The Compressive Strength Development of Alkali Activated Fly Ash/Slag Concretes with Different Alkali Activator Ratios

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Abstract- Recently, geopolymer or alkali-activated concrete takes great attention due to low carbon footprint since fly ash and ground granulated blast furnace slag (industrial by-product materials) has been utilized as binder materials in the alkali-activated concrete. In this research, the compressive strength (CS) development of the alkali-activated fly ash/slag (AAFAS) concrete was investigated in an ambient environment at 7., 14., 28., and 56. days using alkali activator (sodium silicate to sodium hydroxide) ratios of 1, 1.5, 2, and 2.5 with 6M SH (low) concentration. In addition, the effect of delayed oven-curing condition was also studied at 56.day. The results indicated that for the ambient-cured specimens with 6M SH concentration, the maximum and minimum CS were reached in the AAFSS concrete with alkali activator (SS/SH) ratios of 2 and 1, respectively. The AAFAS concrete with an alkali activator ratio of 2.5 showed the lowest CS enhancement after 7.day and 14.day, while the AAFAS specimens with an alkali activator ratio of 1.5 performed the least CS improvement at 28.day in the ambient environment. Meanwhile, the highest CS enhancement was observed in the specimens with an alkali activator ratio of 2 for all ages. Due to the delayed oven-curing, the least and the highest CS enhancements were observed in the AAFAS specimens with alkali activator ratios of 2 and 1.5, respectively. The results pointed out that AAFAS concrete with a higher alkali activator ratio (≥2) should be used for structural applications in the ambient environment.

Keywords Alkali activated fly ash/slag concrete, alkali activator, delayed oven-curing, compressive strength, sodium silicate to sodium hydroxide ratio.

1. Introduction

Due to the increasing population, novel eco-friendly materials are required in order to build sustainable structural applications. Nowadays, ordinary Portland cement (OPC) has been widely utilized as a binder material for the construction of structural elements. However, due to the hazardous influence of the cement material to the environment and high energy demand during cement production [1], alternative binder materials or different concrete types become necessary for the green and sustainable environment and global economy. Generally, fly ash (FA), ground granulated blast furnace slag (GGBS) and silica fume have been partially utilized instead of OPC as binder materials and their favorable effects on the mechanical strength and durability properties of the OPC concrete were reported in the earlier investigation [2]. Recently, geopolymer concrete or alkali-activated concrete, a new type of cementless free concrete, has been emerged into the concrete industry and numerous researches have been conducted in order to use geopolymer or alkali-activated concrete instead of OPC concrete in structural applications [3-7]. A novel cement-free alkali-activated concrete needs less energy during its production [8] and releases approximately 6 times less CO2 than the OPC concrete [9, 10]. Alkali activated concretes includes FA, GGBS, metakaolin, silica fume as binder materials [11] and generally SS and SH were utilized as alkali activators for the geopolymerization reactions [12, 13].

The alkali-activated concretes with FA show slow geopolymerization reactions at the ambient environment and generally requires elevated temperature curing above 60°C for the fast geopolymerization reactions and early strength gain [14]. Therefore, the FA utilization alone can be limited in the precast concrete industry due to the heat-curing requirement. Meanwhile, GGBS consists of a high amount of

CaO that responsible for the strength gain at ambient environment. Therefore, GGBS utilization in the AAFAS concrete becomes significant for the structural applications. However, researchers reported that GGBS utilization alone causes high shrinkage and rapid setting [15, 16], hence combined utilization of the FA and GGBS should be better in terms of structural utilization of the AAFAS concrete specimens.

Alkali activators are responsible for the initiation of the geopolymerization reactions. A strong alkaline medium is required for the surface hydrolysis and molarity concentration of the alkali activator determines the mechanical properties of the AAFAS materials [17]. In an earlier investigation [18], the effect of three different SH molarity (3M, 6M, 9M) was investigated on the FA based geopolymer concrete when the alkali activator ratio (SS/SH ratio) was kept constant and it was reported that the highest CS was obtained on the specimens with 6M SH concentration. The researchers also added that geopolymerization reaction was not strong due to the low SH concentration (3M) and premature coagulation of silica, which causes low CS for the AAFAS concrete specimens with a high molarity concentration (9M). The 6M SH was found as the optimum molarity concentration for the FA based geopolymer concrete.

