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IMPROVEMENT OF MECHANICAL PROPERTIES OF CLAY WITH CALCITE AND SILICA FUME: UNCONFINED COMPRESSIVE STRENGTH

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Abstract

This study investigates the enhancement of clay soil properties by adding calcite and silica fume to address challenges such as low bearing capacity and high compressibility. A total of 51 soil samples were prepared, with 3 samples for each variant, treated with 5% calcite and varying silica fume concentrations (6%, 8%, 10%, 12%). The samples were cured for 0, 3, 7, and 14 days. Unconfined compressive strength (UCS) tests were conducted to evaluate the mechanical properties. Results revealed significant improvements, with UCS increasing from 0.412 kg/cm² in untreated soil to 1.724 kg/cm² in samples treated with 5% calcite and 12% silica fume after 14 days of curing. These values meet or exceed typical strength requirements for construction purposes, reinforcing the effectiveness of calcite and silica fume as stabilizing agents. The enhancement is attributed to the pozzolanic reaction between the additives and the soil, forming calcium silicate hydrate (CSH) and strengthening the soil's microstructure. The findings indicate that calcite and silica fume effectively improve soil stability, offering a promising solution for geotechnical applications. Future research should focus on evaluating the long-term stability of treated soils under various environmental conditions and exploring additional curing methods to optimize the chemical reactions further.

Keywords: Soil Stabilization, Clay Soil, Calcite, Silica Fume, Unconfined Compressive Strength

Introduction

Clay soils are often challenging in geotechnical engineering due to their low shear strength and susceptibility to settlement (Abdila et al., 2022; Nor et al., 2022; Shah et al., 2023). This problem often leads to instability in construction projects (Morissa & Syahril, 2021; Munirwan et al., 2022; Sakr et al., 2021), especially in road and foundation construction (Nugroho et al., 2021; Öztürk & Türköz, 2022). Geotechnical engineers have developed various techniques to overcome the challenges associated with clay soils (Karumanchi et al., 2020; Nor et al., 2022). One approach that is often used is soil stabilization (Hastuty, Roesyanto, Anas, et al., 2020; Nugroho et al., 2021), which is a technique to improve the mechanical properties of soil by adding certain materials that can strengthen the soil structure (Han et al., 2021; Sánchez-Garrido et al., 2022; Syahril et al., 2025). Among the various stabilization methods available (Abd-Allah et al., 2021), the use of additives such as calcite and silica fume has attracted attention as a potential solution in improving the engineering properties of clay soils.

Calcite, which is a form of calcium carbonate, is known to have the ability to react with minerals contained in clay soils. This reaction produces a more stable compound, which can increase the strength of the soil and reduce its plasticity (Pastor et al., 2019). This process is often called a pozzolanic reaction, where calcium ions from calcite interact with silica and alumina present in the clay (Hasan et al., 2019). This reaction produces compounds such as calcium silicate hydrate (CSH) (Phanikumar & Raju, 2020), which significantly increases the strength and structural stability of the soil. CSH is a strong and durable compound, which also helps reduce soil volume changes due to the influence of water, thus making the soil more stable for geotechnical applications.

Besides calcite, silica fume is also an additive that has been widely researched in the field of soil stabilization. Silica fume, which is a by-product of silicon and ferrosilicon metal production (Goodarzi et al., 2016; S et al., 2020), has a very large surface area and high chemical reactivity (Al-Soudany, 2018). Due to these properties, silica fume can play an active role in pozzolanic reactions, similar to calcite. The fine particles of silica fume accelerate the chemical reaction between additives and soil minerals (Yang et al., 2020), which in turn increases the strength and durability of the stabilized clay (Alrubaye et al., 2017; Mishra et al., 2022). The use of silica fume is also known to reduce soil porosity (Bharadwaj & Trivedi, 2016), so that the soil becomes denser and has a higher bearing capacity (Phanikumar et al., 2020).

This research investigates to explores the effectiveness of calcite and silica fume in improving the mechanical properties of clay soils, with a particular focus on improving unconfined compressive strength (UCS). This research will analyze the mechanical and microstructural changes that occur due to the addition of these additives (Ahmed et al., 2024; Hastuty, Roesyanto, & Stephanes, 2020). By studying the mechanisms underlying these improvements in soil properties, it is hoped that this research will provide greater insight into the potential applications of calcite and silica fume in various geotechnical engineering projects (Zhang et al., 2024).

