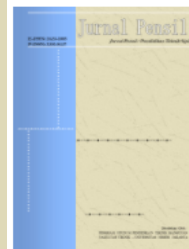


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GEOPOLYMER STABILIZATION OF CLAY SOIL USING EFB ASH AND METAKAOLIN

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Abstract

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Clay soils with low bearing capacity can pose challenges in construction, requiring stabilization to improve their engineering properties. This study investigates the use of empty fruit bunch ash (EFB ash) and metakaolin as geopolymer-based materials for clay soil stabilization. Metakaolin:EFB ash ratios of 75:25, 60:40, and 50:50 were evaluated at binder contents of 10% and 15%. NaOH concentrations of 8 M, 10 M, and 12 M were used as alkaline activators, with curing periods of 52, 77, and 109 days. Unconfined compressive strength (UCS) was evaluated under unconfined axial loading. The untreated soil exhibited a UCS of 0.325 MPa, while the highest UCS after stabilization reached 3.291 MPa, obtained with a 50:50 metakaolin:EFB ash ratio, 10% binder content, 12 M NaOH, and 52 days of curing. This value represents an approximately 10.1fold increase compared with the untreated soil. The results show that the 50:50 metakaolin:EFB ash ratio and 10% binder content generally produced higher UCS values, while 10 M NaOH yielded the highest average UCS among the tested activator concentrations. The higher strength at the 50:50 ratio may be associated with interactions between metakaolin and EFB ash, although this mechanism requires further chemical and microstructural verification. Overall, the results indicate that the metakaolin and EFB ash combination has potential for clay soil stabilization, including applications such as subgrade and stabilized fills, subject to applicable technical requirements.

Keywords: Soil Stabilization, Geopolymer, Oil Palm Empty Fruit Bunch Ash, Metakaolin, Unconfined Compressive Strength

Introduction

Low shear strength, low bearing capacity, and high compressibility often make clay soils problematic in geotechnical works, particularly because their volume changes with variations in water content (Anggraini & Saleh, 2021); (Disu & Kolay, 2021); (Panggabean & Anggraini, 2021); (Setyaningrum et al., 2023); (Pramesti & Roesdiana, 2026). These characteristics can lead to differential settlement, excessive deformation, structural cracking, and even foundation damage if appropriate ground improvement measures are not implemented (Kholis et al., 2018); (Panggabean & Anggraini, 2021); (Purba et al., 2025). Such soil conditions are commonly encountered in the construction of roads, industrial areas, buildings, and other infrastructure built on soft ground (Jeremiah et al., 2021); (Nugraha et al., 2026). Therefore, improving the bearing capacity by modifying the mechanical properties of the soil through stabilization is necessary. Soil stabilization is one of the most widely applied approaches to increase bearing capacity, reduce compressibility, and improve soil stability so that the soil can meet the technical requirements of construction (Anggraini & Saleh, 2020); (Mildawati & Hidayat, 2023); (Prasetyo et al., 2025).

The use of various industrial wastes and agricultural by-products as aluminosilicate-based materials has received increasing attention for improving problematic soils (Nugraha et al., 2026); (Prasetyo et al., 2025); (Abriantoro & Simanjuntak, 2025). Several materials that have been widely investigated include fly ash, ferronickel slag, and Ground Granulated Blast Furnace Slag (GGBFS) (Indera Kusuma et al., 2024); (Toyeb & Ningrum, 2024); (Bagaskara et al., 2025). These materials contain substantial amounts of silica and alumina, which can react with alkaline activators such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). This reaction promotes the dissolution of precursor particles and the formation of new inorganic polymer structures that contribute to strengthening the soil matrix. The effectiveness of this process is strongly influenced by the molarity of the activator, where higher concentrations generally promote the dissolution of reactive components and may result in a denser and stronger binding matrix (Pramesti & Roesdiana, 2026).