The inclusion of the SS to the SH solution improved the mechanical strength of the alkali-activated materials since SS increases the silicate content and SiO2/Na2O ratio in the alkali activator [19]. It was reported that the CS of the alkali-activated materials depends on the SH molarity, SS/SH, SiO2/Na2O, and Na2O/Al2O3 ratios [20]. In this study, the effect of various SS/SH ratios under 6M SH concentration on the CS development of the AAFAS concrete was investigated. Moreover, the effect of the delayed oven-curing condition on the CS of the AAFAS concrete was examined.

2. Materials and Test Methods

2.1. *Alkali Activated Concrete Materials*

The AAFAS concrete consisted of 50% GGBS and 50% F-type FA. The GGBS and FA materials were taken from Iskenderun iron and steel power plant and Çatalağzı thermal power plant, respectively. For the geopolymerization process, combined use of SS and SH solutions were utilized with alkali activator ratios of 2.5, 2, 1.5, and 1 with the 6M SH concentration. The SH pellets and SS liquid with an alkaline modulus of 2 and a specific gravity of 1.39 g/cm3 were taken from a local market. The 6M SH solution and different alkali activator ratios were prepared in the laboratory environment just before the AAFAS concrete production. The sudden heat release emerged during mixing of the SH solution, hence SH solution was waited approximately 15 minutes in order to cool down. A naphthalene based superplasticizer was utilized to reach S4 slump class concrete for structural utilization. For the aggregates, coarse aggregates (5mm – 22mm) and fine aggregates (<4 mm) were used and the aggregate sieve result was given in Fig. 1. The chemical composition and physical properties of the used binder materials were also presented in Table 1.

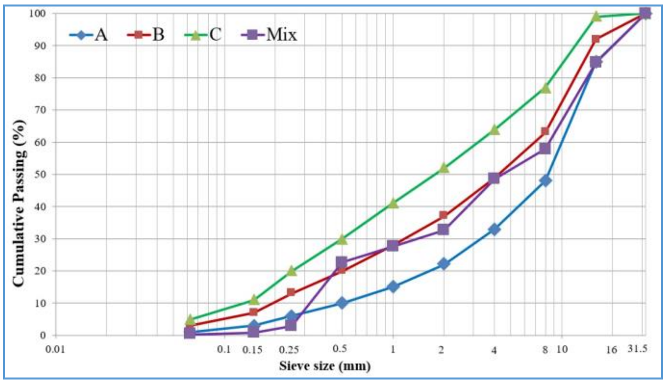

Fig. 1. Aggregate sieve analysis

Table 1. The physical properties and chemical composition of the slag and fly ash

Chemical Composition	Slag	F-type Fly Ash
SiO_2 (%)	37.97	56.15
Al_2O_3 (%)	13.27	26.37
CaO (%)	37.92	1.79
Fe_2O_3 (%)	1.16	6.44
MgO (%)	5.64	2.35
SO_3 (%)	0.23	0.056
Na_2O (%)	0.84	1.1
K_2O (%)	0.56	3.8
Cl (%)	0.015	0.09
Loss on ignition (%)	0.01	2.2
Specific Gravity (g/cm^3)	2.95	2.05
Specific Surface (cm^2/g)	5131	3870

2.2. *Mixture Composition*

Table 2 indicates the mixture composition of the AAFAS concrete with various alkali activator ratios. For the production of the AAFAS concrete, 180 kg/m3 slag (half of the binder) and 180 kg/m3 F-type FA materials were utilized. The used alkali activator ratios were 1, 1.5, 2, and 2.5 and the concentration of the SS was 6M, which was considered to be low molarity concentration. The compressive strength development of the AAFAS concrete under low SH molarity was investigated in this research. For enhanced geopolymerization and workability, and especially cheaper alkali activated concrete productions, water addition into the alkali-activated concrete mixes was reported in the earlier investigations [21, 22]. The used water amount was kept constant for the all AAFAS concrete mixtures, and the superplasticizer amount was changed in order to obtain S4 slump class concrete. It should be noted that the used superplasticizer (SP) amount in the AAFAS specimens decreased as the alkali activator (SS/SH) ratio increased as shown in Table 2.

