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PHYSICAL AND MECHANICAL PROPERTIES OF FLY ASH-BOTTOM ASH GEOPOLYMER MIXTURES ON EXPANSIVE CLAY SOIL STABILIZATION AS A SUBGRADE MATERIAL

Miguel Felix WIJAYA[1], Sito ISMANTI[1,*], Iman SATYARNO[1]

[1] Department of Civil and Environmental Engineering, Gadjah Mada University, Yogyakarta, Indonesia
[*] corresponding author: sito.ismanti@ugm.ac.id

Abstract

The presence of expansive clay causes roads to undergo damage such as wavy, cracked, and even potholes. This type of soil shows that the soil is prone to swelling and shrinking. A base soil handling method against the effects of swelling and shrinking is chemical soil stabilization such as mixing the soil with lime, cement or additional materials. In this study, the stabilization method used was the fly ash and bottom ash geopolymerization reaction. Fly ash and bottom ash is an effective alternative to replace cement. Fly ash and bottom ash with addition of alkali activators of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) can serve as a binder similar to cement. This study aimed to improve the physical property and mechanical property tests of the soil such as bearing capacity and swelling potential as a requirement for subgrade. All physical property test results revealed that using fly ash-bottom ash geopolymer paste can improve qualities such as specific gravity, Atterberg limit, and grain size to improve expansive clay soil. Likewise, the mechanical property test results showed that the subgrade stabilized with fly ash-bottom ash geopolymer can increase its strength to surpass the requirements for road subgrades.

Keywords:

Physical properties;
Mechanical properties;
Fly ash-bottom ash geopolymer;
Expansive clay;
Soil stabilization.

1 Introduction

Expansive clay soil is a problem in road pavement subgrades. Expansive soil has the potential to indicate that the soil is prone to swelling and shrinking. The up-and-down movement of the subgrade and changes in vertical soil volume due to expansive clay start at the edge of the pavement and continue to the middle because the water content is greatly affected by rainwater during the rainy and dry seasons [1]. Road pavements on expansive soil subgrades will incur large maintenance and rehabilitation costs [2]. The movement of subgrade development can cause cracks in the pavement, thus disrupting traffic comfort [3]. Thus, treatment of the base soil against the effects of swelling and shrinkage is imperative.

Improvement of expansive clay soil can be done by using different methods, such as chemical soil stabilization, including mixing the soil with lime, cement, fly ash, or additional materials [4]. Ismanti & Yasufuku [5] stated that using cement to stabilize clay soil is expensive and suggested to replace cement with pozzolanic materials such as fly ash waste or other waste to reduce costs. Fly ash and bottom ash is a waste from burning coal from steam power plants (PLTU). Burning coal produces approximately 80%-90% fly ash and 10%-20% bottom ash [6].

With research development, fly ash geopolymer for solidification is an effective alternative to cement. Fly ash with added alkali activators of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) can serve as a binder. Murmu et al. [7] studied expansive clay type CH (high plasticity) stabilized using geopolymer, which is a mixture of fly ash and alkaline solutions of sodium hydroxide and sodium silicate without using cement. The geopolymer paste content is 5%-20%. Based on the results of the consistency limit and unconfined compressive strength (UCS) tests with a low alkaline solution ratio and an optimum geopolymer paste content of 20%, the PI (plasticity index) value can be decreased by

24.6%. In addition, Syed et al. [8] reported the use of geopolymer as a stabilization material for expansive clay soil with a paste content of 5%-10% and an alkaline solution of sodium hydroxide and sodium silicate used in a low ratio without using cement and lime. Based on the UCS and CBR test results, the optimum of geopolymer paste is 10%, which increases the UCS value to 0.66 MPa and the CBR value to 11.7%. Previous studied by Le et al. [9] used bottom ash from coal combustion residue at a steam power station and showed that bottom ash can serve as a filler to stabilize the soil. They observed that if the content is more than 20%, the ash will reduce the strength.

Maheepala et al. [10] elucidated the stages of the reactions that occur between geopolymer and expansive clay. Starting from clay sheets with a negative charge (anions), when mixed with water molecules, the clay layer spreads into a double layer. An exchange reaction occurs with the cations so that the pores of the clay sheet undergo leaching. The clay particles clump together. If expansive soil is stabilized with a geopolymer, solidified soil particles will form and harden, preventing the soil from expanding. On the other side, Arioz et al. [11] and Wijaya et al. [12] demonstrated that heavy metals were bound within geopolymer reactions, thereby preventing their leaching into the environment. Replacing cement with fly ash or bottom ash can reduce costs because the ash can be obtained from factory waste. In addition, it can reduce carbon dioxide (CO_2) emissions from cement production, mitigate global warming, environmentally friendly and sustainable.

The aim and benefit of this research was to determine the index properties to obtain the physical properties of expansive clay as a road pavement subgrade. We continued studying the mechanical properties of soil stabilized with fly ash-bottom ash (FABA) geopolymer to determine the bearing capacity of the soil used based on road subgrade requirements.

2 Materials

2.1 Research location of the soil sample

The soil sample came from the Kedung Sari area, Pengasih District, Kulon Progo Regency, Yogyakarta Special Region, Indonesia, the location of which is in Fig. 1 and was analyzed by the Soil Mechanics Laboratory, Department of Civil and Environmental Engineering, Faculty of Engineering, Gadjah Mada University. The soil used as a sample was first investigated as the location of expansive soil. Soil samples were taken 0.5 - 1.0 m deep from the ground surface under disturbed conditions.

