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THE USE OF ALKALINE ACTIVATORS WITH HIGH CALCIUM FLY ASH AS SOFT CLAY STABILIZATION MATERIALS

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ABSTRACT: Soft clay has become the main problem of the Waste Facility Development Project on the North Coast of Lamongan, East Java, Indonesia. The soil has a high plasticity index, high moisture content, small shear strength, and low permeability. Therefore, stabilization efforts to improve the soil characteristics are needed to support the construction. Research on soil stabilization using fly ash has been widely conducted. Yet, there have just been a few studies conducted on soil stabilization using fly ash activated by alkaline or geopolymer. This paper compares soil stabilization using fly ash and soil stabilization using fly ash activated with geopolymer. The results show that soil stabilized by fly ash generally has better characteristics than fly ash activated with geopolymer. However, the CBR test result of the soil stabilized with geopolymer-activated fly ash shows a higher value than the soil stabilized using fly ash. The molarity and the curing time of the specimen can be the causing factor. Microstructural analysis using SEM shows conditions of denser soil after it is stabilized with geopolymer. It indicates that the formation of a binder gel increases the interaction between the clay particles and the stabilizing agent.

Keywords: Clay soil stabilization, Compressive strength, Fly ash geopolymer, Micropores

1. INTRODUCTION

The waste treatment facility on the North Coast of Lamongan has poor subgrade conditions and dominantly soft clay. Soft clay soil has special characteristics, including high plasticity index, large settlement, high moisture content, small shear strength, and low permeability. The soil is not good enough as a construction base, and problems are often found in geotechnical construction [1,2]. Thus, soil improvement is needed.

Soil stabilization is an effort to improve the physical and mechanical characteristics of the soil. It can be conducted by using a chemical method by adding chemical materials. Conventional stabilizer materials, e.g., using cement, cause several problems to the environment, including CO_2 emissions, as well as a cost perspective [1–3]. Therefore, pozzolanic materials such as fly ash are used as a substitute for cement to reduce the environmental impact and improve the soil's mechanical performance [3, 4]. To improve the chemical reaction of pozzolanic materials, some researchers add alkaline solutions to activate the polymerization reaction to form geopolymers.

Studies using fly ash have been conducted in several papers. Fly ash enhances the soil density, shear strength [5], and CBR value [6]. Also, fly ash decreased the value of the plasticity index and increased soil strength [7]. Instead, soil stabilization using fly ash activated by alkali (geopolymer) has not been conducted much compared to the same kind of research using fly ash.

Geopolymer-fly ash is generally used in research to produce good-performance concrete because of its strength performance [8–10]. There is research by Sumiyanto [11] alkali activators and fly ash developed optimum compressive soil strength. Geopolymer contributed to clay compressive strength up to five times more than loose clay soil. The advantage of geopolymer is that it uses alkali besides water, acting as an alkaline activator of the binder [12]. The alkaline solutions used are Sodium Hydroxide and Sodium Silicate. The existence of geopolymers offers a promising environmentally friendly alternative to cement [13]. Combining these two solutions forms alkaline activation that causes a geopolymer reaction with low CO_2 emissions. The usage of geopolymer is expected to be able to act as a substitute for calcium-based binders, which bring a negative effect on the environment and initiate lower processing costs [14].

To carry out sustainability studies about soil stabilization, the effects of soil improvement using geopolymer fly ash are investigated to determine the characteristics of stabilized soil in this paper. There has not been published yet. This present study contributes as an alternative to environmentally friendly soil improvement methods.

2. RESEARCH SIGNIFICANCE

This research studies clay stabilization using fly ash and geopolymer-based fly ash.