Table 2. Mixture composition of the AAFAS concrete with different SS/SH ratios

Mixture	SS/SH ratios			
	1	1.5	2	2.5
6M SH	81	64.8	54	46.3
SS	81	97.2	108	115.7
Fly ash	180	180	180	180
Slag	180	180	180	180
No I	560	560	560	560
No II	560	560	560	560
Crushed Sand	373	373	373	373
Sand	373	373	373	373
Superplasticizer	11.56	10.00	8.44	6.88
Water	43.75	43.75	43.75	43.75

During mixing procedure, dry materials (aggregates, FA and GGBS) were included into the mixer and the dry mixture mixed for 2 min. The SS, SH and half of the SP were mixed before in a container and included into the mixer and then mixed for additional 2 min. Finally, water and the remaining SP were also mixed before in a container and the liquid solution was added into the mixer and mixed for additional 2 min. The duration of the total mixing procedure was 6 min.

2.3. *Curing of specimens and compressive strength tests*

The prepared different AAFAS mixes were poured into the 150x150x150 mm cube molds and the required compaction was realized. Then the top surfaces of the cube AAFAS concretes were covered with plastic sheets to prevent the evaporation of the alkaline solutions. After 3 days later, molds were demolded and AAFAS concretes were left in the ambient environment at 6 ± 4°C to investigate the CS development of the AAFAS concretes in winter conditions. The CS tests were performed according to ASTM C39 standard at the ages of 7., 14., 28., and 56. days in order to observe the CS enhancement of the ambient-cured AAFAS concrete specimens with curing time. Three identical AAFAS samples were utilized for each AAFAS specimen in order to calculate average CS of the AAFAS specimens.

In addition to ambient-curing, the delayed oven-curing was also applied to the AAFAS concrete specimens in order to investigate the influence of delayed oven-curing condition on the AAFAS concrete specimens with various SS/SH ratios. In the delayed oven-curing conditions, the AAFAS concretes were waited in the ambient environment for 54 days and then the AAFAS concretes were put in an oven at 70°C for 48 hours (first 56 days for ambient curing condition and the last 2 days for oven-curing condition). The delayed oven-cured AAFAS concretes were tested only at the age of 56. days and three identical AAFAS concrete samples were used to calculate average CS values of the AAFAS concrete specimens at the age of 56.day.

3. Results and Discussions

3.1. *Ambient-cured Specimens*

Fig. 2 shows the CS development of the AAFAS concretes with various alkali activator ratios and 6M SH concentration in the ambient environment. The ambient-cured AAFAS concretes were tested at the ages of 7., 14., 28., and 56. days. As in the case of OPC concrete, the CS of the AAFAS concretes increased with time and the highest CS was attained on the AAFAS concretes at the age of 56. day.

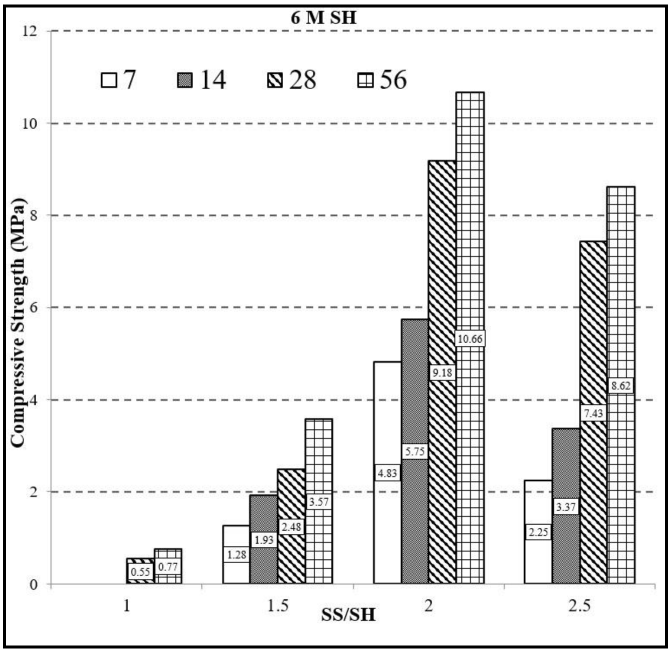

Fig. 2. Compressive strength development of the AAFAS specimens with various SS/SH ratios