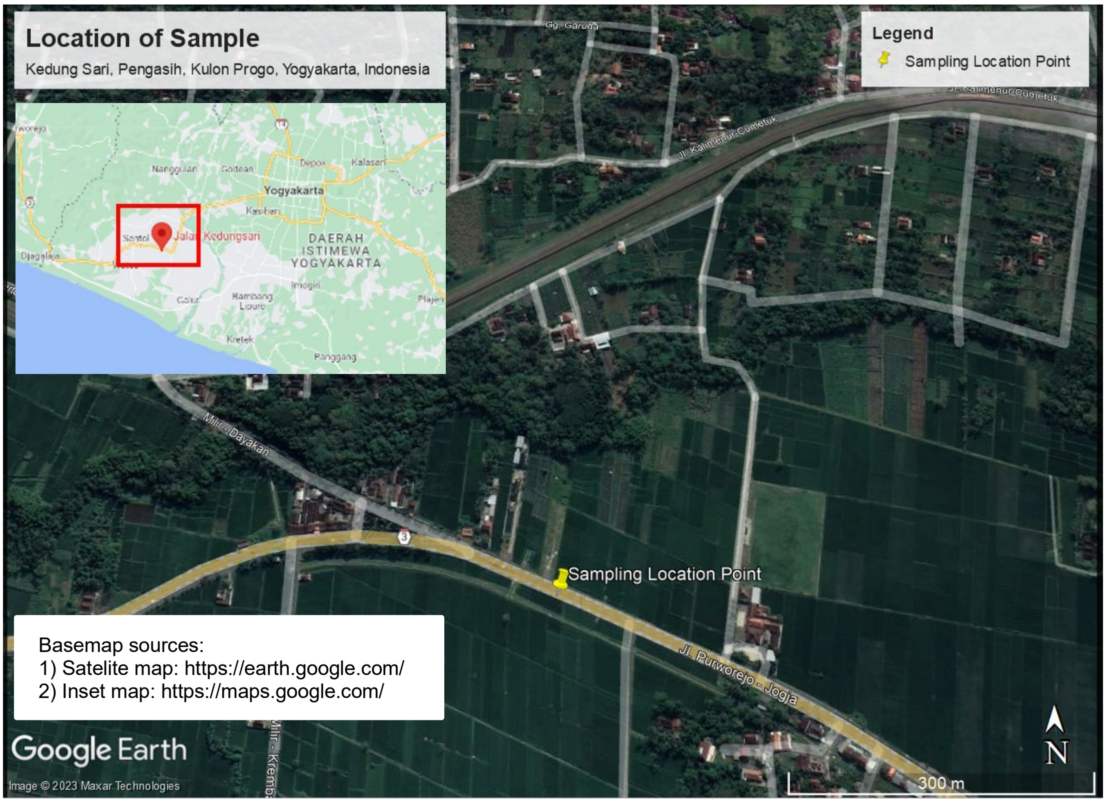


Fig. 1: Location of the sample base soil taken.

2.2 Stabilization Materials

The base soil (BS) used as a sample was clay under disturbed soil conditions. Soil characterization was conducted. Table 1 indicates that the soil is expansive clay soil. The characteristics of the soil are as follows: specific gravity of 2.23 and from the consistency limit, the liquid limit of 70.07%, the plastic limit of 24.39% and the plasticity index of 45.67%. From soil grain analysis and hydrometer, the soil contains finer # 200 as much as 80.34% and a type of cohesive clay with high plasticity based on the AASHTO (American Association of State Highway and Transportation Officials) and USCS (Unified Soil Classification System) soil classification. Other results obtained CBR soaked of 1.55%, CBR swell of 4.16% and UCS soaked of 2.94 kPa. Based on these characteristics, this soil type is considered to be poor for use as a material subgrade.

The stabilization material fly ash waste from Paiton steam power station is displayed in Fig. 2.a. The fly ash passes through sieve No. 200 (0.075 mm). Meanwhile, the bottom ash waste from Sriwidjaja Fertilizer of Palembang is displayed in Fig. 2.b. The bottom ash passes through sieve No. 100 (0.15 mm). The grain size of bottom ash was classified as fine sand according to AASHTO. Table 2 summarizes the chemical components of fly ash and bottom ash by ED-XRF (energy dispersive X-ray fluorescence).

Table 1: Engineering properties of the base soil.

Parameters	Base soil
Specific Gravity (G_s)	2.23
Liquid Limit (LL) [%]	70.07
Plastic Limit (PL) [%]	24.39
Plasticity Index (PI) [%]	45.67
Shrinkage Limit (SL) [%]	10.35
Percentage Finer # 200 [%]	80.34
Clay Fraction (<0,002 mm) [%]	20.95
Activity (PI/C)	2.18
Clasification (AASHTO/USCS)	A-7-6/CH
Max Dry Density (MDD) [g/cm^3]	1.29
Optimum Moisture Content (OMC) [%]	34.20
CBR Soaked [%]	1.55
CBR Swell [%]	4.16
UCS Soaked [kPa]	2.94

a) b)

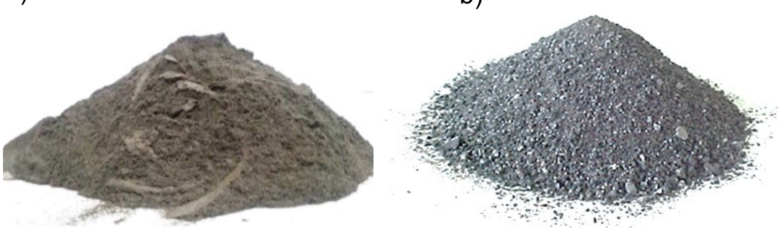


Fig. 2: a) Fly ash and b) bottom ash.

Table 2: Chemical composition of the fly ash and bottom ash.

Components	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	K_2O	TiO_2	SrO	ZrO_2	MnO	BaO
Fly ash	48.70	23.80	11.00	12.70	1.34	0.98	0.75	0.11	0.38	0.16	0.14
Bottom ash	62.73	17.52	13.22	3.45	-	1.17	1.25	0.15	0.11	0.16	-

Table 2 indicates that fly ash and bottom ash have a more dominant silica (SiO_2) component, 48.70% and 62.73%, respectively. The other components are Al_2O_3, Fe_2O_3, and CaO, which are

23.80%, 11.00%, and 12.70% for fly ash and 62.73%, 17.52%, and 13.22% for bottom ash, respectively. From the results, the total accumulation of SiO_2 + Al_2O_3 + Fe_2O_3 = 83.50% > 50%, CaO = 12.70% > 10% and SO_3 = 1.34% < 5%. Based on ASTM C 618 [13], the fly ash used is classified as class C because the percentage of CaO more than 10% and the bottom ash used is classified as class F because the percentage of CaO less than 10%. In addition, the specific gravity of the fly ash was 2.78 and the bottom ash was 2.87.

The alkali activator solution used is made up of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), as shown in Fig. 3. Sodium hydroxide used is in the form of flakes with 98% purity. Sodium hydroxide flakes are dissolved using distilled water into a sodium hydroxide solution with the required concentration. The concentrations of sodium hydroxide used were 5M and 8M. Specific gravity results obtained for the 5M concentration was 1.19 and 8M concentration was 1.30. Sodium silicate is used in solution form with type Be 58. Specific gravity of the sodium silicate solution was 1.68 g/ml. The ratios of sodium silicate and sodium hydroxide of 0.5 and 1.0. The ratios of the weight of sodium silicate and sodium hydroxide to the weight of FABA used were 0.6 and 0.8, respectively. The concentrations and ratios of sodium hydroxide and sodium silicate were obtained from previous studies by Murmu et al. [7] and Adhikari et al. [14].

a) b)

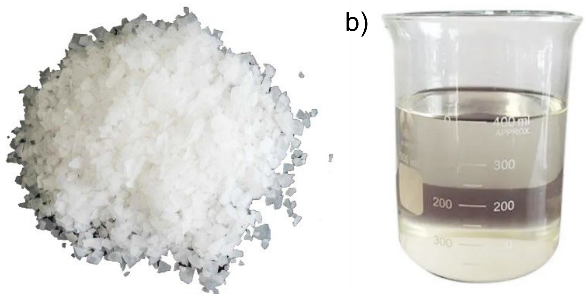


Fig. 3: a) Sodium hydroxide (NaOH) and b) Sodium silicate (Na_2SiO_3).

