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Effect of Borax on Very High Calcium Geopolymer Concrete

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Abstract— **This study examined the effect of borax pentahydrate on alkali-activated very high-calcium fly ash (VHCF)-based geopolymer concrete. The VHCF obtained from the Pangkalan Susu power plant, Langkat, North Sumatra, Indonesia, had 25% CaO and was classified as C-class fly ash according to the new ASTM C618-19. It was activated using an alkali solution produced using Na_2SiO_3 and NaOH at a ratio of 1.5. Moreover, borax pentahydrate was used due to its high-calcium content, and the setting time, compressive strength, split tensile strength, and flexural strength were investigated. It was discovered from the results that the geopolymer paste had a flash final setting time. The findings showed that the initial setting time was 5 minutes while the final was 25 minutes. The addition of 12% borax pentahydrate was observed to have prolonged the setting time from 25 to 80 minutes. Furthermore, the compressive strength of the concrete after 28 days was 50 MPa using NaOH 8 M and 2% borax pentahydrate, while the split tensile strength was 4.7 MPa and the flexural strength was 4.53 MPa. This implies that the borax pentahydrate can be a retarder to prolong the setting time but can reduce the compressive, flexural, and split tensile strengths.**

Keywords—**Very high-calcium fly ash; borax pentahydrate; retarder; geopolymer.**

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I. INTRODUCTION

Concrete is widely used to build several infrastructures, but its application is associated with environmental disruption. This is due to the fact a normal concrete is produced from Portland cement mixed with water and aggregates, and each ton of this Portland cement releases carbon dioxide (CO_2) during its production and usage, which is the main cause of the greenhouse effect. It has been stated that 1 kg of cement production releases 0.82 kg of CO_2 into the air [1]. This indicates a need to substitute this material with green materials to overcome these adverse effects.

An example of these alternatives is an inorganic binder such as an alumina-silica polymer known as geopolymer. It is normally produced with waste materials such as fly ash containing silicate and aluminate using an alkali chemical solution to activate geopolymerization [2]. This geopolymer concrete has the same or even better characteristics than Portland concrete [3]. Although it has slightly lower modulus elasticity [4]. It was also observed that its application to beam and column elements provides the same characteristics as normal concrete as indicated by the collapse mode and crack pattern [5]. Its application on beam and column element also has the same characteristic with normal concrete, including its collapse mode and crack pattern [6]. However, geopolymer has higher shear strength than normal one [7]. Moreover, it has better performance in durability than normal concrete[8]. The dominant aluminosilicate matrix reduced the chemical attack on the concrete [9]. However, it is recommended to use high-calcium fly ash to reduce permeability [10]. It was found that the geopolymer concrete also had tighter bond with reinforcement than normal concrete[11]. In the simulation of bond slip of reinforced concrete it provided comparable result [12]. Although, this advantage requires further investigation of its effect on tension stiffening and deflection [13].

The production process of this material is complicated despite its better performance, especially through the application of very high-calcium fly ash (VHCF). This is based on the fact that there is no standard mix design standard for its production, making its application as cast in-situ or precast system difficult for engineers during construction [14]. A study has already proposed using the ACI method to calculate the mix design [4] but the alkali activator required to activate the silica-rich material is regarded as expensive. Several other studies have also proposed different mix design processes for geopolymer concrete but most also focused on the low-calcium fly ash. Still, there is no standard for designing the composition of geopolymer [15]. It is suggested to design the composition based on the optimum ratio of binder and fly ash [16].

Borax pentahydrate ($Na_2B_4O_{7.5}$ H_2O) can be used as a retarder in Portland concrete [17] and was observed to have extended the setting time of calcium sulfonamide cement (CSA) and calcium aluminate cement. In addition to ordinary concrete, borax can also be used as a retarder in geopolymers. Its application of up to 15% was reported to have prevented flash setting time in geopolymer concrete produced using high calcium fly ash [18]. However, borax is less effective when the CaO content is high, as indicated by the usage of up to 30% with the addition of burnt rice husk ash in a geopolymer concrete which increased the initial setting time [19]. It was also observed that high borax content could also reduce compressive strength due to a decrease in the Si/Al ratio. The studies used VHCF containing a maximum CaO of 18%, and the fly ash is included in the F class according to the ASTM C618-19 standard. Therefore, this present study examined the performance of C-class fly ash based on the latest ASTM standard for geopolymer concrete produced using borax pentahydrate.

