3D Modelling and Laboratory Study on Soil Stabilization with Pedel Soil and Silica Fume for Sustainable Infrastructure

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Abstract

The improvement of road infrastructure quality can be achieved through the stabilization of soils with low bearing capacity. Stabilization is carried out by mixing soft soil with additive materials to enhance its load-bearing capacity. This study aims to improve the soil bearing capacity based on the parameters of unconfined compressive strength and shear strength, followed by 3D modeling to support sustainable infrastructure development. The results show that the unconfined compressive strength (qu) increased by 368% with the addition of 9% pedel soil and 7,5% silica fume compared to the original soil. For the same mixture variation, cohesion increased by 191,4% and the internal friction angle increased by 51% compared to the original soil. The 3D modeling results indicated a decrease in deformation from 0,071 meters in the original soil to 0,063 meters with the addition of 9% pedel soil and 7,5% silica fume. Soil stabilization can reduce stress concentration, achieve a more balanced load distribution, and potentially minimize excessive deformation in supporting soil structures.

Keywords: Soil Stabilization, Compressive Strength, Shear Strength , Pedel Soil, Silica Fume, 3D Modelling.

1. INTRODUCTION

Infrastructure quality is a determining factor in the development of a region [1]. One of the major challenges in achieving high-quality infrastructure is the presence of poor soil conditions, which are characterized by low stability, low bearing capacity, and high settlement [2,3]. Low soil bearing capacity may cause structural deformation, potentially resulting in construction failure [4,5]. In addition, soft subgrade conditions contribute to the accelerated deterioration of road pavements [6,7]. To address these issues, appropriate measures, such as soil improvement techniques, are necessary.

Soil stabilization techniques are applied to enhance soil properties and reinforce soil structure by blending soft soil with specific additives [8–11]. Recently, the adoption of environmentally friendly stabilization materials has become an increasingly preferred approach. In this study, a natural material obtained from pedel soil mines commonly used only as fill. Despite its abundance in Java, particularly in Central and East Java, pedel soil has not been fully exploited. This material has a chalk-like texture and a yellowish-white appearance, similar to that of limestone. In addition to pedel soil, the soil stabilization material used is also silica fume, when added to soil, silica fume serves as a chemical additive that enhances the engineering properties of soft soils due to its high silica content [12]. Its pozzolanic characteristics trigger a pozzolanic reaction, which strengthens the bonding between soil particles, thereby improving the overall soil strength [13–15].

This study examines the stabilization of soft soil using pedel soil and silica fume through laboratory testing followed by 3D modelling analysis to simulate the stress and strain occurring in the soil with the aim of supporting sustainable infrastructure development. there has been no research on the use of pedel soil as a stabilization material, so this research is novel. The results of this study are expected to be applied to soft soil problems in Indonesia, especially on Java, by optimizing the use of pedel soil and silica fume as stabilization materials.

2. MATERIALS AND METHOD

2.1. Materials

2.1.1. Original Soil

This study used original soil taken from Cepu District, Blora, Central Java. Based on the 2019 edition of the Atlas of Soft Soil distribution in Indonesia, the soil type in the study area is classified as soft clay [16]. The soil utilized in the experimental are shown in Figure 1.

Figure 1. Original Soil

2.1.2. Pedel Soil

The stabilizing material, pedel soil, was obtained from Bojonegoro Regency, East Java. This soil possesses a texture and appearance comparable to limestone, with its composition predominantly consisting of calcium oxide (CaO) compounds [17–19]. Calcium oxide reacts with the silica and alumina present in the soil, facilitating the binding of soil particles and consequently enhancing soil strength [20]. The appearance of pedel soil can be seen in the following Figure 2.

Figure 2. Pedel Soil

2.1.3. Silica Fume

Silica fume is widely recognized as an effective stabilizing material for soft soils. It is generated as a secondary product during the manufacturing of silicon and ferrosilicon [21]. Since it is a byproduct, its production does not directly contribute to carbon dioxide (CO_2) emissions into the atmosphere [22]. With an annual global output approaching 100,000 tons [23], proper utilization of silica fume is crucial to prevent it from becoming waste. Silica fume is incorporated due to its pozzolanic properties, which enhance the bonding between soil particles. Commonly referred to as microsilica, silica fume is a non-crystalline, amorphous polymorph of silicon dioxide (SiO_2) with a SiO_2 content ranging from approximately 90% to 96% [13,24–26]. Its high silica content promotes a pozzolanic reaction, thereby strengthening interparticle bonds within the soil [13,15]. In this study, silica fume was sourced from PT. Akbar Budi Sakti, a manufacturer that produces the material through high-temperature industrial processing [27]. Silica fume is shown in Figure 3.

