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Mechanical Properties of Geopolymer Concrete Containing Low-Alkaline Activator

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ABSTRACT

This paper investigates the mechanical properties of the geopolymer concrete using a moderately low alkali activator. The main objective is to ascertain the compressive strength, split tensile strength, elastic modulus, shear strength, flexural strength and bond strength of the said concrete. The experimental program was carried out by reviewing the variables, namely, the amount of alkaline activator which was set at 4%, and the ratio of alkali activator to fly ash (AA/FA) which was varied from 0.35, 0.4, 0.5 to 0.6. Experimental results show that the geopolymer concrete with 4% alkaline activator could still produce concrete compressive strength above 19 MPa for AA/FA ratio of 0.6 and with treatment at room temperature (33°C). On this basis, the authors derived the empirical equations for geopolymer concrete containing low alkaline activator. These equations were compared with the mechanical property model of geopolymer concrete and that of concrete containing Portland cement. The comparison shows that our model has almost the same trend as the other models.

1. INTRODUCTION

Concrete as a construction material is widely used in structures including buildings, bridges, highways, pipes, dams, reservoirs, and drainage canals. Globally, 2.8 billion tons of Portland cement is used to make concrete annually [1]. Environmentalists have, however, sharply criticized the use of cement in concrete mixtures because it generates 4 billion tons of carbon dioxide yearly or 0.8 tons of carbon dioxide gas for every ton of cement produced [2]. To mitigate the negative effect, many researchers have tried to completely replace cement with other elements, producing ecologically friendly products like geopolymer concrete.

Geopolymer concrete has many environmental benefits [3], including carbon reduction, energy-efficient production, waste recycling [4], resistance to chemical elements [5], prevention of chloride penetration [6], and high temperature tolerance [7].

Alkaline activators and precursors rich in aluminum silicate [8] from diverse industrial by-products, including fly ash, slag furnace slag of mine waste, and volcanic ash [9], have been employed to create geopolymer concrete. Among them, fly ash is widely utilized thanks to its low cost and availability [10]. Damayanti [11] revealed that fly ash does not include B3 waste, making it suitable for use in construction materials. With fly ash as the base material, the resulting concrete can achieve a high compressive strength (fc'), which exceeds 45 MPa [12]. Multiple studies have found that a number of factors, such as mixture proportion, precursor type, alkaline activator type, sodium hydroxide molarity, sodium silicate/sodium hydroxide ratio, alkali/fly ash activator ratio, or curing temperature, can affect the compressive strength of geopolymer concrete. Targeting sodium hydroxide, Al Bakri et al. [13] varied the molarity between 6, 8, 10, 12, 14, and 16 M, with a curing temperature of 700°C, and a sodium silicate to sodium hydroxide ratio of 2.5. The results show that a molarity of 12 M produced geopolymer concrete with the maximum compressive strength.

The general way to produce geopolymer concrete is to stir solid ingredients for three minutes before adding an activator solution and stirring the mixture for another four [12]. In order to achieve the appropriate strength and workability, geopolymer concrete needs a proper mix. Ferdous et al. [14] employed 10.8% alkaline activator and 16M NaOH with fly ash. Pavithra et al. [15] adopted 8.5% NaOH and 16M alkaline activator with fly ash. Reddy et al. [16] utilized an 8.5% alkaline activator and 14M NaOH with fly ash, which is added with ground granulated blast furnace slag (GBBS).

Alkaline activator, however, is the most expensive ingredient used to make geopolymer concrete. Since the quality of geopolymer concrete is affected by the treatment temperature and material composition, efficiency must be ensured with a minimum amount of (4%) alkaline activator.

This paper investigates geopolymer concrete with two main objectives. The first objective is to identify the minimum concrete compressive strength, using a low alkaline activator, namely 4%. The compressive strength of concrete that can be produced was measured by varying the treatment temperature between the room temperature 33°C and 60°C. The second objective is to derive the equations for mechanical properties like as compressive strength, split tensile strength, flexural strength, shear strength, bond strength, elastic modulus based on the experimental results.

