Mechanical Properties of Soft Clay Soil Improved with Nanomaterials and Chitosan Biopolymer

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ABSTRACT: Soft clay soil is a concern in geotechnical engineering due to its low strength and high compressibility. Soil improvement with stabilization techniques is an interesting topic in the field of geotechnical engineering and pavements. Nanomaterials and biogeotechnical-based soil improvement are in high demand, as is the case with the objective of this research which is to determine the effect of the addition of nano lime, nano silica, and chitosan biopolymers to soft clay soil on its mechanical properties. The ratio of additives in this study was taken based on previous research, namely 2% nano lime, 4% nano silica, and 0.1% chitosan biopolymer from shrimp shell waste. Specimen variations consist of initial soil, soil mixed with biopolymers, soil mixed with nanomaterials, and soil mixed with biopolymers and nanomaterials. The mixing method in this study was carried out by mixing the additives according to the percentage of the initial soil dry weight, then water was added to the mixture. Compaction and unconfined compression strength (UCS) tests were conducted on each specimen. The results show that mixing soil with nanomaterials and chitosan provides advantages in mechanical properties. This can be seen from the increase in the UCS value which is up to 11 times that of the initial soil and the increase in the maximum dry density value. Soil stabilization using nanomaterials and chitosan biopolymers has a good impact on the environment. Reducing the ratio of lime in soil stabilization on a project scale can reduce CO_2 emissions during production and the use of chitosan biopolymer additives can reduce marine biota waste, especially invertebrates.

KEYWORDS: Soft clay soil, Nanomaterial, Chitosan biopolymer, and Mechanical properties.

1. INTRODUCTION

Soft clay soils are commonly encountered in geotechnical engineering (Govindasamy et al., 2017). Its low strength and high compressibility posed a challenge to engineers (Janani & Ravichandran, 2023). Soft clay soils with a high plasticity index value have a high shrink-swell potential and one of the characteristics of problematic soft clay soils (Nelson et al., 2015). These soil types can affect the durability and mechanical behavior of an infrastructure (Huynh et al., 2022). For example in road pavement, the behavior of soft clay soil as a road subgrade causes heave, subsidence, and irregularity of the road surface, which leads to several types of pavement deterioration, such as the appearance of cracks on the road surface and early deterioration (Yaghoubi et al., 2021). Soil improvement is an interesting topic for engineers, one of which is soil stabilization techniques. Various efforts have been made to improve soil strength by mixing chemical additives to materials that come from living things and are environmentally friendly, this mixing is one of the most efficient approaches for soft clay soils. (Seco et al., 2011). In addition, the exploration of soil improvement schemes based on stabilization materials is of increasing interest in the field of geotechnical and pavement engineering (Choobbasti et al., 2015). Soil improvement techniques to increase strength can be done in various ways, one of which is stabilization. Soil stabilization can be implemented by mixing chemical additives or materials from living waste such as shrimp shells.

In 1959 Richard Feynman put forward his idea of nanotechnology for the first time, with this statement "There is plenty of room at the bottom." After that, this technology developed in all branches of science, including geotechnical engineering (Bayda et al., n.d.; Ghasabkolaei et al., 2017). Mixing soil with specific additives can improve the stability and strength of weak soils. In geotechnical engineering, nanotechnology is the improvement of soil parameters by the application of nanomaterials. Nano materials have a large specific surface area and morphological properties, many interactions occur between the mixed materials and lead to an increase in the strength of the material. Some experiences in soil stabilization adding nanomaterials in combination with lime can improve the mechanical behavior of soils. Bahmani et al. (Bahmani et al., 2014, 2016) analyzed the improvement of mechanical properties of residual soil by adding nano silica with cement. Results showed an increase in the pozzolanic reaction, converting portlandite into a hydrated calcium silicate gel, which implies an improvement in soil properties.

