An Experimental Study on the Mechanical Properties of Low-Aluminum and Rich-Iron-Calcium Fly Ash-Based Geopolymer Concrete

Jack Widjajakusuma[1,*], Ika Bali[2], Gino Pranata Ng[1], Kevin Aprilio Wibowo[1]

[1]Department of Civil Engineering, Pelita Harapan University, Tangerang, Indonesia

[2]Department of Civil Engineering, President University, Cikarang, Indonesia

Received 10 December 2021; received in revised form 24 May 2022; accepted 25 May 2022

DOI: https://doi.org/10.46604/aiti.2022.10525

Abstract

Limited studies have been conducted on low-aluminum and rich-iron-calcium fly ash (LARICFA)-based geopolymer concrete with increased strength. This study aims to investigate the mechanical characteristics of LARICFA-based geopolymer concrete, including its compressive strength, split tensile strength, and ultimate moment. The steps of this study include material preparation and testing, concrete mix design and casting, specimen curing and testing, and the analysis of testing results. Furthermore, the specimen tests consist of the bending, compressive, and split tensile strength tests. The results show that the average compressive strength and the ultimate moment of the geopolymer concrete are 38.20 MPa and 22.90 kN·m, respectively, while the average ratio between the split tensile and compressive strengths is around 0.09. Therefore, the fly ash-based geopolymer concrete can be used in structural components.

Keywords: geopolymer concrete, fly ash, rich iron, low aluminum, mechanical characteristics

1. Introduction

Geopolymer concrete with volcanic ash (class N in the ASTM C 618-19 classification) was used during ancient Roman times as a building material. It is seawater resistant with durability that reaches thousands of years [1]. Many studies showed that the geopolymer concrete from fly ash has better resistance to seawater and chloride in comparison to normal concrete [2-4]. However, the chemical processes behind the formation of geopolymers are not clearly understood. These processes can be simplified into three stages [5-7]. The first is the dissolution of silicate and aluminum elements from fly ash dust in an alkaline solution to produce aluminate and silicate species. Commonly used alkaline solutions include NaOH, KOH, and Na_2SiO_3. Meanwhile, the second is the process of forming aluminosilicate oxide gels, and the third is the polycondensation process which is a gel network arrangement that produces three-dimensional aluminosilicate networks.

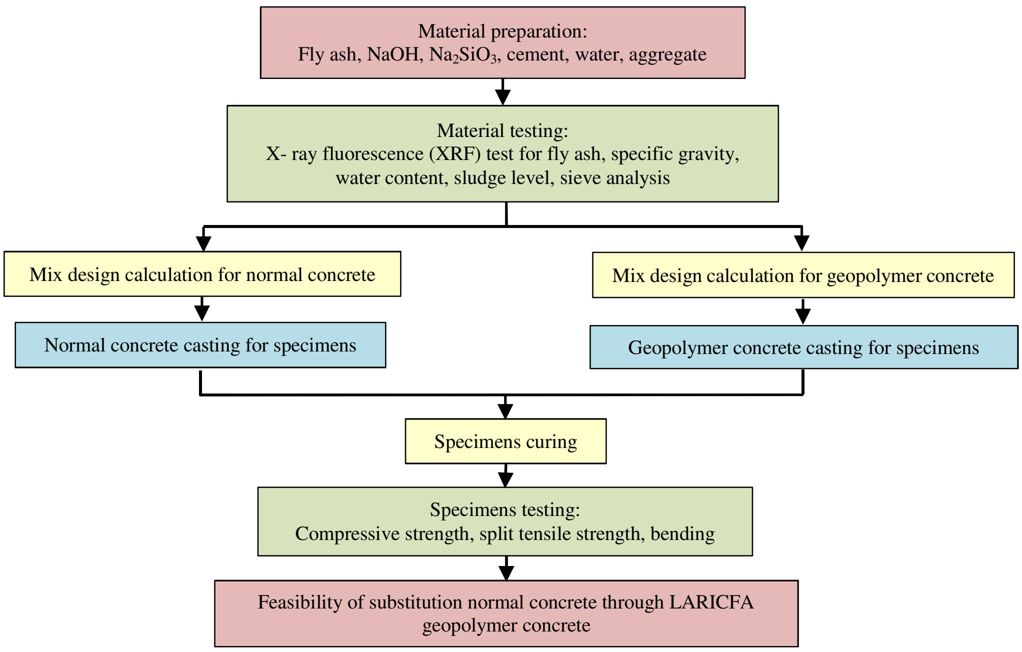
Furthermore, reactive aluminum plays an important role in the structure and strength of fly ash geopolymers [6, 8]. Chemical compounds such as calcium and iron have other effects during polymerization processes. Calcium will react with silicon and aluminum to form various phases of calcium silicate and aluminate hydrates due to the contribution of water. This chemical reaction is accelerated by the presence of aluminate and silicate types dissolved in the geopolymerization process. Similar chemical reactions also occur in Portland and calcium aluminate cement [9]. The presence of calcium plays an important role in accelerating the geopolymer pavement process [5, 10] due to its ability to harden at room temperature [11-12]. Currently, knowledge about the role and location of calcium in geopolymer structures is still very limited [6].