According to the previous literature on the mechanical behavior of geopolymer concrete, the use of alkaline activators falls between 6.7 and 15%. Alkali activator is the most expensive material in the manufacture of geopolymer concrete. As a result, efficiency must be achieved by reducing the alkaline activator fraction to as little as 4%. The mechanical behavior of the geopolymer concrete, including its compressive strength, tensile strength, flexural strength, shear strength, and elastic modulus, will primarily be impacted by the decrease in alkaline and quite considerable activator compared to what is typically utilized. By investigating the mechanical behavior of geopolymer concrete with low alkali activator, this paper successfully derives several new mechanical equations that underpin the structural design using geopolymer concrete.

2. LITERATURE REVIEW

Currently, the most investigated mechanical properties of geopolymer concrete include compressive strength, split tensile strength, flexural strength, shear strength and elastic modulus. In most studies, the fraction of alkaline activator is greater than 6%. Table 1 summarizes some design equations for geopolymer concrete proposed by several researchers. Ferdous et al. [14] examined the mechanical properties of geopolymer concrete with 10.8% alkaline activator, 16M NaOH, and fly ash treated at 60°C. The resulting concrete realized a compressive strength of 30–60 MPa. Similarly, Pavithra et al. [15] used 8.5% alkaline activator, 16M NaOH, and fly ash treated at 60°C, resulting in geopolymer concrete with compressive strength of 23-53 MPa. The concrete was prepared in the form of 100 mm cube specimens. Reddy et al. [16] prepared geopolymer concrete with compressive strength of 32–66 MPa from 8.5% alkaline activator, 14M NaOH, and fly ash with additional GBBS. Diaz-Loya et al. [17] measured that the density of geopolymer concrete is between 1890 and 2371 kg/ m^3, the compressive strength is between 10 and 80 MPa and the elastic modulus is between 6812 and 42878 MPa. Table 1 also lists several design equations for geopolymer concrete related to the mechanical properties obtained through experiments.

ACI 318-19 [18] and AS 3600 [19] formulated the relationships between the compressive strength of concrete with elastic modulus (E_c), tensile strength (f_t), flexural strength (f_r) and shear stress (τ_b), and put forward the design equation for concrete containing cement. Yang et al. [20], prepared geopolymer concrete without fly ash, using GGBS, lime and sodium silicate. Their design equations are given in Table 1.

Ganesan et al. [21] studied the structural elements of confined geopolymer concrete, and made a geopolymer concrete mixture at a curing temperature of 60°C. On this basis, they deduced a form factor formula (r) and elastic modulus (E_c), and devised a confinement model for geopolymer concrete. This formula was adopted by Anggraini and Hardjito [22] to compare the stress-strain relationship of different confined geopolymer concretes.

Table 1. Relationship between the compressive strength of concrete and mechanical properties

Researcher	E_c	f_t	f_r	τ_b	
ACI [18]	*) $4700\sqrt{f'_c}$	$0.59\sqrt{f'_c}$	$62\sqrt{f'_c}$	$\frac{16.67}{d_b}\sqrt{f'_c}$	Adopted in ACI 318-19
AS3600 [19]	$5055\sqrt{f'_c}$	$0.36\sqrt{f'_c}$	$0.6\sqrt{f'_c}$		
Yang et al. [20]	$4900\sqrt{f'_c}$	$0.255f'c^{0.65}$	$0.35f'c^{0.65}$	$0.8f'c^{0.75}$	Without fly ash, using GGBS lime, lime and sodium silicate
Lee, N.K. and Lee, H.K. [23]	$5300\sqrt{f'_c}$	$0.45\sqrt{f'_c}$			Using fly ash and 16.1% GGBS, and 9.1% alkaline activator
Thomas et al. [24]	$4400\sqrt{f'_c}$	$1.08\sqrt{f'_c}$			Using fly ash, 25.5% GGBS and 10.2% alkaline activator
Albitar [25]		$0.6\sqrt{f'_c}$	$0.75\sqrt{f'_c}$		Using 18% fly ash and 6.7% alkaline activator
Bellum et al. [26, 27]		$0.77\sqrt{f'_c}$	$0.98\sqrt{f'_c}$		Using 17% fly ash and 6.8% alkaline activator
Cui et al. [28]	$874.5f'c^{0.85}$	$0.0876f'_c$+0.0585			Using 17.6% fly ash and 8.8% alkaline activator

3. EXPERIMENTS

3.1 Materials

Table 2. Composition of fly ash

Parameter	% Mass
SiO_2	41.96
Al_2O_3	21.00
Fe_2O_3	16.60
CaO	11.79
MgO	3.06
K_2O	0.57
Na_2O	0.66
MnO_2	0.6
SO_3	0.98
TiO_2	1.64
P_2O_5	0.53

The geopolymer concrete stacking materials include fly ash, sodium silicate, sodium hydroxide, fine and coarse aggregate. The fly ash was taken from electric steam power plant (PLTU Lontar). It is a fine dark-brown material that can pass through the 200-mesh filter. The composition of the fly ash is 79.56% (>70%) SiO_2, Al_2O_3 and Fe_2O_3. It belongs to type F ash [29, 30], with more than 10% CaO (Table 2).