Lime is an effective stabilizer, which significantly modifies soil characteristics to produce long-term permanent strength and stability, especially with regard to water action. Research related to soil stabilization was conducted on natural expansive soil dredged from coal mining. Ordinary Portland cement and lime were used as additives to the expansive soil. Test results showed that chemical treatment can increase the strength and modulus of the soil. In addition, chemical treatment can reduce swelling. All of these depend on the chemical ratio and curing time (Chompoorat et al., 2021). A larger amount of lime can increase the strength and bearing capacity of the soil. (Govindasamy et al., 2017) conducted research on the effect of nano lime on unconfined compressive strength. The results show that the addition of 0.5% nano lime is the most optimal in increasing the unconfined compressive strength value than the addition of 5% lime without nano lime. (Thomas & Rangaswamy, 2020) also conducted a study on the mechanism of nano silica-oxidant (nano-SiO_2) for improving soil properties. The results showed that the addition of nano silica to soil can increase the compressive strength of soil by 15%. In addition, the efficiency of soil stabilization with nano lime and nano silica has been studied and validated by many authors (Díaz-López et al., 2023; Karimiazar et al., 2023; Kulkarni & Mandal, 2022). In addition to improving mechanical properties, minimizing shrinkage can also reduce damage to soil cement. The results showed that the use of 15% fly ash as a waste material can fill and reduce the size of voids that cause shrinkage, but does not affect mechanical properties (Chompoorat & Likitlersuang, 2015). The ability to change soil characteristics is characterized by increased density, decreased shrinkage expansion values, increased soil strain and stress (Aranaz et al., 2021; Majeed & Raihan Taha, 2013). Improving the mechanical properties of these soils is critical to ensuring the stability and safety of the infrastructure supported on them.

Much research has been done on soil stabilization with various types and variations of additives. For example, geopolymer is an alternative binder with materials rich in silica and alumina as raw materials. In one study, palm oil fuel ash (POFA) and alumina waste ash (AW) were used to investigate the effect on compressive strength and microstructure. Results showed that density and strength increased due to particle morphology, the surface area of POFA and AW, and chemical composition due to polymerization (Chub-uppakarn et al., 2023). Furthermore, research related to the effect of adding palm fibre to cement-treated sands (CTS) showed a change in the behaviour of CTS from brittle to semi-ductile. Equivalent strength ratio is strongly influenced by fibre content and length. In its application, palm fiber inclusion is suitable as the base and subbase for the bound pavement structure (Chompoorat et al., 2023). (Chompoorat et al., 2022) also conducted research related to soft soil improvement. Improvements in the form of adding ordinary Portland cement (OPC) and fly ash (FA) binders with deep soil mixing method. The results showed an increase in strength and stiffness in soil stabilized by OPC, while those stabilized by FA decreased. Then the shrinkage rate of the sample decreased with increasing FA content.

In addition to chemical additives, microbial-induced calcite precipitation (MICP) is one way of soil improvement to enhance engineering properties in a sustainable and environmentally friendly manner. One study explained that optimal urea-Ca2 input can increase the stiffness and shear strength of samples (Arpajirakul et al., 2021). There are also bio geotechnical-based additives, namely chitosan biopolymers. Biopolymers such as chitosan and lignin can be produced from industrial residual waste, thus having good economic and environmental value. Chitosan is the second most abundant compound after cellulose, which can be found in the shells of crabs, shrimps, mollusca, and other marine invertebrates. (Hataf et al., 2018) investigated the stabilization potential of soft clay soil using chitosan solution from shrimp shell waste. The results showed that the incorporation of chitosan has the potential to increase the interaction between soil particles leading to improved mechanical properties. The utilization of chitosan biopolymers in the mechanical properties of soil has been studied by many authors and resulted in an increase in its strength as the ratio of chitosan biopolymers increases (Ilman & Balkis, 2023; Shariatmadari et al., 2020). Analysis results by Govindarajan (Kannan & Sujatha, 2023) showed biopolymer fibres that can fill voids in the soil matrix and produce a more stiff soil matrix. Although there has been a lot of research on new additives for soil stabilization, there is limited research on the combined effect of using waste derived from living things and raw materials pulverized to nano size. This study presents the improvement of mechanical properties of initial soil from unconfined compression strength (UCS) and compaction testing by mixing added materials in the form of 2% Nano Lime (NL), 4% Nano Silica (NS), and 0.1% Shrimp Shell Chitosan Biopolymer (B) based on previous research.