Figure 3. Silica Fume

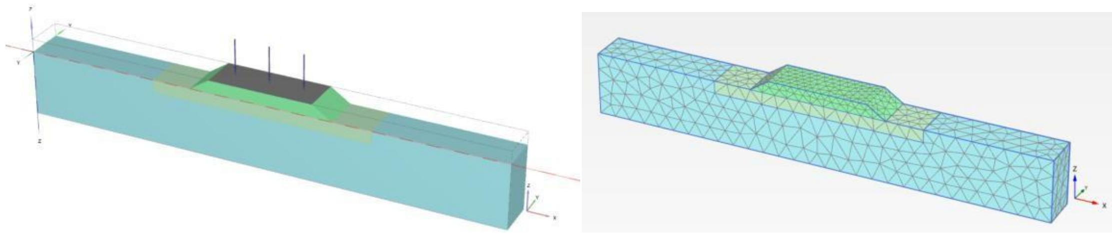
3.1. Method

Soil samples obtained from Cepu District were first dried, either in an oven or under sunlight, then pounded and sieved using a 4.75 mm sieve until all soil passed through. The dried soil was then mixed with water at its optimum moisture content and combined with pedel soil in varying proportions of 9% pedel soil and combining between 9% pedel soil and 7,5% silica fume of the soil's wet weight. The prepared samples were molded in cylindrical tubes measuring 7.6 cm in height and 3.8 cm in diameter, then tested and weighed to obtain the unit weight.

Laboratory testing included UCS (Unconfined Compressive Strength) to determine the compressive strength (qu) and modulus of elasticity, as well as Unconsolidated Undrained (U-U) triaxial tests to obtain cohesion (c) and friction angle (ø). These parameters were then used to evaluate the soil's bearing capacity. The specimen preparation and laboratory test flow is shown in Figure 4.

Figure 4. Specimen preparation and laboratory testing

The outputs from the UCS and triaxial tests were then used as input parameters for the Plaxis 3D modeling, which employed the Mohr–Coulomb model and was analyzed using the finite element method. The finite element method is a numerical analysis technique that simplifies a continuous structure with infinite degrees of freedom into smaller elements with simpler geometries and a finite number of degrees of freedom, allowing for easier analysis [28]. The model was designed to simulate field conditions, where the natural soil at point 0,0 was replaced with stabilized soil to a depth of 1 meter and overlaid with an embankment for road pavement. The loading was modeled by applying an area load of 12 kN/m² on top of the embankment. The 3D modeling can be seen in the following Figure 5.



(a) (b)

Figure 5. 3D Modelling Using Plaxis (a) Input Geometry (b) Finite Element Model

3. RESULTS AND DISCUSSION

3.1. *Unconfined Compressive Strength (UCS) Test*

This test produced unconfined compressive strength (qu) values and modulus of elasticity, which were then used in three-dimensional numerical analysis using Plaxis. Refering to ASTM 2216-13, the principle of this test is to apply a vertical load to specimens until its maximum stress and strain are obtained. The values obtained from the UCS test are presented in Table 1.

Table 1 : UCS test results on soil mix variation

Sample ID	Weight of Content (gr/cm^3)	Saturated Weight (gr/cm^3)	qu (kg/cm^2)	Modulus E (kg/cm^2)
Original Soil	1,586	1,780	0,422	6,051
Soil + Pedel Soil 9%	1,987	2,047	1,620	22,541
Soil + Pedel Soil 9%+ Silica Fume 7,5%	1,892	2,010	1,975	22,820

The optimum compressive strength of soil mixed with pedel soil was achieved at 9%, yielding 1.620 kg/cm² with a corresponding modulus of elasticity of 22.541 kg/cm². This compressive strength represents a 283.8% increase compared to the original soil. Incorporating silica fume further enhanced the mixture's performance with combining the original soil, 9% pedel soil and 7.5% silica fume produced the highest compressive strength of 19,75 kg/cm². This improvement was accompanied by an increase in the modulus of elasticity, reaching 22.82 kg/cm². These findings are consistent with previous studies indicating that the addition of silica fume and limestone enhances soil compressive strength [20,29].