The compressive strength (CS) test results indicated that the CS of the AAFAS concretes increased with an increasing alkali activator ratios up to the value of 2, and the CS of the AAFAS concretes started to be decreased after the further alkali activator ratio (2.5). The maximum and minimum CS were obtained in the AAFAS concretes with alkali activator ratios of 2 and 1, respectively. The CS could not be attained for the AAFAS concretes with an alkali activator ratio of 1. When the alkali activator ratio of the AAFAS specimens was 1.5, the average CS of the AAFAS concretes were 1.28 MPa, 1.93 MPa, 2.48 MPa, and 3.57 MPa at the ages of 7.day, 14.day, 28.day, and 56.day, respectively. For the AAFAS concretes with an alkali activator ratio of 2, the mean CS of the AAFAS specimens were found to be 4.83 MPa, 5.75 MPa, 9.18 MPa, and 10.66 MPa for 7.day, 14.day, 28.day, and 56.day, respectively. For the AAFAS specimens with an alkali activator ratio of 2.5, the mean CS of the AAFAS specimens were obtained as 2.25 MPa, 3.37 MPa, 7.43 MPa, and 8.62 MPa at the ages of 7.day, 14.day, 28.day, and 56.day, respectively. The results indicated that ongoing geopolymerization reactions take place with time in the AAFAS concretes.

Table 3. Compressive strength changes of the AAFAS samples with respect to 56.day compressive strength (%)

Day	SS/SH ratios			
	1	1.5	2	2.5
7	-	36	45	26
14	-	54	54	39
28	71	69	86	86
56	100	100	100	100

Table 3 indicates the CS changes of the AAFAS concretes with respect to 56.day CS values. As stated earlier, there was no CS gain at 7.day and 14.day for the AAFAS concretes with an alkali activator ratio of 1. The CS development became 71% at 28.day with respect to 56.day CS for the AAFAS specimens with an alkali activator ratio of 1. For the AAFAS specimens with an alkali activator ratio of 1.5, the CS enhancements became 36%, 54%, and 69% at the ages of 7.day, 14.day, and 28.day, respectively. For the AAFAS concretes with an alkali activator ratio of 2, the CS enhancements at 7.day, 14.day, and 28.day were 45%, 54%, and 86%, respectively. For the AAFAS concretes with an alkali activator ratio of 2.5, the CS improvements were 26%, 39%, and 86% for 7.day, 14.day. and 28.day, respectively. The CS test results indicated that the lowest CS gain was observed on AAFAS concretes with an alkali activator ratio of 2.5 at the ages of 7.day (26%) and 14.day (39%), while the lowest CS gain at the age of 28.day was observed on the AAFAS concretes with an alkali activator ratio of 1.5 (69%). Meanwhile, the highest CS gain was observed on the AAFAS concretes with an alkali activator ratio of 2 at the ages of 7.day (45%), 14.day (54%) and 28.day (86%). For the AAFAS concretes with an alkali activator ratio of 2.5, approximately 60% CS enhancement was observed between 14.day and 28.day. For the AAFAS specimens with alkali activator ratios of 1 and 1.5, approximately 30% CS increase was observed after 28.day, while for the AAFAS specimens with alkali activator ratios of 2 and 2.5, the CS development became only 14% after 28.day.

3.2. *Delayed oven-cured Specimens*

Figure 3 shows the effect of the delayed oven-curing on the CS of the AAFAS concretes at 56.day. The delayed oven-cured AAFAS concretes indicated as 56-OC in Figure 3. Results indicated that at the end of the 56.day curing period, delayed oven-cured AAFAS concretes yielded higher CS values than the ambient-cured AAFAS concretes. The CS of the AAFAS concrete with alkali activator ratios of 1, 1.5, 2 and 2.5 were increased as 9%, 36%, 8%, and 33%, respectively due to the delayed oven-curing. Results indicated that the lowest CS enhancement was observed on the AAFAS specimens with an alkali activator ratio of 2, while the highest CS enhancement was noticed on the AAFAS concretes with an alkali activator ratio of 1.5. In addition, after the delayed oven-curing procedure, AAFAS concrete with an alkali activator ratio of 2 yielded similar CS values with the AAFAS concretes with an alkali activator ratio of 2.5.