In addition, this research is expected to make an important contribution to the development of more effective and sustainable soil stabilization methods (Andriani et al., 2023). The use of materials such as calcite and silica fume, which are relatively cheap and readily available, offers an economical and environmentally friendly solution to problems associated with clay soil stability (Barman & Dash, 2022). The results of this research can be widely applied to improve the stability and durability of various engineering structures, including transportation, infrastructure, and commercial building projects (Bramhankar et al., 2023; Farichah et al., 2023; Yeganeh & Teymür, 2024).

The selection of clay soils from the West Bandung region in this study was based on the frequent use of clay soils in local construction projects and their unique geotechnical challenges such as low shear strength and high compressibility. These soils are commonly found in infrastructure construction, such as roads, foundations, and slope stabilization projects, making them a representative research object for soil stabilization studies (Arifin & Rahmah, 2022).

The results of this study can be applied to various geotechnical applications. The increase in unconfined compressive strength (UCS) achieved through stabilization with calcite and silica fume can improve the safety and durability of infrastructure in areas with similar soil properties. This improvement not only enhances the load-bearing capacity but also contributes to the long-term stability of the soil, which is essential for construction projects that rely on stable foundations, such as roads, bridges, and buildings (Al-mousawi & Fadhil, 2024; Harish et al., 2023; Zemouli et al., 2024). The results of this study are also expected to inform future soil stabilization practices, particularly in regions with soft or expansive clays that are prone to settlement and deformation under load.

Most of the previous studies only focused on macroscopic changes without delving deeper into the microstructural mechanisms that occur due to the interaction between additives and clay minerals (Oloruntola et al., 2018). In addition, research has rarely explored variations in the proportion of additives to find the optimal combination that gives the best results. In addition, the effect of using calcite and silica fume on the long-term stability of soil under various environmental conditions has not been thoroughly evaluated. Therefore, this study investigates this gap by evaluating the effect of the combination of calcite and silica fume in improving the UCS of clay soils, and understanding the mechanism of changes that occur, both at the mechanical and microstructural levels.

The novelty of this research lies in its comprehensive exploration of both the mechanical improvements and microstructural mechanisms associated with soil stabilization using calcite and silica fume. This study extends previous work by providing insights into the optimal additive combinations and evaluating their long-term effectiveness. Specifically, it aims to achieve a target UCS that meets or exceeds the standard strength requirements for construction applications, which will significantly enhance the engineering properties of clay soils in a cost-effective and environmentally friendly manner.

By providing a deeper understanding of the interaction between clay soils and stabilizing additives, this study contributes to the development of more efficient and sustainable soil stabilization methods. In the future, the findings could be applied to improve the quality and durability of infrastructure projects in regions with similar soil conditions, leading to safer and more reliable construction practices.

Research Methods

This study aims to enhance the mechanical properties of clay soil by using calcite and silica fume as stabilizing agents. The research process involves collecting clay soil samples and the stabilizing materials, followed by testing the soil's physical properties, including moisture content, specific gravity, and Atterberg limits. Additionally, mechanical tests such as compaction and unconfined compressive strength (UCS) are conducted to evaluate the effect of the stabilizers on the soil's strength. The collected data will be analyzed to determine whether the addition of calcite and silica fume improves the UCS of the clay soil. The UCS results are used to determine whether the strength of the treated soil has increased. If the UCS values show improvement, the process proceeds to data analysis and formulation of conclusions. If not, the process loops back to modify the mix design and sample preparation. This iterative process ensures that optimal additive combinations are identified to effectively enhance soil strength. The flowchart provides a clear, structured methodology, emphasizing repeatability and scientific rigor in testing soil stabilization techniques. The research flowchart is provided in Figure 1.