From a chemical perspective, geopolymers can contribute to soil bonding through the formation of calcium silicate hydrate (C-S-H), calcium aluminosilicate hydrate (C-A-S-H), and sodium aluminosilicate hydrate (N-A-S-H) gels, which can fill the pore spaces between soil particles. The formation of these gels may promote agglomeration and flocculation, resulting in changes to the soil structure and contributing to a more stable soil matrix. The resulting physical changes may include a reduction in the plasticity index, an increase in specific gravity, and improved compaction characteristics, reflected by higher maximum dry density (MDD) and lower optimum moisture content (OMC) (Indera Kusuma et al., 2024); (Nugraha et al., 2026). From a mechanical perspective, geopolymer stabilization can significantly improve the California Bearing Ratio (CBR) and unconfined compressive strength (UCS) of soft soils and peat soils (Rokky et al., 2017); (Farichah et al., 2023). Its ability to develop strength within a relatively short period can also be beneficial for construction activities, particularly when a rapid increase in soil strength is required in the field (Ningrum et al., 2023). In addition to producing lower carbon emissions than conventional Portland cement, geopolymers have the potential to improve the mechanical properties of soil. These characteristics make geopolymer-based materials a promising alternative for soil stabilization and support more sustainable use of soil as a subgrade material in infrastructure construction (Jeremiah et al., 2021); (Ayodele et al., 2025).

Laboratory testing of clay soil stabilized with palm ash-based geopolymers has shown that curing time can influence the development of soil strength. In previous studies, the highest UCS values were generally obtained after 28 days of curing (Ningrum, 2022). In addition to improving strength, geopolymer addition can also improve the volumetric properties of the soil. A reduction in the plasticity index and liquid limit can make the soil more stable and less susceptible to changes caused by variations in water content (Prasetyo et al., 2025). From an application perspective, geopolymers also have the potential to reduce settlement while producing lower carbon emissions than conventional Portland cement. Therefore, geopolymer-based materials are increasingly being considered as an alternative for stabilizing subgrade soils in road construction and other types of

infrastructure (Jeremiah et al., 2021); (Toyeb & Ningrum, 2024); (Anggrainil et al., 2022); (Kholis et al., 2018).

In addition to geopolymer-based methods, soft soil stabilization can also be carried out using various types of waste materials. One such approach involves a combination of concrete waste and limestone powder. The use of 15% concrete waste and 10% limestone powder has been reported to improve the characteristics of clay soil by reducing the plasticity index by up to 85.90%. The calcium carbonate (CaCO_3) contained in limestone powder contributes to chemical processes that affect the water content of the soil, while the concrete waste helps improve soil density. The mixture also increased the soaked California Bearing Ratio (CBR) by 523.66% and reduced the swelling potential by up to 89.18%. These results indicate that the combined use of these two waste materials has potential as an alternative stabilization material for road construction (Amalia & Sriwijaya Minaka, 2024). Another alternative is the use of a carbide waste and bottom ash mixture for low-plasticity organic clay. The CaO contained in carbide waste can support pozzolanic reactions, while bottom ash provides silica and aluminum that contribute to the development of a stiffer soil structure. In that study, a mixture containing 10% carbide waste and 5% bottom ash provided the highest improvement in unconfined compressive strength (q_u) compared with the untreated soil (Desiandhy et al., 2024). For more practical field evaluation of soil bearing capacity, another study developed a California Bearing Ratio (CBR) prediction model based on Mackintosh Probe (MP) test results. The results showed a strong linear relationship between the number of MP blows and laboratory CBR values. This relationship can be used to estimate soil bearing capacity without conducting the entire series of laboratory tests, making the evaluation process more efficient (Nugroho et al., 2025). In addition to these approaches, improvements in soil physical properties can also be achieved by using palm shell ash as an additive, with the testing conducted in accordance with applicable soil physical testing standards.

Most previous studies have focused on the effects of one or two mixture parameters, such as binder content and alkaline activator concentration. The curing periods used in these studies have also generally been limited to 7–28 days (Ria & Masri, 2020); (Agus Nugroho et al., 2023). However, geopolymerization does not occur instantaneously but develops gradually throughout the curing process. Therefore, the development of material strength is influenced not only by precursor composition but also by the activator concentration and curing duration (S et al., 2026); (Soewignjo A & Nugroho, 2020). Studies that examine these three factors simultaneously, particularly over longer curing periods, are still relatively limited. (Anggraini & Saleh, 2020), for example, suggested extending the evaluation period to 180 days to obtain a more complete understanding of strength development.