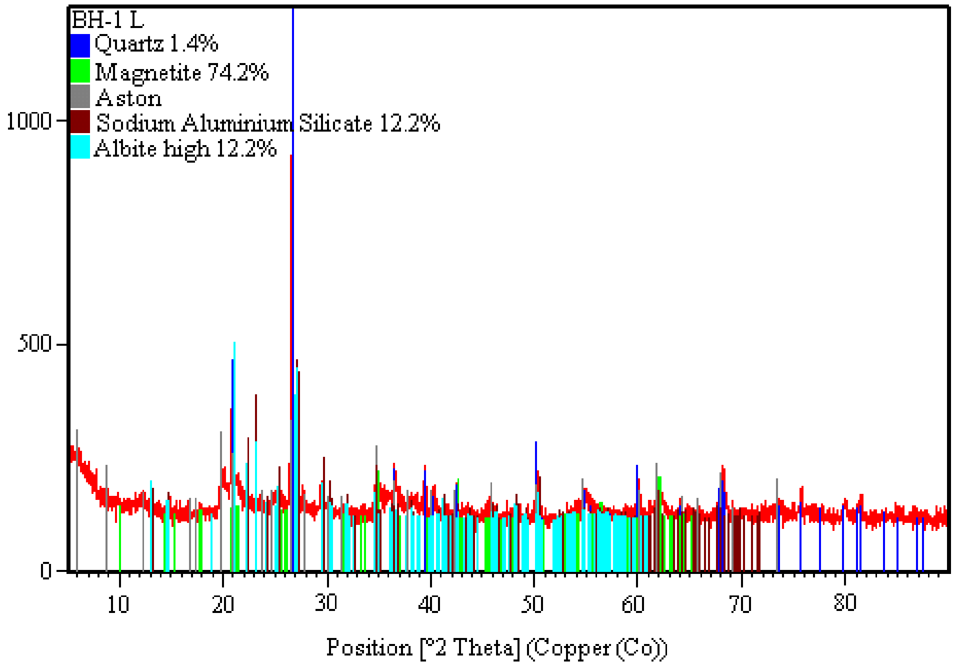


Fig. 1 XRD pattern of initial soil

The clay in this research was taken from the North Coast of Lamongan. The stabilization was conducted using fly ash and fly ash-based geopolymer with the combination of 8M NaOH and Na_2SiO_3 alkaline activator acting as the base activator. The stabilized soil's physical, mechanical, and CBR changes were then analyzed. The chemical changes and soil microstructure were studied with the help of X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM).

3. MATERIALS AND METHODOLOGY

3.1 Material

3.1.1 Fly Ash (FA)

The fly ash is taken from Paiton Power Plant, East Java, Indonesia. X-Ray Fluorescence (XRF) test was conducted to determine the chemical composition of the fly ash. The XRF test results are shown in Table 1. Following ASTM C168, the fly ash is classified as C-class (High calcium fly ash). XRD testing was also carried out to determine the reactivity of Paiton fly ash.

Table 1 Chemical characteristics of fly ash

Chemical Compound	Fly ash C (%)
Alumina (Al_2SiO_3)	8.45
Silica (SiO_2)	27.45
Iron Oxide (Fe_2O_3)	29.35
$Al_2SiO_3 + SiO_2 + Fe_2O_3$	65.25
Calcium Oxide (CaO)	24.7
Magnesia (MgO)	1.45
Kalium (K_2O)	1.31

The test results are shown in Table 2. The XRD fly ash test results showed that the amorphous phase (hkl_phase) was higher than the crystalline phase. This shows that the fly ash consists of many irregular solids ready to react.

Table 2 XRD Results of fly ash

Phase	Fly ash C (%)
Quartz	6.802
Brownmillerite	1.105
Periclase	3.748
Lime	2.157
Maghemite	1.158
Ferrochrimite	1.158
Kristal phase	27.58
Hkl phase	73.297

3.1.2 Soil

This study used soil originating from the North Coast of Lamongan. The results of the XRD test of the original soil are shown in Fig. 1

3.1.3 Alkali Activator

Alkali Activator, consisting of NaOH and Na2SiO3, was used as geopolymer-forming material. This is because sodium cations are more suitable when dealing with silica-alumina elements than silica-alumina elements only [12]. Furthermore, incorporating sodium hydroxide and sodium silica can be an effective activator to increase the strength properties [15]. NaOH (8M) and Na_2SiO_3 (water glass) were provided as a solution. Both materials are used in a 1:1 ratio to support the cementitious level of high calcium fly ash [14].

Table 3 The Composition of The Stabilized Soil

Composition	FA (100%)	Geopolymer (GFA) - (100%)			
		FA (70%)	NaOH 8M (15%)	Na2SiO3 (15%)	Water
	gr	gr	gr	gr	ml
Initial Soil	-	-	-	-	2,059
Soil + FA 3%	245.4	-	-	-	1565.1
Soil + FA 7%	595.5	-	-	-	1248.6
Soil + FA 10%	864.4	-	-	-	1156.3
Soil + GFA 3%	-	170.6	36.8	36.8	1578.3
Soil + GFA 7%	-	391.2	83.8	83.8	1910.3
Soil + GFA 10%	-	546.5	117.1	117.1	2032.9

Table 4 Final NaOH Molarity (Mol.)

Variation	Initial Mol.	Mass NaOH	Initial Volume	Water volume	Final Volume	Final Mol.
%	M	gr	ml	ml	ml	M
3	8	9	4.23	400	404.23	0.1
7	8	21	9.86	500	509.86	0.2
10	8	30	14.08	500	514.08	0.2

3.2 Methodology

3.2.1 Mixing of Soil Stabilizing Material

Fly ash was prepared with different percentages, namely 3%, 7%, and 10% of the dry weight of the soil. Soil samples were prepared in dry conditions. There are three types of mixtures: initial soil, soil+ fly ash, and soil+geopolymer. Fly ash and soil were mixed, and water was added as a solvent. The stabilized soil samples were cured for 24 hours. The samples of the CBR test were cured for three days. The calculations of the stabilization materials are shown in Table 3.

