	2.8	10.3
M23	1	10	16	850.4	850.4	0	a	2.67	24	9.1	11.6		7.1
M24	1	10	16	850.4	850.4	0	w	2.67	24	10.3	13	0.71	12.9
M25	4	13.5	16	825.7	825.7	0	s	0.83	4	24.1	27.6	2.03	12

Table 1 (continued)

Mix name	Lime	Additional water	NaOH molarity	Coarse agg	Sand	Moisture of agg[a]	Curing type	Initial setting time	Final setting time	7 days fcu[c]	28 days fcu[c]	fspt [d]	Voids ratio
	% of fly ash	Total % of fly ash		kg/m^3	kg/m^3	kg/m^3	s, t, a, or w[b]	(h)	(h)	(MPa)	(MPa)	(MPa)	%
M26	0	7.5	16	865.6	865.6	0	t	3.5	30	19.1	29	2.21	8.4
M27	0	13.5	16	834.2	834.2	0	t	5	38	16.5	25.2	2	10.1
M28	2	7.5	16	861.4	861.4	0	s	1.33	6.5	37.4	43	3.07	8.4
M29	2	7.5	12	857.7	857.7	0	s	1.5	6.75	28.6	34	2.9	10.1
M30	2	7.5	8	853.9	853.9	0	s	1.75	8	1.3	1.54	0.1	18.1
M31	4	7.5	12	853.5	853.5	0	s	0.67	5.5	23.4	27.8	2.8	10.4
M32	6	7.5	12	849.3	849.3	0	s	0.42	3	15.3	18.2	1.62	11.6
M33	0	7.5	12	861.9	861.9	0	t	3.67	36	18	22	1.32	10.8
M34	0	7.5	8	858.1	858.1	0	t	3.75	40	5.7	8.1	0.78	11.5
M35	2	5	16	874.5	874.5	0	s	1.17	6.15	39	44	3.25	10.8
M36	2	7.5[a]	16	884	884	17.7[a]	s	1.5	6.5	24.1	28.4		13.5
M37	2	7.5[a]	16	895.2	895.2	26.9[a]	s	1.6	6.5	20.3	24.3		15.6
M38	2	7.5[a]	16	900.7	900.7	45.0[a]	s	1.67	7	16.8	20.2		16.7
M39	0	7.5[a]	16	888.3	888.3	17.8[a]	t	3.5	30	16.5	20		9.4
M40	0	7.5[a]	16	899.6	899.6	27.0[a]	t	3	36	14.2	17.4		9.8
M41	0	7.5[a]	16	904.9	904.9	45.2[a]	t	3	38	9.8	12.3		10.6

[a] The moisture of aggregate was subtracted from the additional water in these specimens, and 0 means oven-dried aggregates. [b]t means thermal curing under 70 °C for 2 days, s means steam curing without pressure for 2 days, a means to be left in ambient temperature in air without curing, and w means water curing up to testing date. [c]Cube compressive strength after 7 days and 28 days. [d]Splitting tensile strength after 28 days

microstructure and chemical compounds of geopolymer mortar containing lime content of 0%, 2%, and 6% of the fly ash weight at NaOH molarity of 16.

Results and discussion

Setting times of fresh concrete

Figure 1 shows the relation between setting times (initial and final) and lime content for additional water contents of 7.5% and 10% and NaOH molarities of 12 and 16. One can observe that increasing lime content considerably decreased the setting times. FGPC (0% lime) set initially and finally at 4 h and 36 h, respectively. This means a delay of demolding for FGPC as indicated by Elyamany et al. [33]. As shown in Table 1, using 1% of lime content yielded a final setting time of 24 h. The use of 2% of lime reduced the setting times to 1.5 h as initial setting time and 7 h as final setting time which is comparable to the traditional concrete setting times. The use of 3% lime content decreased the setting times again (i.e., 1 h as initial setting time and 4.25 h as final setting time) which were still close to the traditional concrete setting times. Using 4 to 6% of lime content significantly decreased the setting times below the traditional concrete setting times. For instant, the initial setting times for 4% and 6% of lime content were less than 45 min. These results and conclusions tend to the presence of lime which accelerates the setting time if compared with that of FGPC. These results synchronize with previous records of Van Deventer et al. [28] and Temuujin et al. [18] as they proposed that the presence of calcium can cause speedy hardening because it provides extra nucleation sites for precipitation of dissolved species. As demonstrated in Fig. 1, initial and final setting times for concrete with NaOH molarity of 16 and 10% additional water content are so close to those of concrete with NaOH molarity of 12 and 7.5% additional water content. This may tend to the almost equal total used water in both two cases (i.e., the summation of water in NaOH solution, sodium silicate solution, and the additional water are almost the same). As shown in Table 1, for constant NaOH molarity of 16 with lime contents of 0%, 2%, and 4% and variation of the additional water content, one can observe that increasing the additional water content increases the setting times for FGPC and L-FGPC. As an example, the increase of additional water from 5 (mix: M35) to 10% (mix: M2) increases initial and final setting times by 28% and 14%, respectively.