On the other hand, the use of empty fruit bunch ash (EFB ash) as a geopolymer material has more commonly been investigated as a supplementary material in concrete or mortar (Diah Sepdayanti et al., 2022); (Misnawati, 2018); (Wibisono et al., 2025). Studies specifically combining EFB ash with metakaolin for clay soil stabilization remain relatively limited. This is particularly evident in studies that use X-Ray Fluorescence (XRF) characterization to determine the chemical composition of the materials before selecting their proportions for the geopolymerization process (Apriyanti et al., 2021); (Jeremiah et al., 2021). From the testing perspective, previous studies have generally used Unconfined Compression Strength (UCS) equipment to evaluate soil compressive strength. In some studies, load measurements were still obtained manually using a proving ring dial (Ayodele et al., 2025); (Silaban et al., 2024); (Oktarise Dwina et al., 2021); (Nurrohman & Ali, 2026). The use of a Universal Testing Machine (UTM) for compressive strength testing of stabilized soils remains relatively uncommon in the literature considered in this study.

Based on these conditions, this study focuses on developing a geopolymer system combining metakaolin and empty fruit bunch ash (EFB ash). The two materials were used together to investigate how the combination of alumina and silica containing materials affects the mixture composition used in the study (Rusan Rangan et al., 2020); (Andajani & Risdianto, 2022). The study then examined three main parameters: the metakaolin-to-EFB ash ratio, binder content, and

NaOH concentration. Testing was conducted at three curing periods, namely 52, 77, and 109 days, to observe the performance of the mixtures over longer curing periods (Silaban et al., 2024); (Jeremiah et al., 2021). Chemical characterization using XRF was also carried out to provide information on the composition of the materials used. Meanwhile, a Universal Testing Machine (UTM) was used for compressive strength testing due to the limited availability of conventional UCS equipment in the laboratory (Nugraha et al., 2026); (Silaban et al., 2024). Through this approach, the study aims to provide an overview of the relationship between mixture composition, the geopolymerization process, and changes in the strength of clay soil.

Based on the identified research gap, this study investigates the effect of combining metakaolin and empty fruit bunch ash (EFB ash) as geopolymer-based materials on the compressive strength of clay soil. The investigated variables include the proportions of the two materials, binder content, NaOH concentration, and curing period (Aprilia et al., 2025); (Lim & Darian, 2022). In addition to identifying the mixture that produces the highest Unconfined Compressive Strength (UCS), this study also explores the potential of empty fruit bunch waste as a component of soil stabilization materials. Due to the limited availability of conventional UCS equipment in the laboratory, compressive strength testing was conducted using a Universal Testing Machine (UTM). In this study, the use of UTM was intended as an alternative testing approach to obtain axial compressive strength data and compare the performance of the different mixtures, rather than to introduce a new testing method. Metakaolin was selected as one of the precursor materials because of its reactivity with alkaline activators, while EFB ash was used because it is derived from biomass waste that still has potential for use as a construction material. The two materials were combined at several ratios to evaluate their effect on soil strength. The results are expected to provide an understanding of the mixture combination that is most suitable for improving the compressive strength of clay soil.

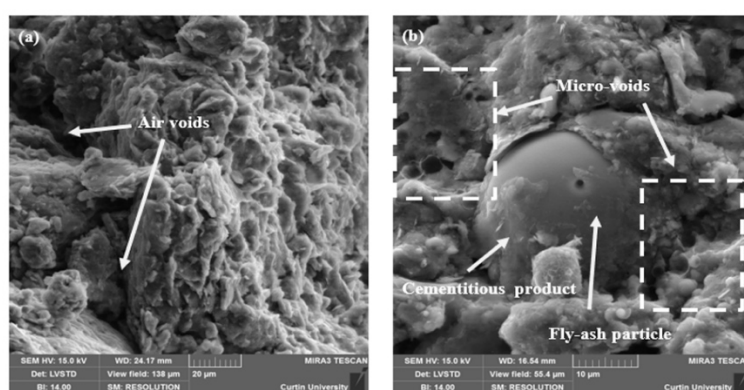


Figure 1. SEM Images of Clay Soil

- (a) untreated clay soil; and
(b) geopolymer-stabilized clay soil after 28 days of curing