3.2.2 Mixing Geopolymer and Soil

The physical characteristics of the initial soil are shown in Table 4. The method of mixing geopolymers was carried out manually. The mixture consisted of 70% fly ash and 30% alkali activator by weight of geopolymer. Each percentage was 3%, 7%, and 10% of the dry weight of the soil. The soil was mixed with 70% fly ash and alkaline activator sequentially, starting with 15% NaOH solution, then 15% Na2SiO3 solution. The mixing steps were according to previous studies with optimal mixing methods [14]. During this stage, water was added to meet the optimum soil content. But it caused the final molarity of NaOH to change. It is shown in Table 4.

3.2.3 Soil Physical Test

The soil physical examination included unit weight, moisture content, void ratio, and Atterberg limit. All soil mixtures were prepared at optimum density conditions. Therefore, it is necessary to test soil compaction using a standard proctor test (mechanical test).

3.2.4 Soil Mechanical Test

The standard proctor test was carried out to obtain optimum moisture content (OMC) and soil's maximum dry weight (MDD). Soil samples were tested according to the standard proctor compaction rules in SNI 1742-2008. Soil strength testing includes CBR and unconfined tests (UCT). The CBR test was carried out according to the SNI 1744-2012 standard to determine the CBR value after soaking treatment (soaked) was given. The objective was to form a soil density following its MDD and OMC. The UCT test was carried out according to SNI 3638-2012 to evaluate the effect of fly ash and geopolymer percentage at different levels.

4. RESULTS AND DISCUSSION

4.1 Initial Condition

The result test initial condition of clay soil for physical and mechanical properties is presented in Table 5. Based on the results of the sieve test and the Atterberg limit, according to the USCS classification, the soil is in the category of medium plasticity clay (CL). Meanwhile, according to the AASHTO system that shows A-5-7, the soil is categorized into clay type.

The results of the XRD testing of the initial soil are shown in Fig. 1. Based on the test results, the main elements in the soil are magnetite (74.2%), albite (12.2%), and sodium aluminum (12.2%). Magnetite (Fe_3O_4) is an iron oxide mineral found in igneous, metamorphic, and sedimentary rocks. Meanwhile, albite crystallizes with triclinic pinacoidal forms. Albite almost always exhibits crystal twinning, often as minute parallel striations on the crystal face. Albite often occurs as fine parallel segregations alternating with pink microcline in perthite because of exolution on cooling.

Table 5 Soil properties at initial condition

	Type of test		Value
1.	Water content	(w, %)	25.10
2.	Degree of saturation	(Sr, %)	78.34
3.	Unit weight	(γt, gr/cm³)	1.81
4.	Specify gravity	(Gs)	2.71
5.	Void ratio	(e)	0.87
6.	Clay fraction	(%)	54
7.	Sand fraction	(%)	27
8.	Atterberg limits, LL	(%)	49.4
	PL	(%)	20.9
	IP	(%)	28.5
9.	Cohesion	(c, kPa)	14.5
10.	CBR value	(%)	0.98
11.	Compressive strength value (qu)	(kPa)	29

Source: a laboratory experiment

4.2 Physical Characteristics of Stabilized Soil

The results of the test of the physical condition of the studied soil before and after the stabilization are shown in Fig. 2 to Fig. 9.