Sodium hydroxide (NaOH), which is in the form of white flakes, was purchased from chemical stores. NaOH solution was prepared by dissolving the NaOH flakes in water. The mass of solid NaOH in the solution varied depending on the molar concentration of the solution (M). The relative atomic mass of NaOH is 40. The NaOH solution with a concentration of 14 M can be made by dissolving as much as 560g of NaOH flakes (14×40) into water, and dilute the volume to 1L.

The ratio of sodium silicate or NaOH of geopolymer concrete belong to the range of 1.5 and 2.5. It is widely recognized that NaOH is more expensive than sodium silicate. To ensure efficiency, this study sets the sodium silicate/NaOH ratio to 2.5, which is in line with Al Bakri et al. [13], Ferdous et al. [31] and Puput et al. [32]. This ratio leads to geopolymer concrete with higher compressive strength than that using other ratios.

The washed-Bangka white sand was adopted as the fine aggregate. The mud content is less than 5%, and the resulting specific gravity is 2527 kg/m^3.

The washed-rumpin crushed stone was adopted as the coarse aggregate. The mud content is less than 1% with a specific gravity of 2542 kg/m^3. According to the wear test with the Los Angeles engine, the wear rate stood at 19.1%, as required by ASTM C 131-89 [33].

The gradation of the mixed aggregate meets British standards: the percentage of sand and crushed stone is 37% and 67%, respectively. The fine and coarse aggregates are in SSD condition.

The ratio of alkaline fly ash (AA/FA) was varied from 0.35, 0.4, 0.5, to 0.6. All in all, the geopolymer concrete was prepared from the following stacking material: 4% alkaline activator, 14 M NaOH and a sodium Silicate/NaOH ratio of 2.5 per one cubic meter of concrete (Table 3).

Table 3. Composition of geopolymer concrete

Ratio of fly ash alkaline activator solution (AAS/FA)	0.35	0.4	0.5	0.6
FA (kg/ m^3)	286	250	200	167
NaOH (kg/m^3)	29	29	29	29
Na_2SiO_3 (kg/ m^3)	71	71	71	71
Fine aggregate	728	744	766	782
Coarse aggregrate	1,246	1,274	1,313	1,339
Water	35	35	35	35

3.2 Specimen preparation and test method

The specimens were prepared is in accordance with ASTM C192 [34] and SNI 2493 [35]. The compressive test target is a cube of the size 100 ×100 mm (Figure 1). The target for split tensile strength and elastic modulus test is a cylinder with a diameter of 100 × 200 mm (Figure 2). The target for the flexural strength test is a beam of the size 150 × 150 × 600 mm (Figure 3). The target for the direct shear strength test is of the size 70 × 150 × 300 mm (Figure 4). The target for the bond strength test is shown in Figure 5.

The day before the test objects were made, an alkaline activator solution was made by combining sodium silicate and NaOH at a ratio of 2.5 as the first step in this study. The test items were created by combining fly ash, fine aggregate, and coarse aggregate in a mixer. The alkaline activator solution was added to the mixer after the mixture has been thoroughly blended. The homogeneous mixture was taken out from the mixer for testing [36].

Figure 1 shows the specimens of the compressive strength test in accordance with the ASTM C39. Figure 2 displays the specimens of the split tensile strength test in accordance with the ASTM C 496 [37] and the elastic modulus test in accordance with the ASTM C469 [38]. Figure 3 specimens the process of the flexural strength test in accordance with the ASTM C293. Figure 4 reports the specimens of the direct shear strength test. Figure 5 displays the specimens of the bond strength test [39].

To compute the compressive strength, the compressive test results of the cube specimens above were converted to produce a compressive strength equivalent to the results of a cylinder test on a specimen with a diameter of 150 × 300 mm at the age of 28 days (fc).