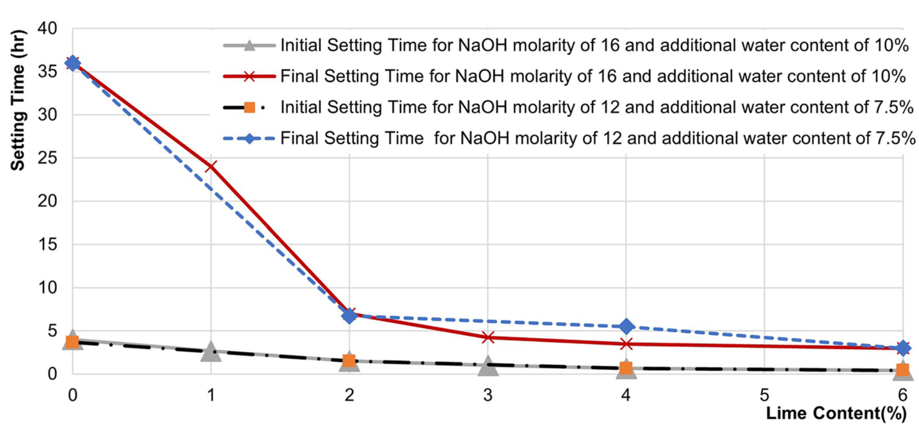

Fig. 1 The relation between initial and final setting times of fresh concrete and lime content

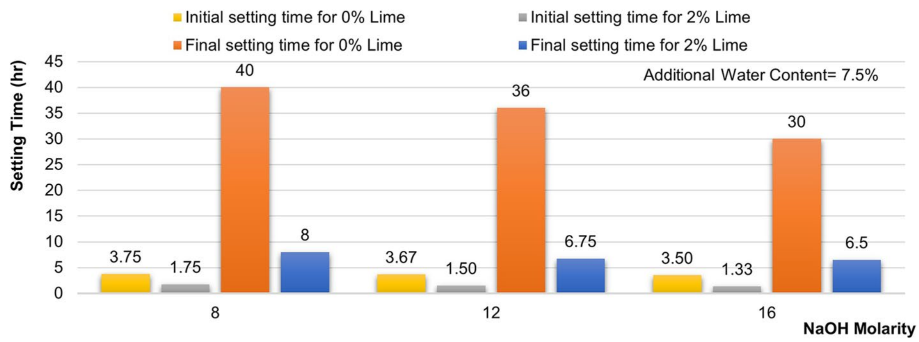

Fig. 2 The effect of NaOH molarity on the initial and final setting times for additional water content of 7.5%

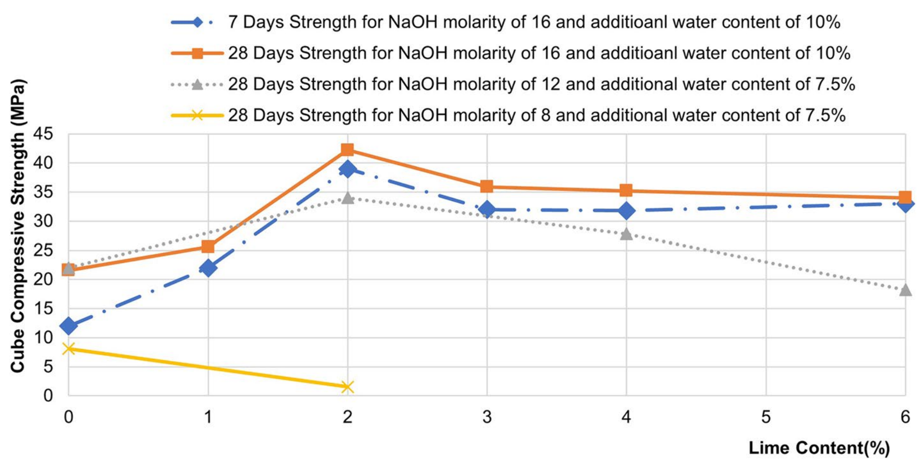

Fig. 3 The effect of lime content on 7 days and 28 days compressive strength for different NaOH molarities and different additional water contents

The increase of additional water content may decrease the concentration of the activator and the lime, consequently, which delays the geopolymerization process. This agrees with Elyamany et al. [33] results for FGPC.

Figure 2 shows the effect of NaOH molarity at constant additional water content of 7.5% for FGPC and L-FGPC with 2% lime content on initial setting times and final setting times. It is obvious that increasing NaOH molarity decreases the setting times for both FGPC and L-FGPC. Increasing the NaOH molarity increases the concentration of the activator and decreases the total used water in the concrete mix, which causes an acceleration in the geopolymerization process.