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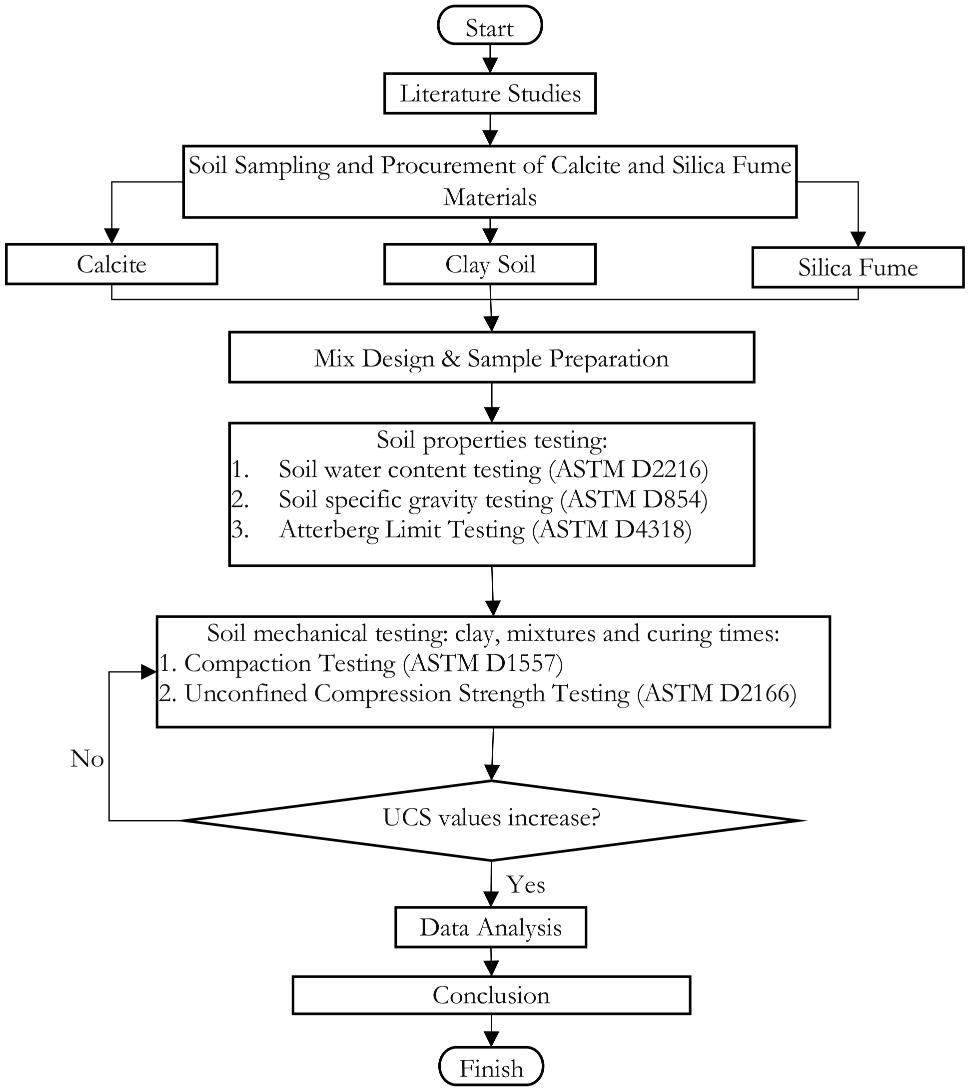

Figure 1. The Research of Flowchart

Materials

In this study, calcite and silica fume were utilized as stabilizing agents to enhance the properties of the soil. The clay soil used in this experiment was collected from the Cihampelas area in West Bandung Regency, known for its geotechnical challenges, including low shear strength and high compressibility. This makes it a suitable candidate for studying the effects of soil stabilization techniques.

Calcite, a form of calcium carbonate ($CaCO_3$), was sourced from BP Chemical Paint & Farm, a local supplier of high-purity calcite for industrial applications. Calcite plays a significant role in soil stabilization by undergoing a pozzolanic reaction with silica and alumina present in the clay. This reaction forms calcium silicate hydrate (CSH), which strengthens the soil structure and reduces its plasticity, improving its overall stability and mechanical properties.

Silica fume, produced by PT Akbar Budi Sakti, is a by-product of silicon and ferrosilicon metal production. Silica fume is composed of over 90% amorphous silica (SiO_2) and has an extremely fine particle size, which makes it highly reactive. Due to its high surface area, silica fume accelerates the pozzolanic reactions between calcite and the clay minerals, enhancing the soil's strength and durability. In addition, silica fume reduces soil porosity, thereby increasing the soil's density and improving its load-bearing capacity.