Comparing the results in Tables 4 and 5, it can be generally said that the compressive strength of our geopolymer concrete will increase, if it is treated at 60℃ or higher (Figure 7). This echoes with the finding of Hardjito et al. [12]: as the curing temperature increases, the compressive strength of fly ash-based geopolymer concrete would grow.

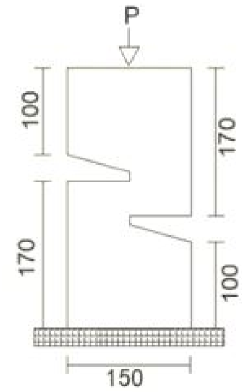
Besides, the compressive strength of the concrete will increase as the AA/FA ratio decreases. This trend was observed at both treatment temperatures of 33℃ and 60℃.

Figure 1. Specimens for compressive strength test (cube 100x100x100 mm)

Figure 2. Specimens for tensile strength test and elastic modulus test (cylinders 150x300 mm)

Figure 3. Specimens for flexural strength test (prism 150x150x600 mm)

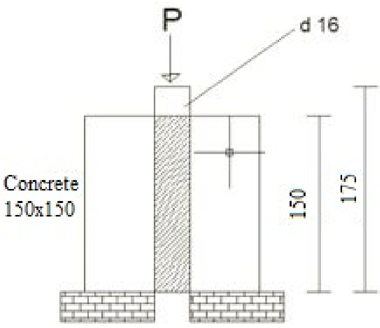
(a) Direct shear test specimen



(b) Schematic of direct shear test

Figure 4. Shear test specimens

(a) Bond strength test specimen



(b) Schematic of bond strength test

Figure 5. Bond strength test specimens

3.3 Relationship between compressive strength and AA/FA ratio

Based on the data in Table 5, the authors modeled the relationship between compressive strength and the AA/FA ratio for low-lying geopolymer concrete with 4% alkali activator through nonlinear regression (Figures 6 and 7). For the treatment temperature of 33°C, the following equation can be derived as:

$$f_c = 13.65\ \text{AAL/FA}^{-0.847} \quad (1)$$

For the geopolymer concrete with 4% alkali activator, the relationship between compressive strength and the AA/FA ratio at 60°C can be derived as:

$$f_c = 16.87\ \text{AAL/FA}^{-0.766} \quad (2)$$

Table 4. Compressive strength of 28d 4% AA geopolymer concrete at 33°C

Specimen code	AAL/FA	Unit weight (kg/m^3)	f_c (MPa)
BGT431	0.6	2.188	19.2
BGT432	0.6	2.234	21.7
BGT433	0.6	2.259	24.1
BGT434	0.5	2.303	21.1
BGT435	0.5	2.308	27.1
BGT436	0.5	2.414	22.5
BGT437	0.4	2.394	32.2
BGT438	0.4	2.367	32.7
BGT439	0.4	2.345	26.8
BGT4310	0.35	2.341	32.6
BGT4311	0.35	2.409	36.5
BGT4312	0.35	2.363	30.5

Table 5. Compressive strength of 28d 4% AA geopolymer concrete at 60°C

Specimen code	AAL/FA	Unit weight (kg/m^3)	f_c (MPa)
BGT461	0.6	2.177	23.2
BGT462	0.6	2.207	23.0
BGT463	0.6	2.203	25.9
BGT464	0.5	2.207	32.8
BGT465	0.5	2.325	25.5
BGT466	0.5	2.237	32.8
BGT467	0.4	2.310	32.6
BGT468	0.4	2.310	40.0
BGT469	0.4	2.325	32.5
BGT4610	0.35	2.252	40.7
BGT4611	0.35	2.402	35.3
BGT4612	0.35	2.379	33.6

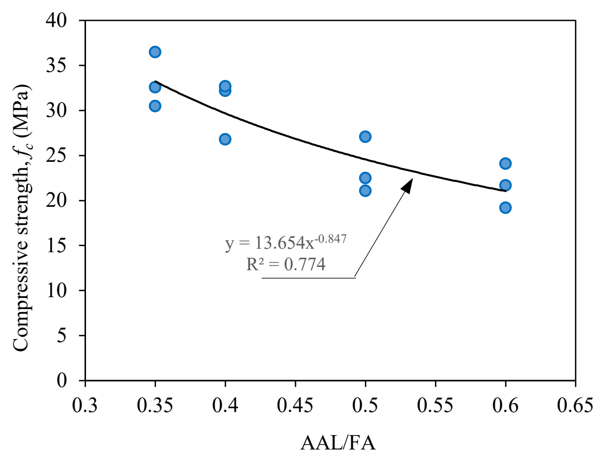


Figure 6. Relationship between compressive strength and the AA/FA ratio for the geopolymer concrete with 4% alkali activator at 33°C