2. MATERIALS

2.1 Properties of Initial Soil

The physical and mechanical properties and classification of the soil taken in Kadipaten District, Majalengka are listed in Table 1. The initial soil was taken at a shallow depth by removing 0.5 m from the ground surface first. The natural moisture content was 33.45% (ASTM D-2216, 2019) while the maximum dry density (γ_{dmax}) and optimum moisture content (ω_{opt}) are 1496 kg/m^3 and 24.54%. Liquid limit (LL) = 66.91%, plastic limit (PL) = 21.34%, and plasticity index (PI) = 45.58% (Method et al., n.d.). According to the unified soil classification system (USCS), the soil is classified into the CH (Clay High) (Practice, 2018). This soil does not contain gravel. The sand, silt, and clay fractions are 0.36%, 55.07%, and 44.57%, respectively (ASTM, 2007, 2017). Figure 1 presents the particle size distribution of the initial soil.

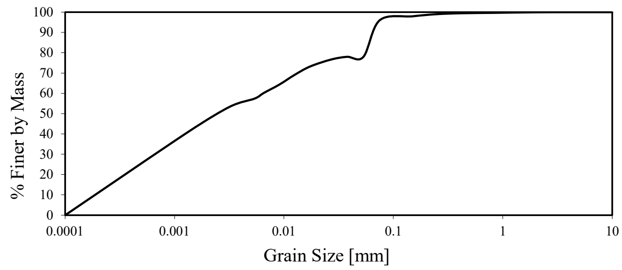

Figure 1 Particle size distribution curve of initial soil

Table 1 Basic properties of initial soil

Soil properties	**Value**	**Test Standard**
Natural moisture content, (ω_n) (%)	33.45	ASTM D-2216
Maximum dry density, (γ_{dmax}) (kg/m^3)	1496	ASTM D-698
Optimum moisture content, (ω_{opt}) (%)	24.54	
UCS, (q_u) (kN/m^2)	112.8	ASTM D-2166
Liquid limit (LL) (%)	66.91	ASTM D-4318
Plastic limit (PL) (%)	21.34	
Plasticity index (PI) (%)	45.58	
USCS Classification	CH	ASTM D-2487
Specific gravity (Gs)	2.47	ASTM D-854
% Gravel	0.00	ASTM D-422 ASTM D-1140
% Sand	0.36	
% Silt	55.07	
% Clay	44.57	

Initial soil testing was conducted to determine the physical and mechanical properties of the soil. The test results explained that the soil had poor characteristics. The soil has a very high degree of expansion with a plasticity index value of more than 35% and the soil is classified as a high plasticity clay (CH). In addition, the soil has a UCS value of 1.128 with a medium to stiff clay consistency (Randhawa et al., 2021). Furthermore, the initial soil characteristics will be compared with the soil mixed with the added materials to investigate the effect.

2.2 Additive Materials

In this study, the additives used for soil improvement were nano lime (NL), nano silica (NS), and chitosan biopolymer (B) from shrimp shell waste. The lime material was obtained from Bratachem in Figure 2 (a) and the silica material was obtained from Sika Indonesia in Figure 2 (b).

Both materials are pulverized through a milling method which makes the surface area of the sample larger due to the constant friction and collision that occurs between the balls and the rotating vial wall. This causes the particle size of the resulting sample to be smaller to nano size (10^{-9}) (Pohshna & Mailapalli, 2023). Material pulverization process using the services of Nano Center Indonesia. The presence of small amounts of nanomaterials in soil can significantly affect the physical and chemical behavior of soil. This is due to their very large specific surface area and morphological properties (Alireza et al., 2013).