Cube compressive strength

Effect of lime content

Figure 3 shows the relation between 7-day and 28-day cube compressive strengths and lime content at different NaOH molarities and different additional water contents. One can observe that increasing lime content from 0 to 2% enhanced the concrete compressive strength. Increasing lime content more than 2% decreased the concrete compressive strength; however, their compressive strengths were still higher than that of FGPC with steam curing or thermal curing for NaOH molarity of 16 and additional water content of 10%. The compressive strength of steam-cured L-FGPC with 6% lime content and NaOH molarity of 12 was less than that of thermally cured FGPC. The optimum value of the concrete compressive strength was recorded at 2% lime content for different NaOH molarities and different additional water contents. Using up to 2% of lime content added more sodium alumina silicate geopolymer bond as lime acted as a catalyst for the geopolymerization process. On the other hand, increasing the lime content more than 2% increased the calcium content which obstructed the geopolymerization process which has been previously observed by Catalfamo et al. [34]. They indicated that using Cao in fly ash with percentages above 3% by weight interferes with crystallization during synthesis of zeolites from fly ash. Also, Fig. 3 shows that NaOH molarity of 8 caused a reduction in the compressive strength for both of FGPC and L-FGPC, and the compressive strength of steam-cured L-FGPC was less than that of thermally cured FGPC. It seems that L-FGPC needs more NaOH molarity than 8, and lime may act as an obstacle to the geopolymerization process instead of being a catalyst.

Effect of NaOH molarity

From Table 1 and Fig. 3, for constant additional water content of 7.5%, one can observe that increasing NaOH molarity significantly increased the concrete compressive strength for both FGPC and L-FGPC with 2% lime content. For example, the increase in NaOH molarity from 12 (mix: M29) to 16 (mix: M28) increased 28 days cube compressive strength by 26.5%. Previous researches [35, 36] confirm this observation for FGPC. The increase in NaOH concentration increases in leaching of silica and alumina from the fly ash particles to the solutions [37] producing a dense and strong geopolymer matrix which increases compressive strength of the concrete [35]. This research confirms that the same behavior applies on L-FGPC too. The increase of NaOH molarity enhanced the geopolymerization process and decreased the voids ratio in the hardened concrete as shown in Table 1 which was affected by the water content in the NaOH solution that was used in the concrete mix. More study should be carried out using low NaOH molarities to investigate the lowest NaOH molarity that should be used with L-FGPC.

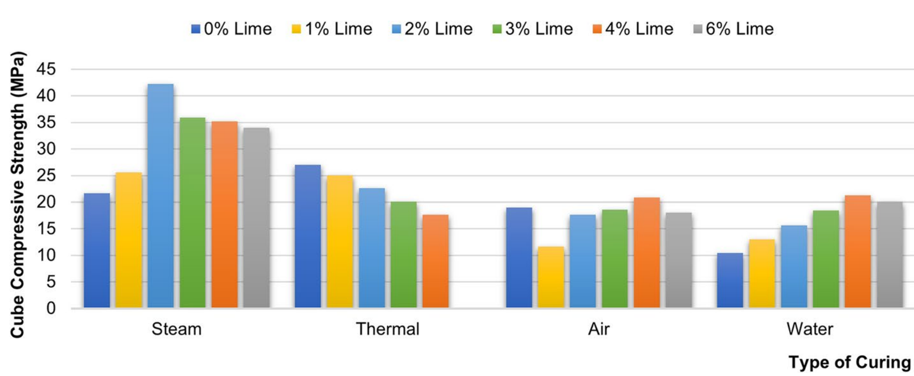

Fig. 4 The effect of curing type on the 28-day concrete compressive strength for different lime contents and for constant NaOH molarity of 16

Effect of curing type

Figure 4 shows the effect of the curing procedure on the 28-day concrete compressive strength for different lime contents and for the same additional water content of 10% and same NaOH molarity of 16. This figure indicates that FGPC achieved its highest 28-day concrete compressive strength using thermal curing (agrees with all previous researches on FGPC [38, 39]), while all the L-FGPC from 1 to 6% lime contents achieved their highest 28-day concrete compressive strengths using steam curing. Steam curing contributes towards reducing efflorescence and increases alkali aluminosilicate gel in geopolymer concrete [24]. It should be mentioned that using L-FGPC with 1% lime content achieved 28-day concrete compressive strength of 25.6 MPa and 25 MPa using steam curing, and thermal curing, respectively. This means that using 1% lime content will produce concrete that may be cured using thermal or steam curing, because using only 1% lime content will produce a concrete that is between FGPC and L-FGPC. Increasing lime content in thermally cured L-FGPC decreased its concrete compressive strength. This agrees with research done by Temuujin et al. [18] who confirmed that calcium compound addition reduces mechanical properties of thermally cured geopolymer concrete. One can conclude that it is not recommended to use thermal curing with L-FGPC. Also, it is obvious that FGPC had its lowest concrete compressive strength with water curing. Air and water curing were not effective much as steam curing for L-FGPC and thermal curing for FGPC. Table 1 confirms that the previous conclusions for 28-day concrete compressive strength applies for 7-day concrete compressive strength for steam and thermal curing.