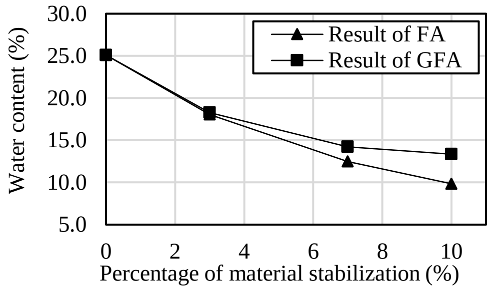


Fig. 2 Water content of the stabilized soil

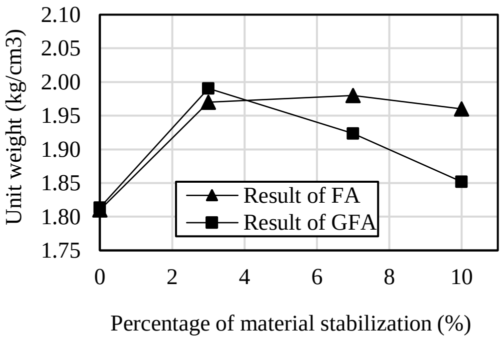


Fig. 3 Unit weight of the stabilized soil

Based on Fig. 2 to Fig. 3, the soil's water content and unit weight decreased with the addition of fly ash and geopolymer. Adding 3%, 7%, and 10% of fly ash decreased the water content value by 60.79% while adding geopolymer decreased the water content value by 46.81%. A different phenomenon occurs in the unit weight. There is a maximum condition, and then it decreases. The addition of fly ash increased the soil unit weight value by 8.29%, while the addition of geopolymer increased the soil unit weight by 2.12%. From Fig. 3, at the addition of 10% of the stabilization material, the specimens added by fly ash have a smaller water content than the specimens added by geopolymer.

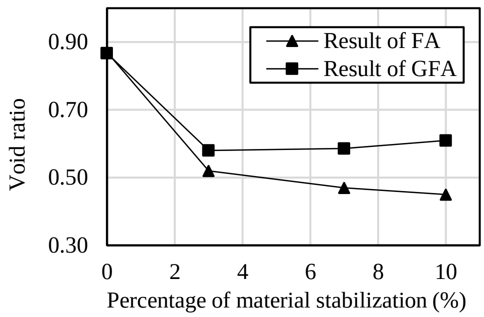


Fig. 4 Void ratio of the stabilized soil

The void ratio (Fig. 4) is reduced due to the addition of fly ash and geopolymer. This phenomenon occurs allegedly due to the reduction of pore volume in the stabilized specimen as the fly ash in the stabilized specimen, with the help of water, carries out hydration. In the stabilized specimen, the quantity of hydrogen atoms increases so that the hydration ability also increases, and it is suspected that the solid grains formed are increasing.

It can be seen from Fig. 2 that due to the addition of fly-ash and geopolymer to the unit weight of the soil, for the same percentage addition, the specimens stabilized with fly-ash had a void ratio of 2.8% smaller than the specimens stabilized with geopolymer. This is thought to be influenced by the high-water content in the mixture. As a result, the alkali molarity is disturbed, and the geopolymerization reaction slows down.

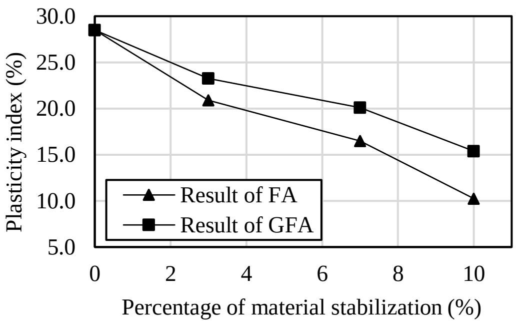


Fig. 5 Plasticity index of the stabilized soil

Based on Fig. 5, the mixture of clay and fly ash from the initial to 10% percentage of material stabilization resulted in a decrease in the plasticity index by 60.79%, while the addition of geopolymer decreased the plasticity index by 46.81%. From the Fig. 5, at the addition of 10% of the stabilization material, the specimens added by fly ash have a smaller plasticity index than the specimens added by geopolymer.

Based on Fig. 2 and Fig. 5, the plasticity index test also showed the same results as water content. The mixture of clay and fly ash resulted in a decrease in the plasticity index by 60.79%, while the addition of geopolymer decreased the plasticity index by 46.81%. This decrease occurred due to the cement-binding properties of fly ash, so that the soil plasticity was low [6]. This proves that adding fly ash to clay reduces its activity, according to the results of Hasriana's research [3].

The results of the proctor test in the form of optimum moisture content (OMC) and maximum dry density (MDD) are illustrated in Table 6. The results of stabilization with fly ash show a decrease in the optimum moisture content and an increase in the dry density of the stabilized soil. Water content is decreased because adding fly ash reduces the attraction of soil and water. As a result, the clay-fly-ash mixture binds to less water than the initial soil [4].

Table 6 The Compaction Results of The Stabilized Soil

Density Test		Initial Soil	Stabilized Soil		
			3%	7%	10%
OMC (%)	FA	25.10	18.03	12.46	9.84
	GFA	25.10	18.27	22.90	24.07
MDD (gr/cm3)	FA	1,52	1,67	1,76	1,80
	GFA	1,52	1,67	1,61	1,56

The addition of geopolymer causes an increase in the OMC and a decrease in the MDD of the soil. This can be explained by the geopolyrimerization reaction, which takes time, and the alkali molarity between 4M - 12M [6,7,13]. Meanwhile, adding water and NaOH mass triggers the decrease of alkali molarity between 0.1-0.2M. The increase in optimum water content and a decrease in dry density can be influenced by the alkali molarity and a short curing time which slows down the geopolymerization reaction.