II. MATERIALS AND METHOD

This study used geopolymer concrete to produce VHCF, alkali solution, fine and coarse aggregates, borax pentahydrate, and superplasticizer. The VHCF was obtained from the Pangkalan Susu Coal Power Plant, Langkat, North Sumatera, Indonesia, which uses pulverized coal (PC) boiler generating 200 MW. The alkali solution was produced using sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Meanwhile, Borax pentahydrate ($Na_2B_4O_{7.5}$ H_2O) is the chemical compound used as a retarder for the geopolymer concrete, and the superplasticizer used was Plastimen VZ. The experiment was initiated by mixing the paste, after which the geopolymer concrete was produced.

The geopolymer material was assessed through material characterization, paste, and concrete tests. The characterization involved the application of X-ray fluorescence (XRF) and scanning electronic microscopy (SEM) on the fly ash material. The XRF was used to determine the chemical composition, while the SEM examined the microscopic form of its particles.

The paste tested was produced from the binder consisting of only VHCF and alkali solution. The focus was on the setting time and compressive strength based on ASTM C191 and C39, respectively. It is important to note that the setting time determines the effect of borax on the geopolymer paste. This study used a G1 mix design, as indicated in Table 1, after which the addition of 2% and 4% borax by binder weight was compared.

TABLE I
MIX DESIGN OF GEOPOLYMER PASTE

Mix Code	Mix percentage (%)	
	Fly ash	Alkali activator (Na_2SiO_3: NaOH = 1,5)
G1	70	30
G2	75	25

The compressive strength of the paste was determined to know the mix designs with the highest value between G1 and G2. Moreover, the molarity of the NaOH solution was varied at 6, 8, 10, and 12 M for each specimen designed as a 5×5×5 cm cube. It is important to note that all the samples were tested at the age of 3, 7, 14, 28, and 56 days.

The geopolymer concrete was produced using a binder mixed with aggregates, borax, and superplasticizer based on the composition presented in Fig. 1. Moreover, a 30% alkali activator was applied due to its optimum performance recorded in a previous study [20]. The characterization test was also focused on the compressive, split tensile, and flexural strengths. Moreover, seven mix designs were produced based on the content of borax pentahydrate added, as listed in Table 2. The compressive strength was tested at 3, 7, 14, and 28 days while the split tensile and flexural strengths were determined on the 28th day based on ASTM C496 and C78, respectively. It is important to note that the compressive and splitting tensile strengths were tested using a 100×200 mm cylinder sample, while the flexural strength was through a 100×100×500 mm beam.

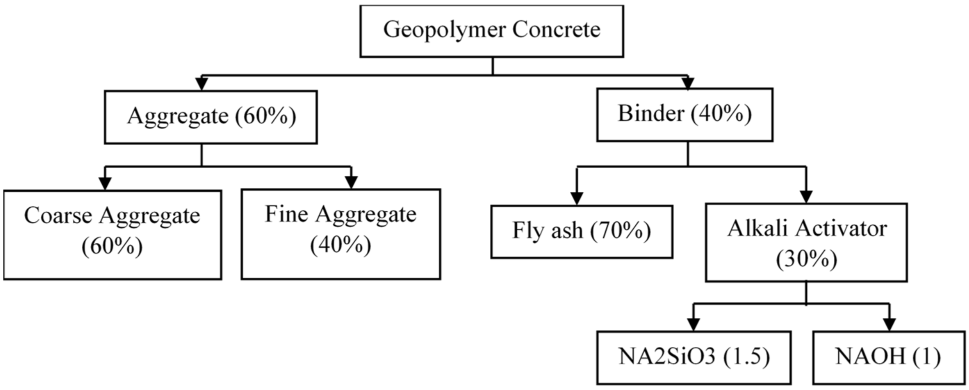

Fig. 1 Mix design of geopolymer concrete.

TABLE II

SAMPLE VARIATION OF BORAX AND SUPERPLASTICIZER.