Effect of additional water content

From Table 1, for NaOH molarity of 16 and for variable lime contents of 0%, 2%, and 4%, increasing the additional water content in the concrete mix decreased the concrete compressive strength. For instance, the decrease of additional water from 13.5% (mix: M25) to 10% (mix: M3) increased the 28-day cube compressive strength by 27.5%. This finding agrees with the findings of other researches for FGPC [39, 40]. This can be due to increasing the additional water decreases the activator concentration (sodium silicate and sodium hydroxide) and yields more voids ratio in the hardened concrete as indicated in Table 1. It should be mentioned that increasing the additional water content increased the workability of the geopolymer as indicated by most of scholars [3, 41, 42]. Concrete slump increased from 40 to 90 mm when additional water content increased from 5 to 13.5%.

Effect of aggregate moisture (i.e., water content in the used aggregate)

This effect is different than the effect of the additional water that was previously discussed, taking into consideration that the moisture of the aggregate (i.e., coarse and fine aggregates) was subtracted from the additional water added to the concrete mix (i.e., the total free water will be constant and equal to the summation of the aggregate moisture and the additional water added to the mix). From Table 1, one can observe that the increase of the aggregate moisture in the geopolymer concrete mix with constant NaOH molarity of 16 decreases the concrete compressive strength. For example, the decrease of the aggregate moisture from 2.5 (mix: M38) to 0% (i.e., oven-dried aggregate) (mix: M28) increased the 28-day cube compressive by 113%. Thus, it is recommended to pre-dry the used aggregate in the geopolymer concrete mix.

Splitting tensile strength

From Table 1 and Fig. 5, using lime in the steam cured L-FGPC substantially enhanced the concrete splitting tensile strength compared with thermally cured or steam-cured FGPC when NaOH molarities of 12 or 16 were used. On the other hand, using NaOH of 8 decreases the splitting tensile strength of steam-cured L-FGPC compared with thermally cured FGPC. For NaOH molarities of 12 and 16, the highest splitting tensile strength was recorded when using L-FGPC with 2% lime content. In comparison with the ACI-318 equation for splitting tensile strength shown in Fig. 5, FGPC has lower ratio between the splitting tensile strength and the square root of the compressive strength than that of the traditional Portland concrete. Ryu et al. [43] had the same conclusion for FGPC. On the other hand, L-FGPC with lime content more than or equal 2% achieved almost the same ratio of the ACI-318 code. One can conclude that ACI-318 equation for concrete splitting tensile strength can be used for L-FGPC with 2 to 4% lime contents. As shown in Table 1, increasing the NaOH molarity increased the concrete splitting tensile strength for both FGPC and L-FGPC. It was observed that FGPC and L-FGPC with 1% lime content achieved their highest splitting strength using thermal curing. Also, thermally or steam-cured L-FGPC with 1% lime content has higher splitting tensile strength than that of FGPC. Increasing the additional water content in the concrete mix with constant NaOH molarity decreased the concrete splitting tensile strength for different lime contents as indicated in Table 1 which agrees with the findings of other researches for FGPC [40].

Modulus of elasticity

The modulus of elasticity of some specimens with different lime contents and different curing types (i.e., 0% lime content with thermal curing, 2% of lime content with steam curing, 4% of lime content with steam curing, and 6% of lime content with steam curing) having the same NaOH molarity of 16 and the same additional water content of 10% was recorded. The recorded values were presented in Fig. 6 and compared with the calculated

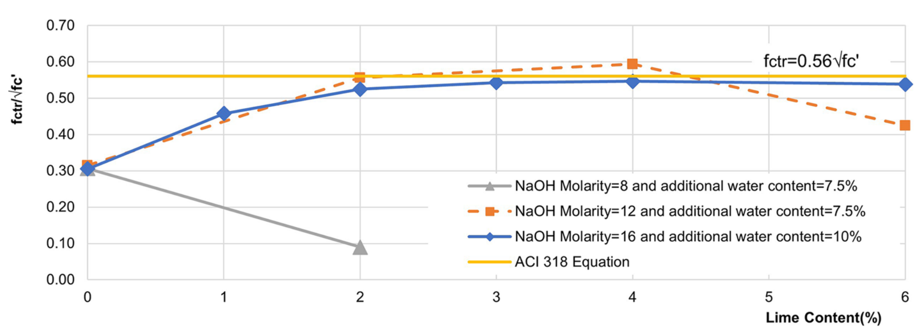

Fig. 5 The effect of lime content on the ratio between concrete splitting tensile strength and the square root of the compressive strength for different NaOH molarities and different additional water contents