3 Methods

The research method began with preparing materials, such as base soil, fly ash, bottom ash, and an alkaline activator solution. After the material preparation was complete, the planning of the geopolymer paste mixture and the calculation of its Job Mix Formula (JMF) were conducted. Subsequently, the mixing of geopolymer paste and soil, followed by the compaction and molding of stabilized soil samples, was performed for testing. The study focused on a laboratory scale, examining the physical and mechanical properties without considering cost comparisons. This limitation was primarily due to the complexity of conducting a comprehensive cost analysis of fieldwork methods.

3.1 Job Mix Formula (JMF) of geopolymer paste

The planning of geopolymer paste mixture composition does not yet have a governing standard, therefore the Job Mix Formula (JMF) for geopolymer paste used was from Satyarno et al. [15]. The calculation of the composition of the geopolymer paste is based on the absolute volume method assuming that the paste is solid. The total paste components are calculated per unit volume using Eq. (1).

$$V_{FA} + V_{BA} + V_{Ss} + V_{Sh} = 1\ [m^3], \tag{1}$$

where:

V_{FA} - volume of fly ash [m^3],

V_{BA} - volume of bottom ash [m^3],

V_{Ss} - volume of sodium silicate [m^3],

V_{Sh} - volume of sodium hydroxide [m^3].

In Eq. (1), it can be seen a 1 m^3 of paste. Then, Eq. (1) is reduced to Eq. (2). For Eqs. (3), (4) and (5) are comparison ratios.

$$\frac{W_{FA}}{Gs_{FA}\gamma_w} + \frac{W_{BA}}{Gs_{BA}\gamma_w} + \frac{W_{Ss}}{Gs_{Ss}\gamma_w} + \frac{W_{Sh}}{Gs_{Sh}\gamma_w} = 1\ [m^3], \quad (2)$$

$$R = \frac{W_{Ss}}{W_{Sh}}, \quad (3)$$

$$A = \frac{W_{Ss} + W_{Sh}}{W_{FA} + W_{BA}}, \quad (4)$$

$$P = \frac{W_{BA}}{W_{FA}}, \quad (5)$$

By correlating Eqs. (3), (4) and (5) to Eq. (2), we obtain Eq. (6).

$$\frac{W_{FA}}{Gs_{FA}\gamma_w} + \frac{PW_{FA}}{Gs_{BA}\gamma_w} + \frac{\frac{AR\,(1+P)}{(1+R)}W_{FA}}{Gs_{Ss}\gamma_w} + \frac{\frac{A(1+P)}{(1+R)}W_{FA}}{Gs_{Sh}\gamma_w} = 1\ [m^3]. \quad (6)$$

where:

W - weight [kg],

G_s - specific gravity,

γ_w - unit weight of water [kg/m^3],

R - ratio of weights of sodium silicate and sodium hydroxide,

A - ratio of weights of alkali activator and binder,

P - ratio of weights of bottom ash and fly ash.

3.2 Mixture design of the geopolymer paste

The geopolymer paste is a mixture of FABA and alkaline activator solution. In this study, the variables used were as follows: 5M and 8M NaOH (Sh), ratios of sodium silicate and sodium hydroxide (R) of 0.5 and 1.0, and ratios of the weight of sodium silicate and sodium hydroxide to the weight of FABA (A) of 0.6 and 0.8. The use of variables is based on several earlier studies. After setting the variables, the trial mix initial setting times to determine the time the geopolymer paste starts to harden are listed in Table 3. The expected initial setting time is in accordance with the cement criteria. The optimum initial setting time of the geopolymer paste was used as a fixed variable for the mix variation binder (fly ash and bottom ash) of compressive strength. Table 4 shows a mixed variation of the optimum geopolymer paste for compressive strength test.

Table 3: Trial mix initial setting times of the geopolymer paste.

Trial mix ID	Sh [M]	R	A	FA [%]	BA [%]
M5R0.5A0.6F100B0	5	0.5	0.6	100	0
M8R0.5A0.6F100B0	8	0.5	0.6	100	0
M5R0.5A0.6F70B30	5	0.5	0.6	70	30
M8R1.0A0.6F70B30	8	1.0	0.6	70	30
M8R0.5A0.6F70B30	8	0.5	0.6	70	30
M8R0.5A0.8F70B30	8	0.5	0.8	70	30

Table 4: Mix variation binder of the geopolymer paste for compressive strength.

Mix ID	FA [%]	BA [%]	Description
GP F100	100	0	Sh, R, and A are optimum value from trial mix initial setting times
GP F92B8	92	8	
GP F85B15	85	15	
GP F78B22	78	22	
GP F70B30	70	30	

3.3 Fly ash-bottom ash geopolymer paste tests

Before mixing with soil, the geopolymer paste was first tested for initial setting time based on ASTM C191-21 [16] and compressive strength based on ASTM C109-20 [17] to determine the optimum alkali activator variation.

3.4 Mixture design of the geopolymer paste and stabilized expansive clay soils

The optimum initial setting time and compressive strength of the geopolymer paste were used as a fixed variable for the mixture design with the expansive clay to be stabilized. Table 5 shows the mixture design of the geopolymer paste for soil stabilization. The percentage of geopolymer paste is 12% of the dry weight of the soil, which is a substitute for the optimum cement content of 12% from previous studies [18-21]. Meanwhile, the variables used were as follows: percentages of fly ash (FA) of 70%, 78%, 85%, 92%, and 100%, and percentages of bottom ash (BA) of 0%, 8%, 15%, 22%, and 30%.

Table 5: Mixture design of the geopolymer paste for soil stabilization.