3.2. Triaxial Test

This test refers to ASTM D 2850–87, with the principle of applying a load to a specimen confined by a rubber membrane and subjected to cell pressure in all directions. The results of this test are the soil cohesion and internal friction angle, which are used as input parameters in the stress and strain analysis in Plaxis 3D. The triaxial test results are presented in the following table.

Table 2 : Shear strength test results on soil mix variation

Sample ID	**c (kg/cm^2)**	**Ø (^{0})**
Original Soil	0,291	8,890
Soil + Pedel Soil 9%	0,775	13,022
Soil + Pedel Soil 9%+ Silica Fume 7,5%	0,848	13,422

Table 2 shows that the highest cohesion value, 0.775 kg/cm², was obtained at a 9% pedel soil content, marking a 158% improvement over the original soil. The friction angle followed the same pattern, reaching an optimum of 13.022°, which is 46.3% higher than that of the untreated soil. Incorporating 7,5% silica fume into the 9% pedel soil mixture further enhanced shear strength, increasing cohesion by 9.4%. These results align with earlier studies reporting that silica fume contributes to improvements in both friction angle and cohesion [15].

Based on the laboratory test results, the addition of pedel soil significantly increased soil strength, as pedel soil particles formed a more compact microstructure, thereby enhancing inter-particle interaction and positively affecting soil strength. The addition of silica fume resulted in a comparatively smaller increase, as silica fume requires a longer curing period to strengthen the bonds between soil particles.

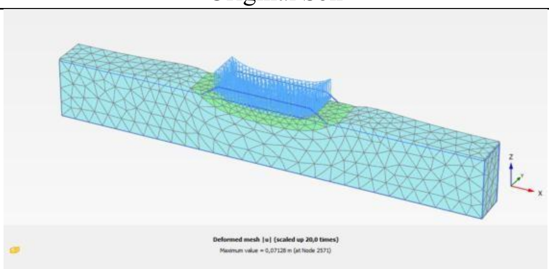
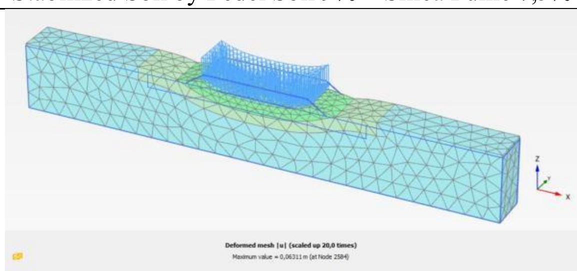
3.3. 3D Modelling

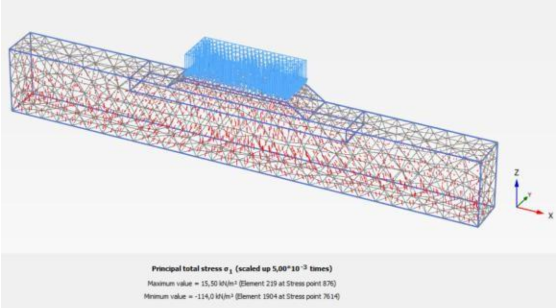
Soil modeling using Plaxis 3D showed that stabilized soil experienced smaller deformation compared to soil without stabilization. The results obtained from the Plaxis 3D modeling are presented in Table 3 below.