4.3 Mechanical Characteristics of Stabilized Soil

The results of UCT and CBR testing indicate the changes in the mechanical characteristics of the soil. The results of the mechanical test are shown in Fig. 6 to Fig. 9. UCT test results in the form of soil stress-strain behavior for soil+fly ash and soil+geopolymer are shown in Fig. 6 to Fig. 7. All those figures show that the soil strength has increased after being stabilized with fly-ash and geopolymer.

Fig. 6 shows that adding fly ash can increase soil stress by adding all levels of fly ash. This occurs due to the filling of voids by fly ash so that the soil is compacted [7]. When the soil compacts, the void ratio decreases, the soil particles become closer together, the electrostatic force increases; thereby, the strength of the soil increases.

For the addition of geopolymer, adding 3% content increases the soil stress value. Meanwhile, adding 7% and 10% geopolymer content has a lower stress value than the 3% geopolymer content. Based on Fig. 8, for all the additions of fly ash and geopolymer content, the addition of fly ash generates a higher strength value than the addition of geopolymer.

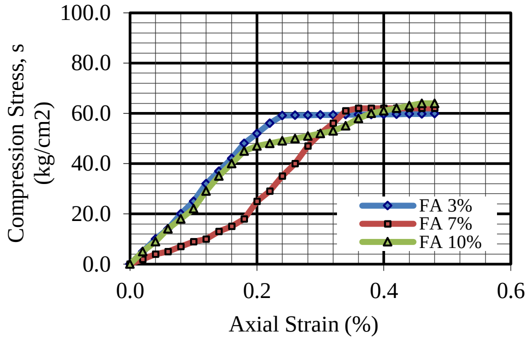


Fig. 6 Stress-strain relationship of the stabilized soil with fly ash (FA)

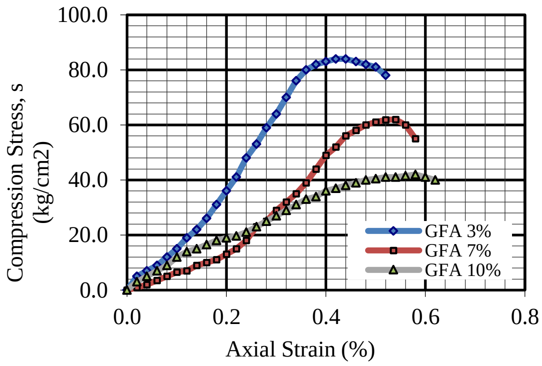


Fig. 7 Stress-strain relationship of the stabilized soil with geopolymer (GFA)

As previous studies have obtained, this research shows an increase in soil strength with the addition of fly ash and curing time [6,9,13,14]. For the addition of geopolymer, the slight increase in soil strength is influenced by alkali molarity and curing time.

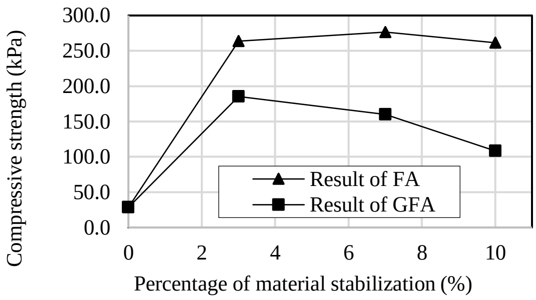


Fig. 8 Compressive strength of the stabilized soil

The decrease in molarity causes the water content of the soil stabilized with geopolymer to be higher than that of the soil stabilized with fly ash. At higher water content, geopolymer-stabilized soil is suspected of having poorer hydration ability. As a result, it has lower compressive strength than fly ash. In addition, the short curing time is considered to lower the reactivity of silica and alumina [4]. Thus, the reaction of fly ash and alkali becomes incomplete.

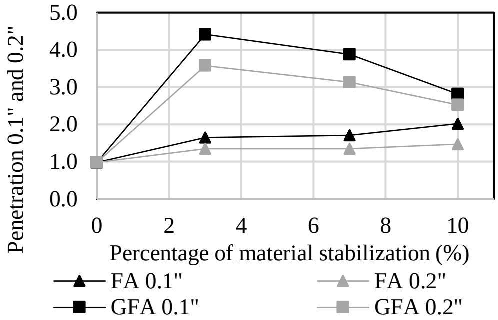


Fig. 9 CBR value of the stabilized soil

In accordance with Fig. 9, the CBR value of the soil stabilized with fly ash and geopolymer has increased with the addition of stabilizing agent. For adding the same stabilizing agent, soil stabilized with geopolymer has a higher CBR value (+18%) than soil stabilized with fly ash. This phenomenon is different from the results of other parameter tests. This can be influenced by the curing time. CBR test curing time, which is three days, affects the cementation of the soil.