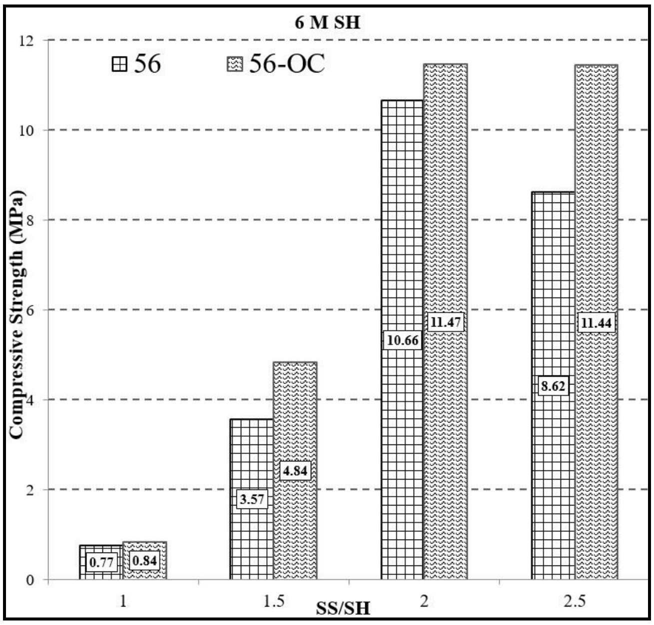

Fig. 3. Compressive strengths of the ambient cured and delayed oven-cured AAFAS specimens

4. Conclusions

In this study, the effect of various alkali activator ratios on the CS development of the AAFAS concretes was investigated using 6M SH concentration at the ages of 7.day, 14.day, 28.day, and 56.day. In addition, the effect of delayed oven-curing on the CS of the AAFAS concretes was also investigated and the results were summarized below;

- The results showed that the CS of the AAFAS concrete specimens increased with time similar to OPC concrete. The CS test results indicated that ongoing geopolymerization reactions take place in the AAFAS concretes up to the 56.day.

- The CS of the AAFAS samples with 6M SH concentrations enhanced with an increase in the alkali activator ratio up to the alkali activator ratio of 2, then the CS of the AAFAS samples were found to be decreased for the increased alkali activator ratio of 2.5.

- For the ambient-cured AAFAS concretes, the highest and the lowest CS were obtained in the AAFAS concrete specimens with alkali activator ratios of 2 and 1, respectively.

- The AAFAS concrete specimens with an alkali activator ratio of 1 showed very low CS (<1 MPa), which can be attributed to the low SH concentration in the used alkali activator.

- The ambient-cured CS test results of the AAFAS specimens also revealed that the lowest CS enhancement was obtained in the AAFAS specimens with an alkali activator ratio of 2.5 at the ages of both 7.day and 14.day, while the lowest CS improvement was observed in the AAFAS concretes with an alkali activator ratio of 1.5 at 28.day. In addition, the highest CS enhancement was reached in the AAFAS concretes with an alkali activator ratio of 2 for all the tested ages.

- The ambient-cured AAFAS specimens with alkali activator ratios of 1 and 1.5 showed approximately 30% CS increase between 28.day and 56.day, whereas for the AAFAS specimens with alkali activator ratios of 2 and 2.5, the CS enhancement became around 14% between 28.day and 56.day. Therefore, AAFAS concrete with a higher alkali activator ratio ($\geq$2) should be utilized in the structural applications in ambient environments.

- The delayed oven-cured AAFAS specimens yielded higher CS values than the ambient-cured AAFAS specimens. The lowest CS enhancement was obtained in the AAFAS specimens with an alkali activator ratio of 2, while the highest CS improvement was achieved in the AAFAS specimens with an alkali activator ratio of 1.5 due to the delayed oven-curing at 56.day.

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References

[1] S. A. Hasanein, H. M. Khate, S. A. A. El-Enein, and H. A. El-Sayed, “Resistance of alkali activated water-cooled slag geopolymer to sulphate attack”, Ceramics-Silikáty, vol. 55, no. 2, pp. 153–160, 2011.

[2] A. Niş, ‘‘Mineral katkılı betonların kimyasal durabilitesinin toplam bağlayıcı miktarı ve eşdeğer su/çimento parametreleriyle beraber incelenmesi’’, Balıkesir Üniversitesi Fen Bilimleri Enstitüsü Dergisi, vol. 21, no. 1, pp. 459-473, 2019.

[3] A. E. Kurtoglu, R. Alzeebaree, O. Aljumaili, A. Nis, M. E. Gulsan, G. Humur, and A. Cevik, ‘‘Mechanical and durability properties of fly ash and slag based geopolymer concrete’’, Advances in Concrete Construction, vol. 6, no. 4, pp. 345–362, 2018.

[4] A. Çevik, R. Alzeebaree, G. Humur, A. Niş, and M. E. Gülşan, ‘‘Effect of nano-silica on the chemical durability and mechanical performance of fly ash based geopolymer concrete’’, Ceramics International, vol. 44, no. 11, pp. 12253-12264, 2018.

[5] R. Alzeebaree, M.E Gulsan, A. Nis, A. Mohammedameen, and A. Cevik, ‘‘Performance of FRP confined and unconfined geopolymer concrete exposed to sulfate attacks’’, Steel and Composite Structures, vol. 29, no. 2, pp. 201-218, 2018.