Table 3 : 3D Modelling Results

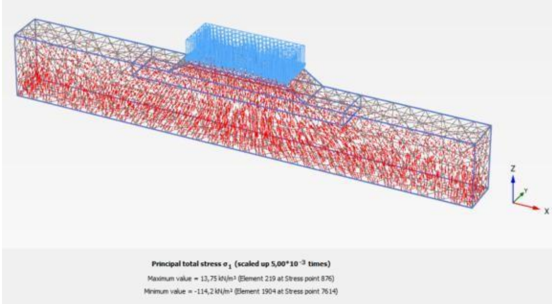
Results/ Type of Soil	**Deformation (m)**	**Maximum Stress (kN/m^2)**	**Maximum Strain**
Original Soil	0,07128	15,50	0,1085 x 10^{-3}
Soil + Pedel Soil 9%	0,06505	13,75	0,1170 x 10^{-3}
Soil + Pedel 9% + Silica Fume 7,5%	0,06311	13,75	0,1170 x 10^{-3}

In Table 3, a significant reduction in deformation of 8.7% is observed when comparing soil without additives to soil mixed with 9% pedel soil. A decrease in stress is also noted in the stabilized soil, with the maximum stress value reduced by 11.3% compared to soil without additives.

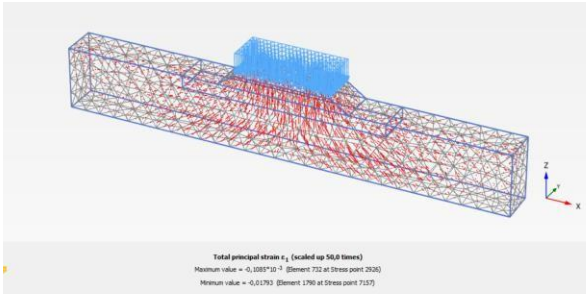
Original Soil	Stabilized Soil by Pedel Soil 9% + Silica Fume 7,5%
	
(1a) Deformation on original soil	(2a) Deformation on stabilized soil



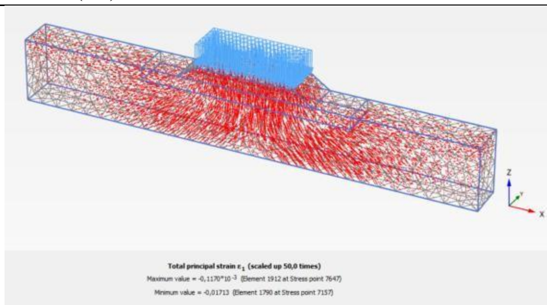
(1b) Maximum stress of original soil



(2b) Maximum stress of stabilized soil



(1c) Maximum strain of original soil



(2c) Maximum strain of stabilized soil

From the comparison of the two Plaxis 3D analysis results between original soil and stabilized soil by pedel soil 9% and Silica fume 7,5%, it was found that the maximum principal stress (σ_1) in the first condition reached 15.50 kN/m², whereas in the second condition it decreased to 13.75 kN/m². This drop of 1.75 kN/m² reflects a reduction in peak stress, indicating a more even load distribution. The minimum stress values in both conditions are nearly identical, around −114 kN/m², suggesting that the area and intensity of the largest compression zone remain essentially the same. Regarding the stress vector distribution, maximum stress of original soil (1b) condition shows vectors predominantly directed vertically downward beneath the applied load, resulting in a concentration of stresses in specific areas. Meanwhile, in the maximum stress of stabilized soil (2b), the vectors are more laterally oriented, demonstrating improved load dispersion into the surrounding soil mass. the results highlight that soil stabilization can lower stress concentration, achieve a more uniform load distribution, and potentially reduce excessive deformation in supporting soil structures.

4. CONCLUSIONS

The addition of pedel soil has been shown to improve soil properties, particularly its strength and bearing capacity. Moreover, the use of silica fume also contributes to enhancing soil strength, especially when the mixed soil is cured for a longer period. Based on the unconfined compressive strength test, adding 9% pedel soil increased the original soil's compressive strength by up to 283.8%, and this improvement to 368% with the inclusion of silica fume compared to the untreated soil. A similar trend was observed in the triaxial test, where soil cohesion increased by 158% and the internal friction angle rose by 46.3% compared to the original soil's cohesion and internal friction angle. Pedel soil and silica fume particles formed a more compact microstructure, thereby enhancing inter-particle interaction and positively affecting soil strength.

The modeling results indicate that mixing soil with 9% pedel soil leads to a significant 8.7% reduction in deformation compared to soil without additives. Furthermore, the stabilized soil also experiences a decrease in stress, with the maximum stress value reduced by 11.3% relative to soil without additives. Soil stabilization can lower stress concentration, achieve a more uniform load distribution, and potentially reduce excessive deformation in supporting soil structures.

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