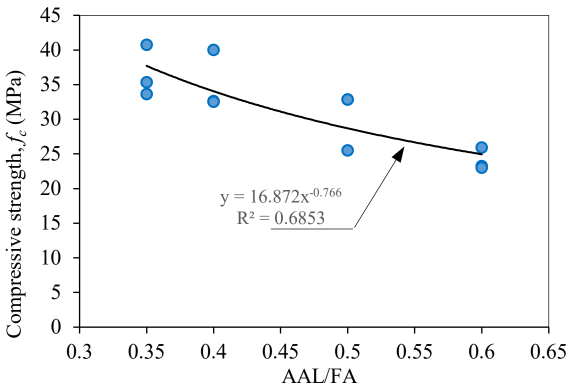


Figure 7. Relationship between compressive strength and the AA/FA ratio for the geopolymer concrete with 4% alkali activator at 60°C

3.4 Empirical equations

As shown in Tables 4 and 5, the compressive strength of the geopolymer concrete with 4% alkali activator at 33°C ranged between 19 and 34 MPa. All specimens have a compressive strength above the minimum requirements for structural concrete in the relevant standard. With the exception of the BGT431 specimen, the compressive strength results all met the requirements for earthquake-resistant building structures (minimum 20.7 MPa). Therefore, this subsection intends to further discuss the results of specimens with 4% alkaline activator at the treatment temperature of 33°C. The relevant mechanical properties, such as split tensile strength, flexural strength, direct shear strength, elastic modulus and bond strength, are shown in Table 6.

3.4.1 Relationship between compressive strength and split tensile strength

For the geopolymer concrete with 4% alkali activator treated at 33°C, the relationship between split tensile strength and compressive strength can be derived from the regression results in Figure 8 using the data in Table 6:

$$f_t = 0.0566(f_c)^{1.0959} \quad (3)$$

The model comparison in Figure 8 suggests that our model is inferior to the design equations according to ACI, Arbitar et al. and Bellum et al, while being superior to the model based on AS3600, and Yang's model, especially when the concrete compressive strength was higher than 28 MPa.

3.4.2 Relationship between compressive strength and flexural strength

For the geopolymer concrete with 4% alkali activator treated at 33°C, the relationship between flexural strength and compressive strength can be derived from the regression results in Figure 9 using the data in Table 6:

$$f_r = 0.011(f_c)^{1.5785} \quad (4)$$

The model comparison in Figure 9 indicates that our model predicted lower flexural strength than the other models.

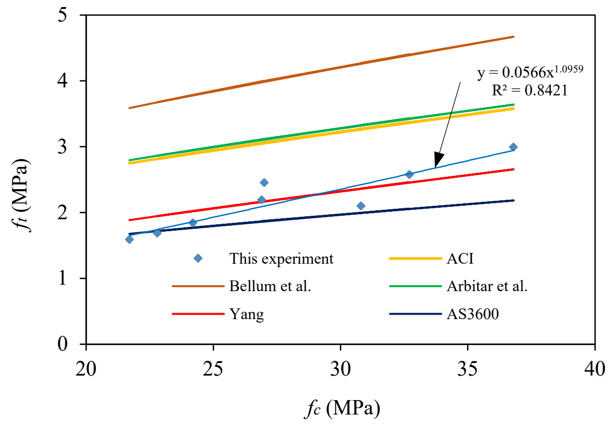


Figure 8. Model comparison (regression of compressive strength vs. split tensile strength)

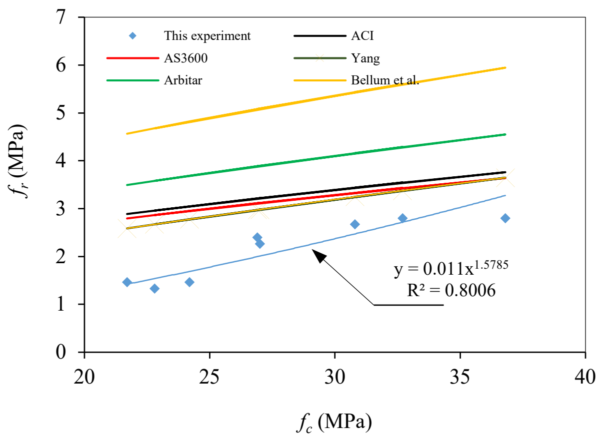


Figure 9. Model comparison (regression of compressive strength vs. flexural strength)