Additive Compound	Mix percentage						
	G	B2	B4	B6	B8	B10	B12%
borax pentahydrate	0%	2%	4%	6%	8%	10%	12%
plastimen VZ	2%	2%	2%	2%	2%	2%	2%

III. RESULT AND DISCUSSION

A. *XRF result of Pangkalan Susu fly ash*

The XRF results in Table 3 showed that the total SiO_2 + Al_2O_3 + Fe_2O_3 was 63.12% while the CaO was 25.39%. This led to the classification of the fly ash as class C pozzolan in line with ASTM C618-19. It was also observed to have a low loss of ignition (LOI), which complied with the standard (<6%), and this implies its carbon content is low. Meanwhile, this fly ash is the new C class with high CaO content than those recorded in other studies. Nuaklong [19] used fly ash with 18% CaO and rice husk ash. Antoni [18] also used fly ash with CaO 18% at max.

TABLE III

XRF RESULT OF PANGKALAN SUSU FLY ASH.

Composition	Content (%)
Silicon dioxide (SIO_2)	34.81
Alumunium oxide (Al_2O)	16.49
Iron (III) oxide (Fe_2O_3)	11.82
Calcium oxide (CaO)	25.39
Magnesium oxide (MgO)	4.92
Sodium oxide (Na_2O)	2.39
Pottasium oxide (K_2O)	0.56
Titanium dioxide (TiO_2)	0.76
Manganese dioxide (MnO_2)	0.37
Chromium (III) oxide (Cr_2O_3)	0.01
Phosphorus pentoxide (P_2O_5)	0.12
Sulfur trioxide (SO_3)	1.47
Loss of ignition (LOI)	0.89

B. *SEM Result of Pangkalan Susu fly ash*

The SEM results presented in Fig. 2 showed that the fly ash has a perfect sphere due to the pulverization of the coal into fine particles by the PC boiler before combustion. The coal ash residue also has the shape of the coal and was subsequently used to determine the absorption rate of the fly ash [21]. It was also observed that the fly ash could activate the geopolymerization process at the lower percentage of alkali solution due to its lower surface area caused by small round particles. Moreover, these particles reduced the porosity of concrete due to the close microstructural gap in the interfacial transition zone area [22] and increased the silica reactivity in the fly ash [23].

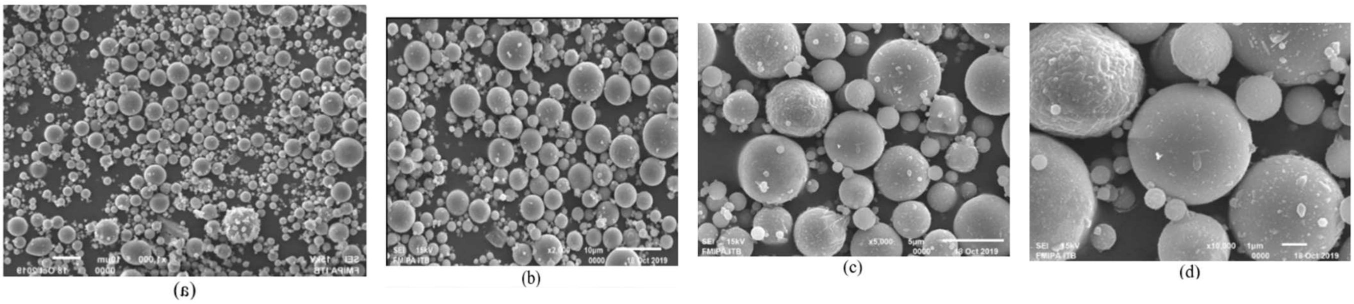

Fig. 2 SEM results of Pangkalan Susu fly ash with different magnification: (a) 1,000×; (b) 2,000×; (c) 5,000×; (d) 10,000×.

C. *Setting Time of Geopolymer Paste*

The setting time of the VHCF and alkali activator paste mixed at a ratio of 75:25 was tested. It is pertinent to restate that the activator was a blend of sodium silicate (Na_2SiO_3) and 8 M sodium hydroxide (NaOH) solution mixed at a ratio of 1.5:1. Moreover, the borax was added to the mix using the variations in Table 2. The setting time test results are presented in Fig 3.

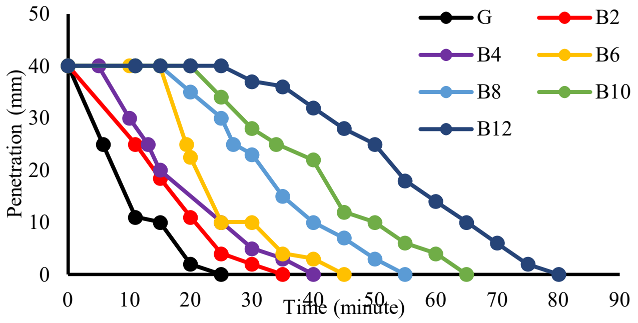

Fig. 3 Setting time test result of geopolymer paste using Borax and superplasticizer.