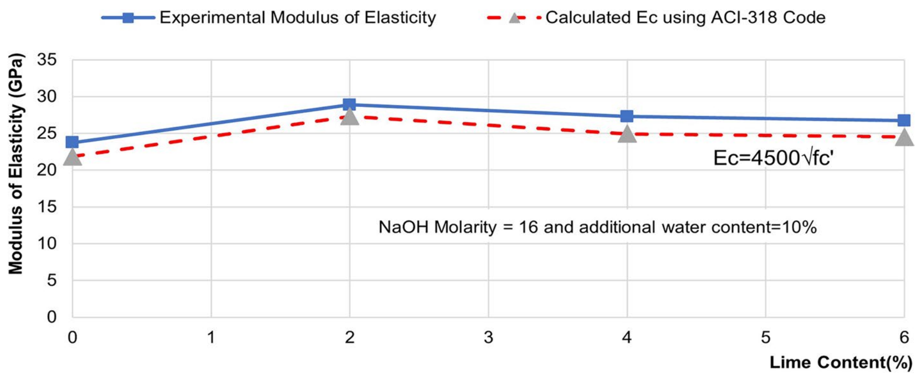

Fig. 6 The relation between lime content and concrete modulus of elasticity for NaOH molarity of 16 and additional water content of 10% compared with the modulus of elasticity equation of ACI-318 code for ordinary concrete

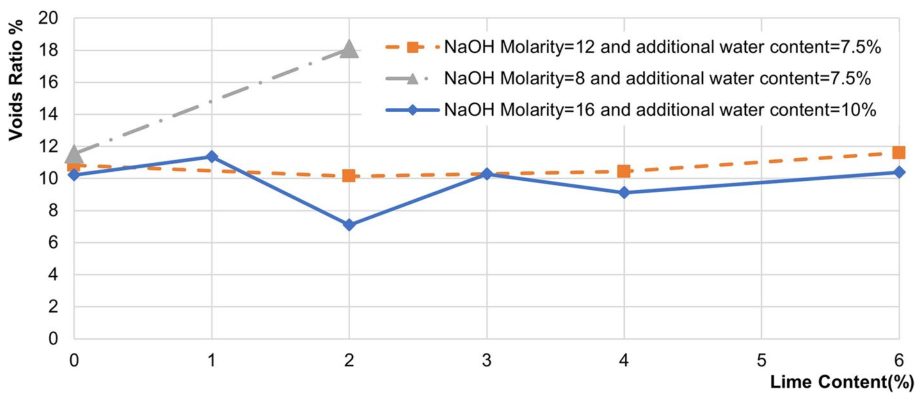

Fig. 7 The relation between lime content and void ratio % at 90 days from casting for different NaOH molarities and different additional water contents

modulus of elasticity using the ACI-318 code equation for normal concrete for the same concrete strengths (fc'). As shown in Fig. 6, using steam-cured L-FGPC achieved higher modulus of elasticity than that of thermally cured FGPC for the same NaOH molarity of 16 with additional water content of 10%. Using lime content of 2% achieved the highest modulus of elasticity compared to the other specimens. Moreover, there is a fair agreement between the equation of the ACI-318 code for the relation between the modulus of elasticity and the concrete compressive strength (i.e., Eq. 1). This conclusion agrees with Thomas et al. [44] observation that Young's modulus of elasticity varies linearly with compressive strength for FGPC, and that existing equations of ACI 318 fit reasonably well despite the wide variation in the data. Thus, it is recommended to use the same relation shown in Eq. 1 for calculating L-FGPC's modulus of elasticity.

$$E_c = 4700\sqrt{fc\prime} \quad (1)$$

Voids ratio

As shown in Fig. 7, for NaOH molarities of 12 and 16 and additional water contents of 7.5% and 10%, respectively, the least voids ratio at 90 days from casting was achieved with 2% lime content. The void ratios of the two molarities are so close to each other, and the behavior is almost the same mostly due to the roughly equal total used water in both two cases. The voids ratio decreased when the added lime content increased from 0 to 2%. Then, the voids ratio increased when the added lime content increased from 2 to 6%. This goes with the results of the highest achieved concrete compressive strength and highest splitting tensile strength of the L-FGPC with 2% lime content. On the other hand, using NaOH molarity of 8 and additional water content of 7.5% caused higher voids ratio.

As indicated in Table 1, increasing the NaOH molarity decreased the voids ratio for different lime contents with different curing types as more geopolymer binding materials were produced for FGPC and L-FGPC. The least voids ratio after 90 days of casting was recorded for the specimens without curing at ambient temperature (air). For FGPC, using water curing and air curing caused lower voids ratio than that if steam curing or thermal curing was used. Huseien et al. [36] indicated that the water absorption of samples cured at ambient temperature showed lower absorption compared to FGPC samples cured at elevated temperatures. The reason of that may tend to the homogeneity of the produced gel which is not accelerated by thermal or steam curing. Temuujin et al. [18] suggested that water evaporation from geopolymer matrix during thermal curing may be the reason of the higher porosity of the thermally cured specimens. Furthermore, as shown in Table 1, increasing the additional water content or increasing the aggregate moisture in the concrete mix with constant NaOH molarity increased the voids ratio.