3.4.3 Relationship between compressive strength and elastic modulus

The elastic modulus equation can be generated from the regression in Figure 10:

$$E_c = 2673(f_c)^{0.65} \quad (5)$$

Table 6. Mechanical properties of 28d 4% AA geopolymer concrete at 33°C

Code	Compressive strength f_c (MPa)	Split tensile strength f_t (MPa)	Flexural strength f_r (MPa)	Direct shear strength τ (MPa)	Modulus of elasticity E_c (MPa)	Bond strength τ_b (MPa)
BGM1	21.70	1.59	1.47	2.31	19254	2.69
BGM2	24.20	1.84	1.47	2.15	21276	2.65
BGM3	27.00	2.46	2.27	5.45	23521	3.58
BGM4	22.80	1.69	1.33	1.98	20146	2.79
BGM5	32.70	2.58	2.80	5.45	24035	4.91
BGM6	26.90	2.20	2.40	5.29	23441	3.58
BGM7	36.80	2.99	2.80	7.27	27652	7.17
BGM8	30.80	2.10	2.67	4.13	26536	3.72

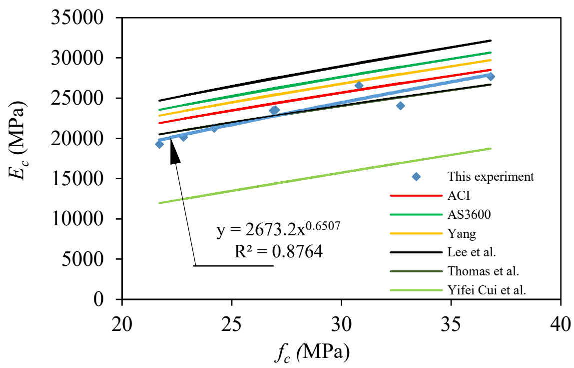


Figure 10. Model comparison (regression of compressive strength vs. elastic modulus)

As shown in Figure 10, the proposed model differed significantly from the other models, such as ACI, AS3600, Yang, Lee et al., and Thomas et al, particularly from the model by Cui et al. [28], which predicted a very low elastic modulus.

3.4.4 Relationship between compressive strength and bond strength

The bond strength model was derived from the regression shown in Figure 11:

$$\tau_b = 0.011\ (f_c)^{1.7554} \qquad (6)$$

Figure 11 compares our model with other models in the regression compressive strength vs. bond strength. It can be seen that our model produced a very conservative prediction of bond strength, compared to other models.

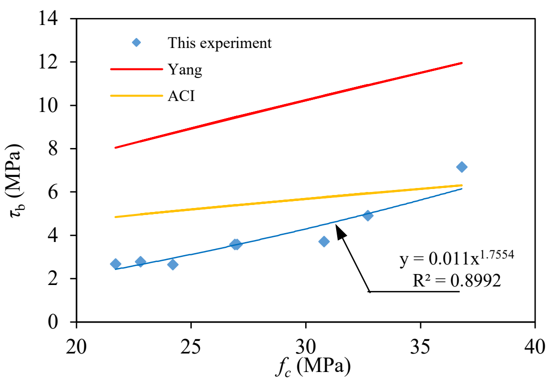


Figure 11. Model comparison (regression of compressive strength vs. bond strength)

4. CONCLUSIONS

The main conclusions of this paper are as follows:

1. The low alkaline activator geopolymer concrete (4%) treated at 33°C and 60°C can reach the compressive strength in the range of 19-40 MPa.
2. Despite the relatively low level of alkaline activator, the proposed geopolymer concrete qualifies as a structural material.
3. In most cases, our geopolymer concrete specimens treated at a higher temperature can achieve a higher compressive strength.
4. Based on the test results, Eqns. (1) and (2) were derived to determine the relationship between the compressive strength of concrete and the AA/AF ratio.
5. Eqns. (3)-(7) can reveal the relationship between compressive strength and other mechanical properties of the geopolymer concrete with 4% alkali activator treated at 33°C.

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