Both calcite and silica fume play a vital role in enhancing the quality of construction materials, improving their strength, corrosion resistance, and long-term stability. The combination of these two additives significantly improves the mechanical properties of clay soils, making them more suitable for use in various geotechnical applications, such as road and foundation construction.

Methods

Soil samples were collected from the Cihampelas area in West Bandung Regency, which is known for its soft and compressible clay soils. A total of 51 soil samples were prepared for this study. These samples were divided into five groups: one control group (untreated soil) and four experimental groups, each with varying proportions of silica fume (6%, 8%, 10%, and 12%) added to 5% calcite. The proportions of silica fume were based on the dry weight of the soil, and each group included 3 replicate samples to ensure consistency and reliability of the results.

For sample preparation, the molding dimensions were standardized at 37 mm in diameter and 76 mm in height, which is in accordance with the standard dimensions recommended for Unconfined Compressive Strength (UCS) testing. These dimensions allowed for uniform sample sizes across all groups and ensured that the testing could be accurately replicated. The samples were compacted into cylindrical molds using a standard compaction method to achieve the required density, following best practices in geotechnical testing.

In terms of curing conditions, the samples were kept under controlled room temperature throughout the testing period. To evaluate the effect of curing time, the samples were cured for different durations: 0, 3, 7, and 14 days. During this period, the samples were maintained in a moist environment to prevent premature drying, which could interfere with the chemical reactions between the soil and the additives. This controlled curing process was essential to allow sufficient hydration of the additives, particularly for the pozzolanic reactions to occur.

The moisture content for each sample was determined using standard gravimetric methods. The soil samples were oven-dried at 105°C until a constant weight was achieved. Based on this, water was added to the soil mixture to achieve the optimum moisture content (OMC), which is necessary for proper compaction and activation of the chemical reactions between the soil, calcite, and silica fume. The amount of water added was adjusted to reach the OMC that facilitated optimal compaction and the best possible interaction between the soil particles and the additives.

To evaluate the mechanical properties of the treated soils, Unconfined Compressive Strength (UCS) tests were performed on the samples following ASTM D2166 standards. This standard outlines the procedure for conducting UCS tests on soil samples under unconfined conditions, specifying the dimensions of the sample, the loading rate, and the equipment used. UCS tests were conducted to determine how the strength of the soil changed with the addition of calcite and silica fume, as well as with varying curing times.

Following the UCS tests, the changes in soil strength were analyzed using descriptive statistics, including the mean and standard deviation, to summarize the results. Additionally, ANOVA (Analysis of Variance) was applied to determine whether the differences in strength between the various groups were statistically significant. This analysis helped to identify the optimal combination of calcite and silica fume that produced the highest unconfined compressive strength and provided insight into the relationship between curing time, additive proportions, and the mechanical properties of the treated soil.

Sample Preparation

The first step in preparing the soil samples involved screening the clay soil to remove rocks, large particles, and other undesirable materials. The screening was done using a No. 4 sieve (4.75 mm) to ensure only fine soil particles were used in the mixture, as larger particles could affect the consistency of the results. After screening, the soil was divided into fractions to ensure uniformity before mixing with the stabilizing agents.

Next, various proportions of calcite and silica fume were added to the soil to create different mixtures. A fixed 5% calcite was used, and the silica fume content varied between 6%, 8%, 10%, and 12%, based on the dry weight of the soil. Silica fume, composed almost entirely of amorphous silica (SiO_2), was added to improve the soil's density and strength, while calcite ($CaCO_3$) acted as a binder, enhancing the soil structure and improving its stability by promoting chemical reactions with the soil.

The soil, calcite, and silica fume were thoroughly mixed until the mixture was uniform. The goal was to ensure that the additives were evenly distributed throughout the soil to allow for the best possible chemical reactions during curing.

After mixing, water was added to the mixture to achieve the optimum moisture content (OMC) required for testing. The OMC was determined using compaction based on the ASTM D1557 standard, which involves performing a Proctor test to find the moisture content at which the soil achieves its maximum dry density. This ensured that the soil mixture was in the ideal condition for compaction and testing.