Figure 2 Materials (a) Nano lime; (b) Nano silica

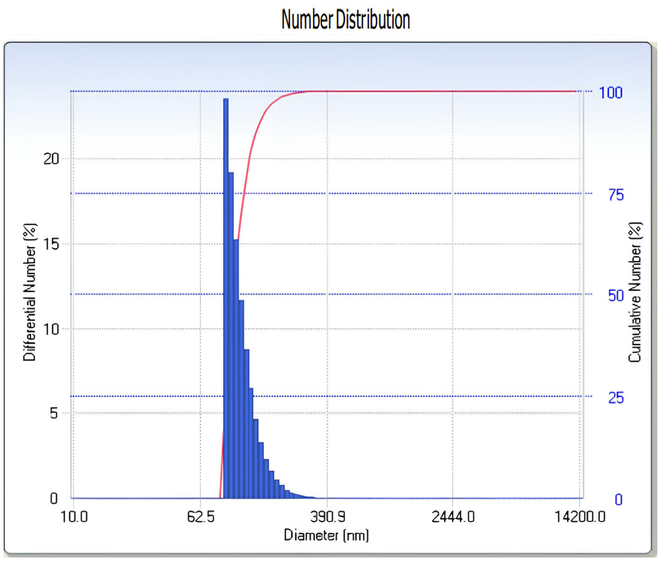

Figure 3 Particle Size Analyzer graph of lime after milling

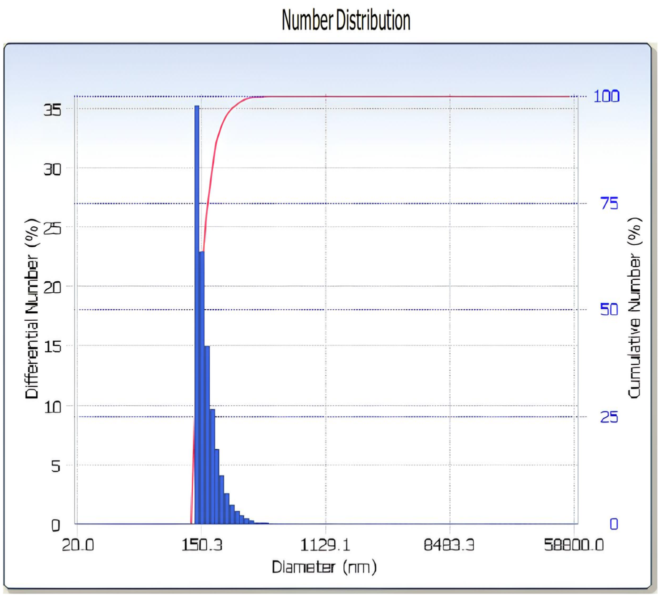

Figure 4 Particle Size Analyzer graph of silica after milling

Based on the results of the PSA (Particle Size Analyzer) test in Figure 3 and Figure 4, the grain size of lime powder after milling is 100.5 nm from the size before the milling process is 1344.6 nm. While on silica powder after milling is 146 nm from the size before the milling process is 1221.8 nm. Then for the chitosan biopolymer material in the form of shrimp shell waste which is already in powder form and obtained from CV Phy Edumedia in Figure 5. This chitosan biopolymer additive is not pulverized like lime and silica. The use of chitosan biopolymer materials is expected to have a significant effect on soft soil characteristics. The biodegradable and non-toxic nature of biopolymers makes them an environmentally friendly material with potential as a soil binder (Muxika et al., 2017).

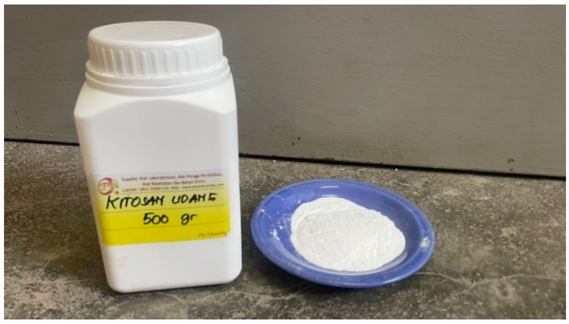

Figure 5 Shrimp shell chitosan biopolymer in powder form

3. METHODOLOGY

In a simple way, the stages of completion carried out in the research work with the title Mechanical Properties of Soft Clay Soil Improved with Nanomaterials and Chitosan Biopolymer can be seen in the flow chart in Figure 6 below.