Fig. 3 shows that the class C fly ash had a faster time than the normal paste produced using cement and water in ASTM C150 as indicated by the minimum initial time of 45 minutes and a minimum final setting time of 375 minutes. This implies the VHCF had a flash setting time because of the high CaO content, which led to the absorption of the water content in the geopolymer system [2]. Another study also confirmed that applying a high calcium fly ash accelerated the calcium silicate hydrate (C-S-H) formation during the hardening process [24]. However, this formation led to lower compressive strength than Natrium aluminosilicate hydrate (N-A-S-H) gel [25]. It was also observed that adding borax slowed down the setting time, as indicated by the inclusion of up to 12%, which increased the duration from 25 to 80 minutes and reduced the initial setting time to 45 minutes. Meanwhile, it was observed to have a fast-setting time compared to Portland cement.

The setting time of the geopolymer paste produced using 10% borax (B10) was compared with another study conducted by Antoni [18] using two fly ashes with CaO at 17% (FA1) and 18.2% (FA2), respectively, as indicated in Table 4. It was discovered that B10 has a longer initial setting time than FA2 but a faster final setting time. This is associated with the high 25% CaO which reduced the setting time of the paste. Therefore, it was confirmed that borax pentahydrate could function as a retarder to prolong the setting time of geopolymer concrete [26].

TABLE IV
COMPARISON OF SETTING TIME WITH ANTONI [18].

Setting time	FA1	FA2	B10
Initial setting time	20	17	34
Final setting time	75	98	65

D. The Compressive Strength of Geopolymer Paste

The mix design of the paste was based on the different molarity of NaOH in Table 1, and the compressive strength obtained for each mix is presented in Fig. 4 for G1 and Fig. 5 for G2.

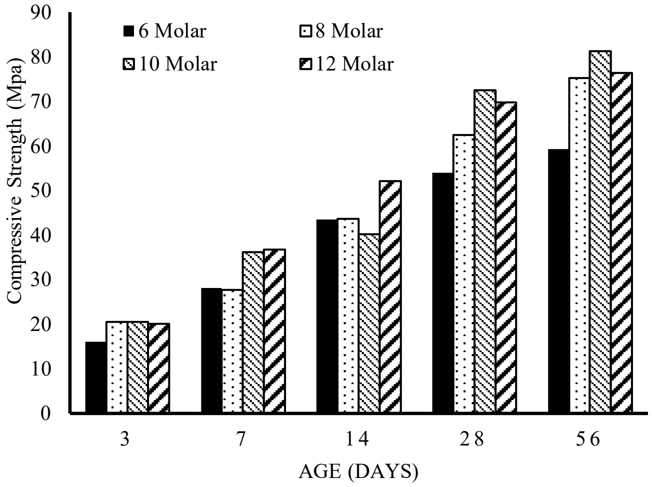

Fig. 4 Compressive strength of G1 mix for geopolymer paste.

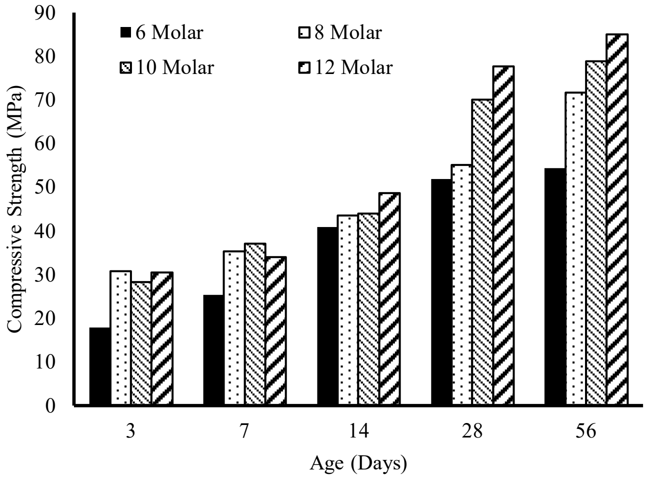

Fig. 5 Compressive strength of G2 mix for geopolymer paste.