X-ray diffraction analysis (XRD) and microstructure (using SEM)

X-ray diffraction analysis (XRD)

X-ray diffraction analysis was carried out for fly ash geopolymer mortar (i.e., 0% lime content) with NaOH molarity of 16 cured in 70 °C for 2 days and for lime-activated fly

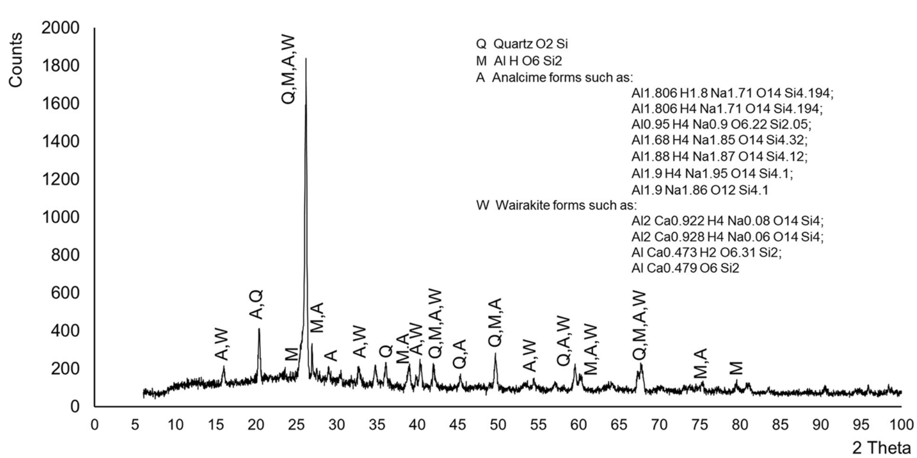

Fig. 8 X-ray diffraction analysis test results for fly ash geopolymer mortar (i.e., 0% lime content) after thermal curing of 70 °C for 2 days

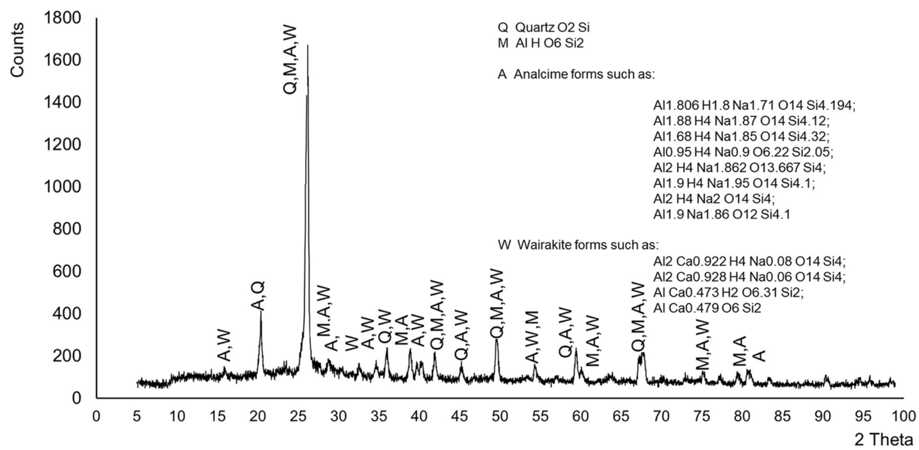

Fig. 9 X-ray diffraction analysis test results for 2% lime content fly ash geopolymer mortar after steam curing for 2 days

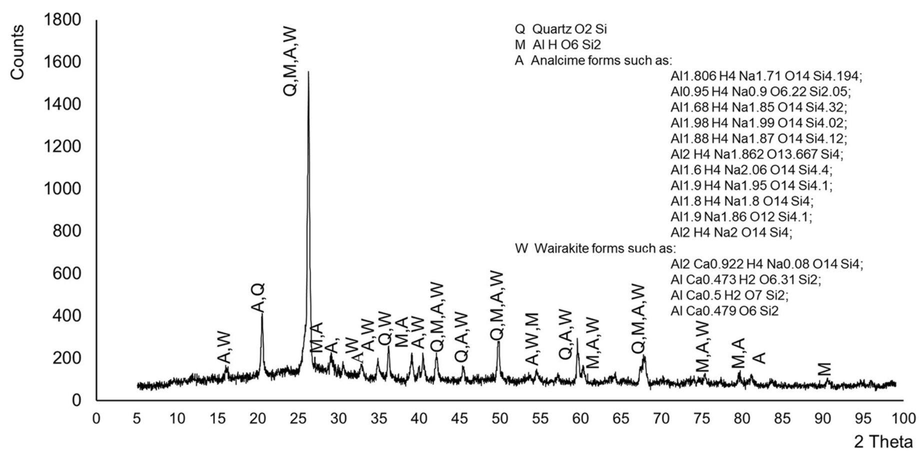

Fig. 10 X-ray diffraction analysis test results for 6% lime content fly ash geopolymer mortar after steam curing for 2 days

ash geopolymer mortar with NaOH molarity of 16 (i.e., using 2% and 6% lime contents) cured in steam without pressure for 2 days.