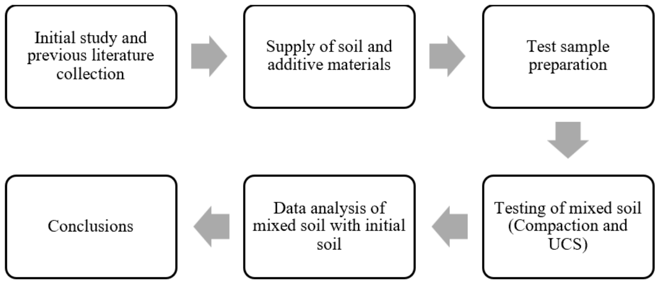

Figure 6 Simple flow chart of research completion

3.1 Test Sample Preparation

The samples prepared for the compaction and UCS tests were initial soil, soil mixed with biopolymers, soil mixed with nanomaterials, and soil mixed with biopolymers and nanomaterials. The percentage of additives mixed into the soil based on previous research was 2% nano lime, 4% nano silica, and 0.1% chitosan biopolymer. Based on previous research, the addition of 0.1% chitosan biopolymer to expansive soil can reduce the plasticity index value up to 67% and change the level of soil expansion from very high to moderate (Firmansyah et al., 2024). The mixing method in this study was carried out by mixing the additives according to the percentage of the initial soil dry weight, then water was added to the mixture. This soil mixing refers to the third draft of the building construction materials and civil engineering guidelines on planning soil stabilization with powdered binders for road construction by the Ministry of Public Works (Depatemen Pekerjaan Umum, 2007).

In the compaction test, 9%, 12%, 15%, 18%, and 21% water from the dry weight of the soil was added for the soil mixture with biopolymer. Then as much as 18%, 21%, 24%, 27%, and 30% water from the dry weight of the soil was added for the soil mixed with nanomaterials and for the soil mixed with both biopolymers and nanomaterials. In the preparation of the UCS test samples were obtained from the compaction results. The soil mixture was added with optimum moisture content according to each mixture. Then a cylindrical mold is inserted which will be removed by an extruder.

On the raw materials of lime and silica, nanoparticles were synthesized using the Wet Milling Top-Down method, which pulverizes particles from a large size to a small size reaching nano size. This particle pulverizer uses a device called a Planetary Ball-Mill (PBM) in Figure 7 with a rotational speed of 800 rpm. This machine has an even distribution of the mill size.

Figure 7 Planetary Ball-Mill (PBM)

3.2 Compaction

Compaction in Figure 8 was conducted using the standard proctor method based on ASTM D698-89. In practice the soil was placed and compacted into a mold with a volume of 943.3 cm^3, a 2.5 kg hammer with a free fall height of 12" (30 cm). The mold is filled with 3 layers of soil with 25 impacts for each layer (ASTM International, 2003).

3.3 Unconfined Compression Strength

The cylindrical specimens used for UCS averaged 37.5 mm in diameter and 76.8 mm in height with a strain rate of 0.760 mm/min. These specimens were obtained from compaction results which were then extruded. The test was conducted based on ASTM D2166-89. The purpose of this test was to calculate the shear strength of the initial soil and evaluate the strength of the mixed soil (ASTM D2166−00, 2000). UCS testing machine as shown in Figure 9.

4. RESULTS AND DISCUSSIONS

4.1 Effect of Additives on Compaction Tests

The soil mixtures with nanomaterials and chitosan biopolymer additives are illustrated in Figure 10 and summarized in Table 2. As shown in Figure 10, the average maximum dry density value of the mixtures increased and their optimum moisture content decreased. This is due to the process of mixing the materials contained in the nanomaterials and chitosan biopolymer with the soil, which occurs rapidly and causes changes in the soil structure.