Mix ID	FA [%]	BA [%]	Description
BS	-	-	Base soil
F100	100	0	Base soil (BS) + 12% geopolymer paste
F92B8	92	8	
F85B15	85	15	
F78B22	78	22	
F70B30	70	30	

The technique of mixing the geopolymer paste with the soil to be stabilized was based on the research of Hosseini et al. [22] due to the absence of applicable standards and the variety of materials used. The clay soil and water were mixed using a mixer, stirred and the soil reached the optimum moisture content. The fly ash and bottom ash were mixed and stirred until evenly distributed. The alkaline activator solution was added to the fly ash-bottom ash mixture to form a geopolymer paste. The geopolymer paste was mixed with clay soil at optimum moisture content using a mixer. The mixing process is completed according to the initial setting time results to prevent the mixture from hardening.

3.5 Physical and mechanical property tests for soil stabilization

3.5.1 Physical properties

The physical property tests performed were specific gravity (G_s) testing according to ASTM D854-02 [23], cosistency limits (Atterberg limits) according to ASTM D4318-00 [24] and ASTM D427-98 [25], standard sieve analysis according to ASTM D421-58 [26] and hydrometer ASTM D422-63 [27].

3.5.2 Mechanical properties

The mechanical property tests performed were Proctor standard according to ASTM D698-00a [28], California bearing ratio (CBR) testing according to ASTM D1883-99 [29], unconfined compressive strength (UCS) testing according to ASTM D2166-06 [30].

4 Results and discussion

4.1 Geopolymer paste

4.1.1 Initial setting time of the geopolymer paste

The initial setting time test was conducted using a vicat with a 1 mm diameter needle and an ebonite ring containing geopolymer paste based on ASTM C191-21 [16]. The initial setting time is obtained when the needle drops to 25 mm on the ebonite ring in Fig. 4, by making a graph with the settlement time (minutes) and the amount of settlement (mm). The initial setting time test of the geopolymer paste was conducted in different variations in Table 3 and Fig. 5 plots the initial setting time results. The M8R05.A0.8F70B30 variation shows the longest setting time of 176 min, followed by M8R0.5A0.6F70B30 (95 min), M5R0.5A0.6F70B30 (67 min), M8R1.0A0.6F70B30 (47 min), M8R0.5A0.6F100 (45 min) and M5R0.5A0.6F100 (27 min). This shows that the use of bottom ash can prolong the initial setting time while the use of fly ash only has the fastest setting time. Setting time refers to the time limited by the mixing work in the field; therefore, it is an important parameter in the selection [31]. Based on the results, selecting the optimum geopolymer paste for initial setting time should be near that of cement (90-120 min); thus, M8R0.5A0.6F70B30 was employed as the geopolymer variation.

Fig. 4: Initial setting time test.

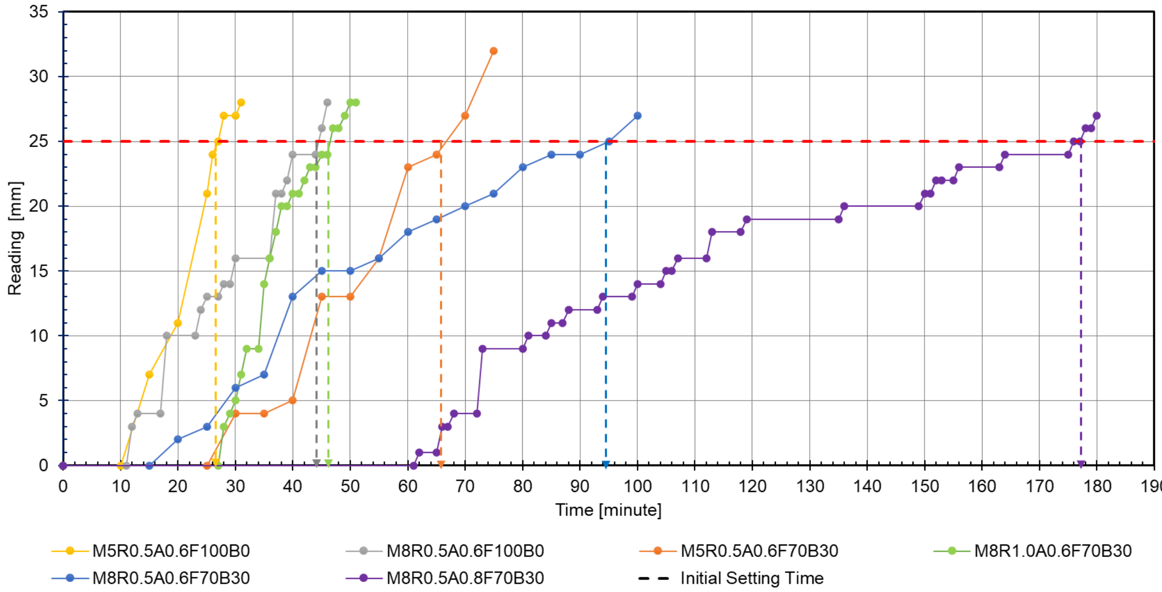


Fig. 5: Initial setting time results of geopolymer paste.

4.1.2 Compressive strength of the geopolymer paste

The compressive strength test of the geopolymer paste for 1 day, 7 days, and 28 days was performed with different variations in Table 4 and Fig. 6 plots the compressive strength results. After 28 days, the highest value in the mixture sample of GP F100 (without bottom ash) was 57.97 MPa, followed by GP F85B15 (51.52 MPa), GP F78B22 (47.56 MPa), GP F92B8 (45.90 MPa) and F70B30 (42.17 MPa). These results show that with increasing curing age, the compressive strength value also increases. Based on the results, the GP F85B15 sample with 15% bottom ash is the optimum mix design (OMD) for compressive strength value compared with other percentages of bottom ash. Although the compressive strength without bottom ash is higher, using bottom ash can make the initial setting time of geopolymer paste longer so that the working time in the field is better. One of the disadvantages of applying geopolymer fly ash paste (without bottom ash) for fieldwork is that the initial setting time is fast (under 1 hour) [31].

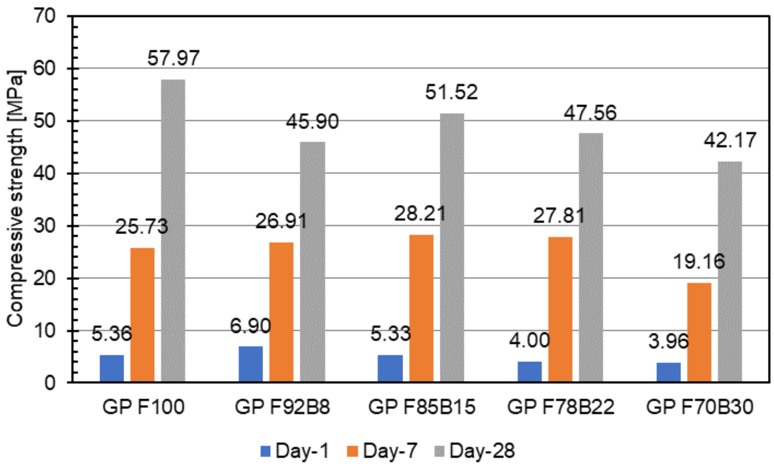


Fig. 6: Compressive strength results of the geopolymer paste.