The geopolymerization reaction does not only apply water but also an alkaline solution which helps produce more silica and alumina. Silica and alumina reactivity will form a binding gel. It creates a more complex soil structure than fly ash alone [2].

However, as the percentage of geopolymer increases, the CBR value decreases. This behavior can be seen from the condition of the decreased alkaline molarity. Low alkalinity affects the consistency of the mixture. Hence, the expected geopolymer reaction does not meet the complex soil structure.

Meanwhile, the increase in CBR value due to the addition of fly ash can be explained by the value of soil compaction when stabilized with fly ash. Mixing soil and fly ash only adds water, making it easier for fly ash to bind cations from the soil [19].

4.4 Mineralogy Test of Soil Stabilization

The results of the mineralogy test of soil stabilization with several variations of geopolymer compositions are shown in

Fig. 10. The XRD graphic results of stabilized soil from the laboratory are not shown because there was a failure during the test. The software "MATCH!" helps to show the XRD graphic based on COD databases from the laboratory of the stabilized soil.

The result XRD test at the initial conditional (Fig. 1) mineralogical of soil consists of magnetite, sodium aluminum silicate, and albite. After the stabilization with geopolymer, quartz and berlinite are found (

Fig. 10). The newly formed mineral berlinite ($AlPO_4$) is one type of nano clay that is widely used together with illite [15]. New minerals indicate that mixing clay with geopolymers produces new compounds.