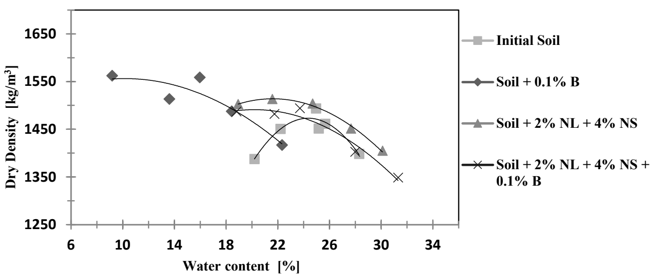

Figure 8 Compaction curves of various specimens

Table 2 Results of the compaction test

Specimens	g_{dmax} (kg/m^3)	w_{opt} (%)
Initial Soil	1496	24.54
Soil + 0.1 % B	1558	15.96
Soil + 2% NL + 4% NS	1504	24.69
Soil + 2% NL + 4% NS + 0.1% B	1494	23.70

From the results of compaction testing on each specimen, the largest maximum dry density is produced by soil with a biopolymer mixture of 1,558 kg/m^3 with a smaller optimum moisture content compared to other specimens of 15.96%. Unlike the case with soil containing nano material in it has a greater optimum moisture content value of 24.69% in soil with a mixture of nano material and 23.70% in soil with a mixture of nano material and biopolymer.

The hydration process of lime in the mixture absorbs more water and thus tends to increase towards its optimum moisture content. In addition, nanomaterials have a more specific area and will require more water to hydrate. Unlike the case with the chitosan biopolymer mixture which does not undergo the hydration process thus reducing the optimum moisture content to be smaller. The increase in maximum dry density in mixed soils for standard proctor compaction can be attributed to the presence of small particles of the additives that are able to fill the soil voids in micro to nano sizes.

Other research in line with the improvement of soil mechanical properties was conducted by adding micro-sized mine dust to the engineering behavior of cement-stabilized lateritic soils. Laboratory investigations showed an increase in maximum dry density in most specimens for each optimum moisture content. In addition, significant increases were observed in California Bearing Ratio (CBR) and Unconfined Compression Strength (UCS) values with the addition of micro-sized quarry dust stabilizer (Kufre Etim et al., 2021).

4.2 Effect of Additives on Unconfined Compression Strength

Figure 11 and Figure 12 show the increase in strength of soil mixed with chitosan biopolymer, nanomaterials, or a combination of both. Soil without additives has a UCS of 112.8 kN/m^2.

The increase in UCS value is quite significant. In the soil mixture with 0.1% chitosan biopolymer, the UCS value became 486.3 kN/m^2 and increased 4 times from the initial soil with a percentage increase of 331.31%. In soil mixtures with 2% nano lime and 4% nano silica, the UCS value became 601.1 kN/m^2 and increased up to 6 times that of the initial soil with a percentage increase of 433.07%. When the soil was mixed with a combination of both materials, the UCS value increased greatly to 11 times that of the initial soil at 1264.5 kN/m^2 with a percentage increase of up to 1000%.

Nanomaterials provided a noticeable improvement in the UCS test. The strength of the mix with nanomaterials was higher when compared to the chitosan biopolymer mix alone. This may be due to the higher ability of nanomaterials to flocculate and agglomerate soil particles compared to chitosan biopolymer. In biopolymer mixed soils, the decrease in interparticle adhesion will reduce the soil strength (Yadav & Tiwari, 2019). Chitosan is a biopolymer that can be biodegraded depending on the curing period and biopolymer ratio. The literature explains that chitosan is susceptible to degradation when used in solution form (Makarios-Laham & Lee, 1995).

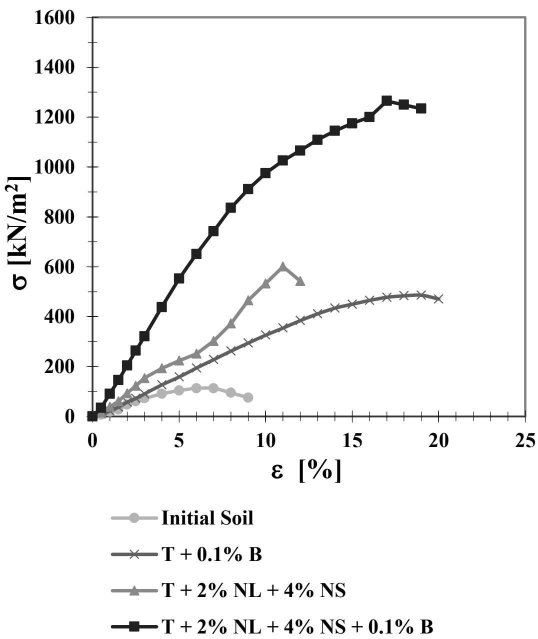

Figure 9 Unconfined compression strength versus axial strain of various specimens