Fig. 4 shows that the highest strength on the G1 mix composition was 81 MPa, obtained with 10 M NaOH, while the highest in G2 as indicated in Fig. 5 was 85 MPa recorded with 12 M NaOH. This implies that the higher molarity of NaOH produced higher compressive strength [27]. Meanwhile, the best workability was found with 8 M, which had higher compressive strength on the G1 mix than the G2 mix, and it was used for easier workability based on its performance.

E. The Compressive Strength of Geopolymer Concrete

The compressive strength results presented in Fig. 6 showed that Na_2SiO_3:NaOH of 1.5 for class C fly ash produced a high strength of 50 MPa. This indicates this is the optimum ratio, as confirmed by the findings of previous studies [28]. It was also recommended by Cornelis [29] for high-calcium fly ash. It was further observed that the high-calcium geopolymer concrete had high strength at 28 days due to the high content of CaO. Meanwhile, the compressive strength was reduced by adding the borax pentahydrate as a retarder. This was indicated by the reduction to 27.4 MPa at 28 days due to the addition of 12% borax. This is in line with the findings of a previous study that borax can reduce compressive and flexural strength [19] because the Si/Al ratio of the geopolymer was reduced.

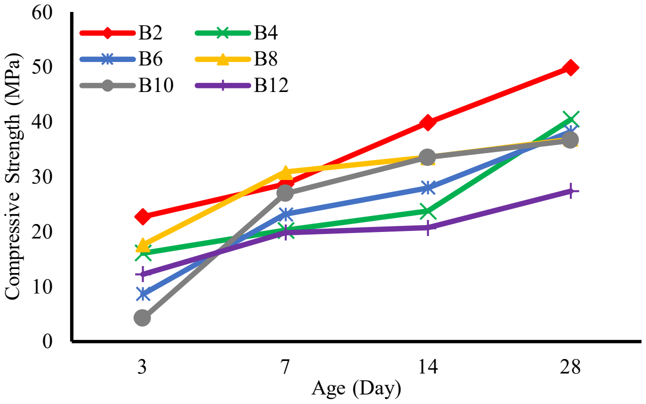

Fig. 6 Compressive strength test result of geopolymer concrete with different borax and superplasticizer contents.

F. The Splitting tensile strength of geopolymer concrete

The splitting strength method is normally used to determine concrete shear strength, which is considered very important in designing reinforced concrete for roads and airports. In these construction conditions, the shear strength is more decisive than the compressive strength. Therefore, the results of the split tensile strength for the geopolymer concrete are presented in the following Fig. 7.

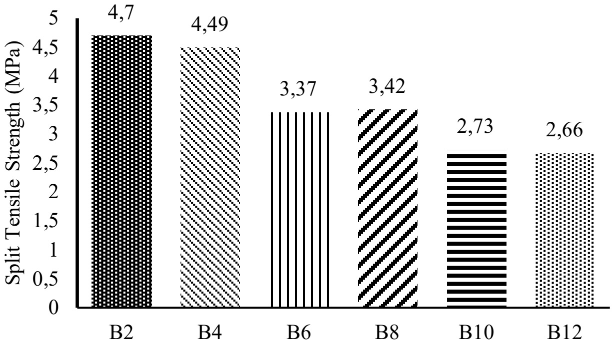

Fig. 7 Splitting tensile strength of Geopolymer concrete.

It was discovered from the figure that the highest splitting tensile strength, 4.7 MPa, was recorded in B2, and this indicates it is the optimum mix for geopolymer concrete. Moreover, the tensile strength and compressive strength ratio for each sample were between 9-12%, with an average of 9%, similar to the normal concrete.

G. Flexural Strength of Geopolymer Concrete

The flexural strengths obtained are presented in Fig. 8, and it was surprisingly discovered that B2 has a higher value than normal concrete, which is required to be 4.5 MPa according to the Bina Marga specification [30]. This signifies that geopolymer concretes are potentially applicable in road construction.