4.2 Physical properties of the geopolymer stabilized expansive clay soils

4.2.1 Specific gravity

The specific gravity trends are plotted in Fig. 7. The specific gravity of the F85B15 sample had the highest, at 2.43, an increase of 8.97% from the base soil (BS) sample of 2.23. This is followed by F92B8, F100, F78B22 and F70B30 with 2.42, 2.37, 2.34 and 2.23, respectively. The addition of bottom ash at the start will increase the specific gravity, but after the addition of more than 15% bottom ash, the specific gravity decreases, as observed for F70B30 with 2.23, which is the same as that of the base soil, which is in agreement with Le et al. [9]. These results confirm that the optimum addition of bottom ash can increase the specific gravity, but excessive addition reduces the specific gravity similar to base soil.

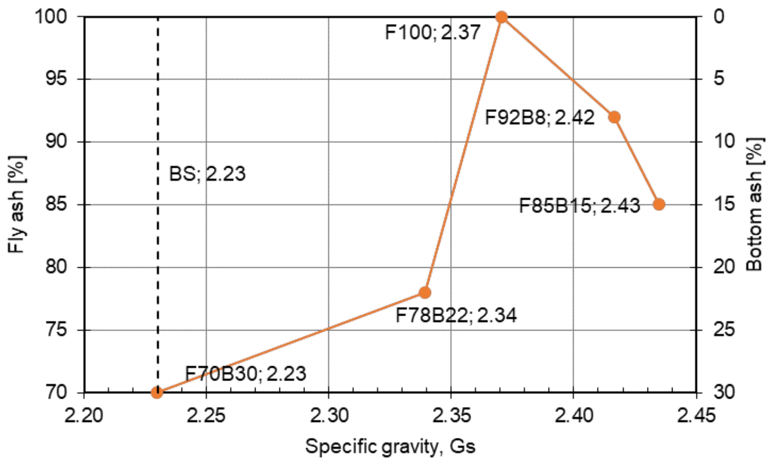


Fig. 7: Specific gravity results for geopolymer stabilized and expansive clay soil.

4.2.2 Atterberg limit (consistency limit)

The results of the Atterberg limit test are shown in Fig. 8. It can be observed that the liquid limit (LL) value in the soil decreases with the use of 15% bottom ash (for F85B15 57.83%). The highest LL value was obtained by F70B30 with 71.83%. The addition of bottom ash from F92B8 to F70B30 causes the plastic limit (PL) to exhibit an increasing trend. The highest decrease was obtained in the sample with the lowest substitution, i.e. F92B8 with 35.21%. The smallest plasticity index (PI) value was obtained by the F85B15 sample, where the substitution is 15% bottom ash. The PI value in the sample with the highest substitution bottom ash on the geopolymer is still better than the PI value in the base soil. This study agrees with the findings of Mishra et al. [32].

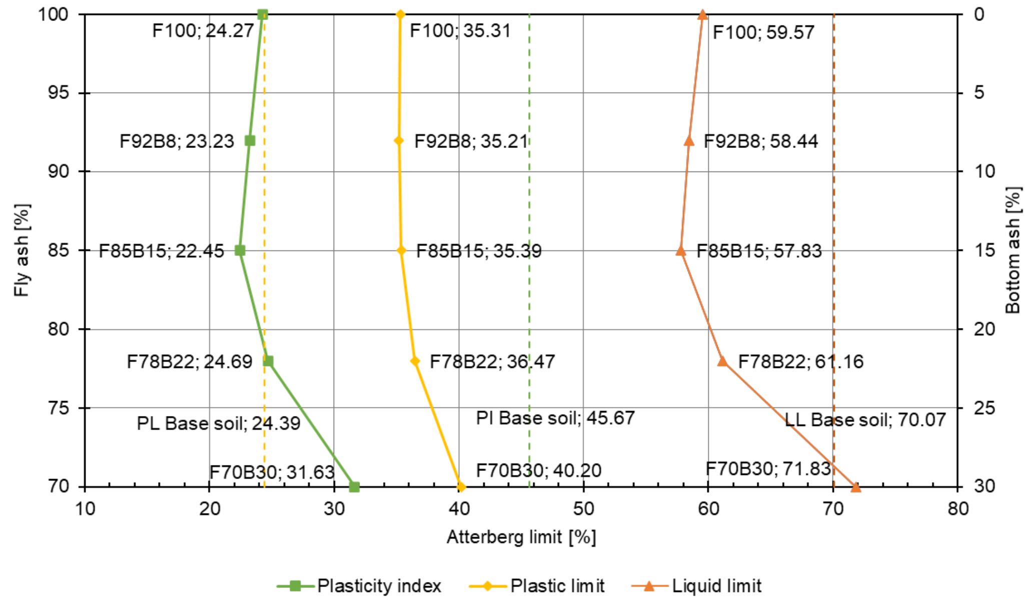


Fig. 8: Atterberg limit results for geopolymer stabilized and expansive clay soil.

4.2.3 Grain size analysis

Analysis was conducted on each sample and the results are shown in Fig. 9. The effect of substitution is plotted in Fig. 10. The test results showed a change in composition of the soil fraction. The base soil (BS) sample was initially dominated by a finer # 200 (clay/silt) fraction of 80.34% and after mixing with geopolymer paste, the clay/silt fraction was reduced by 23.63% for F100 and 16.53% for F85B15. The reduction in the clay/silt fraction in the geopolymer samples was followed by an increase in sand fraction, which was initially observed in the BS sample. Our findings where the use of geopolymer results in a decrease in the clay/silt fraction are in accordance with Chen et al. [33].