As shown in Figs. 8, 9, and 10, geopolymer materials are prevailingly of X-ray amorphous character where the diffraction crystals are those of the original materials (i.e., quartz and mullite). Amorphous humps are observed in the diffraction pattern due to the presence of amorphous glassy materials. It is clear that the main binding material of FGPC is N-A-S–H gel which possesses a three-dimensional structure [12]. Also, N-A-S gel was observed. These N-A-S–H and N-A-S gels (e.g., analcime as a form of zeolite crystal) consisted of alumina, silica, and sodium. In addition, N-A-S–H and N-A-S gels containing calcium (e.g., Wairakite as a form of zeolite crystal containing a calcium ion) were present with low concertation compared with the previous mentioned N-A-S–H and N-A-S gels because the used fly ash had low Cao (i.e., 1.09%).

With the use of 2% lime content, an increase of 16% in the summation of the recorded analcime forms and an increase of 11% in the summation of recorded Wairakite forms were observed compared with that of FGPC. This observed increase in the summation of the recorded analcime and Wairakite forms supports that lime may act as a catalyst when 2% lime content is used. On the other hand, using 6% lime content caused a reduction of 6% in the summation of the recorded analcime forms and an increase of 6% in the summation of recorded Wairakite compared with that of FGPC. In addition, the recorded amorphous phases were 80.11%, 75.58%, and 78.69% of the total phases for FGPC with 0%, 2%, and 6% lime contents, respectively. Using 2% and 6% of lime contents increased the degree of crystallinity by 22.8% and 7.1% compared with FGPC. This goes well with the enhanced behavior of L-FGPC when 2% lime content was used and the reduction of the enhanced behavior when higher lime content of 6% was used. It should be mentioned that Temuujin et al. [18] and others [45] proposed that the new reaction products may be calcium aluminosilicate or calcium silicate hydrate in amorphous or poorly ordered crystalline form which would be difficult to detect by X-ray diffraction analysis.

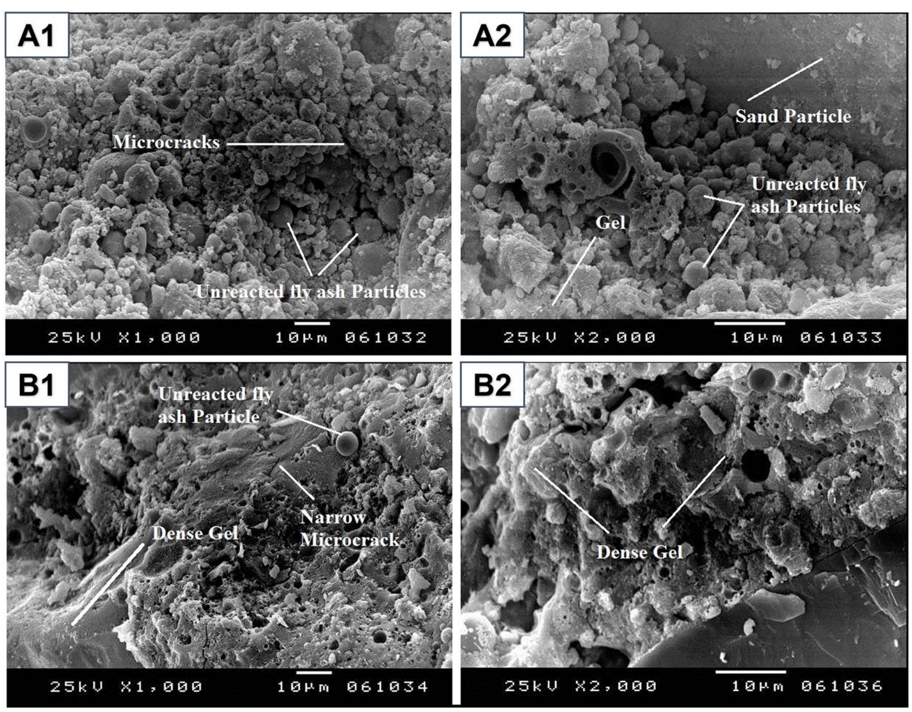

Fig. 11 **A1** and **A2** and **B1** and **B2** Represent SEM images for thermally cured FGPC and steam cured L-FGPC with 2% lime content at different scales. **A1** Thermally cured FGPC using X1000. **A2** Thermally cured FGPC using X2000. **B1** Steam cured L-FGPC with 2% lime content using X1000. **B2** Steam cured L-FGPC with 2% lime content using X2000

Scanning electron microscopy (SEM)

Previous results confirmed that a 2% lime content is the optimum lime content that produces the best mechanical behavior. Thus, a comparison between the microstructure of steam-cured L-FGPC (using 2% lime content) and thermally cured FGPC were conducted after 28 days of casting using scanning electron microscopy (SEM) using × 1000 and × 2000 scaling images. These images are presented in Fig. 11 for FGPC and L-FGPC.