The mixture was then placed into cylindrical molds with a 37 mm diameter and 76 mm height. The soil was compacted into the molds to the required density, following the compaction procedure in ASTM D1557, to simulate field conditions for the unconfined compressive strength (UCS) testing.

After achieving the desired moisture content and compaction, the soil samples were cured at room temperature for 0, 3, 7, and 14 days. The curing process was conducted under controlled conditions, ensuring the samples were kept moist to prevent drying out. This moisture was critical for the chemical reactions between the soil and additives to be fully activated, improving the soil's strength and stability.

After the designated curing periods, the samples were tested for UCS to measure the improvements in the soil's bearing capacity. The UCS tests were conducted following the ASTM D2166 standard, which outlines the procedures for determining the unconfined compressive strength of soil. The mixture proportions of soil, calcite, and silica fume used in this study are detailed in Table 1.

Table 1. The Proportion of The Weight of the Sample Soil

Weight of Soil (gram)	**Weight of Calcite (gram)**	**Weight of Silica Fume (gram)**	**Weight of Soil Sample (gram) (1-2-3)**
(1)	(2)	(3)	(4)
4000	0	0	4000
4000	200	240	3560
4000	200	320	3480
4000	200	400	3400
4000	200	480	3320

In this study, a total of 51 samples were prepared for testing. The samples were prepared using a mixture of 5% calcite and different proportions of silica fume (6%, 8%, 10%, and 12%). The number of samples used for each mixture variation was tested across four different curing times (0, 3, 7, and 14 days), as outlined in Table 2.

Table 2. Number of UCS Samples

No.	Soil & Mixtures	UCS Test	Quantity of Sample
1	Soft clay	3	3
2	Soil + Calcite 5% + SF 6%	12	12
3	Soil + Calcite 5% + SF 8%	12	12
4	Soil + Calcite 5% + SF 10%	12	12
5	Soil + Calcite 5% + SF 12%	12	12
	Total		**51**

UCS Test

UCS (Unconfined Compressive Strength) testing is designed to assess the compressive strength of soil without lateral restraint, which is commonly used to evaluate the initial stability of the material. The process begins by preparing soil samples that have been mixed with varying proportions of calcite and silica fume. In this study, calcite was used at a 5% concentration, and silica fume was added at 6%, 8%, 10%, and 12%, based on the dry weight of the soil. These soil samples were then compacted into cylindrical molds following standard testing protocols and subjected to curing for periods of 0, 3, 7, and 14 days.

During the curing phase, it is essential to maintain the samples in a moist environment to facilitate the chemical reactions between the silica fume, calcite, and the soil, thereby optimizing the stabilization process. Once the curing period was completed, the samples underwent UCS testing, as specified in ASTM D2166. This standard outlines the procedure for measuring the unconfined compressive strength of soil. In this test, a uniaxial compressive testing machine is used to apply a vertical load incrementally to the soil sample until failure occurs. The UCS results provide a clear indication of how much the compressive strength of the soil has improved as a result of stabilization with calcite and silica fume.

Research Results and Discussion

Testing of the Soft Clay

The soil property index test was performed to classify the type of soil used in this study. The physical properties tests included specific gravity, Atterberg limits, sieve analysis, and mechanical properties tests, such as compaction, and unconfined compressive strength of the clay soil. These tests were conducted on the soft clay soil, and the results are presented in Table 3.

Table 3. Index Properties of Soft Clay Soil

No	Index Properties	Symbol	Unit	Value
1	Water Content	ω	%	41.48
2	Specific Gravity	Gs	gr/cm^3	2.591
3	Weight of Content	γ	gr/cm^3	1.895
4	Dry Weight	γd	gr/cm^3	1.339
5	Pore Value	e	-	0.9344
6	Porocity	n	-	0.4831
7	Atterberg Limit	%		
	- Plastic Limit	PL	%	29.93
	- Liquid Limit	LL	%	59
	- Plasticity Index	PI	%	29.45