* Corresponding author. E-mail address: jack.widjajakusuma@uph.edu
Tel.: +62(0)21 5460901; Fax: +62(0)21 5460910

Several recent studies stated that iron oxide has an important role in the formation of geopolymers [13-14]. Venyite et al. [15] stated that limited aluminate leads to the replacement of aluminum (Al) by iron (Fe) atoms to form ferro-silicate-aluminate. Furthermore, studies on the role of iron oxide in the polymer formation process are still very limited. This is due to limited methods for analyzing geopolymer structures. The method most often used in geopolymer analysis is nuclear magnetic resonance spectroscopy (NMR), which will be disturbed in the analysis if there is a high iron element [15-16]. The study from Gomes et al. [17] stated that iron oxide decreases the strength of geopolymer concrete, although Venyite et al. [15] had a different result. Apart from the chemical content of fly ash, several parameters that also determine the strength of geopolymer concrete are dust grains fineness, temperature and duration of curing, type and molarity of alkali activator, and pH [5, 10, 18]. This study is motivated to investigate the fly ash-based geopolymer concrete, due to the limited studies on rich-iron and low-aluminum fly ash-based geopolymer concrete with increased strength.

In addition, this study is motivated by the need of using local waste in the form of fly ash as a substitute for cement in Indonesia. According to a new regulation enacted by the Indonesian government, i.e., Government Regulation No. 22 of 2021 on the Implementation of Environmental Protection and Management, the classification of the fly ash resulting from combustion at steam power plants has been revised from toxic waste to non-toxic waste. Through this regulation, the Indonesian government encourages the use of fly ash as much as possible. One possible application is to use fly ash as construction materials. Since 2015, the Indonesian government has launched a program to build a million houses per year for the people of Indonesia. In particular, since the COVID-19 pandemic occurred in 2019, the need for “fit-for-purpose” housing has been one of the needs that must be met because almost all activities, including work, study, and worship, are carried out within homes.

This study aims to investigate the mechanical characteristics (e.g., the compressive strength, split tensile strength, and ultimate moment) of low-aluminum and rich-iron-calcium fly ash (LARICFA)-based geopolymer concrete. The results are expected to aid the Indonesian government in substituting normal concrete with LARICFA-based geopolymer concrete and building residential houses that are environmentally friendly and cheaper than those made from Portland cement. In this study, the specimens made are treated at room temperature and meet the requirements for compressive strength and ultimate moment. Furthermore, the fly ash used has low Al_2O_3 (< 10%), which is equivalent to the content in Portland cement. It also has a very high Fe_2O_3 (nearly 50%) and calcium content (>10%). To carry out the investigation, the study steps are divided as shown in Fig. 1.



\

Fig. 1 Study methodology

2. Material and Method

The main study materials for geopolymer concrete formation are fly ash, alkaline solution (as an activator), and coarse and fine aggregates, which are described in this section. The fly ash used is obtained from the Steam Power Plant of Suralaya, Banten, Indonesia. Furthermore, Table 1 provides chemical compositions based on the results from the X-ray fluorescence (XRF) test. The content of SiO_2 + Al_2O_3 + Fe_2O_3 is equal to 76.14% which is greater than 70%. Based on the ASTM C 618-19 standard, the fly ash belongs to class F, with high iron oxide impurities and low alumina content. Its CaO content is also high (18.24%), which causes geopolymers to quickly harden at room temperature [19].