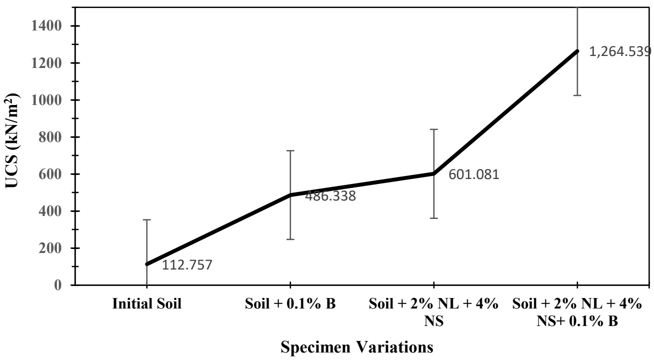

Figure 10 Increase in UCS value of various specimens

The incorporation of waste materials as soil binders has also been carried out previously on loess soils. The added materials of residual calcium carbide and fly ash can increase the compressive strength value (UCS). In addition, the effects of wetting and drying cycles were studied. The findings show a sustainable approach for environmentally friendly soil stabilization and its application in construction (Julphunthong et al., 2024). Improved mechanical properties of the soil were also shown by the soil mixture with PAM. The results proved good performance on shear strength, bearing capacity parameters, and consolidation. The ratio of 0.4% PAM is the minimum ratio to meet the requirements of backfill materials and can be the basic material in improving the bearing capacity of soil for future pavements (Dewi et al., 2023).

One of the researchers explained the potential of polyacrylamide polymer (PAM) additives in reducing cracks during wetting-drying cycles. Experimental results showed the role of PAM with different ratios (0.2%; 0.4%; 0.6%; 0.8%; and 1.0% by weight of soil) in reducing the initial void ratio and increasing the bearing capacity. The reduction of potential cracking is due to the interaction between PAM and soil particles. This was confirmed by the SEM test, which showed pores of soil particles (Amalia et al., 2023).

The shape of the cracks in the UCS test is done by observing Figure 13. The shape of the cracks that occur varies with each specimen. In the soil + 0.1% B specimen the cracks were diagonal in type homogeneous shear and affected almost every layer of compaction. Whereas the soil + 2% NL + 4% NS specimen had thinner cracks lines than the soil with chitosan biopolymer only. The cracking lines are diagonal and vertical at the top to the middle of the layer with a type of combination axial and local shear. The soil + 2% NL + 4% NS + 0.1% B specimen had thinner cracks lines too, but the cracking line is vertical only at the top of layer with a type of axial splitting. This indicates that the soil with nanomaterials mixed in it has greater stiffness and strength in accepting external stresses.

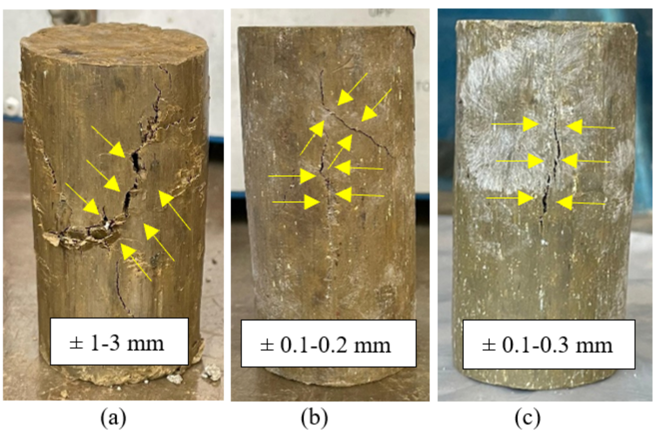

Figure 11 The type of the cracks in the UCS (a) Soil + 0.1% B (b) Soil + 2% NL + 4% NS (c) Soil + 2% NL + 4% NS + 0.1% B

The theoretical distribution of stress in a soil sample is in the direction of the force applied to the soil sample. In reality, the stress direction is not in the same direction as the force applied to the soil sample due to the influence of the pressing plate on the UCS machine that crushes the soil sample or the unevenness on the surface of the soil sample. This results in various forms of cracks in the soil sample. The type of cracks in a soil sample depends on the level of durability and quality of the surfaces that are in direct contact with the surface during loading.