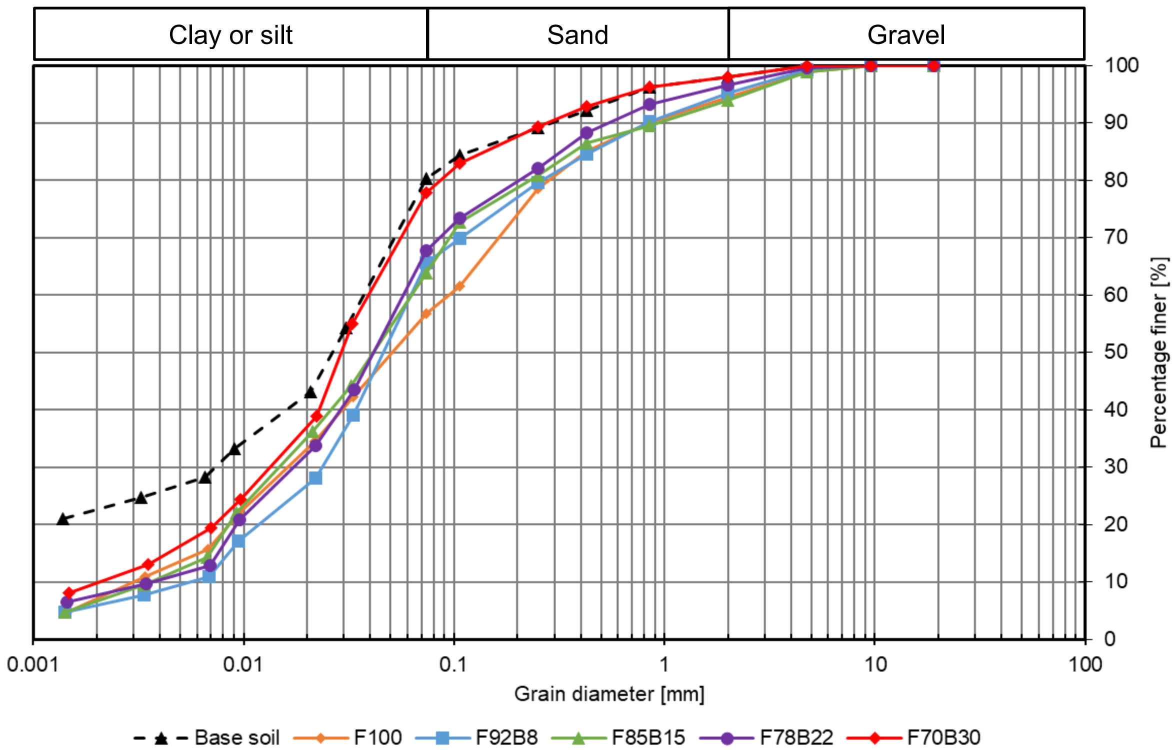


Fig. 9: Grain size analysis of geopolymer stabilized and expansive clay soil.

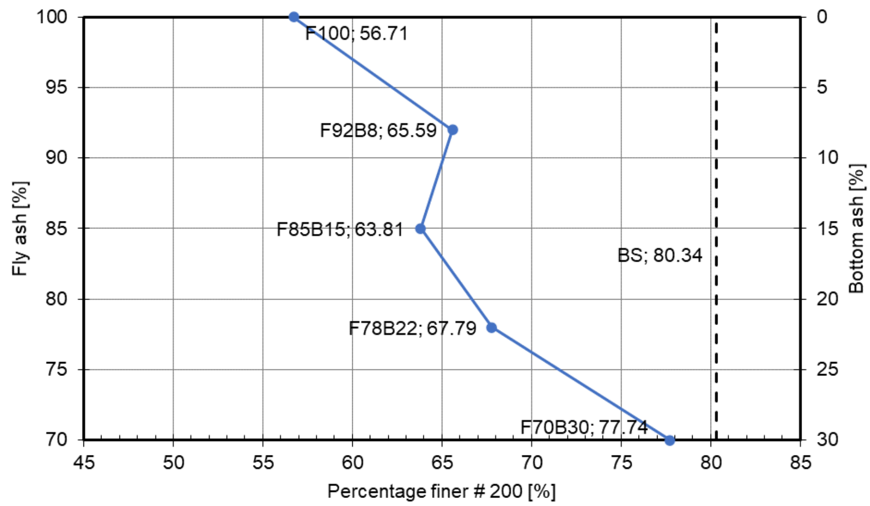


Fig. 10: Percentage finer results of geopolymer stabilized and expansive clay soil.

4.3 Mechanical properties of the geopolymer stabilized expansive clay soils

4.3.1 Soil compaction

The results of soil compaction are shown in Figs. 11-13. The effect of substitution on optimum moisture content (OMC) values showed that a decreasing percentage of bottom ash and an increasing percentage of fly ash led to a regular decrease in OMC values. However, the OMC value at the highest bottom ash percentage variation remained below that of the base soil (BS) sample. This reveals that a decrease in OMC in the soil occurs when geopolymer paste is added, but if the content of fly ash is reduced and replaced by more bottom ash, there is a decrease in the water absorption rate, increasing the OMC. An increase in OMC is always followed by a decrease in maximum dry density (MDD). A similar result was obtained by Murmu et al. [7], who studied geopolymers in expansive clay soil.

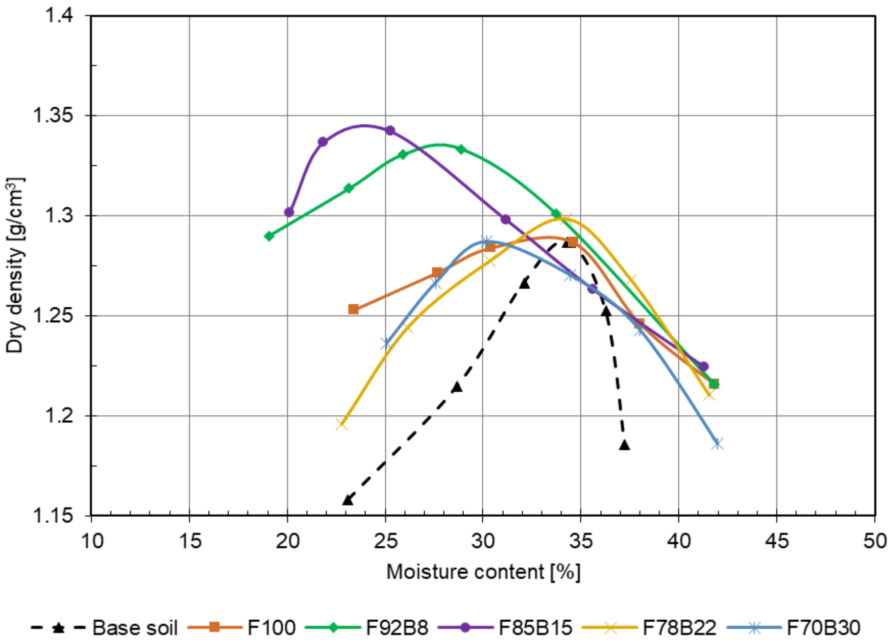


Fig. 11: Curve results from the Proctor standard for geopolymer stabilized and expansive clay soil.