The Table 3 presents the index properties of the soft clay soil before stabilization. The water content was found to be 41.48%, indicating the proportion of water present in the soil relative to its dry weight. This high water content is typical for soft clay soils and plays a critical role in the soil's behavior, influencing its workability, compaction, and strength. The specific gravity of the soil particles was measured at 2.591 gr/cm^3, which is within the common range for clayey soils. This value represents the ratio of the density of the soil particles to the density of water and is used to classify the soil. A specific gravity around 2.591 gr/cm^3 suggests the soil consists primarily of silicate minerals, typical for clay. The weight of content, or bulk density, was measured at 1.895 gr/cm^3, which includes both the soil particles and water. This value helps in understanding the compactness of the soil and its suitability for various engineering applications. The dry weight of the soil was 1.339 gr/cm^3, indicating how compact the soil is without the water content. Additionally, the pore value of 0.9344 and porosity of 0.4831 reveal the amount of void space within the soil, affecting its permeability and behavior under load. Lastly, the Atterberg limits show that the soil has a plastic limit of 29.93% and a liquid limit of 59%, resulting in a plasticity index of 29.45%. These values are crucial for classifying the soil's consistency and behavior when wet, with a high plasticity index indicating that the soil is highly cohesive and can retain moisture, making it susceptible to swelling or shrinkage under changing moisture conditions. These properties are essential for understanding the soil's stability and its response to the stabilization process.

The mechanical properties of the soft clay, as determined from the test results, are provided in Table 4. These results include key parameters such as compaction characteristics, and unconfined compressive strength, which are essential for understanding the behavior and stability of the soil under various conditions.

Table 4. Mechanical Properties of the Soft Clay

No	Mechanical Properties	Symbol	Unit	Value
1	Compaction	ω_{opt}	%	20.5
2	Unconfined Compression Strength	q_u	kg/cm^2	0.412
		C_u	kg/cm^2	0.206

Table 4 shows the mechanical properties of soft clay soil before stabilization. The optimum moisture content (OMC) is 20.5%, indicating the ideal moisture level for achieving maximum compaction. The unconfined compressive strength (qu) is 0.412 kg/cm^2, which is low and indicates that the soil has limited strength, making it unsuitable for most construction applications without improvement. The consolidated unconfined compression strength (cu) is 0.206 kg/cm^2, further confirming the soil's weak shear resistance. These values highlight that the untreated soft clay is not strong enough for construction and requires stabilization to improve its load-bearing capacity.

Unconfined Compressive Strength Testing (UCS)

The unconfined compressive strength (UCS) test involves applying an axial load to a cylindrical soil sample while ensuring it remains free from any lateral pressure until failure occurs. The UCS is defined as the maximum load that the soil sample can bear before collapsing. After performing the UCS test, the qu (unconfined compressive strength) and cu (consolidated unconfined compressive strength) values of the clay soil mixed with calcite and silica fume were obtained, and the results are shown in Table 5. These values provide insight into the soil's capacity to resist compressive forces, which is crucial for evaluating the effectiveness of the soil stabilization process.

Table 5. Result of Unconfined Compression Strength

No	Soil & Mixtures	Curing (Days)	q_u kg/cm²	C_u kg/cm²
1	Soft Clay	-	0.412	0.206
2	Soil + Calcite 5% + SF 6%	0	0.594	0.297
		3	1.036	0.518
		7	1.146	0.573
		14	1.235	0.618
3	Soil + Calcite 5% + SF 8%	0	0.942	0.471
		3	1.122	0.561
		7	1.222	0.611
		14	1.246	0.623
4	Soil + Calcite 5% + SF 10%	0	1.181	0.590
		3	1.233	0.617
		7	1.259	0.629
		14	1.297	0.648
5	Soil + Calcite 5% + SF 12%	0	1.284	0.642
		3	1.569	0.784
		7	1.661	0.831
		14	1.724	0.862