Research Methods

The clay soil used in this study was collected from Cikarang, West Java. Its initial characteristics were determined through index property testing at an external soil mechanics laboratory. The stabilizing materials consisted of metakaolin and empty fruit bunch ash (EFB ash), which were characterized using X-Ray Fluorescence (XRF). The mixtures were prepared using metakaolin ash ratios of 75:25, 60:40, and 50:50, with binder contents of 10% and 15% based on the dry weight of the soil. The alkaline activator consisted of NaOH at concentrations of 8 M, 10 M, and 12 M, combined with Na_2SiO_3 at a 1:1 ratio. Specimen preparation and testing were carried out with reference to SNI 3638:2012, which adopts ASTM D2166/D2166M for the determination of the unconfined compressive strength (UCS) of cohesive soils. Cylindrical specimens, 38 mm in

diameter and 76 mm in height ($H/D = 2.0$), were compacted in three layers to achieve a target dry density of 1.35 t/m^3 . Three specimens were prepared for each mixture and wrapped in plastic during curing for 52, 77, and 109 days. Since the mixture compositions at the different curing ages were not completely identical, the three curing periods were treated as separate experimental conditions. They were therefore used to compare the UCS results among the tested specimens rather than to evaluate the strength development of the same mixture over time. For the stabilized soil specimens, the UCS test was conducted using a Universal Testing Machine (UTM). This approach is consistent with the basic principle of the UCS test, which requires controlled axial loading under unconfined conditions. The UTM allows controlled axial loading under strain control while continuously recording the applied load and axial deformation, in accordance with the fundamental testing principle of ASTM D2166/D2166M. Each specimen was positioned vertically and centered between the loading platens before continuous axial compression was applied without lateral confinement until failure. The UTM was operated at a strain rate of 1.0% per minute, corresponding to an axial displacement rate of 0.76 mm/min for the initial specimen height of 76 mm. Load and deformation were continuously recorded during testing. The compressive stress was calculated from the measured axial load and the corrected cross-sectional area accounting for axial deformation. The maximum compressive stress reached before failure was taken as the UCS. The untreated soil specimens were tested using conventional UCS equipment at an external laboratory. Although different testing equipment was used, both methods employed the same fundamental unconfined axial compression principle, with no lateral confinement, and determined the UCS from the maximum axial compressive stress at failure. Therefore, the comparability of the results was based on the equivalence of the testing principle, loading condition, and resulting UCS parameter, rather than on the type of equipment used. The results from both methods were reported using the same stress unit to ensure consistency in the comparison. The use of a UTM for unconfined compression testing of stabilized soil is also consistent with approaches reported in previous studies using ASTM D2166. Nevertheless, the use of different testing equipment represents a methodological limitation that should be acknowledged. Accordingly, the comparison between untreated and stabilized soils was interpreted based on the UCS response obtained under comparable unconfined axial loading conditions and was not intended to constitute a direct validation of the equivalence of the two testing systems.

Research Results and Discussion

The untreated soil was first tested to obtain an initial strength value for comparison with the stabilized soil. The results showed that the untreated soil had an Unconfined Compressive Strength (UCS) of 0.325 MPa. This value indicates that the soil had relatively low strength in its original condition, highlighting the need for stabilization to improve its capacity to support construction loads.

Table 1. Summary of Laboratory Index Properties Tests of the Untreated Soil

Test	Value	Unit
<i>Natural Water Content, w_n</i>	44.52	(%)
<i>Unit Weight, γ</i>	1.81	(t/m^3)
<i>Dry Unit Weight, γ_d</i>	1.35	(t/m^3)
<i>Specific Gravity, G_s</i>	2.59	
<i>Void Ratio, e</i>	0.923	
<i>Porosity, n</i>	0.480	
<i>Degree of Saturation, S</i>	100.00	(%)

Table 2. Unconfined Compressive Strength (UCS) of the Control Specimen

Sample Condition	Unconfined Compressive Strength, q_u (kPa)	Undrained Shear Strength, c_u (kPa)	Modulus, E (kPa)	Modulus Secant, E (kPa)
(Disturbed Sample)	325.51	162.75	21364.51	6510.13
(Remolded Sample)	231.26	115.63		

Geopolymer Stabilization Concept and Mix Design

The selection of stabilization materials in this study was based on the geopolymerization process, which involves the reaction of silica (SiO_2) and alumina (Al_2O_3) with an alkaline activator to form a binding gel that can contribute to improving soil strength (Davidovits, 1991; Duxson et al., 2007). EFB ash was selected because it contains a relatively high proportion of SiO_2 and is derived from an available biomass waste, while its Al_2O_3 content is relatively low. The X-Ray Fluorescence (XRF) analysis of the materials used in this study also showed this characteristic, as presented in Table 3. Therefore, EFB ash was not used as a standalone material but was combined with metakaolin to complement the components required for the geopolymer system. The two materials were then combined at several mixture ratios to evaluate their effect on soil strength.