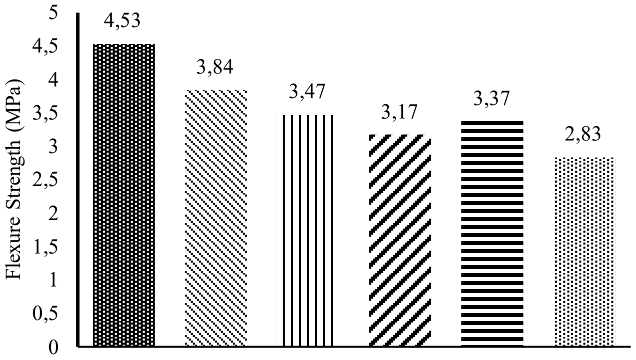

Fig. 8 Flexural strength of Geopolymer concrete.

H. The Relation of the Compressive Strength between the Geopolymer Concrete and the Paste

The compressive strength from the geopolymer concrete was associated with the G1 paste to produce a parabolic regression equation applied as defined in Fig. 9. Moreover, the closer equation obtained with an R-square of 0.97 is presented in Equation (1) which was used to predict the compressive strength of geopolymer concrete at different NaOH molarities based on the data from G2 mix as indicated in Fig. 10.

$$y=2.7231x^{0.7065} \tag{1}$$

Fig. 9 shows that the geopolymer concrete produced using 6 M NaOH in the G2 mix was predicted to reach 46 MPa at 28-days. Meanwhile, the sample with 12 Molar was estimated to achieve 55 MPa during the same period but this value was slightly lower than the value obtained at 10 Molar. This implies the compressive strength of the geopolymer paste increased gradually as the NaOH molarity increased. However, the potential production of high strength geopolymer concrete based on these results needs to be confirmed with an actual experiment.

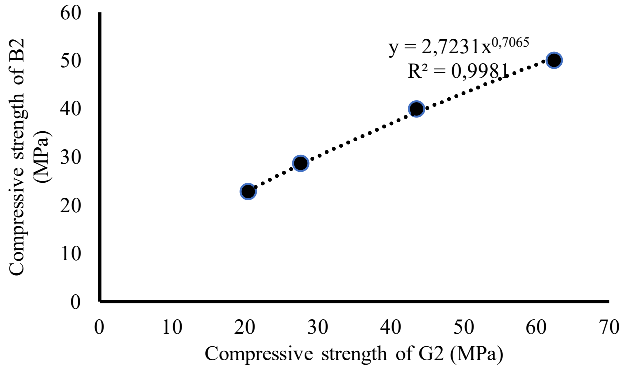

Fig. 9 Parabolic regression of compressive strength between geopolymer concrete and paste.

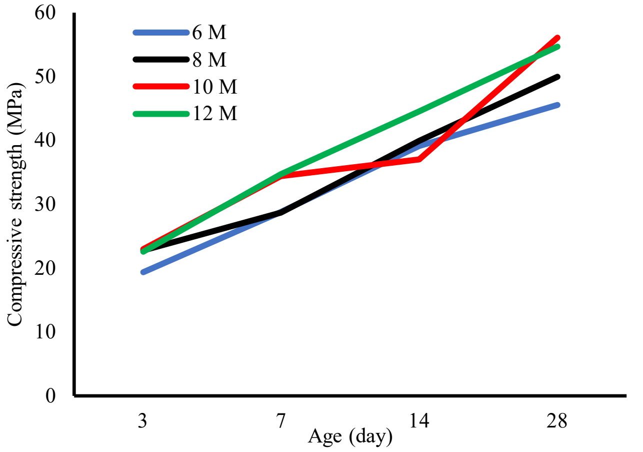

Fig. 10 Compressive strength result of geopolymer concrete at different NaOH molarities based on the equation of regression.

IV. CONCLUSION

This study focused on determining the effect of borax pentahydrate on the physical and mechanical performance of geopolymer in the paste and concrete forms using high-calcium fly ash. The geopolymer concrete mix design using class C fly ash from Pangkalan Susu power plant, Langkat, North Sumatra, Indonesia. It consists of a binder with VHCF and alkali activator at a ratio of 75:25 using Na_2SiO_3:NaOH at 1.5, 2% borax pentahydrate, and 2% superplasticizer had a high compressive strength of 50 MPa. This study also observed that the class C fly ash has a rapid setting time because of the high content of CaO, which is inappropriate for geopolymer concrete. Therefore, adding borax pentahydrate up to 12% prolonged the plastic state of the mix and increased setting time but reduced the compressive, splitting tensile, and flexural strengths.

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