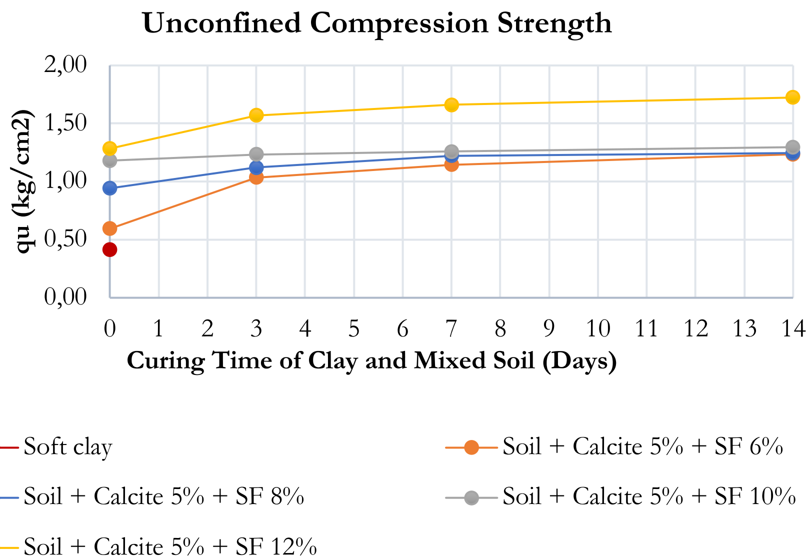

Figure 2. Result of Unconfined Compression Strength Testing

Based on the UCS test results presented in Table 5, it can be observed that the addition of calcite and silica fume, along with the curing period, significantly improves the compressive strength of soft clay. Initially, the unconfined compressive strength (qu) of untreated soft clay was 0.412 kg/cm², and the consolidated unconfined compression strength (cu) was 0.206 kg/cm², indicating low strength and limited suitability for construction.

After adding 5% calcite and varying amounts of silica fume (6%, 8%, 10%, and 12%), the soil's qu value showed a clear upward trend, reflecting the beneficial effects of the stabilizing agents. For example, after 14 days of curing, the qu value reached 1.724 kg/cm² for the mixture with 12% silica fume, and the cu value increased to 0.862 kg/cm². This represents a significant increase from the initial values, indicating that the soil's compressive strength was improved by more than 4 times due to the stabilization process.

The significant increase in qu and cu values suggests that the interaction between the calcite, silica fume, and water created a cementitious reaction, which effectively bonded the soil particles together, improving the soil's strength and cohesion (Bargi et al., 2021). When these additives interact with water and soil, they create an adhesive medium that binds the soil particles together (Jiang et al., 2022). The process of cementation helped to form a stronger and more durable soil mixture, capable of withstanding higher compressive loads (Ali & Karkush, 2021; Hoque et al., 2023). These results are consistent with industry standards for UCS, which typically require a minimum qu value of 1-1.5 kg/cm² for soils to be considered suitable for load-bearing applications. The results show that, after stabilization, the soil meets and exceeds this standard, particularly with the mixture containing 12% silica fume. The improvement in strength over time with the addition of silica fume also highlights the importance of the curing period, as the cementitious process becomes more effective with longer curing times.

In conclusion, the addition of calcite and silica fume, combined with an adequate curing period, greatly enhances the mechanical properties of the soft clay, making it suitable for various geotechnical applications such as foundation construction.

Conclusion

The incorporation of calcite (5%) and silica fume (up to 12%) significantly enhanced the mechanical properties of clay soils, as evidenced by the increase in unconfined compressive strength (UCS) from 0.412 kg/cm² in untreated soil to 1.724 kg/cm² after treatment with these additives and a curing period of 14 days. This improvement demonstrates that the combination of calcite and silica fume is an effective, sustainable method for enhancing the geotechnical properties of clay soils. The novelty of this study lies in its exploration of the combined effects of these two additives, optimizing their proportions for superior stabilization results. While previous studies have examined each additive separately, this research is the first to assess their synergistic effects in clay soil stabilization, offering new insights into their practical application. This approach provides a cost-effective, environmentally friendly solution for improving soil strength, making it suitable for infrastructure applications. The findings have significant implications for infrastructure projects in areas with weak or expansive clay soils, as stabilizing these soils with calcite and silica fume can enhance their stability, reduce the risks of settlement and deformation, and ensure safer, more durable infrastructure. Future research should focus on the long-term stability of treated soils under various environmental conditions, explore alternative curing techniques, and assess the economic feasibility of large-scale implementation to optimize this stabilization method for widespread use in construction projects.

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