Table 3. Chemical Composition of Burned Empty Fruit Bunch (EFB) Ash Determined by X-Ray Fluorescence (XRF)

Compound	Content (%)
K_2O	40.80
SiO_2	26.40
CaO	10.30
MgO	7.60
P_2O_5	4.90
SO_3	4.00
Fe_2O_3	2.90
Cl	1.60
MnO	0.50
Rb_2O	0.30
ZnO	0.20
CuO	0.10
Gd_2O_3	0.10
SrO	0.10
TiO_2	0.10
Al_2O_3	0.00

Table 4. Chemical Composition of Metakaolin Determined by X-Ray Fluorescence (XRF)

Compound	Content (%)
SiO_2	51.642
Al_2O_3	41.334
MgO	1.181
Fe_2O_3	1.619

TiO ₂	1.696
K ₂ O	0.661
P ₂ O ₅	0.768
SO ₃	0.417
Cl	0.173
CaO	0.172
V ₂ O ₅	0.055
Cr ₂ O ₃	0.036
MnO	0.014
Rb ₂ O	0.008
SrO	0.011
Others	~0.000

In contrast, the XRF analysis of metakaolin showed a relatively high Al₂O₃ content, with a more balanced composition of SiO₂ and Al₂O₃, as presented in Table 4. This composition makes metakaolin suitable for use as one of the materials in the geopolymerization process. Metakaolin serves as a source of alumina that contributes to the formation of the binding structure within the geopolymer matrix (Silaban et al., 2024). In this study, metakaolin was combined with EFB ash to complement the composition of the two materials. The Si/Al ratio was considered when determining the mixture composition because it is related to the formation and strength of the geopolymer structure (Ayodele et al., 2025). Therefore, the selection of metakaolin and EFB ash was based not only on their availability and individual characteristics but also on the XRF results obtained from the materials used in this study.

Mixture Proportions and Experimental Parameters

To evaluate the performance of geopolymer-based soil stabilization, this study investigated several mixtures of metakaolin and empty fruit bunch ash (EFB ash). The metakaolin:EFB ash ratios were 75:25, 60:40, and 50:50, with binder contents of 10% and 15% based on the dry weight of the soil. The alkaline activator consisted of NaOH at concentrations of 8M, 10M, and 12M, combined with Na₂SiO₃ at a 1:1 ratio. These variations were used to examine the effects of material composition, binder content, and activator concentration on soil compressive strength. The prepared mixtures were homogenized, molded following the testing procedure, and cured for 52, 77, and 109 days. Since not all mixture compositions were tested at all three curing ages, the curing periods were not used to represent strength development of the same mixture over time. Instead, the results at each curing age were compared across the tested mixture variations to identify the combination that produced the highest UCS value. This approach allowed the mixture condition that provided the greatest improvement in compressive strength to be determined based on the experimental results.

Table 5. Geopolymer Mix Composition with a Metakaolin-to-EFB Ash Ratio of 60:40

Sample Code	Binder (%)	MK (g)	EFB (g)
B10-60-8	10	12	8
B10-60-10	10	12	8
B10-60-12	10	12	8
B15-60-8	15	18	12
B15-60-10	15	18	12
B15-60-12	15	18	12

Table 6. Geopolymer Mix Composition with a Metakaolin-to-EFB Ash Ratio of 50:50

Sample Code	Binder (%)	MK (g)	EFB (g)
B10-50-8	10	10	10
B10-50-10	10	10	10
B10-50-12	10	10	10
B15-50-8	15	15	15
B15-50-10	15	15	15
B15-50-12	15	15	15

Table 7. Geopolymer Mix Composition with a Metakaolin-to-EFB Ash Ratio of 75:25

Sample Code	Binder (%)	MK (g)	EFB (g)
B10-75-8	10	15	5
B10-75-10	10	15	5
B10-75-12	10	15	5
B15-75-8	15	22.5	7.5
B15-75-10	15	22.5	7.5
B15-75-12	15	22.5	7.5