In polymer concrete, the alkaline solution acts as an activator that dissolves and binds silica and alumina contained in fly ash so that a polymerization reaction occurs. The alkaline solutions used in this study are natrium hydroxide (NaOH) and natrium silicate (Na_2SiO_3). Furthermore, the coarse aggregate used for both the polymer and normal concrete is screened and has a maximum size of 1.50 cm. The fine aggregate used in this study is silica sand passing sieve no. 30 (600 μm).

Both the coarse and fine aggregates are tested according to ASTM C127, ASTM C128, ASTM C33, and SNI 1964-2008. Therefore, the specific gravity test results under saturated surface dry (SSD) conditions for coarse and fine aggregates are 2.38 and 2.62, respectively, with a 0.55% water content by the aggregate weight and a 4.92% sludge content by the aggregate weight. Cement such as Portland composite cement is used as a binder in normal concrete.

For the ultimate moment testing of concrete beams, the reinforcing steel used is BJTP-24 with diameters of 8 and 12 mm and the average yield stress (f_y) of 392.85 MPa. The mix design of the geopolymer (8 Molarity/M NaOH) and normal concrete (target compressive strength 30+10 MPa) in this study can be seen in Table 2.

Furthermore, the NaOH content prepared is 8 M and placed at room temperature for 24 hours before use. Na_2SiO_3, commonly called water glass, is one of the materials that make up an alkaline solution which can be in the form of a liquid or a solid. In this study, the water glass used is a liquid with 55% natrium silicate concentration and 45% water. Natrium silicate is made by mixing SiO_2 with natrium (Na_2SiO_3) or potassium carbonate (K_2CO_3) dissolved with high-pressure steam leading to a thick (semi-viscous) liquid nature [20].

Table 1 Chemical composition of fly ash

Compound name	Concentration (%)
Fe_2O_3	48.51
SiO_2	21.06
CaO	18.24
Al_2O_3	6.58
K_2O	1.42
P_2O_5	1.02
SO_3	0.87
BaO	0.69
MnO	0.55
SrO	0.47
MgO	0.30
ZnO	0.10
ZrO_2	0.08
Na_2O	0.05
Rb_2O	0.03
Cl	0.02
Br	0.02
Y_2O_3	0.01

Table 2 Mix design of the geopolymer and normal concrete

Material (kg/m^3)	Geopolymer concrete	Normal concrete
Coarse aggregate	853.95	1033.64
Fine aggregate	727.44	497.68
Fly ash (type F)	470.51	-
Water glass	179.97	-
NaOH	15.30	-
NaOH water	44.69	-
Water	-	205.00
Cement	-	508.69

Fig. 2 Reinforcement steel for geopolymer concrete-1 and normal concrete-1 beams

Fig. 3 Compressive strength test

Fig. 4 Tensile strength test

Fig. 5 Bending test on the concrete beam

The concrete specimens used in this study are cylinders with a diameter and height of 100 and 200 mm, respectively, for determining the compressive and split tensile strength. Meanwhile, the beam specimens for conducting the bending test have dimensions of 1600 mm × 125 mm × 250 mm. The geopolymer concrete beam dimensions are selected to analyze the casting process and test the object characteristics so that the geopolymer concrete beams can be compared with typical beams used in the structure of standard residential houses.

All beam specimens use an upper reinforcement of 2 Ø8, while for lower reinforcement there are two variations, namely 2 Ø12 and 3 Ø12. The lower reinforcement 2 Ø12 is used for the geopolymer and normal concrete-1 specimens (Fig. 2). Meanwhile, for the specimens of geopolymer and normal concrete-2 beams, the lower reinforcement used is 3 Ø12.

In this study, the curing process for geopolymer concrete specimens in the form of cylinders and blocks are carried out by the placement at room temperature (± 25°C) until the day of testing. The curing period for cylindrical and beam specimens for the geopolymer concrete-1 and concrete-2 is 65 days. The curing process for normal concrete is carried out by keeping the concrete wet to enable optimality and water availability for the cement hydration process. Furthermore, normal cylindrical concrete is placed in a container filled with water, while normal beam concrete is covered with fabric and watered every day. The duration of treatment for the normal concrete-1 and concrete-2 is 69 and 68 days, respectively.