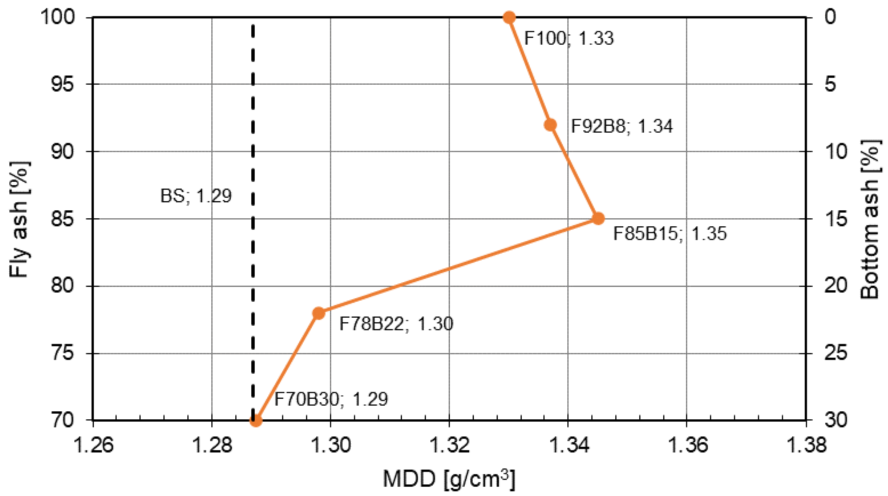


Fig. 12: Max dry density results for geopolymer stabilized and expansive clay soil.

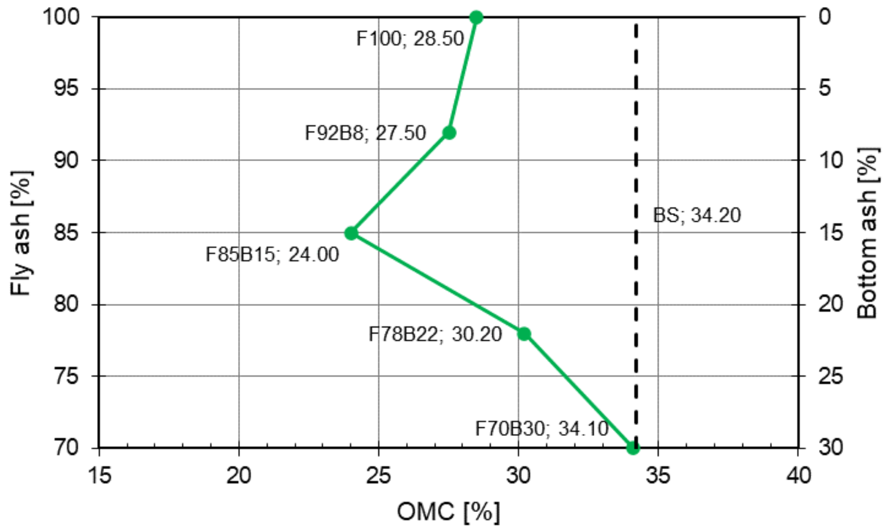


Fig. 13: Optimum moisture content results for geopolymer stabilized and expansive clay soil.

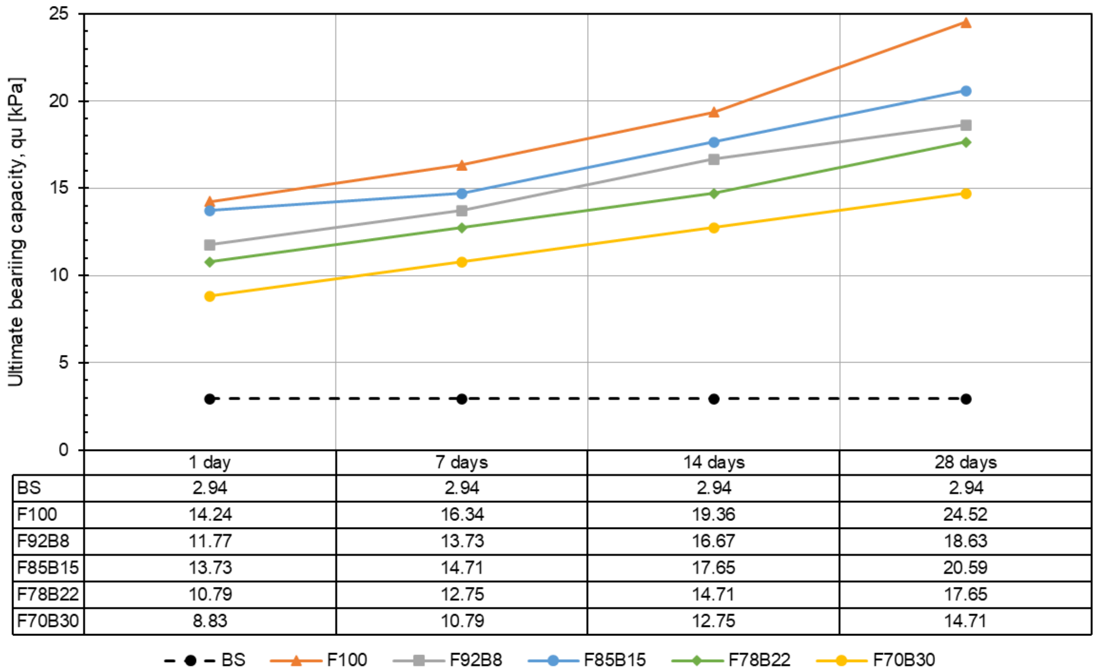
4.3.2 Unconfined compressive strength (UCS)

In the unconfined compressive strength (UCS) test, the samples were formed using a mold and were dependent on the Proctor tests (soil compaction) previously performed. The treatment applied to the test was varied for 1 day, 7 days, 14 days, and 28 days under soaked conditions for 4 hours in Fig. 14. In Fig. 15, it can be observed that the UCS value increases with the geopolymer stabilized expansive clay soil. The highest value in the mixture design sample of F100 (without bottom ash). Initially, in the base soil sample, the UCS value of 2.94 kPa increased by 400% to 14.24 kPa after 1 day of curing. At 28 days of curing, the UCS value increased by 733% to 24.52 kPa. These results show that with increasing curing age, the UCS value also increases. For F85B15, the UCS value at 28 days of curing increased by 633% to 20.59 kPa. The order of UCS values from largest to smallest are F100, F85B15, F92B8, F78B22, and F70B30. The F85B15 sample shows that adding 15% bottom ash is the optimum mix design (OMD) for the UCS value compared with other percentages of bottom ash. These results were consistent with the research by Dissanayake et al. [34] and Parhi et al. [35] which explained the effect of fly ash and bottom ash content on expansive soil.