4.3 Environmental Impact

Additives that are mixed into the soil need to be confirmed for their impact on the environment before promoting the material as a suitable soil stabilizer. Soil stabilization using chemicals such as lime can emit large amounts of CO_2 emissions during production and pollute the soil due to unwanted chemical reactions with the soil (Chang & Cho, 2012). J. Rosales conducted a study on soil stabilization using nanomaterials. Results showed that the use of nanomaterials can reduce the thickness of the pavement layer by 30 cm, thereby reducing the use of lime and mechanical means in the preparation of road sections. Stabilization of subgrade soils with lime, generally a lime content of between 3 to 8 percent by weight of dry soil is used.

In this study, the use of a ratio of 2% nano lime and 4% nano silica has reached its optimum ratio in terms of reducing the level of soil expansion and reducing the use of lime. With life cycle assessment, the use of nanomaterials can reduce environmental impact (Rosales et al., 2020). The use of chitosan as a fertilizer has the advantage of preserving soil mycorrhizae and showing no pollution of the soil (Sharif et al., 2018). Chitosan composites also have non-toxic properties as they can flocculate suspended impurities and remove metal ions in water treatment applications (Kangama et al., 2018). These factors indicate that soil stabilization based on nanomaterials and chitosan biopolymers has a fairly positive impact on the environment in its application.

Reducing the ratio of lime to soil stabilization on a project scale can reduce CO_2 emissions during production. This will have a good impact on the environment, especially the level of air pollution. Then the addition of environmentally friendly additives in the form of chitosan biopolymers, in addition to improving soil mechanical properties, the use of these additives can reduce marine biota waste, especially invertebrates. So that it can have an impact on the environment, especially marine and coastal areas. Based on (Leknoi et al., 2022) research, there are 11 factors that influence the success of community engagement towards low carbon cities. One of these factors is the level of concern about climate change. Therefore, as engineers we must start and develop an environmentally friendly and sustainable soil improvement system.

5. CONCLUSIONS

In this study, the effect of adding chitosan biopolymer, nano lime, and nano silica on the mechanical properties of soft clay soil was investigated. From the results and discussion chapter, the following conclusions were obtained.

1. The maximum dry density tends to increase in each mixed soil specimen. An increase in optimum moisture content occurs in soils that have nanomaterials in them due to the hydration process. The increase in maximum dry density indicates that the additive can fill the voids/pores in the soil.
2. Soils with a mixture of nanomaterials and chitosan biopolymer which is 2% NL + 4% NS + 0.1% B showed advantages in soil improvement in terms of mechanical properties. Especially the ability of nanomaterials to flocculate and agglomerate soil particles. The UCS value of the mixed soil increased significantly even with an increase of up to 11 times that of the initial soil. So that the soil with this ratio will be more resistant to interference or external stress.
3. Soil stabilization using nanomaterials and chitosan biopolymers has a good impact on the environment. This can be achieved by

reducing the ratio of the use of lime materials after nanomanufacturing and the use of other additives that come from living things by utilizing natural waste such as shrimp shells. Where the properties of biopolymers such as biodegradable and non-toxic.

Due to the limitations in this research, the researcher provides several recommendations for further research. In strengthening the results of the analysis of soft clay stabilization on its mechanical properties, microstructural testing and analysis can be carried out. Tests can be Scanning Electron Morphology (SEM), Energy-Dispersive X-ray (EDX), Fourier Transformation Infrared (FTIR), and X-Ray Diffraction. In addition, this research can be tested as a subgrade improvement for road pavement with certain modelling and scaling to represent the situation in the field. The trials are expected to make the materials added to this research an alternative in the improvement of soft subgrade soils to enhance the performance of pavement structures.

6. ACKNOWLEDGMENTS

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