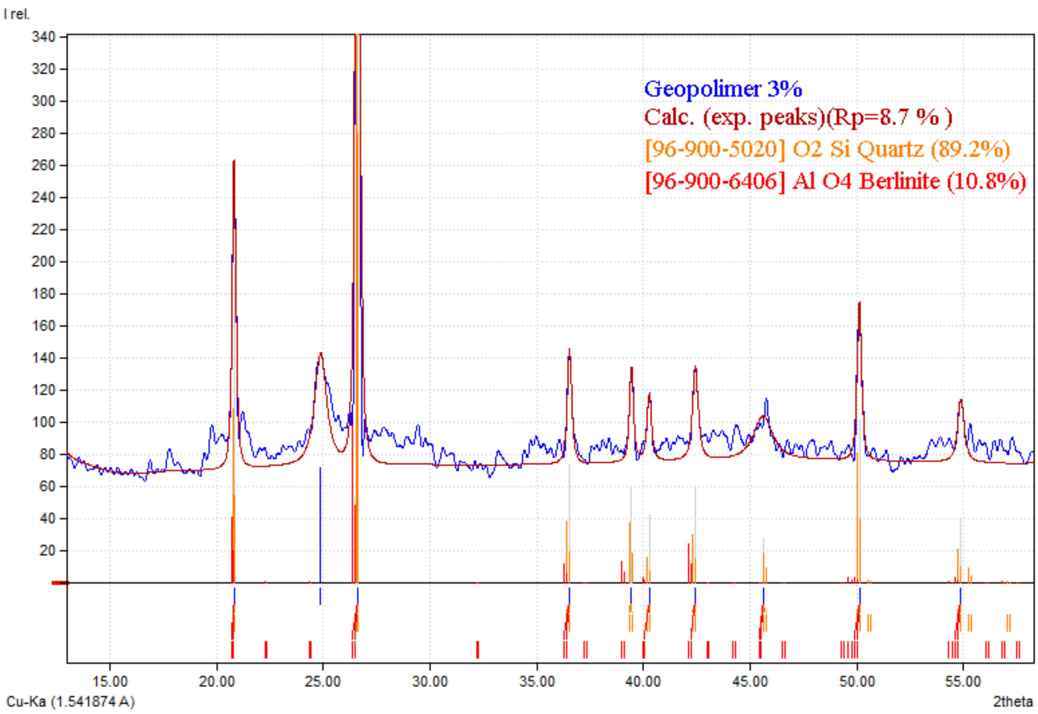
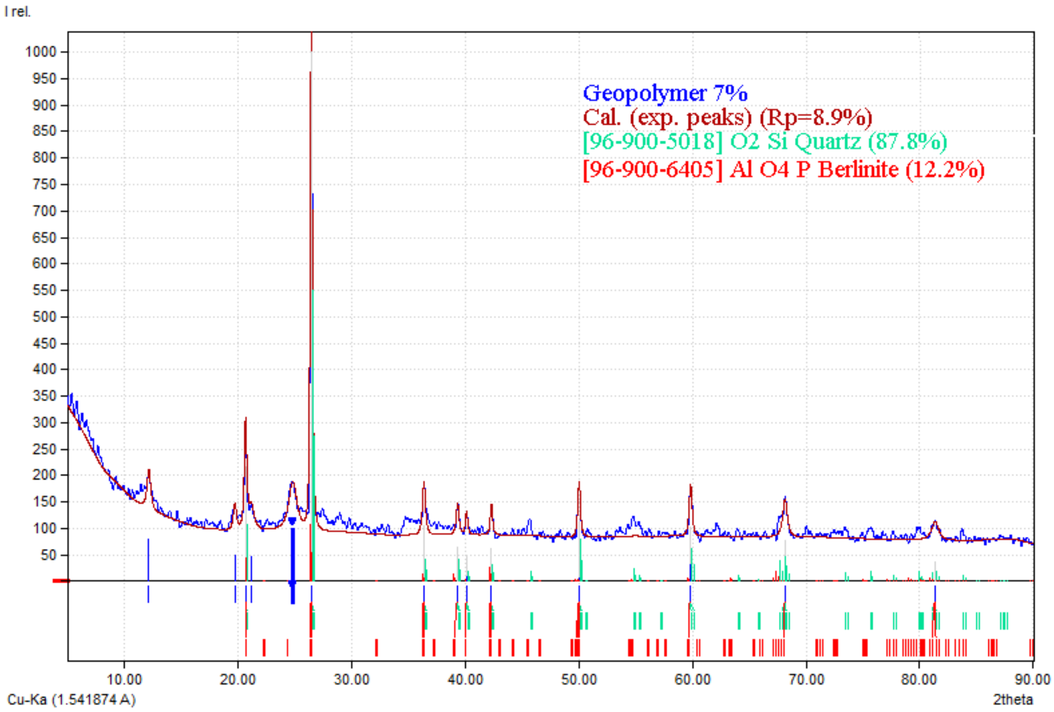
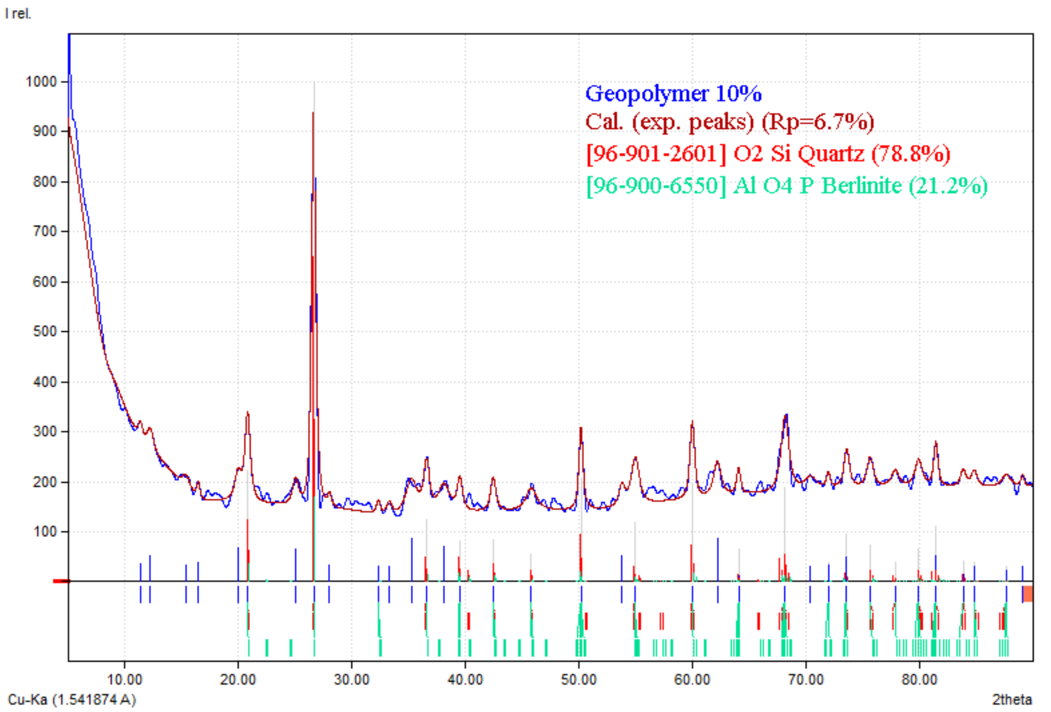