Soaking the samples for 4 hours

Conducting UCS test

Fig. 14: UCS soaked test.



	1 day	7 days	14 days	28 days
BS	2.94	2.94	2.94	2.94
F100	14.24	16.34	19.36	24.52
F92B8	11.77	13.73	16.67	18.63
F85B15	13.73	14.71	17.65	20.59
F78B22	10.79	12.75	14.71	17.65
F70B30	8.83	10.79	12.75	14.71

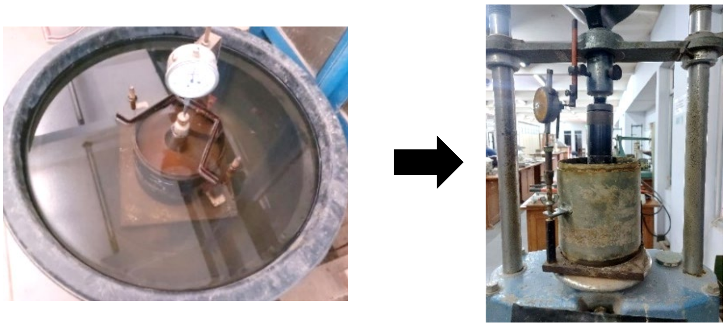
Fig. 15: UCS results for geopolymer stabilized and expansive clay soil.

4.3.3 California bearing ratio soaked (CBR soaked)

Before testing, samples were made in soaked conditions for 4 days in Fig. 16. In Table 6, it can be observed that the CBR soaked value increased in the optimum mix design (OMD) sample of expansive clay stabilization with geopolymer. Initially, in the base soil (BS) sample, the CBR value of 1.55% increased by 753% to 13.22% in the OMD sample (F85B15). The CBR value also increased by 827% to 14.37% in the sample without bottom ash (F100). These results revealed that using bottom ash can slightly reduce the CBR value. However, all results showed that the obtained CBR is greater than the 6% required for material subgrades based on the Road Pavement Design Manual by the Ministry of Public Works and Housing [36].

Table 6: CBR values of geopolymer stabilized and expansive clay soil.

Mix ID	FA [%]	BA [%]	CBR [%]	CBR requirements [%] [36]	Increasement [%]
Base soil	0	0	1.55	> 6%	-
F100	100	0	14.37		827
F85B15	85	15	13.22		753



Soaking the sample for 4 days

Conducting CBR test

Fig. 16: CBR soaked and CBR swell test.

4.3.4 California bearing ratio swell (CBR swell)

In the CBR soaked test, samples were attached to a dial gauge for CBR swell readings and performed at 0, 1, 2, 4, 8, 12, 24, 36, 48, 72, and 96 hours in Fig. 16. The swelling results of the CBR soaked test are shown in Table 7, showing that the CBR swell value decreased in the optimum mix design (OMD) sample of expansive clay stabilization with geopolymer. The CBR swell of base soil (BS) of 4.16% decreased by 73.56% to 0.99% in the OMD sample (F85B15). The CBR swell also decreased from 76.20% to 0.99% in the sample without bottom ash (F100). All results revealed that the obtained CBR swell is less than the 2% required for material subgrades based on the Road Pavement Design Manual by the Ministry of Public Works and Housing [36].

Table 7: CBR-swell values of geopolymer stabilized and expansive clay soil.

Mix ID	FA [%]	BA [%]	CBR swell [%]	CBR swell requirements [%] [36]	Decreasement [%]
Base soil	0	0	4.16	< 2%	-
F100	100	0	0.99		76.20
F85B15	85	15	1.10		73.56

5 Conclusion

This study examined the physical and mechanical properties of expansive clay stabilized by FABA geopolymer paste. The results of physical and mechanical property tests showed that the soil and geopolymer mixture performed satisfactorily to stabilize the subgrade. Thus, the FABA geopolymer can be utilized as a stabilization material for expansive clay with the optimum mix design (OMD). Based on the results and discussion the following conclusions were made:

1) Selection of optimum geopolymer paste based on initial setting time testing obtained variation M8R0.5A0.6F70B30. M8R0.5A0.6F70B30 is a variation with sodium hydroxide concentration of 8M, sodium silicate and sodium hydroxide weight ratio (R) of 0.5, alkali activator and binder weight ratio (A) of 0.6.

2) Based on the results of the paste compressive strength test, GP F85B15 (geopolymer 85% fly ash and 15% bottom ash) became the optimum mix design (OMD) with a compressive strength value of 51.52 MPa. GP F100 (100% fly ash geopolymer) was used as a comparison with a compressive strength value of 57.97 MPa.

3) The results of physical property tests conducted on the geopolymer stabilized expansive clay soil, using fly ash and bottom ash geopolymer paste can improve qualities such as specific gravity, Atterberg limit, and grain size. The specific gravity test results increased from base soil (BS) of 2.23 to 2.43 in F85B15. Atterberg limit test results showed a decrease in LL value from BS of 70.07% to 57.83% and PI value also decreased from BS of 45.67% to 22.45% in F85B15. In the grain size, the largest decrease in the percentage of the fine fraction was in F100 at 56.71% from BS at 80.34% followed by F85B15 at 63.81%. Based on all the test results, the optimum mix design (OMD) percentage was obtained for variation F85B15, with a mixture of soil and geopolymer paste using 85% fly ash and 15%

bottom ash. However, adding more bottom ash instead of fly ash will reduce the quality to the same level as the soil before stabilization such as F70B30.

4) The mechanical property test results show that the subgrade stabilized with geopolymer can increase its strength to exceed the requirements used for road subgrades such as soil compaction, UCS, CBR soaked, and CBR swell. Soil compaction test results showed the highest MDD in F85B15 increased from BS of 1.29 to 1.35 and OMC decreased from BS of 34.20% to 24%. The UCS test results showed the highest value at 28 days of F100 of 24.52 kPa followed by F85B15 of 20.59 kPa. The results of the soaked CBR test showed that BS of 1.55% increased to 13.22% in F85B15 and 14.37% in F100. These results indicate that using bottom ash can reduce the CBR value. The results show that the CBR obtained is greater than the required 6%. The results of the CBR swell test, BS of 4.16% decreased to 1.10% in F85B15 and 1.00% in F100. The results show that the CBR swell obtained is less than the required 2%.

5) For further study, it is recommended to investigate the long-term performance of geopolymer stabilized expansive clay soil and to explore important aspects including but not limited to: the use of other Job Mix Formula (JMF) for geopolymer paste, the technique of mixing the geopolymer paste with the expansive clay soil and the proper construction methods to maintain the mix performing as expected.

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