In this study, the mechanical characteristics of geopolymer concrete are obtained using the compressive and split tensile strength tests based on ASTM C39/C39M-0 (Fig. 3) and ASTM C496/C496M-17 (Fig. 4), respectively. Furthermore, the bending test based on ASTM C78/C78M-2 is used to determine the ultimate moment of the concrete beam (Fig. 5). The testing results of the mechanical characteristics of polymer and normal concrete are then compared.

3. Results and Discussion

The test results of compressive strength (f'_c), split tensile strength (f_{ct}), and ultimate moment (M_u) on the geopolymer and normal concrete specimens are shown in Table 3. From the data in Table 3, the compressive strength (f'_c) of these two concrete specimens is almost the same. The average compressive strength of geopolymer concrete reaches 38.2 MPa, which is 13% lower than normal concrete. This value indicates that it can be rationally accepted as an alternative material to normal concrete. The split tensile and compressive strengths of geopolymer concrete are 9.27% and 8.54%, while the split tensile and compressive strengths of normal concrete are 10.87% and 13.77%, respectively (Table 3). Normal concrete has a bigger ratio than geopolymer concrete, but this is not a problem because the tensile strength is not the primary function of concrete (the reinforcement can provide the tensile strength).

A bending test (Fig. 6) is carried out to obtain the ultimate moment of the concrete beam (in the middle of the beam), which is calculated as:

$$M_u = (\frac{P_u}{2} + Q_{sw} \times \frac{l}{2}) \times \frac{l_o}{2} - \frac{P_u}{2} \times \frac{l_o}{3} - Q_{sw} \times \frac{l}{2} \times \frac{l}{4} \quad (1)$$

where P_u is the force from the bending test (kN), Q_{sw} is the concrete self-weight (kN/m), l is the concrete length (m), and l_o is the support-to-support length (m).

Likewise, for the ultimate moment (M_u), those of geopolymer and normal concrete are close to each other. The average ultimate moment of geopolymer concrete reaches 22.90 kN·m in this study, which is relatively slightly better than normal concrete (Table 3). This shows that the bonding between the plain rebar and geopolymer concrete is relatively better than normal concrete (Fig. 7-8). The condition of the plain rebar which supports the occurrence of this strong bond with geopolymer concrete is the absence of rust.

Table 3 Testing results of the geopolymer and normal concrete

Concrete type	Cylinder specimen Ø × h (mm)	f'_c average (MPa)	f_{ct} average (MPa)	Beam specimen $l \times b \times h$ (mm)	f_y average (MPa)	M_u (kN·m)
Geopolymer concrete-1	100 × 200	36.08	3.34	1600 × 125 × 250	392.85	17.15
Geopolymer concrete-2	100 × 200	38.20	3.26	1600 × 125 × 250	392.85	22.90
Normal concrete-1	100 × 200	43.93	4.77	1600 × 125 × 250	392.85	17.02
Normal concrete-2	100 × 200	35.01	4.82	1600 × 125 × 250	392.85	22.65

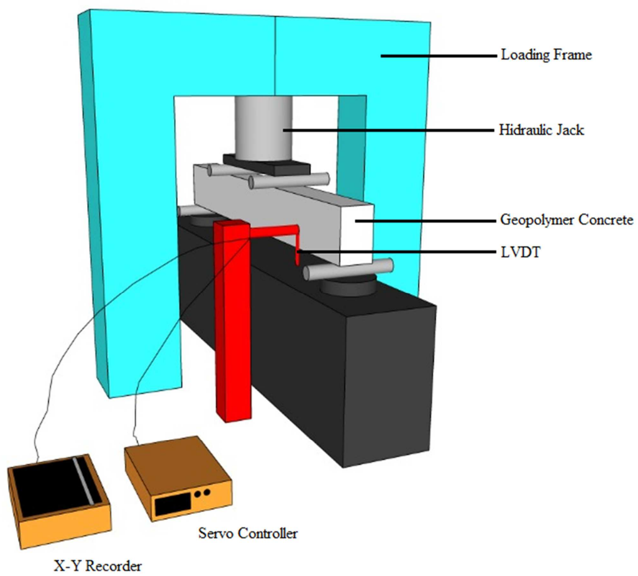


Fig. 6 Configuration of the bending test on the concrete beam

Fig. 7 Bonding of the geopolymer concrete beam to the plain rebar

Fig. 8 Bonding of the normal concrete beam to the plain rebar

Based on the testing results of mechanical properties, the compressive strength (f_c'), split tensile strength (f_{ct}), and ultimate moment (M_u) between the geopolymer and normal concrete are almost the same. Due to the relatively high calcium content of fly ash in geopolymer concrete (18.24%), the designed strength can be achieved with curing at room temperature as shown in the results from other studies [22-23]. Even though the Al_2O_3 content in fly ash is very low (6.58%), the relatively high Fe_2O_3 content (48.51%) enables iron atoms to replace ferro-silicate-aluminate aluminum atoms [6], which allows the strength of geopolymer concrete to reach above 30 MPa with the NaOH activator that has relatively low molarity (8 M).