[6] R. Alzeebaree, A. Çevik, B. Nematollahi, J. Sanjayan, A. Mohammedameen, and M.E. Gülşan, ‘‘Mechanical properties and durability of unconfined and confined geopolymer concrete with fiber reinforced polymers exposed to sulfuric acid’’, Construction and Building Materials, vol. 215, pp. 1015-1032, 2019.

[7] M. E. Gülşan, R. Alzeebaree, A. A. Rasheed, A. Niş, and A.E. Kurtoğlu, ‘‘Development of fly ash/slag based self-compacting geopolymer concrete using nano-silica and steel fiber’’, Construction and Building Materials, vol. 211, pp. 271-283, 2019.

[8] F. N. Okoye, S. Prakash, and N. B. Singh, ‘‘Durability of fly ash based geopolymer concrete in the presence of silica fume’’, Journal of Cleaner Production, vol. 149, pp. 1062-1067, 2017.

[9] J. Davidovits, Geopolymer Chemistry and Applications., 2nd Edn., Inst. Geopolymer, SaintQuentin, France, 2008.

[10] J. Davidovits, ‘‘Geopolymer cement to minimize carbon-dioxde greenhouse-warming’’, Ceram. Trans., vol. 37, pp. 165–182, 1993.

[11] S. Saha and C. Rajasekaran, ‘‘Enhancement of the properties of fly ash based geopolymer paste by incorporating ground granulated blast furnace slag’’, Construction and Building Materials, vol. 146, pp. 615-620, 2017.

[12] A. Fernández-Jiménez, J. G. Palomo, and F. Puertas, ‘‘Alkali-activated slag mortars: mechanical strength behaviour’’, Cement and Concrete Research, vol. 29, no. 8, pp. 1313-1321, 1999.

[13] K. Somna, C. Jaturapitakkul, P. Kajitvichyanukul, and P. Chindaprasirt, ‘‘NaOH-activated ground fly ash

geopolymer cured at ambient temperature'', Fuel, vol. 90, no. 6, pp. 2118-2124, 2011.

[14] T. Bakharev, ''Durability of geopolymer materials in sodium and magnesium sulfate solutions'', Cement and Concrete Research, vol. 35, no.6, 1233-1246, 2005.

[15] C. B. Cheah, M. H. Samsudin, M. Ramli, W.K. Part, and L.E. Tan, L. E. ''The use of high calcium wood ash in the preparation of Ground Granulated Blast Furnace Slag and Pulverized Fly Ash geopolymers: A complete microstructural and mechanical characterization'', Journal of Cleaner Production, vol. 156, pp. 114-123, 2017.

[16] N. K. Lee, J. G. Jang, and H.K. Lee, ''Shrinkage characteristics of alkali-activated fly ash/slag paste and mortar at early ages'', Cement and Concrete Composites, vol. 53, pp. 239-248, 2014.

[17] M. Hu, X. Zhu, and F. Long, ''Alkali-activated fly ash-based geopolymers with zeolite or bentonite as additives'', Cement and Concrete Composites, vol. 31, no. 10, pp. 762-768, 2009.

[18] G. Görhan, and G. Kürklü, ''The influence of the NaOH solution on the properties of the fly ash-based geopolymer mortar cured at different temperatures'', Composites part b: engineering, vol. 58, pp. 371-377, 2014.

[19] P. Duxson, , J. L. Provis, G. C. Lukey, S. W. Mallicoat, W. M. Kriven, and J. S. Van Deventer, ''Understanding the relationship between geopolymer composition, microstructure and mechanical properties'', Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol. 269, no. 1-3, pp. 47-58, 2005.

[20] G.B. Singh, and K. V. Subramaniam, ''Evaluation of sodium content and sodium hydroxide molarity on compressive strength of alkali activated low-calcium fly ash'', Cement and Concrete Composites, vol. 81, pp. 122-132, 2017.

[21] M. Albitar, M. M. Ali, P. Visintin, and M. Drechsler, ''Durability evaluation of geopolymer and conventional concretes'', Construction and Building Materials, vol. 136, pp. 374-385, 2017.

[22] M. Soutsos, A. P. Boyle, R. Vinai, A. Hadjierakleous, and S. J. Barnett, ''Factors influencing the compressive strength of fly ash based geopolymers'', Construction and Building Materials, vol. 110, pp. 355-368, 2016.