Table 8. Binder Content and Alkaline Activator Parameters for Geopolymer Mixtures

Parameter	Value
Dry Soil Weight	200 g
Binder Content (10%)	20 g
Binder Content (15%)	30 g
Na ₂ SiO ₃ /NaOH Ratio	1 : 1
NaOH Volume (10% Binder)	8 ml
NaOH Volume (15% Binder)	12 ml
Na ₂ SiO ₃ Volume (10% Binder)	8 ml
Na ₂ SiO ₃ Volume (15% Binder)	12 ml
Total Activator Volume (10% Binder)	16 ml
Total Activator Volume (15% Binder)	24 ml
NaOH Molarity	8M, 10M, 12M

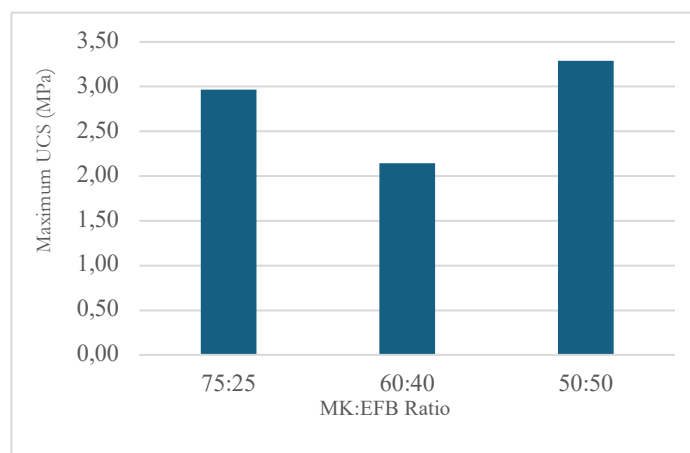


Figure 2. Effect of the Metakaolin-to-EFB Ash Ratio on Unconfined

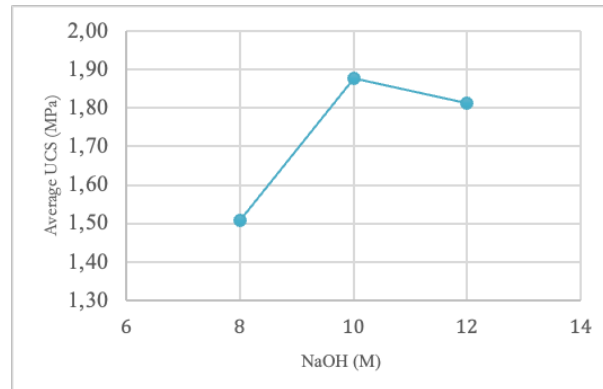


Figure 3. Effect of NaOH Molarity on Unconfined Compressive Strength (UCS)

Effect of the Metakaolin-to-EFB Ash Ratio on UCS

Based on Figure 2, different metakaolin-to-empty fruit bunch ash (EFB ash) ratios resulted in different Unconfined Compressive Strength (UCS) values. The highest UCS value was obtained at an MK:EFB ratio of 50:50, reaching 3.291 MPa, while the 75:25 and 60:40 ratios resulted in UCS values of 2.964 MPa and 2.141 MPa, respectively. These results indicate that the 50:50 ratio provided the highest compressive strength under the testing conditions. Based on the XRF characterization results, differences in the chemical composition of metakaolin and EFB ash may provide one possible explanation for the variation in strength. The combination of the two materials at a 50:50 ratio may provide a more suitable composition for supporting the geopolymerization process than the other ratios. These findings indicate that the metakaolin-to-EFB ash ratio should be considered when determining the mixture composition that provides the greatest improvement in compressive strength.

Effect of NaOH Molarity on UCS

Based on Figure 3, variations in NaOH molarity resulted in different compressive strength values for the stabilized soil. The highest average UCS value was obtained with 10 M NaOH, reaching 1.877 MPa, while the 8 M and 12 M mixtures resulted in 1.509 MPa and 1.813 MPa, respectively. These results indicate that the 10 M concentration produced the highest compressive strength among the tested molarity variations under the investigated mixture conditions. Meanwhile, increasing the NaOH concentration to 12 M did not result in a further increase in UCS, as its value was slightly lower than that obtained with 10 M NaOH. This difference indicates that a higher activator concentration does not necessarily lead to greater compressive strength.