The bending test shows that the deflection of geopolymer concrete-1 and 2 are 39 and 22 mm, while the deflection of normal concrete-1 and 2 are 16.6 and 12.4 mm, respectively. This shows that the geopolymer concrete beam and its modulus of elasticity are more flexible and smaller than normal concrete, respectively.

All specimens of geopolymer concrete and normal concrete experience flexural cracks and crack patterns that are almost the same (Fig. 9-12). The specimens of geopolymer concrete reach the ultimate moment and show dominant flexural cracks. Meanwhile, for normal concrete beam specimens, the dominant flexural and shear cracks occur in normal concrete-1 and normal concrete-2, respectively. The flexural crack width shown in geopolymer concrete is larger than in normal concrete. This is due to the lower tensile strength and modulus of elasticity of geopolymer concrete compared to normal concrete. Furthermore, the cracks are wider and more evenly distributed in the pure flexural region (between the two loading points) for the geopolymer concrete beams. This phenomenon can be seen in geopolymer concrete-1 beam (Fig. 8). Thus, geopolymer concrete beams provide greater deformation opportunities before failure.

In the casting process, the difference between the geopolymer and normal concrete is the duration of the setting time. Geopolymer concrete has a setting time of about 30-60 minutes, while for normal concrete it is between 1-2 hours. The casting and molding of fresh geopolymer concrete are carried out very quickly and require more energy. Furthermore, the workability of geopolymer concrete is lower than normal concrete. The viscosity of geopolymer concrete is higher than that of normal concrete, and it is more difficult to compact or pound geopolymer concrete than normal concrete. The compaction process in this study uses a rubber hammer and a vibrator. Although the workability of geopolymer concrete is lower, the specimen results have only a few pores which are the same as the case of normal concrete (Fig. 13-14). This is due to the compaction being carried out properly, despite its high energy requirements.

Fig. 9 Flexural crack of geopolymer concrete-1

Fig. 10 Flexural crack of geopolymer concrete-2

Fig. 11 Flexural crack of normal concrete-1

Fig. 12 Shear crack of normal concrete-2

Fig. 13 Visible pore holes in the geopolymer concrete beam

Fig. 14 Visible pore holes in the normal concrete beam

4. Conclusions

The mechanical characteristics testing of the LARICFA-based geopolymer concrete is carried out for determining the compressive strength, split tensile strength, and ultimate moment. According to the results, the following conclusions can be obtained:

(1) The use of LARICFA has great practical advantages with its characteristics of low Al_2O_3 (6.58%), high Fe_2O_3 (48.51%), and CaO (18.24%) contents. One of the advantages is that the geopolymer concrete with LARICFA can reach an average compressive strength of 38.2 MPa only through treatment at room temperature.

(2) The ratio between the split tensile and compressive strengths of geopolymer concrete is almost the same as that of normal concrete.

(3) Furthermore, the average ultimate moment of geopolymer concrete reaches 22.9 kN·m, which is relatively better than that of normal concrete. This indicates better bonding between geopolymer concrete and plain rebar than with normal concrete.

(4) Geopolymer concrete can be recommended for use as a structural component in simple house construction because it has mechanical characteristics that are almost the same as normal concrete.

Acknowledgments

This study was partly supported by the Directorate for Research and Community Service, Directorate General of Research and Development Strengthening, Ministry of Research, Technology and Higher Education of Indonesia No. 100.ADD/LL3/PG/2020, Centre for Research and Community Development, and the Pelita Harapan University through grant P-031-FaST/I/2019.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] M. D. Jackson, et al., "Phillipsite and Al-Tobermorite Mineral Cements Produced through Low-Temperature Water-Rock Reactions in Roman Marine Concrete," American Mineralogist, vol. 102, no. 7, pp. 1435-1450, July 2017.