As shown in Fig. 11 A1 and A2 regarding FGPC, lots of fly ash particles were not geopolymerized or activated with the alkaline solution, and microcracks were observed. On the other hand, regarding L-FGPC with 2% lime content shown in Fig. 11 B1 and B2, most of fly ash particles were activated and bonded with the aggregate, and an additional dense gel was observed as confirmed by the X-ray diffraction analysis. Furthermore, voids ratio and extended microcracks were remarkably decreased because of the dense gel that filled these voids and microcracks. Adding lime caused more homogeneous, compact, and finer microstructure similar to that observed by Dombrowski et al. [45]. Thus, it is believed that lime acted as a catalyst in the L-FGPC mixture when 2% of lime content was used.

Conclusions

From this study, one can conclude the following:

- The increase in the lime content from 0 to 6% of (class F) fly ash content in lime-fly ash geopolymer concrete (L-FGPC) decreases the initial and final setting times. The use of 2% and 3% of lime content yielded setting times which are comparable to Portland cement concrete setting times in room temperature.
- Steam curing for L-FGPC achieves the best mechanical properties (i.e., cube compressive strength, splitting tensile strength, and modulus of elasticity) compared with water curing, thermal curing, and air curing. On the other hand, the best mechanical properties for FGPC occur when thermal curing is used.
- Using L-FGPC with 2% lime content and steam curing with different NaOH molarities larger than 8 produce the best mechanical properties and the least voids ratio compared with L-FGPC with 1%, 3%, 4%, and 6% lime contents and fly ash geopolymer concrete (FGPC) with thermal or steam curing. For instance, the use of 2% lime with NaOH molarity of 16 and steam curing enhanced the cube compressive strength, splitting tensile strength, and modulus of elasticity by 56.3%, 52.5%, and 4%, respectively, compared with those of thermally cured FGPC of the same NaOH molarity.
- The increase of the additional water content increases the initial and final setting times of FGPC and L-FGPC. Also, it decreases their cube compressive strength and splitting tensile strength and increases their voids ratio.
- The increase of NaOH molarity decreases the setting times and voids ratio for both FGPC and L-FGPC. Also, it increases their cube compressive strength and splitting tensile strength.

- Increasing the aggregate moisture in the geopolymer concrete mix decreases the cube compressive strength and the splitting tensile strength of FGPC and L-FGPC. Thus, it is recommended to pre-dry the aggregates used in fly ash geopolymer concrete production.
- Scanning electron microscopy (SEM) and X-ray diffraction analysis revealed that using 2% lime content in L-FGPC with steam curing enhances the geopolymerization process causing homogeneous, compact, and finer microstructure and produces dense gel that decreases the voids ratio.
- ACI-318 equation for concrete modulus of elasticity can be used for the studied L-FGPC. Also, ACI-318 equation for concrete splitting tensile strength can be used for L-FGPC with 2 to 4% lime contents.
- Two percent is the optimum lime content that achieves appropriate setting time and best mechanical properties of class F fly ash geopolymer concrete (FGPC) using steam curing. Adding this small lime content to the FGPC mix facilitates the use of FGPC produced by (class F) fly ash in the cast-in situ applications and precast concrete industry. The produced L-FGPC sets fast and produces better behavior compared with FGPC which make it a feasible alternative to ordinary FGPC with much easier curing procedures and with less consumed energy.

Abbreviations

FGPC	Fly ash geopolymer concrete
L-FGPC	Lime-fly ash geopolymer concrete
SEM	Scanning electron microscopy
BS	British standards
ACI	American Concrete Institute
NaOH	Sodium hydroxide
N-A-S	Alkali aluminosilicate gel
N-A-S–H	Alkali aluminosilicate hydrate gel
ASTM	American Society for Testing and Materials
F_c'	Twenty-eight-day concrete cylinder compressive strength
f_{cu}	Twenty-eight-day concrete cube compressive strength
E_c	Concrete elastic modulus
f_{spt}	Concrete splitting tensile strength after 28 days

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Authors' contributions
MAD: conceptualization, methodology, analysis, interpretation, writing, and editing. The author(s) read and approved the final manuscript.

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Availability of data and materials
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Declarations

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Consent for publication
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Competing interests

The author declares no competing interests.

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