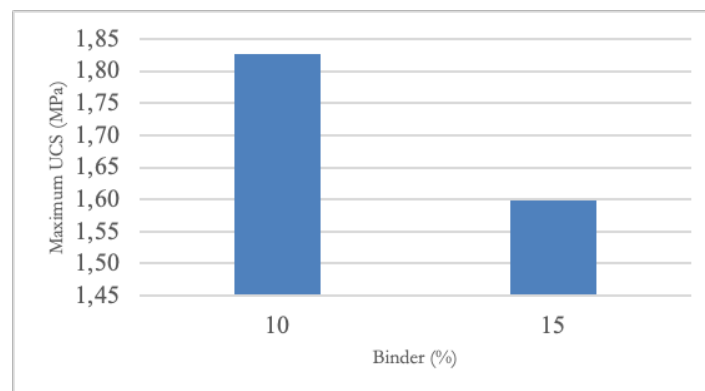


Figure 4. Effect of Binder Content on Unconfined Compressive Strength (UCS)

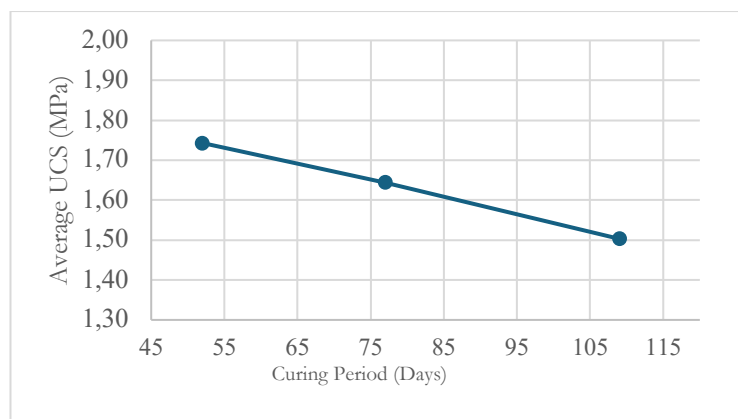


Figure 5. Effect of Curing Period on Unconfined Compressive Strength (UCS)

Effect of Binder Content on UCS

Figure 4 shows that a binder content of 10% resulted in an average UCS value of 1.826 MPa, while the 15% binder content produced an average value of 1.599 MPa. Thus, increasing the binder content from 10% to 15% did not result in a higher compressive strength. Under the mixture conditions investigated, the 10% binder content produced a higher UCS value than the 15% binder content. These results indicate that increasing the binder content does not necessarily lead to higher soil strength. Therefore, the binder content needs to be considered in relation to the mixture composition and testing conditions.

Effect of Curing Period on UCS

Based on Figure 5, the average UCS values at curing ages of 52, 77, and 109 days were 3.291 MPa, 1.644 MPa, and 1.503 MPa, respectively. These values do not show a consistent increase in compressive strength with increasing curing age. Since the mixture compositions at the different curing ages were not entirely identical, the differences in UCS values were not used to indicate the effect of curing age on the strength development of a single mixture. Instead, the results at the three curing ages were used to compare the compressive strength of specimens with the respective mixture compositions tested at each curing age. Based on this comparison, the highest average UCS value was obtained at a curing age of 52 days, reaching 3.291 MPa.

Comparison Between Untreated and Stabilized Clay

As shown in Figure 6, the untreated clay had a UCS of 0.325 MPa, while the mixture with an MK ratio of 50:50, 10% binder content, and 12 M NaOH achieved the highest UCS of 3.291 MPa. This value represents an approximately 10.1 fold increase compared with the untreated soil, indicating a substantial improvement in compressive strength following stabilization with metakaolin and EFB ash through alkaline activation. The comparison was made using the same fundamental UCS testing principle, namely axial compression without lateral confinement, with UCS determined from the maximum compressive stress reached during loading. The stabilized specimens were tested using a Universal Testing Machine (UTM), whereas the untreated soil was tested using conventional UCS equipment at an external laboratory. Thus, the results were compared based on the testing principle, loading condition, and UCS parameter rather than solely on the type of equipment used. Nevertheless, the use of different testing equipment may introduce a degree of experimental uncertainty. Therefore, the 10.1 fold increase is interpreted as a comparison of the measured UCS values under comparable unconfined compression conditions, while recognizing this methodological limitation. Within the conditions investigated, the combination of an MK ratio of 50:50, 10% binder content, and 12 M NaOH produced the highest measured UCS of 3.291 MPa.