[2] D. Reddy, et al., "Durability of Fly Ash-Based Geopolymer Structural Concrete in the Marine Environment," Journal of Material in Civil Engineering, vol. 25, no. 6, pp. 781-787, 2012.

[3] P. Chindaprasirt, et al., "Effect of Sodium Hydroxide Concentration on Chloride Penetration and Steel Corrosion of Fly Ash-Based Geopolymer Concrete under Marine Site," Construction and Building Materials, vol. 63, pp. 303-310, July 2014.

[4] M. S. Darmawan, et al., "Shear Strength of Geopolymer Concrete Beams Using High Calcium Content Fly Ash in a Marine Environment," Buildings, vol. 9, no. 4, Article no. 98, April 2019.

[5] Z. G. Ralli, et al., "State of the Art on Geopolymer Concrete," International Journal of Structural Integrity, vol. 12, no. 4, pp. 511-533, 2020.

[6] P. Duxson, et al., “Geopolymer Technology: The Current State of the Art,” Journal of Materials Science, vol. 42, no. 9, pp. 2917-2933, 2007.

[7] M. Łach, et al., “Development and Characterization of Thermal Insulation Geopolymer Foams Based on Fly Ash,” Proceedings of Engineering and Technology Innovation, vol. 16, pp. 23-29, August 2020.

[8] N. Zhang, et al., “On the Incorporation of Class F Fly-Ash to Enhance the Geopolymerization Effects and Splitting Tensile Strength of the Gold Mine Tailings-Based Geopolymer,” Construction and Building Materials, vol. 308, Article no. 125112, November 2021.

[9] A. Fernández-Jiménez, et al., “New Cementitious Materials Based on Alkali-Activated Fly Ash: Performance at High Temperatures,” Journal of the American Ceramic Society, vol. 91, no. 10, pp. 3308-3314, October 2008.

[10] M. Sambucci, et al., “Recent Advances in Geopolymer Technology. A Potential Eco-Friendly Solution in the Construction Materials Industry: A Review,” Journal of Composites Science, vol. 5, no. 4, Article no. 109, April 2021.

[11] W. Kurdowski, Cement and Concrete Chemistry, Netherlands: Springer, 2014.

[12] J. Temuujin, et al., “Influence of Calcium Compounds on the Mechanical Properties of Fly Ash Geopolymer Pastes,” Journal of Hazardous Materials, vol. 167, no. 1-3, pp. 82-88, August 2009.

[13] T. Tho-In, et al., “Pervious High-Calcium Fly Ash Geopolymer Concrete,” Construction and Building Materials, vol. 30, pp. 366-371, May 2012.

[14] T. Nongnuang, et al., “Characteristics of Waste Iron Powder as a Fine Filler in a High-Calcium Fly Ash Geopolymer,” Materials, vol. 14, no. 10, Article no. 2515, May 2021.

[15] P. Venyite, et al., “Effect of Combined Metakaolin and Basalt Powder Additions to Laterite-Based Geopolymers Activated by Rice Husk Ash (RHA)/NaOH Solution,” Silicon, vol. 14, no. 4, pp. 1643-1662, 2021.

[16] J. Davidovits, et al., “Ferro-Sialate Geopolymers (-Fe-O-Si-O-Al-O-),” https://www.geopolymer.org/news/27-ferro-sialate-geopolymers/, 2020.

[17] K. C. Gomes, et al., “Iron Distribution in Geopolymer with Ferromagnetic Rich Precursor,” Materials Science Forum, vol. 643, pp. 131-138, March 2010.

[18] N. Essaidi, et al., “The Role of Hematite in Aluminosilicate Gels Based on Metakaolin,” Ceramics Silikati, vol. 58, no. 1, pp. 1-11, July 2014.

[19] J. C. Petermann, et al., “Alkali-Activated Geopolymers: A Literature Review,” Technical Report AFRL-RX-TY-TR-2010-0097, Air Force Research Laboratory, July 20, 2010.

[20] P. Chindaprasirt, et al., “Effect of Calcium-Rich Compounds on Setting Time and Strength Development of Alkali-Activated Fly Ash Cured at Ambient Temperature,” Case Studies in Construction Materials, vol. 9, Article no. e00198, December 2018.