Fig.10a Clay soil + Geopolymer 3%



b. Clay soil + Geopolymer 7%

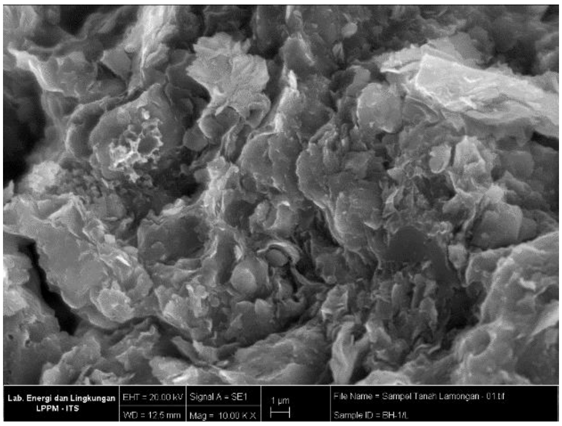


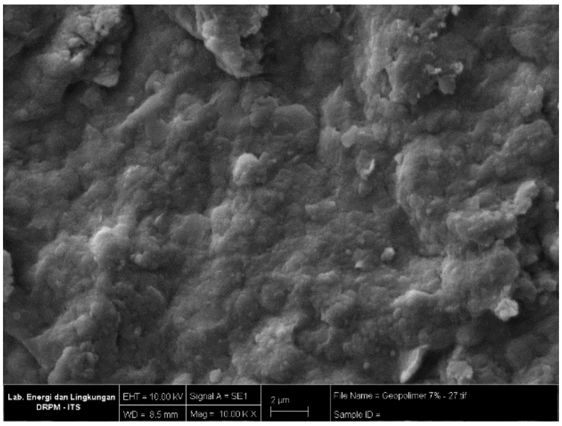
c. Clay soil + Geopolymer 10%

Fig. 10 XRD pattern of soil conditions (a) geopolymer stabilization 3% (b) geopolymer stabilization 7% (c) geopolymer stabilization 10%

4.5. Analysis of SEM Test Results

Geopolymer mixed soil was then tested with SEM with a magnification of 10.000 times. The test results are shown in Fig. 11. Fig. 11 shows the SEM results of clay in the initial conditions and the soil after stabilization with geopolymer. The initial conditions indicate that there are medium to large soil pores. This allows the voids between the grains to be filled with water or air, which causes low soil density.


(a) Clay soil at initial condition


(c) Clay soil + Geopolymer 7%


(b) Clay soil + Geopolymer 3%

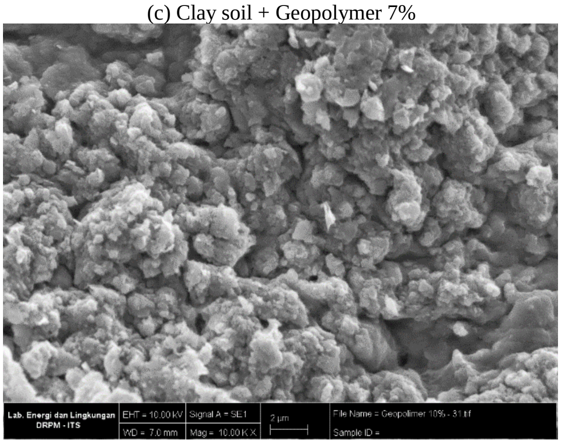

(d) Clay soil + Geopolymer 10%

Fig. 11Fig. 11 Micropores of clay (a) initial conditions (b) geopolymer stabilization 3% (c) geopolymer stabilization 7% (c) geopolymer stabilization 10%

After being stabilized with a geopolymer, the result shows that the soil pores are starting to close. The results of the geopolymer reaction are evenly distributed through the soil particles. Although the soil surface is still rough, the gaps between particles are filled [1]. The presence of high alkalinity breaks the soil particles and allows the rearrangement of the particles to form a fine three-dimensional Si-O-Al and Si-O-Si structure [17].

5. CONCLUSIONS

The results show that the soil mixture with fly ash reduced the plasticity index value by up to 10.25%, while the geopolymer soil reduced the plasticity index value by up to 15.39%. The results of the soil proctor test with fly ash increased MDD by 1.8% and decreased OMC by 9.84%. The mixture of soil and geopolymer increases MDD by 1.67% and decreases OMC by 18.27%. The addition of fly ash increases the compressive strength of the soil by ten times higher than the initial soil. In comparison, adding geopolymer increases the compressive strength of the soil seven times higher than the initial conditions.

On the other hand, the CBR value of soil and fly ash increased by 1.65%, while soil and geopolymer increased by 4.42%. The results above show an inconsistency between the soil mixture with fly ash and soil with geopolymer.

The difference in yield can be influenced by a significant decrease in molarity and a short curing time, which causes the geopolymer reaction to slow down to form a more complex soil structure. Microstructural analysis shows the addition of geopolymer causing denser soil structure, indicating an increase in the interaction between soil and alkaline binders from the initial soil condition.

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