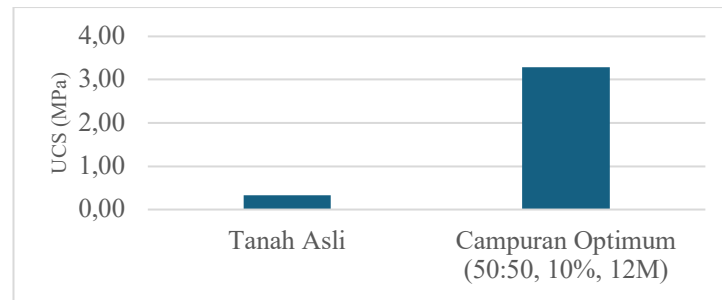


Figure 6. Comparison of Unconfined Compressive Strength (UCS) Between Untreated Clay and the Optimum Mixture

Conclusion

Based on the results, stabilization of clay soil using a combination of metakaolin and empty fruit bunch ash (EFB ash) increased the unconfined compressive strength (UCS) compared with the untreated soil. The untreated soil had a UCS of 0.325 MPa, while the highest UCS obtained for the stabilized soil was 3.291 MPa, representing an approximately 10.1-fold increase. The untreated soil was tested using the UCS method at an external laboratory, whereas the stabilized specimens were tested using a Universal Testing Machine (UTM) under axial loading until failure. The UCS of the stabilized specimens was determined from the maximum compressive stress calculated from the load and deformation data recorded during testing. The comparison of UCS values was based on the same fundamental testing principle, namely axial compressive loading without lateral confinement, with UCS determined from the maximum compressive stress reached during loading. The stabilized specimens were tested using a UTM, while the untreated soil was tested using conventional UCS equipment at an external laboratory. Therefore, the results were compared based on the testing principle, loading condition, and UCS parameter rather than solely on the type of equipment used. Nevertheless, the use of different testing equipment may introduce a certain degree of experimental uncertainty. Accordingly, the 10.1-fold increase is interpreted as a comparison of the measured UCS under comparable unconfined compression conditions, while recognizing this methodological limitation. Different metakaolin ratios resulted in different compressive strength values. Among the 75:25, 60:40, and 50:50 ratios, the 50:50 ratio produced the highest UCS. Binder content also affected the test results, with the 10% binder content producing a higher average UCS than the 15% binder content. Meanwhile, the average UCS values obtained at NaOH concentrations of 8 M, 10 M, and 12 M were 1.509, 1.877, and 1.813 MPa, respectively, with the highest average value obtained at 10 M NaOH. However, the maximum UCS of 3.291 MPa was obtained from the combination of a 50:50 metakaolin-to-EFB ash ratio, 10% binder content, and 12 M NaOH. Under the conditions investigated, this combination produced the highest measured UCS. The higher UCS obtained at the 50:50 ratio may be associated with the interaction between metakaolin and EFB ash during stabilization; however, this mechanism could not be experimentally confirmed because chemical and microstructural characterization of the stabilized products was not conducted in this study. The specimens were tested after curing periods of 52, 77, and 109 days. As shown in Figure 5, the average UCS values at these curing periods were 3.291, 1.644, and 1.503 MPa, respectively. These values did not show a consistent increase in compressive strength with increasing curing time. This is because the mixture compositions at the different curing periods were not completely identical. Therefore, the differences in UCS among the three curing periods were not used to interpret the effect of curing time on strength development for a single mixture. Instead, the results at the three curing periods were used to compare the compressive strength of specimens based on the respective mixture compositions tested under the available experimental conditions. Based on this comparison, the highest average UCS was obtained at a curing period of 52 days, with a value of 3.291 MPa, which also represented the highest UCS measured among the mixture conditions investigated. Overall, the combination

of metakaolin and EFB ash showed potential as a stabilization material for clay soil. The maximum UCS of 3.291 MPa represents a substantial increase in compressive strength and may support soil improvement applications such as subgrade stabilization and stabilized fills, subject to the technical requirements of each application. The use of EFB ash also provides an opportunity to utilize biomass waste as a soil stabilization material, although the environmental sustainability of the proposed system was not quantitatively evaluated in this study.

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